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List of contributions

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1 Theory of quantum fluids and solids

Free energy functionals and thermodyanmics for superfluid ^{3}He in aerogel

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We present a free energy functional for superfluid ^{3}He in the presence of homogeneously distributed impurity disorder. The functional, which is stationary with respect to variations of the order parameter, $\Delta(\hat{\mathbf{p}})$, extends the Ginzburg-Landau free energy functional to all temperatures. The functional is obtained by a reduction of the Luttinger-Ward functional to leading order in the expansion parameters of Fermi-liquid theory. We report results for the thermodynamic potential, entropy and heat capacity for dirty B-phase of superfluid ^{3}He for homogeneous disorder. In the unitary scattering limit the B-phase exhibits gapless behavior over the entire phase diagram for high-porosity aerogels with an elastic mean-free path $\ell_{\text{el}} = 1500\,\text{Å}$. For modest pair-breaking, $\alpha = 1/2\pi\tau T_{c0} < 0.1$, corresponding to $\ell_{\text{el}} > 1600\,\text{Å}$ at $p = 33\,\text{bar}$, C_s/T is a non-monotonic function of T, however the limiting low-temperature heat capacity is linear in temperature, $C_s \rightarrow \gamma_{\text{S}} T$, where γ_{S} is the Sommerfeld coefficient for temperatures below the impurity bandwidth, $T \lesssim \gamma_{\text{imp}} \approx \sqrt{\Delta_0/2\tau}$. We also compare the density of states at the Fermi level, $N(0)$, inferred from the Sommerfeld coefficient, $\gamma_{\text{S}} = \frac{2}{3}\pi^2 N(0)$, with the spectrum calculated directly from the retarded Greens function and impurity self-energy, $N(\varepsilon) = -\frac{1}{\pi}\text{Im}\, g^R(\varepsilon)$.

Keywords: Superfluid ^{3}He, Aerogel, Gapless Superfluid, Free Energy, Thermodynamics

Fast moving electrons in liquid ^{4}He

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We present theoretical results, based on fully three-dimensional Density Functional calculations, describing the steady-state motion of electron bubbles in liquid ^{4}He both at zero and negative pressures. As the velocity increases, the moving electron bubble is squeezed along the direction of motion while it expands in the transverse directions. When the electron speed is large enough, as a consequence of this change of shape, a vortical fluid motion is induced around the bubble which eventually results in the formation of a quantized vortex ring as a critical velocity is reached. The nascent ring appears spontaneously, girdling the bubble cavity along the equatorial line perpendicular to the direction of motion and then expands during the minimization. This process occurs at P=0 and at negative pressures down to ~ -1.2 bar. Below this value, the bubble becomes mechanically unstable and explodes as soon as the critical velocity is reached. Our results show that electron bubbles explode in the pressure range where unidentified electron objects have been found to explode in recent cavitation experiments[1].

1. A. Ghosh and H. J. Maris, Phys. Rev. Lett. **95**, 265301 (2005).

Keywords: 4He, electron, vortices

Quantum fluids and solids as seen by path integrals

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This talk is a review of the theory of quantum fluids and solids as derived by the imaginary-time path integral method. The history of this method and its relation to computational approaches is summarized. Then, some recent developments and applications, in particular to supersolids, helium droplets and cold atom systems is given. Finally, the limitations of path integrals for fermion systems is discussed.

Keywords: overpressurized ^{4}He, rotons, dynamic structure factor, analytic continuation

INVITED PAPER

Quantum critical phenomena of ^{4}He in nanoporous media

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In experiments on ^{4}He on nanoporous Gelsil glass with average pore diameter of 2.5 nm a suppression of the λ- transition under pressurization has been observed. The novel feature of this suppression with respect to similar effects in other porous media observed in the past, Vycor glass for example, is that for a pressure of about 3.4 MPa the superfluid transition decreases to zero Kelvin. We argue that this system indeed exhibits quantum critical phenomena. The mapping of the effective model of the system, the 3D quantum rotor model, to a (3+1)D classical XY model yields a phase boundary between the superfluid and the normal fluid regime of the form $p_c(0) - p_c(T) \sim T^2$. This is in remarkable agreement with experiment as are also the expressions we obtain for the superfluid density as a function of pressure in the limit of zero temperature. It is known that disorder and particle-hole symmetry breaking are relevant perturbations and would alter the universality class. However, we show that in the accessible temperature range the perturbations do not yield sizable effects and thus establish the validity of the (3+1)D XY model picture. Furthermore we present an argument that explains why quantum phenomena have not been observed in ^{4}He filled in porous media with pore sizes larger than Gelsil.

T.E., M. Oshikawa, K. Shirahama: arXiv:1004.4004

Keywords: Quantum Phase Transitions, ^{4}He, Disordered Substrates

Theoretical study of quantum gel formation in superfluid ^{4}He

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Diffusion mediated clustering of atoms and molecules in superfluid helium may be significantly affected by the weak long-range interactions at low temperatures. When impurities are solvated in the liquid, the possible attractive van der Waals binding introduces strongly inhomogeneous helium solvent layers to form around them (i.e., the snowball structure). As two impurities approach each other in the liquid, the interaction between the solvent layers surrounding them causes deviation from the regular gas phase pair interaction where the overlap between the solvent layers introduces an energy barrier for impurity–impurity recombination. Previously we have shown that the recombination barrier between two solvated neon atoms is approximately 3 K in superfluid ^{4}He.[1] In this study the formation energetics of neon based quantum gel in various geometries was systematically studied. Furthermore three new candidates were also studied: Ar, H_2, and atomic fluorine. The first two were not found to be good candidates for quantum gel formation whereas the latter species displays remarkable effects due to its strongly bound and anisotropic pair potential with helium and the recently discovered *ca.* 12 K high long-range potential barrier for molecular recombination. The results imply that the formation of ground state F_2 should be strongly suppressed in superfluid helium. This work demonstrates the basic concept of "solvent guiding", which may be used to alter the reaction routes at low temperatures.

1. J. Eloranta, Phys. Rev. B 77, 134301 (2008).

Keywords: superfluid helium, quantum gel, solvation

Vortex-loop thermodynamics of superfluid ^{4}He under pressure

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The thermodynamic quantities of pressurized superfluid ^{4}He near the λ-transition are calculated using a vortex-loop renormalization method. The superfluid density, specific heat, vortex core size, and vortex core energy are determined as functions of pressure and temperature, and compared with experiments. The theory predicts exponents describing the critical behavior of the superfluid density and specific heat in agreement with recent high-precision theoretical simulations. The vortex core size is found to increase with pressure, while the core energy decreases. The specific heat, though strongly dependent on both of these parameters, is found to scale with pressure in agreement with experimental measurements.

Keywords: superfluid transition under pressure, vortex loops, superfluid density, specific heat

Roton energies in overpressurized ^{4}He inferred from exact quantum Monte Carlo simulations

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We have studied liquid ^{4}He at T= 0 K in the pressure range $P \simeq 0 - 100$ bar by means of the exact Shadow Path Integral Ground State (SPIGS) method[1]. The pressure range we have considered goes well above freezing into the metastable region. SPIGS is known to reproduces accurately the crystalline phase as the result of a spontaneously broken translational symmetry. By monitoring the static strucutre factor during the simulations, the disordered phase is found persistent up to 100 bar and this makes the measurement of ground state and excited state properties possible also in the metastable region. We have applied a new strategy, called Genetic Inversion via Falsification of Theories (GIFT)[2], to extract information about real time dynamics of overpressurized ^{4}He from imaginary time correlation functions computed via SPIGS. We recover sharp elementary excitation peaks with spectral functions displaying also the multiphonon branch. In the full pressure range 0-100 bar sharp roton excitations are always present in the spectral functions. The roton energy decreases at higher pressures in good agreement with experimental data also in the metastable region[3]. The roton energies (wave vectors) have essentially a linear trend with pressure, going from about 7.4 K (2.04 Å^{-1}) near freezing to about 3.4 K (2.24 Å^{-1}) at about 98 bar. The pressure at which the linear trend would extrapolate to a zero roton energy turns out to be about 167 bar, with a roton wave vector of about 2.47 Å^{-1}.

1. D.E. Galli, and L. Reatto, *Mol. Phys.* **101**, 1697 (2003). 2. E. Vitali, M. Rossi, L. Reatto and D.E. Galli, arXiv:0905.4406. 3. J.V. Pearce *et al.*, *Phys. Rev. Lett.* **93**, 145303 (2004).

Keywords: overpressurized ^{4}He, rotons, dynamic structure factor, analytic continuation

Quantum Monte Carlo study of Rb*, Rb$_2$ and other alkali in helium clusters

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Spectroscopy of doped helium nanodroplets has become, in recent years, a popular tool for the study of both finite size samples of the helium quantum fluid and molecules isolated in this sub Kelvin environment. While many dopants migrate to the center of the droplet, alkali (Ak) atoms in their ground electronic state, because of their so weak interaction with He, remain at the surface, the latter being in this way slightly distorted exhibiting a dimple. However, when in their first excited states, Ak atoms are forming exciplexes. These are anisotropic with the central atom surrounded by a ring of He atoms located in the nodal plane of the valence electron p$_z$ orbital. Structural properties, obtained by DMC and PIMC, are presented here for some Ak* - He$_n$ exciplexes.

Ak$_2$ dimers in helium environment have also gained interest in this last decade, in connexion with the generation of ultracold molecules. When attached to helium droplets, Ak atoms can float on the surface and form molecules in cold collisions. DMC and PIMC methods are used to compute energetics and structural informations for Rb$_2$ in helium. In particular, the orientation of the dimer relative to the droplet surface is examined.

1. Leino, M., Viel A., Zillich R., (2008). ”Electronically excited rubidium atom in a helium cluster or film”. The Journal of Chemical Physics 129, 184308.

Keywords: doped helium droplets, alkali atoms and dimers, geometrical structure of clusters, quantum Monte Carlo

Heterophase fluctuations in solid helium near the hcp-bcc phase transformation line and melting curve

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It is shown that in crystals whose melting curve lies close to a line of structural transitions on the PT phase diagram, heterophase fluctuations can have a crystal-liquid structure and consist of crystallites of the nonequilibrium phase surrounded by a layer of liquid [1]. It is shown that such crystal-liquid inclusions can form in the bcc phase of the ^{4}He crystal, which provides an explanation for the features of the kinetic, thermodynamic, and structural properties of the ^{4}He crystal in the bcc region.

1. A.I. Karasevskii. Low Temp. Phys., 32, 913 (2006).

Keywords: Theory of quantum fluids and solids, quantum solids: growth, transport, dynamics.

Complexes in rare-gas solid solutions

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It is shown that complexes - equilibrium nanoclasters of impurity atoms - can form in dilute rare-gas solid solutions consisting of two speciees of atoms with substantially different radii; the thermodynamic stability of these complexes is due to relaxation of the excess elastic energy when the impurity atoms combine into a cluster [1]. Two types of complexes can occur: vacancy complexes (VCs) and cluster complexes (CCs). In the VC case, impurity atoms are bound in the first coordination sphere of a vacancy. The VCs are separete formations, and their equilibrium concentration can be significanly higher than that of isolated vacancies. In the CC case, clusters of n impurity atoms with a volume close to that occupied by n-1 host atoms (in the clustering of n atoms of smaller radius than the host) or n+1 host atoms (in the clustering of n atoms of larger radius) can form. An analysis is made of the particular case of a dilute solution of ^{4}He in ^{3}He, where, on account of the mass difference of ^{3}He and ^{4}He, the effective radii of the atoms in the crystal are different, giving rise to elastic stresses around a ^{4}He impurity atoms in the crystal.

1. A.I. Karasevskii. Low Temp. Phys., 31, 1003 (2005).

Keywords: Theory of quantum fluids and solids, quantum solids: growth, transport, dynamics.

Excess pressure of the phonon gas in nanocrystals

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A theoretical model is presented to explain size influence on thermodynamic properties and melting of mesoscopic nanocrystals. We show that size-dependent quantization of vibrational eigenmodes affects thermal properties of nanocrystals, similarly to size effect on thermodynamic properties of phonon gas of blackbody radiation in a confined space. In our opinion, the physical mechanism of this effect is closely connected to presence of size-dependent excess pressure of the phonon gas in nanocrystals.

1. A.I. Karasevskii and V.V. Lubashenko. Eur. Phys. J. B, 66, 375 (2008).

Keywords: Theory of quantum fluids and solids, quantum solids: growth, transport, dynamics.

Two-dimensional ^{3}He: a crucial system for understanding fermion dynamics

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Keywords: 2D ^{3}He

INVITED PAPER

Elementary excitations in superfluid ^{3}He-^{4}He mixtures within a density functional approach

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We have studied the dynamic structure function of superfluid ^{3}He-^{4}He mixtures at zero temperature as a function of pressure and ^{3}He concentration. Results obtained in the full Random-Phase approximation (RPA) plus Density Functional theory and in a generalized Landau-Pomeranchuk approach are presented and compared with experiment.[1] Analytic expressions for several sum rules of the dynamic structure functions[2] have been determined, and have been used to obtain average energies of the collective excitations.

In the RPA approach, the dispersion relation of the collective modes shows typical features of level repulsion between zero sound-like and phonon-roton-like excitations.[3] The structure of the coupled RPA equations for the mixture leads in a natural way to the hybridization of the collective modes.

The mixed ^{3}He-^{4}He dynamic structure function quenches the zero sound-like mode before it crosses the phonon-roton branch, causing that the former mode only appears with enough strength after the crossing.

1. B. Fåk, K. Guckelsberger, M. Körfer, R. Scherm, and A. J. Dianoux, Phys. Rev. B **41**, 8732 (1990).
2. J. Boronat, F. Dalfovo, F. Mazzanti, and A. Polls, Phys. Rev. B **48**, 7409 (1993).
3. E. Krotscheck and M. Saarela, Phys. Rep. **232**, 1 (1993).

Keywords: liquid helium mixtures, elementary excitations

Polarization effects in superfluid ^{4}He

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A theory of thermoelectric phenomena in superfluid ^4He is developed. It is found an estimation of the dipole moment of each helium atom arising due to electron shell deformation caused by pushing forces from the side of its surrounding atoms in presence of accelerated motion of liquid. In correspondence with the experimental findings made for accelerated relative motion of normal and superfluid components the derived ratio of the amplitudes of temperature and electric polarization potential was proved to be practically temperature independent. Its magnitude is in reasonable correspondence with the observations. The polarity of electric signal is determined by the sign of temperature gradient in accordance with the measurements. The roton excitations dipole moment is also discussed.

Keywords: Superfluid ^4He, polarization effects

INVITED PAPER

Accurate density response function of superfluid ^{4}He at freezing pressure: Is DFT successful for superfluid freezing?

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An accurate density response function $\chi(q)$ of superfluid ^{4}He at zero temperature and at freezing pressure, up to about $q = 8$ Å^{-1}, has been obtained via dynamic structure factors, $S(q, \omega)$, extracted from imaginary time density–density correlation functions computed with an exact Path Integral projector method. A new statistical approach[1] to inverse problems has been used to extract $S(q, \omega)$; contrarily to analogous "analytic continuation" approaches, this new method has been found able to separate a well defined elementary excitation peak from muti–phonon contributions. We have applied density functional theory (DFT) to a superfluid–solid transition with the obtained $\chi(q)$. With this accurate input, DFT gives unphysically unstable superfluid against solidification which is consistent with conventional works. We discuss the possible defect of DFT.

1. E. Vitali, D.E. Galli, and L. Reatto, *J. Phys.: Conference Series* **150**, 032116 (2008); E. Vitali, M. Rossi, L. Reatto, and D.E. Galli, arXiv:0905.4406.

Keywords: quantum freezing, solidification, DFT, density functional theory, density response function, He-4, superfluid, analytic continuation

Two-time temperature Green's function formalism in the study of bosonic mixtures

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The Hamiltonian of a two-component bosonic mixture is written using the so called collective variables $\rho_{\mathbf{k}}$ being the Fourier components of the density fluctuations. It appears to have the leading terms quadratic in $\rho_{\mathbf{k}}$ and $\partial_{\mathbf{k}} = \partial/\partial\rho_{-\mathbf{k}}$ plus a correction. The equations of motion for the two-time temperature Green's functions $\langle\langle\rho|\rho\rangle\rangle$, $\langle\langle\partial|\rho\rangle\rangle$, etc. are exactly solvable if the correction is neglected. Effective consideration of the non-quadratic terms of the Hamiltonian, cf. [1], including different types of decoupling is analyzed to obtain the excitation spectrum of the system. The temperature dependence of the condensate fraction and specific heat is calculated numerically for a model system with parameters corresponding to a mixture of ytterbium isotopes [2].

1. Rovenchak, A. (2003). "Effective mass of atom and the excitation spectrum in liquid helium-4 at $T = 0$ K", Low Temp. Phys. **29**, 105-107.
2. Kasamatsu, K. and M. Tsubota (2008). "Static and dynamic properties of multicomponent Bose–Einstein condensates of ytterbium atoms", J. Low Temp. Phys. **150**, 599-604.

Keywords: bosonic mixtures, excitation spectrum

New version of quantum mechanics at finite temperatures as a ground for description of nearly perfect fluids

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We develop a version of the universal theory that is unlike to the particular theory proposed earlier for explaining of ratio 'shear viscosity to specific entropy' in quark-gluon plasma. We suggest a more general than quantum statistical mechanics (QSM) microdescription of objects in a heat bath taken into account a vacuum. We call it ($\hbar$, k)-dynamics ($\hbar$ kD). This approach allows us in a new manner to calculate some important macroparameters and to modify standard thermodynamics. For features description of nearly perfect fluids in various mediums we describe the thermal equilibrium state in term of a wave function the amplitude and phase of which have temperature dependence. We introduce a new generative operator, Schroedingerian, or stochastic action operator. We demonstrate that a new macroparameter, namely the effective action , can be obtained through averaging of the Schroedingerian over the temperature dependent wave function. It is established that important macroparameters and their fluctuations can be expressed through this quantity. We show an universal link of transport coefficients, including shear viscosity and the diffusion coefficient, with the effective action. On this ground we can explain non-zero value of minimal entropy, the minimal but non-zero value of viscosity, and the universality of the ratio 'effective action to effective entropy' for different mediums at zero temperature and its minimal value in the form $\hbar/2k_B$. This result corresponds to experimental data, taken recently in the area of nearly perfect fluids, and is principally different from result in the frame of QSM. We hope that $\hbar$ kD can serve as an initial microtheory fit for very small objects at ultra-low temperatures.

Keywords: nearly perfect fluids, ($\hbar$, k)-dynamics, temperature dependent wave function, ratio 'shear viscosity to specific entropy', Schroedingerian, effective action

Kinetic energy of ^{4}He atoms in the solid phase at T=0

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The kinetic energy of systems that obey Bose statistics decreases if its temperature is lowered bellow the transition temperature. However this is a difficult quantity to measure and compute at very low temperatures. Using a robust implementation of the Hellmann-Feynman theorem in a diffusion Monte Carlo calculation the kinetic energy in the solid phase is determined at $T = 0$. The results might lead to a speculation that a Bose condensate could exist in this phase.

Keywords: kinetic energy, Bose-Einstein condensate, supersolid

Ground-state of spin-polarized hydrogen and its isotopes: from bulk properties to small clusters

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Keywords: Spin-polarized hydrogen
INVITED PAPER

Topological superconductors and Majorana fermions

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Recently, a new class of topological states has been theoretically predicted and experimentally realized. The topological insulators have an insulating gap in the bulk, but have topologically protected edge or surface states due to the time reversal symmetry. I shall review briefly the recent theoretical and experimental progress. Topological superconductors and superfluid have been theoretically proposed recently, in both two and three dimensions. They have a full pairing gap in the bulk, and their mean field Hamiltonian look identical to that of the topological insulators. However, the gapless surface states consists of a single Majorana cone, containing only half the degree of freedom compared to the single Dirac cone on the surface of a topological insulators. I shall discuss their physics properties and the search for these novel states in ^{3}He-B phase and other real materials.

Keywords: Topological superconductors, Majorana fermions
INVITED PAPER

2 Superfluid ^{3}He and ^{4}He

NMR measurements of the deformed superfluid ^{3}He-B confined in a single 0.6 micron slab

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We present our NMR study of superfluid ^{3}He confined to a 0.6 micron thick slab. The slab is defined by a nanofabricated cavity and NMR is used both to identify the phases and make quantative measurements of the suppression and distortion of the order parameter. Confinement on a length scale comparable to the superfluid coherence length results in a suppression of the order parameter and an alteration of the relative stability of different phases.
We observe the confinement to have a profound effect on the phase diagram, stabilising A phase over a wide range of temperature below T_c at low pressures. At higher pressures and low temperatures, where the coherence length is the shortest,the B phase with an inhomogeneous planar distortion is also observed; in this case the NMR measurements have distinguished both stable and metastable configurations. The non-linear NMR response has been used to quantify the inhomogeneous planar distortion for comparison with the predictions of quasi-classical theory. By preplating the walls of the cell with ^{4}He we tune the surface scattering as observed by the change of T_c^{slab}, A-B transition temperature, and the order parameter suppression as measured by the NMR frequency shift in both A phase and planar distorted B Phase.
These experiments open the way for studies of surface bound excitations, and of new superfluid groundstates stabilized by confinement.

Keywords: superfluid, Helium-3, confinement, slab, NMR, the B phase, planar distortion, majorana, stripe phase

INVITED PAPER

High magnetic field transverse acoustics in superfluid ^{3}He-B

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We present the results of transverse acoustics studies in superfluid ^{3}He-B at fields up to 0.1 T. Using acoustic cavity interferometry, we observe the acoustic Faraday effect[1,2] for a transverse sound wave propagating along the magnetic field, and we measure Faraday rotations up to 990°, significantly more extensive than has been previously reported. We use these results to extend previous calculations of the Landé g factor. We also find the field dependence of cavity interference oscillations resulting from coupling to the imaginary squashing mode. Measurements in large magnetic fields were performed up to the pair breaking threshold where there has been a recent report[3] of a new collective mode of the order parameter with total angular momentum, $J = 4$. Support for this work from the NSF, grant DMR-0703656, is gratefully acknowledged.

1. G.F. Moores and J.A. Sauls, J. Low Temp. Phys. **91**, 13 (1993).
2. Y. Lee *et al.*, Nature **400**, 431 (1999).
3. J.P. Davis *et al.*, Nature Physics **4**, 571 (2008).

Keywords: acoustic Faraday effect,collective modes,transverse acoustics,magnetic field

NMR studies of superfluid phases of ^{3}He in aerogel

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As well as for bulk ^{3}He, nuclear magnetic resonance methods proved to be very effective for investigations of superfluid phases of ^{3}He in aerogel. A short review of the NMR studies of superfluid ^{3}He in aerogel will be given with the focus on investigations of the A-like phase in weakly and strongly anisotropic aerogels.

Keywords: ^{3}He, aerogel

INVITED PAPER

Nuclear spin relaxation in glass states of ^{3}He-A in stretched aerogel

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We present results of pulsed NMR investigations of superfluid A-like phase of ^{3}He in stretched aerogel. In this case we have anisotropic orbital glass (OG) with two possible types of ordering in spin space – ordered spin nematic (OG-SN) or disordered spin glass (OG-SG) state.[1] It was found that longitudinal relaxation of magnetization was non-exponential in both states and depended on temperature and on homogeneity of external steady magnetic field. At the same conditions the relaxation in OG-SG state was more rapid than in OG-SN state. For transverse orientation of the magnetic field relative to the anisotropy axis the duration of free induction decay signal was longer than in the normal phase. It may be explained by formation of coherently precessing spin state similar to that observed in squeezed aerogel.[2]

1. V. V. Dmitriev, D. A. Krasnikhin, N. Mulders, A. A. Senin, G. E. Volovik, A. N. Yudin, Pis'ma v ZhETF **91**, 669 (2010).
2. P. Hunger, Y. M. Bunkov, E. Collin, H. Godfrin, J. Low Temp. Phys. **158**, 129 (2010).

Keywords: 3He, aerogel

Orbital glass and spin glass states of ^{3}He-A in aerogel

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Glass states of superfluid A-like phase of ^{3}He in aerogel induced by random orientations of aerogel strands are investigated theoretically and experimentally. In anisotropic aerogel with stretching deformation two glass phases are observed. Both phases represent the anisotropic glass of the orbital vector $\hat{\mathbf{l}}$ - the orbital glass (OG). The phases differ by the spin structure: the spin vector $\hat{\mathbf{d}}$ can be either in the ordered spin nematic state (SN) or in the disordered spin-glass (SG) state. For identification of phases we used continuous wave and pulse NMR with different orientation of magnetic field. These measurements allows us to determine the parameter of the global anisotropy of the orbital glass induced by deformation. Most of the results were recently published in [1].

1. V.V. Dmitriev et. al. "Orbital glass and spin glass states of 3He-A in aerogel". Pis'ma v ZhETF, vol. 91, iss. 11, pp. 669-675.

Keywords: Superfluid ^{3}He, Aerogel

A new experiment using characterised quartz tuning forks to probe the superfluid ^{3}He AB interface

D. I. Bradley, M. J. Fear, S. N. Fisher, A. M. Guénault, R. P. Haley, C. R. Lawson, G. R. Pickett, R. Schanen, V. Tsepelin, and L. A. Wheatland

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The AB transition in superfluid ^{3}He is an exemplar first order phase transition and the interface between the two is arguably the most highly ordered to which there is experimental access. Theoretically, it is generally accepted that the A phase order parameter transforms to the B phase via the planar phase, and that the interface thickness is on the order of a few coherence lengths. However, no direct measurements of the boundary region have yet been undertaken. We have been developing techniques to investigate the properties of the interface at the lowest achievable temperatures, approaching 100 μK, where the superfluid is in the pure condensate limit. At zero pressure, we induce the transition from B to A by applying a magnetic field of 340 mT, and use a shaped field profile to stabilize and control the interface. These large field gradients make it difficult to probe the interface region with vibrating wire resonator loops because they are driven by the Lorentz force and their motion inferred from the induced Faraday voltage. Consequently we have turned to quartz tuning forks as an alternative mechanical probe, since they are driven and detected piezoelectrically and thus operate independently of any applied magnetic field. We have built an experimental cell containing probe forks in which we can move the AB interface and monitor the interaction with the forks. Here we detail the efforts involved in building such an experiment, not least in tuning the fork frequencies so that they do not interfere with each other, and present preliminary data.

Keywords: phase transition, quantum fluid, helium-3, quartz tuning fork

Branes, strings and boojums; defects in ^{3}He and the cosmos

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The order parameter of the superfluid ^{3}He condensate exhibits broken symmetries that show close analogs with those broken in the various transitions undergone by the Universe after the Big Bang. Fortunately for us, the ^{3}He order parameter is also sufficiently complex that the superfluid may exist in several phases, the two most stable being the A and B phases. At Lancaster we have developed techniques to investigate the properties of the interface between the A and B phases in the pure condensate limit, far below the superfluid transition temperature. The order parameter transforms continuously across the A–B boundary, making this interface the most coherent two-dimensional structure to which we have experimental access. It has been argued that this ordered 2-d surface in a 3-d bulk matrix, separating the two phases, can provide a good analog of a cosmological brane separating two distinct quantum vacuum states. In superfluid ^{3}He the creation of such 2-branes must lead to the formation of point and line defects in the texture of the 3-d bulk, simply as a result of the constraints imposed by the interplay of the order parameter symmetries and the geometry of the container. Furthermore, our experiments have shown that removing the 2-branes from the bulk, in a process analogous to brane annihilation, creates new line defects in large quantities. Such observations may provide insight into the formation of topological defects such as cosmic strings arising from brane interactions in the early Universe. Up to now our experimental techniques have only allowed us to infer the properties of the interface and defects by measuring how they impede the transport of quasiparticle excitations in the superfluid, which is essentially a remote measurement. Our new experiments allow us to directly probe the interface, its annihilation, and the defects spawned.

Keywords: superfluid, helium-3, A phase, B phase, interface, phase transition, topological defects
INVITED PAPER

Absorption spectrum of Mg atoms in pressurized liquid ^{4}He and superfluid helium mixtures

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We present theoretical results, based on fully three-dimensional Density Functional calculations,[1] describing the excitation spectrum of the $3s^2\ ^1S_0 \rightarrow 3s\ 3p\ ^1P_1$ transition of Mg impurity in liquid helium at zero temperature as a function of pressure (P) and ^{3}He concentration (x_3). In the case of pure liquid ^{4}He, our calculations reproduce the line shape and shift of the absorption spectrum as a function of P.[2]
We predict that the dependence of the absorption line on x_3 is very weak. This is due to the fact that line shift and shape is mostly sensitive to the total He density in the impurity environment, and not to its actual composition. Since the atomic shift for impurities immersed in liquid ^{4}He and ^{3}He is very different, our result may lead to an experimental confirmation of the calculated structure of the first solvation shell around Mg and other dopants in liquid He mixtures.[3]

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3. M. Barranco *et al.*, J. Low Temp. Phys. **142**, 1 (2006).

Keywords: liquid helium, atomic impurities, absorption spectrum

Proximity-induced odd-frequency pair in liquid ^{3}He in aerogel

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We discuss the proximity effect in superfluid ^{3}He filled partly with high porosity aerogel. When impurity effect by the aerogel is strong enough (at low pressures) to destroy p-wave superfluidity in the aerogel, the system can be regarded as a dirty normal Fermi liquid/spin-triplet p-wave superfluid junction. The proximity effect in such a system is quite unconventional in a sense that the proximity-induced superfluidity is dominated by the Cooper pairs with odd-frequency s-wave symmetry. Although the order parameter of superfluid ^{3}He is purely p-wave, any partial wave components of the pair amplitude can coexist near the interface owing to broken translational symmetry. From general symmetry consideration for Green's function, one can classify those spin-triplet Cooper pairs into even-frequency odd-parity and odd-frequency even-parity. Among the Cooper pairs near the interface, only the s-wave pair, which is robust against impurity scattering, can penetrate deep into the aerogel. We have performed detailed numerical calculations for the spatial dependence of the pair amplitudes near the interface using the quasiclassical Green's function method. Based on fully self-consistent calculations, we show that the admixture of odd-frequency and even-frequency pairs, in fact, occurs near the aerogel/superfluid ^{3}He-B interface and thus the odd-frequency s-wave superfluidity is expected in the aerogel layer.

Keywords: proximity effect, impurity effect, spin-triplet superfluid

INVITED PAPER

Superfluid ^{3}He immersed in radially squeezed aerogel : BEC of magnons and superfluid phase transition.

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The squeezing of aerogel orients the orbital part **L** of the order parameter of the superfluid along the direction of squeezing[1]. We investigated the properties of superfluid ^{3}He-B immersed in a radially squeezed aerogel that orients **L** in the plane of squeezing[2], perpendicular to the magnetic field. We performed pulsed NMR experiments in the B phase of the superfluid where the anisotropy of the aerogel should stabilize a new mode of coherent precession called HPD2[3]. We observed long lived signals of free induction decay that prove that a Bose Einstein condensate of magnons[4] can exist in these conditions without any external pumping. We also studied the normal to superfluid phase transition in this sample using continuous wave NMR. At cooling, the first signature of the superfluid phase on the NMR line appears as a positive frequency shift before the transition temperature T_c defined by interpolation from the B phase. When this signal disappears at temperatures below T_c, we observe the usual A and B phases. This phenomenon is also observed at warming, but with a positive frequency shift. Although not fully understood yet, it might be the signature of an intermediate state between the normal and superfluid phases.

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Keywords: superfluid ^{3}He, aerogel, magnon BEC, phase transitions, NMR

Features of interaction of microwaves with He II

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Based on interrelation between the thermodynamic and electromechanical phenomena in superfluid helium, the explanation of experimentally found features of microwave interaction in the frequency range of 40-200 GHz in works $^{1-3}$ is given. Due to fast roton-roton and roton-phonon interactions this excitation relaxes and forms a wide pedestal. Alongside these fast processes, there are also slower processes of rotons' scattering by microwave photons taking place, which lead to additional absorption of energy of resonant microwaves and to the appearance of a narrow resonant peak on the background of a wide pedestal. The theoretical explanation of the influence which streams exert on resonant absorption of microwaves is given. The critical velocity of stream at which absorption of microwaves was replaced by their radiation is found. Similar effects take place in the plasma physics at the description of linear and nonlinear Landau attenuation of plasma waves on particles, and also excitation of these waves by streams of particles, moving with the velocity higher than some critical. The account of the component in roton, that is linear in electric field, allows an experimental of linear splitting of a resonant line on two symmetric lines.

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Keywords: resonant absorption, rotons, microwaves

Controlled flow measurements in superfluids

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We are developing a novel device to probe the flow of superfluids which allows for precise control of the velocity for both oscillatory and DC motion. This consists of a large (25x8mm) square-shaped vibrating wire that has a low resonant frequency, on the order of a few tens of Hertz, and large intrinsic damping. Placed in a vertical magnetic field, a drive current through the wire causes deflection owing to the Lorentz force. A small, higher frequency probe current is superimposed on the drive current, so that the position and motion of the wire can be detected by small pickup coils placed nearby. Preliminary measurements have been made in superfluid helium-4, showing that we can accurately control the instantaneous velocity of the wire by controlling the drive current. In superfluid helium-3 we will use the device to probe frequency dependence of the critical velocity for breaking Cooper pairs. This has been studied widely for vibrating wires at frequencies on the order of 1 kHz, where pair-breaking occurs at roughly one third of the Landau velocity, owing to the oscillatory nature of the flow, and the suppression of the order parameter at the wire surface which leads to bound states. Crucially, pair-breaking below the full Landau velocity depends on there being partial occupation of the bound states. For steady motion these states should be fully occupied, and thus the full Landau critical velocity recovered. Our experiments will search for this cross-over region for flow-induced pair-breaking.

Keywords: DC Wire, Vibrating Wire, Superfluid

Superfluid ^{3}He confined in a single 0.6 micron slab: the phase diagram and properties of the A phase

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We present our NMR study of superfluid ^{3}He confined to a 0.6 micron thick slab. Preliminary results were reported earlier[1,2]. The slab is defined by a nanofabricated cavity and NMR is used both to identify the phases and make quantative measurements of the suppression and distortion of the order parameter.

Confinement on a length scale comparable to the superfluid coherence length results in a suppression of the order parameter and an alteration of the relative stability of different phases. We observe the confinement to have a profound effect on the phase diagram. The superfluid transition temperature $T_c^{\rm slab}$ is suppressed compared to the bulk value. The A phase is stable in a wide range of the phase diagram below $T_c^{\rm slab}$. At higher pressures and low temperatures where the coherence length is the shortest, the B phase with a planar distortion is observed. Its properties and the underlying NMR model are presented on a separate poster.

By preplating the walls of the cell with ^{4}He we tune the surface scattering as observed by the change of $T_c^{\rm slab}$, A-B transition temperature, and the order parameter suppression as measured by the NMR frequency shift.

1. R. G. Bennett *et al.*, *JLTP* **158** (2010)
2. L. V. Levitin *et al.*, *JLTP* **158** (2010)

Keywords: superfluid, Helium-3, confinement, slab, NMR, phase diagram, the A phase

Superfluid ^{3}He confined in a single 0.6 micron slab: the B phase with a strong planar distortion

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We present our NMR study of the superfluidity of ^{3}He confined to a 0.6 micron thick slab. The experimental setup, phase diagram and properties of the A phase are presented on a separate poster. In a narrow slab the isotropic B phase develops a large planar distortion due to the anisotropic boundary conditions. This distortion is inhomogeneous across the slab. We extend the model of spin dynamics of the uniform distorted B phase[1] to include inhomogeneities on a length scale short compared to the dipolar length. The agreement of this model with our non-linear NMR measurements enables us to identify the phase as the planar distorted B phase and to quantify the gap distortion. The state with a negative frequency shift observed earlier[2] is found to be a metastable configuration of the same phase stabilised by the magnetic field.

Recently the stability of a *stripe phase*, a periodic structure of domains of distorted B phase, in a slab of ^{3}He was predicted.[3] We discuss the future prospects for detecting this state with NMR.

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3. A. B. Vorontsov and J. A. Sauls, *PRL* **98** (2007)

Keywords: superfluid, Helium-3, confinement, slab, NMR, the B phase, planar distortion, stripe phase

Quantum and classical turbulence in superfluids in the zero temperature limit

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Keywords: Turbulence
INVITED PAPER

Majorana edge modes of superfluid ^{3}He-A and B phases confined in a thin film

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Keywords: Majorana edge modes
INVITED PAPER

Effects of Majorana edge fermions on dynamical spin susceptibility in topological superfluid ^{3}He-B

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The low-energy quasiparticle structures in the vicinity of the specular surface of the superfluid ^{3}He-B are theoretically investigated, based on the Bogoliubov-de Gennes (BdG) framework. A non-trivial topological invariant in the bulk of ^{3}He-B ensures the existence of surface Andreev bound states. The remarkable point is that the topologially protected edge modes are made up of the equivalent contribution from the particle and hole excitations, called the Majorana edge fermions. In contrast to Majorana zero modes in spinless supefluids,[1] the Majorana fermions in the B-phase are accompanied with their counterpart by the time-reversal symmetry, giving rise to the Ising-like anisotropy of the spin dynamics.[2,3,4] Here, we study the anisotropic spin dynamics, based on the numerical diagonalization of the BdG equation, where the effect of the pair creation and annihilation is underlined. We also propose an experimental way to detect the low-lying spectra of the edge modes through the power law behavior of the low-temperature surface specific heat.

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4. G.E. Volovik, JETP Lett. **90**, 398 (2009).

Keywords: Andreev bound states, ^{3}He, p-wave superfluids, Majorana fermions

Superfluidity of ^{4}He in a nanopore array of porous alumina

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Recent experiments on superfluid ^{4}He confined in nanoporous media have unveiled a number of intriguing phenomena caused by interplay of nanoscale confinement and interatomic correlation. ^{4}He in a porous glass whose pore diameter is 2.5 nm undergoes a quantum phase transition by pressurization[1]. This unexpected result strongly suggest that the superfluid order parameter is suppressed even if the pore size is an order of magmitude larger than the superfluid coherence length ($\xi \sim 0.3$ nm). This anomalous suppression is not only interesting as a novel correlation effect of confined Bosons, but also useful in developing a new superfluid Josephson junction. Josephson effect in superfluid ^{4}He has been observed only by using micron-sized apertures in the very vicinity of bulk lambda point, at which ξ becomes comparable to the aperture size[2].

Here, we propose a novel Josephson device working at arbitrary temperature based on the superfluid suppression in the nanopores. We employ well-characterized porous alumina (PA) plates as a possible junction. By controlling the anodization process or by depositing diamond-like carbon on the PA plate, we aim to realize an array of hundred millions nanopores of 2$\sim$5 nm in pore size. We have examined superfluid ^{4}He in a regular triangular nanopore array (pore size: 45 nm, distance between the pores: 100 nm) using an annulus-type torsional oscillator. The preliminary results will be discussed.

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2. E. Hoskinson and R. E. Packard, Phys. Rev. Lett. **94**, 155303 (2005).

Keywords: superfluid ^{4}He, restrict geometry, Josephson junction

Surface Majorana cone of the superfluid ^{3}He B phase

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In the vicinity of a surface of unconventional superfluids and superconductors, density of states is modified from the bulk one and additional low energy states are formed within the energy gap Δ. These new states are called surface Andreev bound states (SABS) and are the universal feature in such systems. SABS are strongly affected by the surface specularity S. In the specular scattering limit $S = 1$, the bound state quasiparticles in superfluid ^{3}He B phase, which satisfy the Majorana condition: the equivalence of particle and antiparticle, have a linear dispersion which is referred to as the Majorana cone.
To study SABS we measured a transverse acoustic impedance, which was very sensitive to the surface states. S can be controlled by coating the surface with ^{4}He. Double peak structure of the impedance develops as increasing S while only a single peak is observed in diffusive limit $S = 0$.[1] The new peak at lower temperature is reproduced by a theory which properly takes into account the S dependence of the surface density of states. The growth of the new peak is a result of the formation of clearer Majorana cone at higher S and is the experimental indication of the surface Majorana fermion in superfluid ^{3}He B phase.

1. S. Murakawa *et al.*, Phys. Rev. Lett. **103**, 155301 (2009); K. Nagai *et al.*, J. Phys. Soc. Jpn. **77**, 111003 (2008).

Keywords: superfluid ^{3}He, surface bound states, Majorana fermion

Study for surface states of superfluid ^{3}He in non-unitary phases at high magnetic fields

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Recently, surface states of unconventional superfluids and superconductors attract a lot of attentions. The surface density of states is drastically modified from the bulk one and unique surface states are formed near the Fermi energy. It is pointed out that the surface states of superfluid ^{3}He-B are recognized as the surface Majorana fermions.
It was found that transverse acoustic impedance of liquid ^{3}He is a good probe to study the surface states of superfluid ^{3}He.[1] We carried out the impedance measurements at high magnetic fields up to 13 T to study the surface states of superfluid ^{3}He in non-unitary phases called A_1 and A_2 phases. In our previous experiments, the behavior in each phase was different quantitatively. This difference could not be explained in a naive weak-coupling theory. One possible origin of the difference is the magnetic scattering of quasiparticles off the localized ^{3}He atoms on the surface. To eliminate this effect, we coated the surface with about 2 layers non-magnetic ^{4}He. Preliminary results show that the localized ^{3}He does not affect the surface state much.

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Keywords: Superfluid ^{3}He A_1 and A_2 phase, surface state, acoustic impedance

Relation between thermodynamic parameters and electric potential in the standing second sound wave

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Superfluid ^{4}He possesses a number of unique features. One of them is existence of second sound. The conditions of second sound excitation are well-known and were described long ago [1]. It is known that temperature and heat flow resonances are observed in case of second sound excitation with an oscillating heat flow. This phenomenon was described in [1,2]. The experiments [1,2] showed that there are not only temperature resonances but electric induction ones too. And electric induction resonances correlate with temperature resonances. In this work we described theoretically temperature and heat spread in helium. We considered heater and helium as the double-layer system. Temperature and heat transfer in the first layer (heater) was described with usual thermal conductivity equation. Temperature and heat transfer in the second layer (superfluid 4He) was described with the system of equations for superfluids with taking into account both dissipative thermal conductivity mode and second sound mode. Resonance frequency and amplitude dependence on length of the first layer was studied. Also we studied what part of the heat emitted in the first layer was transferred to the superfluid layer in dependence of the first layer length and heat wave length. The obtained results may be used for describing phenomena taking place in experiments [3]. [1]

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Keywords: superfluid, resonance

Radiation and propagation of phonon pulses in superfluid helium at high pressures

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Using the derived expression for the signal on the detector of phonon pulses we consider experimental data for various spatial situations of heater and detector under pressure of 24 bar, when phonons move in ballistic regime. This consideration allows us to study radiation of phonons by gold heater to superfluid helium via acoustic and background channels and determine main peculiarities of these mechanisms of radiation.

Keywords: phase transition, quantum gas, condensation, Nobel Prize

Fourth sound of superfluid ^{3}He in aerogel

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Keywords: ^{3}He, aerogel
INVITED PAPER

Surface Andreev states and surface Majorana states on superfluid ^{3}He-B

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The surface Andreev bound state of ^{3}He-B was found to be probed by the resonance of shear mode impedance of the quartz transducer. If the resonance frequency is set at around the gap energy, the wall motion is strongly affected by the quasi-particles scattering, which enables us to investigate the bound state in a spectroscopic way. The fantastic point of ^{3}He experiment is that we can change the boundary condition for the quasi-particles by coating the wall with superfluid 4He film. Systematic measurement with changing ^{4}He film thickness, that is to change the boundary condition (specularity), revealed that the response was excellently reproduced by the theoretical calculation of the Andreev bound state in P wave superfluid. The important result was that the spectral density at E=0 (Fermi energy) was decreased, and comparatively enhanced at higher energy as the specular parameter S was increased from 0 (completely diffusive) toward 1 (specular limit). This variation of density of state was observed as an extra anomaly in the impedance[1].

Recently Majorana Fermion, which is still an elementary particle within a theory, is theoretically predicted to be realized in the surface bound state of ^{3}He-B at the specular interface. Though the impedance does not probe the bound state at the specular limit, the experimental results are strongly suggestive to the Majorana surface state close to the specular limit.

1. S. Murakawa *et al.*, Phys. Rev. Lett. **103**, 155301 (2009)

Keywords: Superfluid ^{3}He, Surface Andreev Bound State, Majorana Fermion
INVITED PAPER

Unconventional textural properties of superfluid ^{3}He-B in isotropic aerogel

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Low density silica aerogels provide an avenue to explore the role of impurity scattering on the unconventional superfluid phases of ^{3}He. Of particular interest is the affect of disorder on the orientation of the superfluid order parameter. Experiments show that it is possible to realize oribital textures in ^{3}He in aerogel not possible in the bulk superfluid[1−4]. We have performed pulsed nuclear magnetic resonance (NMR) experiments on ^{3}He-B in isotropic 98.1% porosity aerogel. The cylindrical aerogel sample was characterized with an optical, cross-polarization technique[5] to confirm the absence of globally preferred directions. With decreasing temperature we find a smooth crossover from a dipole-locked $\hat{n}$-texture near T_c to a dipole-unlocked texture at temperatures, $T \leq 1.2$ mK at P = 25.75 bar. We find that this textural conversion is reproducible on both warming and cooling. Additionally, the dipole-locked configuration can be prepared at low T with the application of tipping angles exceeding $\sim 40°$. Experiments are currently ongoing to investigate the temperature, pressure and tip angle dependence of this phenomenon. Support for this work from the NSF, grant DMR-0703656, is gratefully acknowledged.

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Keywords: aerogel, superfluid ^{3}He, impurity effects, unconventional pairing

The possibility of magnon BEC in antiferromagnetic $MnCO_3$

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The Bose-Einstein condensation (BEC) of magnons was observed in 1984 in superfluid ^{3}He-B [1]. For a last 25 years there was found 5 different magnon BEC states in superfluid ^{3}He [2]. The other similar magnetic system is the coupled nuclear-electron system in some antiferromagnets. Particularly, in $MnCO_3$ the frequency of antiferromagnetic resonance can be very low, about few GHz, and the frequency of NMR ^{55}Mn in a hyperfine field is about 600 MHz. The modes of coupled nuclear electron precession depends on the relative orientation and its frequency changes with the deflection of nuclear magnetization from the axis of hyperfine field [3]. The theoretical investigations shows the possibility to create the magnon BEC with a 90° deflected nuclear magnetization in $MnCO_3$ and similar antiferromagnets.
This work is supported by the Ministry of Education and Science of the Russian Federation (FTP "Scientific and scientific-pedagogical personnel of the innovative Russia" contract N 02.740.11.5217)

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Keywords: Superfluid ^{3}He, magnon BEC, Phase transition, NMR

Majorana edge modes of superfluid ^{3}He A- and B-phases

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Majorana quasi-particles (QPs), which are defined by $\gamma^\dagger = \gamma$ implying that the particle and antiparticle are identical, have attracted much attention in the wide research field. One of the candidate systems that support existence of the Majorana QPs is a spin triplet superfluid. The Majorana modes, which are associated with the Andreev bound states, appear at the edge of the superfluid. Motivated by a recent experiment of the superfluid ^{3}He confined in a thin slab[1], we design a concrete experimental setup to observe the Majorana edge modes. By solving the quasi-classical Eilenberger equation, which is quantitatively reliable, we evaluate the local density of states (LDOS) and the mass and spin currents along the edge. It is demonstrated that the peak energy of the angle-resolved LDOS forms a "Dirac valley" and the mass current flows at the edge for the A-phase[2]. In contrast, the angle-resolved LDOS in the B-phase reveals the existence of the Majorana cone and the spin current is found to flow three-dimensionally. Based on the quantitative results, we propose feasible and verifiable experiments of the specific heat and torque due to the edge current to check the existence of the Majorana edge modes.

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Keywords: Majorana modes, slab geometry, quasi-classical theory

A novel approach to measure force-velocity behaviour of flow in superfluid ^{4}He

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Measurements of the relation between driving force and velocity for objects immersed in superfluid helium-4 are used to probe the dynamics of superfluid flow, for example in studying the transition from laminar to turbulent flow. Such measurements are often made with oscillating objects such as vibrating wire loops. These loops are placed in a magnetic field and set into motion by the Lorentz force when a drive current is passed through them. The loops are typically on the order of a few mm in size, and vibrate at kHz frequencies. Here we have developed a new technique to study the DC flow around a moving object. A much larger loop of wire is bent into a "goalpost" shape with leg length 25mm long and cross-bar 10mm. This gives it a low resonant frequency of a few tens of Hertz, and a resonance with a low quality factor. We can then control the drive current so that the wire can be accelerated and brought into steady DC motion, sweeping from one side to another, rather than oscillating. Further, we apply an additional small AC current to the wire and measure the signal induced in two pickup coils placed either side of the wire. Thus we are able to measure the position of the wire in real time with micron accuracy. We have used the technique to measure force-velocity curves in both normal and superfluid helium-4, and compare these with oscillatory flow measurements.

Keywords: Superfluid ^{4}He, DC Flow

A novel design of a spin pump cell in superfluid ^{3}He-A$_1$ phase

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Recent experimental studies of superfluid ^{3}He A$_1$ phase indicate that enhancement of spin polarization can be achieved by a mechanical spin pump method[1]. In the spin pump cell, the spin-polarized superfluid is forced through a superleak into a small chamber to increase the polarization in the chamber. So far, measurements in an applied static magnetic field of 5 tesla indicate that the spin polarization increased by 40% from that produced by the static field. We present here a new design for spin pump cell to achieve much higher polarization. Using the new cell, we are planning to measure changes in (1)NMR frequency, (2)viscosity, (3)the simple mechano-spin effect, $\delta P \propto \delta S$ (where P is pressure and S is spin density), (4)spin relaxation rate, and (5)the transition temperatures (T$_{c1}$ and T$_{c2}$) of the A$_1$ phase, as polarization is increased.

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Keywords: Superfluid ^{3}He, A$_1$ phase, Highly polarized ^{3}He

Mg$_m$ clusters in superfluid ^{4}He droplets

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Capturing atoms in ^{4}He nanodroplets allows to assemble cold nanoclusters in a well controlled step-by- step way. We present calculations of small Mg$_m$ clusters in larger ^{4}He droplets that provide a full multi-scale description of all degrees of freedom of such a system: the electrons of the Mg$_m$ cluster, the motion of the ions of the cluster and the motion of the ^{4}He atoms surrounding the cluster. We employ density functional theory (DFT) for the electronic structure of Mg$_m$ and path integral Monte Carlo (PIMC) simulations for the superfluid ^{4}He droplet. We have developed a phenomenological model for the interaction between the cluster and the surrounding ^{4}He, and show that simple pair-wise potential models fail. By minimzing the total energy, the Mg ion positions of the clusters are annealed in the ^{4}He environment, including the ^{4}He response self-consistently. We discuss the effect of the ^{4}He matrix on the electronic structure and the equilibrium configuration of the Mg$_m$ cluster.

Keywords: helium nanodroplets, quantum matrix, metal clusters

3 Hydrogen

Metastable liquid para-H_2 at very low temperatures

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Using quantum Monte Carlo methods, we have studied the ground-state properties of metastable liquid para-H_2 in the limit of zero temperature. With the help of a proper importance sampling, we have been able to frustrate the formation of the crystal which is the true ground state of the bulk phase. The equation of state of the liquid and related properties are then studied and compared with the ones of the stable solid phase. The study has also been extended to small clusters to analyze the stability of liquid versus solid clusters, pointing to the existence of stable liquid clusters up to a quite large number of molecules. Finally, we report results on the frustration of the crystal at finite temperatures. In this case, we observe the formation of a glass or amorphous solid phase that becomes superfluid at temperatures close to 1K.

Keywords: hydrogen, superfluid

INVITED PAPER

Detailed low T study of PdH_x system by torsional oscillator: x dependent responses

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Hydrogen atoms dissolve in Pd at densities up to one H atom per Pd, which provides higher atomic H density than in solid H_2. They are known to have large diffusion coefficient due to quantum tunneling. Torsional oscillator(TO) technique is employed to investigate the phases of H in Pd, which is known to show phase boundaries at the lowest T among metal-hydrogen (MH) systems. Specific heat measurements have been performed for PdH_x with x up to high H concentration specimens[1,2] to establish the unique $x - T$ phase diagram. We have, in addition, been performing TO experiments, which is a well-established, powerful method to investigate superfluidity and quantum vortices of liquid He as well as dislocation dynamics, in order to study the atomic H dynamics in the $PdH(D)_x$ system. Our TO experiments have shown the resonance frequency shift and the Q value change for PdH_x, $0.16 =< x =< 0.75$ specimens at the lowest T, which can be largely explained by the lattice deformation by H intrusion. This x dependent contribution has a smaller additional change depending on x and T. We will show the details of experimental data and discuss the possible occurrence of quantum phenomena for the hydrogen system.

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Keywords: phase transition, hydrogen, palladium, specific heat, torsional oscillator, frequency shift

Atomic hydrogen in thick H_2 films at temperatures 0.05-2 K

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We describe experiments on hydrogen atoms stabilized in 100 μm thick H_2 film at temperatures between 0.05 and 2 K. The molecular hydrogen matrix was condensed directly from natural hydrogen gas. The H atoms are produced with a plasma discharge at temperatures below 1 K and studied with 130 GHz electron spin resonance. The highest H densities of 2×10^{19} cm^{-3} in solid H_2 were observed. The results indicate that H atoms in the samples are stable for weeks of observation below 500 mK and their lowest two hyperfine states have non-thermal populations. In addition to dramatically confirming the large departure from Boltzmann statistics seen earlier,[1,2] it was found that the ESR resonance lines consisted of two closely spaced components with different widths indicating separate regions of high and low concentrations of H atoms in the H_2 matrix. Upon warming, the two components show very different rates of recombination with the higher density component having a faster recombination rate. We discuss the atomic interactions and mobility, and also the structure of the samples of H atoms in the H_2 matrix.

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Keywords: solid hydrogen, quantum solids

Dynamics of HD molecules trapped in the cages of zeolite

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There is considerable interest in the use of mesoporous structures (e.g. zeolites and metal organic frameworks) for hydrogen storage[1] but little is known about the molecular interactions and the dynamics of molecules inside the cages of these structures. In order to determine these properties we have measured the nuclear magnetic spin-lattice and spin-spin relaxation times of HD molecules trapped in the α-cages of Zeolite 13X for a wide temperature range $1.6 < T < 20K$. The measurements were made using the technique of nuclear relaxation spectroscopy[2] for which the relaxation process can be described in terms of a set of connected energy baths. The spin-lattice relaxation times depend directly on the heat capacities of the energy baths and thus on the translational modes of the trapped HD molecules[3]. Distinct peaks are observed for the spin-lattice relaxation times while the spin-spin relaxation times are temperature independent below 16 K followed by a jump by a factor of 650 at 16 K, corresponding to the onset of intercage diffusion.

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Keywords: hydrogen storage, magnetic resonance, thermal relaxation, quantization

Exchange tunneling chemical reactions of hydrogen isotopes in nanoclusters immersed in superfluid helium.

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We review results of studying exchange tunneling chemical reactions of atoms and molecules of hydrogen isotopes in impurity-helium condensates. Impurity-helium condensates are formed by injection atoms and molecules from radio-frequency discharge into bulk superfluid ^{4}He at T=1.5 K and they consist of collection of nanoclusters of impurity immersed in superfluid helium. It was found that stabilized atoms mostly reside on the surfaces of the nanoclusters.[1] The rate of exchange tunneling chemical reactions of hydrogen isotopes in impurity-helium condensates are usually faster compared to that in bulk molecular matrices of hydrogen isotopes.[2]

In the mixed krypton-hydrogen nanoclusters light impurities form a layer on the krypton core.[3] By changing the thickness of the layer of hydrogen isotopes it is possible to influence the rate of exchange tunneling chemical reactions. In the thin layers of H_2 molecules on the surfaces of Kr nanoclusters the recombination of H atoms was completely suppressed.

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Keywords: atomic and molecular hydrogen, exchange tunneling reactions, nanoclusters

INVITED PAPER

Matrix isolation of H atoms at low temperatures

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The recent history of the matrix isolation of atomic free radicals at low temperatures started with a research program at the US National Bureau of Standards and continuied with the important breakthrough at Chernogolovka in Russia where a jet containing atomic free radicals was directed onto the surface of superfluid ^{4}He. The samples collected consisted of gel-like substances made up of molecular nanoclusters, allowing the atomic free radicals to be isolated from one another and studied at 1.3 K. More recently, techniques were developed at Turku University which have been made the region T$\leq$1 K accessible for studies of H atoms entrapped in H_2 films. Very high concentrations of H atomic free radicals ($\sim 10^{18}$ - 10^{19} atom cm^{-3}) have been attained using both the Turku and Chernogolovka methods.A discussion of the most recent experiments at Cornell and Turku will be given. Microwave and mm wave electron paramagnetic resonance techniques, as well as preliminary SQUID measurements have been employed in these experiments. These techniques permitted studies of the exchange tunneling chemical reaction $D+HD \rightarrow H+D_2$. Diffusion of H atoms through solid H_2 proceeds via the reaction $H+H_2 \rightarrow H_2+H$, leading to recombination at higher temperatures ($H+H \rightarrow H_2$). Quantum overlap of H atoms is thought to be responsible for exotic behavior of H atoms in solid H_2 films below 1 K, including a significant departure from the Boltzmann distribution of the relative populations of the two lowest hyperfine levels of atomic H.

Keywords: Matrix Isolation, Atomic and Molecular Hydrogen, Magnetic Resonance

INVITED PAPER

Magnetic resonance study of H atoms in solid H_2 at temperatures below 1K

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We review our recent experiments with H atoms embedded in films of H_2 at temperatures below 1 K [1]. Solid H_2 films were created by slow recombination of H atoms in the gas phase or by direct deposition from H_2 vapor. We implemented a novel method of generating atomic populations inside the H_2 films, using a direct dissociation by a pulsed low power r.f. discharge in the sample cell. With this method we achieved record high atomic concentrations exceeding 2×10^{19} cm^{-3}. The samples were characterized by means of magnetic resonance: electron spin resonance (ESR) and electron-nuclear double resonance (ENDOR) in a magnetic field of 4.6 T. We observed density dependent broadening and shifts of the ESR lines due to the dipolar interactions, and resolved these effects for like and unlike atoms. We also found two narrow lines in the ENDOR spectra of H in H_2 films shifted to the red from the position for free atoms. This indicates two possible substitutional positions of the atoms in H_2 matrices, both characterized by very homogeneous crystalline fields. Relaxation of the relative hyperfine populations was measured as a function of temperature for H in H_2 films grown on different substrates. For H_2 films on Mylar substrates the relative equilibrium populations of the two lowest hyperfine states of H were found to deviate substantially from the prediction of Boltzmann statistics. We discuss the possibility of observing collective quantum phenomena in this system.

1. J. Ahokas, O. Vainio, S. Novotny, J. Järvinen, V. V. Khmelenko, D. M. Lee, and S. Vasiliev Phys. Rev. B 81, 104516 (2010)

Keywords: quantum diffusion, supersolids, BEC, Electron-Spin Resonance

INVITED PAPER

4 Helium hydrodynamics

Classical turbulence on the surface of quantum liquids

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Superfluid helium-4 is a unique liquid for experimental study of capillary wave turbulence due to its very low viscosity in comparison with conventional liquids (water, for example). The use of He-II allowed us to investigate classical capillary turbulence in two different regimes: kinetic mode of wave turbulence (WT) and discrete mode of wave turbulence (DWT). In the case of DWT, contrary to the kinetic mode of wave turbulence, the influence of discreteness of experimental cell resonant frequencies on the behaviour of turbulent cascade is a key factor. In our experiments with strong excitation of surface waves at a resonant frequency of the cell, as well as in experiments with noisy pumping in frequency band, WT regime is realized, and turbulent spectra are well described by power law function (Kolmogorov-Zakharov spectrum). Whereas in measurements with moderate amplitudes of resonant frequency excitation of waves, the both states are observed: WT is realised at low frequencies, and DWT – at high frequencies. Namely, it was found that at low frequencies turbulent distribution was described by Kolmogorov-Zakharov spectrum, while at high frequencies local maximum was formed – wave energy accumulation near high-frequency edge of inertial interval ω_d. In our model the formation of local maximum is caused by detuning effect of nonlinear harmonic frequencies and resonant frequencies of surface oscillations in the cell, because the ratio of resonance width (which is determined by both nonlinear interaction and viscous dissipation) to the distance between two neighbour resonances has minimum and is less than unity near ω_d.[1] The work was supported by RFBR grants No 09-02-01146 and 07-02-00728.

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Keywords: superfluid helium-4, capillary waves, wave turbulence

INVITED PAPER

A study of the motion of particles in superfluid helium-4 and interactions with vortices

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We describe experiments in which a sound pulse is used to inject small particles into liquid helium at temperatures between 1 and 3 K. The motion of these particles is then observed. We are able to observe the effect of applying an impulse to a particle that is attached to a vortex. We also report on a number of surprising motions of particles and discuss possible explanations.

Keywords: superfluid helium-4, vortices, particle motion

INVITED PAPER

Acoustic resonance of superfluid ^{3}He in parallel plates

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We have performed an acoustic resonance experiment of superfluid ^{3}He confined in a stack of parallel plates. The stack consists of the polyimide films, parting and spacer strips, which are brought down by the laser-cutting technique. Thickness of spacers are 13, 25 and 50 μm. The magnetic fields is possible to apply in arbitrary direction to parallel plates. The anisotropy of superfluid ^{3}He will appear conspicuously by applying the constraint of the direction of the magnetic field in addition to a geometric one. A similar experiment was done by Kojima[1], but it was only superfluid density that was measured. Because we developed a high sensitivity sensor, it is possible to obtain hydrodynamic properties by measuring the line width of the resonance line, in addition to superfluidity density. As a result, we found the fourth sound resonance. From its velocity, we have calculated the superfluid density, revealing no size effect because the gap between parallel plates are much larger than the superfluid coherence length. From its line width, we have calculated the energy loss of the resonance. We found that the hydrodynamic theory[2] qualitatively describes its temperature dependence, but it cannot describe the gap width dependence. Possible explanations will be discussed. Moreover, we have found the new resonance that appears only in a simple slab geometry and that is not able to assign to known sound.

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Keywords: Supefluid, confined geometry, hydrodynamics

Turbulent convection :
does the ultimate regime really follow Kraichnan prediction ?

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Gaseous and liquid He convection cells allow to explore the laws of highly turbulent heat transfer with unprecedented accuracy. Surprisingly, experimental results fall into two categories : some evidence an abrupt enhancement of the heat transfer while others do not. The origin of this apparent disagreement is presently unexplained and has generated a long-standing controversy. We present the result of a 6 years long systematic study of the regime with an enhanced heat transfer, originally named the “Ultimate Regime” of convection. In particular, we varied independently the 3 control parameters of the system (cell aspect ratio, Rayleigh and Prandtl numbers) in order to disentangle their relative contribution.

Among the main results, it is found that :
i) most experiments reaching very high Ra are not in disagreement if small differences in Prandtl numbers are taken into account,
ii) the transition is not directly triggered by the large scale circulation present in the cell as assumed in the literature,
iii) the sidewall of the cell have a significant influence on the transition.

The characteristics of this Ultimate regime are summarized and compared with R. Kraichnan prediction for the asymptotic regime of convection.

Keywords: turbulence, Rayleigh-Benard convection, ultimate regime

On sound emission of quartz tuning forks in liquid helium

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Commercially produced quartz tuning forks have recently become a widely used tool in quantum fluids research. By measuring the resonance characteristics of the sensitive devices valuable information on the kinematic viscosity, cavitation, transition to classical and quantum turbulence have been obtained for ^{4}He, ^{3}He and ^{3}He-^{4}He mixtures. While for tuning forks oscillating at relatively low frequencies (in many cases for the most common 32 kHz ones as well, except at very low temperatures, the losses due to acoustic emission of first sound could usually be neglected, however, for higher frequency forks (e.g., 77 kHz and 100 kHz available ones), acoustic emission becomes the dominant dissipative process. We present a systematic experimental study over a wide temperature range including the zero temperature limiting gaseous, normal liquid and superfluid ^{4}He as well as in ^{3}He-^{4}He mixtures backed up by theoretical considerations, demonstrating clearly the relative importance of acoustic emission and laminar viscous drag for various types of tuning forks in ^{4}He. Moreover, experimental evidence is presented that forks affect each other via their acoustic velocity fields in classical fluids as well as in superfluids.

Keywords: quartz tuning fork, sound emission, cryogenic helium

Fractional hydrodynamic of superfluid helium and Galilean non-invariance

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It was shown[1,2] that to describe superfluid dynamics in nanoporous media with fractional dimension it's necessary to take into account the nonuniform (fractal) structure of confinement. In the present work we use the fractional Hamiltonian[3] and show that it leads to the Galilean non-invariance of dynamics equation for superfluids. As a consequence one needs to choose the especial reference frame where, for example, nanoporous media is in a rest as well as to introduce additional potential into two-fluid hydrodynamic model.
This work is supported by the Ministry of Education and Science of the Russian Federation (FTP "Scientific and scientific-pedagogical personnel of the innovative Russia" contract N 02.740.11.0797).

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Keywords: nanoporous media, superfluid hydrodynamic, fractional dimension

5 Quantum turbulence

Non-classical velocity statistics in superfluid turbulence

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Keywords: Turbulence
INVITED PAPER

Fractal dimension of quantised vortex filaments and emission of vortex rings in the Kelvin wave cascade

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The idea of the Kelvin waves cascade was introduced [1,2,3] to explain the observed decay of superfluid turbulence at very low temperatures [4]. We report results of numerical simulations of the time evolution of quantized vortex filament following a vortex reconnection. We study the resulting Kelvin waves cascade and compare the amplitude spectrum with existing theories [5,6]. We show that the vortex filaments become fractal, and that large-amplitude twisting of the filaments leads to secondary reconnections and the emission of small vortex rings.

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Keywords: Kelvin waves cascade, Kelvin waves, quantum turbulence, vortex ring, fractal dimension

Formation of quantized vortices by vibrating bodies in He II at $T \to 0$ K

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We are studying the oscillations of quartz tuning forks and a copper grid, and their mutual interactions, in He II at temperatures down to $T \sim 10$ mK. The free decay of grid vibrations fell into three distinct regions: (a) a high amplitude regime where the energy loss was extremely fast, probably associated with production of quantum turbulence (QT) around the grid; (b) an intermediate amplitude regime of slower decay that we may associate with the formation of individual vortices; and (c) a lower amplitude regime corresponding to energy loss only through "nuisance damping" of the grid. With one fork used as a generator of vortices, and the other as a detector at a distance of ~1 cm, we observed that the quality Q and resonant frequency of the detector were sensitive to an increase in the amplitude of generator fork once a critical velocity v_{c1} ~1 cm/s was exceeded. The detector behaviour changed again when the generator velocity exceeded $v_{c2} \sim 15$ cm/s and generator fork created QT. Similar behaviour was observed with the grid used either as a detector or a generator. We suggest that v_{c1}, the oscillation amplitude above which the fork prongs exhibit increased dissipation and the grid starts to exhibit faster decay, may correspond to a process in which Kelvin waves on pinned vortices lead to reconnection and production of vortex rings. These rings can traverse the generator-detector separation and influence the detector response provided that they are not screened by QT created by the detector.

Keywords: Quantum turbulence, superfluidity, vortexes

Turbulent superfluid profiles in a counterflow channel

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We have developed a two-dimensional model for the numerical evolution of quantised vortices moving under the influence of applied normal fluid and superfluid in a counterflow channel [1]. We predict superfluid and vortex-line density profiles which could be experimentally tested using recently developed visualization techniques [2,3]. The numerical simulations are performed employing different spatial distributions of the nucleation events and varying the vortex-line density. The numerical results obtained are compared to a laminar solution of the Hall-Vinen-Bekarevich-Khalatnikov two-fluid equations proposed by Geurst for a channel in comparable nucleation regimes [4].

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Keywords: Quantised Vortex dynamics, Two-Fluid Model, Counterflow Channel

Strongly interacting charged vortices in superfluid ^{4}He at low temperatures

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We present results of the investigation of the dynamics of strongly interacting quantized vortex lines, nucleated by injected ions and then forced by an applied electric field that exerts force on the ions trapped on vortex cores. Charged vortex rings at low densities were found to propagate independently. However, when the density reaches the value $n \sim 4 \times 10^{-4} R^{-3}$, where R is the radius of vortex rings, the rings begin to reconnect leaving behind a slower moving tangle of charged vortex loops. The dynamics of this tangle are markedly different from that of isolated charged vortex rings. While at moderate densities and applied fields the trapped ions seem to drift with the tangle, after more intensive pumping in stronger fields the trapped ions begin to propagate through the tangle much faster than it drifts. Long intensive injections of current through the tangle result in sufficient momentum transfer to the superfluid so that a quasi-steady flow that fills the experimental container develops. After the pumping is discontinued, the vortex density of the flow was found to decay with time as $t^{-3/2}$, that is expected for quasi-classical turbulence. However, the value of the inferred effective kinematic viscosity is about an order of magnitude higher than that obtained from a similar free decay of turbulence generated by an impulsive spin-down.

Keywords: quantized vortex, quantum turbulence, superfluid turbulence, charged vortex tangle

Dynamics of vortex tangles in superfluid ^{4}He at low temperatures

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We investigated the dynamics of vortex tangles generated by either injected ions in an applied electric field or a change in the angular velocity of rotation of cubic containers. Injected ions initially propagate as charged vortex rings of growing radius R, but when their density reaches the value $\sim 4 \times 10^{-4} R^{-3}$ most rings reconnect leaving behind a slower moving tangle of charged vortex loops. Thanks to the randomizing action of frequent reconnections of these loops, the dynamics of this tangle are markedly different from that of isolated charged vortex rings. While at moderate densities and applied fields the trapped ions seem to drift with the tangle, after more intensive pumping in stronger fields the trapped ions begin to propagate through the tangle much faster than it drifts. Long intensive injections of current through the tangle result in sufficient momentum transfer to the superfluid so that a quasy-steady flow in all experimental container developes. After the pumping is discontinued, the vortex density of the flow decays with time as $t^{-3/2}$, that is expected for quasi-classical turbulence. However, the value of the inferred effective kinematic viscosity is about an order of magnitude higher than that obtained from a similar free decay of turbulence generated by an impulsive spin-down. If time permits, various experiments on the dynamics of turbulence at steady rotation will also be described. In these, with changing the amplitude of pumping, a crossover between a weakly perturbed array of rectilinear vortex lines (highly polarized nearly 2-dimensional quantum turbulence) to nearly isotropic 3-dimensional turbulence is observed.

Keywords: quantized vortex, quantum turbulence, superfluid turbulence, charged vortex tangle

INVITED PAPER

Numerical studies of superfluid spin down from rotation

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At constant rotation velocity vortices form a regular array where the superfluid component is in solid body motion with the container. After a sudden stop of rotation the equilibrium state is one with no vortices where the superfluid component is at rest. We study, especially at low temperatures where the vortex motion is typically turbulent, how this vortex-free state is reached by using the vortex filament model and numerical simulations. In cylindrically symmetric geometries (with respect to the initial rotation axis) the motion of vortices is dominated by radial laminar motion, where the polarization of the vortex tangle remains high and vortex length decays as $L \propto t^{-1}$. This is supported by the Helsinki measurements[1] in a cylindrical cell where the decay time, $\tau = 1/2\Omega_0\alpha$, is simply determined by the initial rotation velocity Ω_0 and the mutual friction parameter α. Annihilation proceeds on the cylindrical wall and is accompanied by a thin turbulent layer with a thickness of order intervortex distance. When cylindrical symmetry is broken, i.e. in a box geometry, or by tilting the cylinder with respect to the rotation axis, the decay of vorticity becomes faster, indicating a turbulent decay, $L \propto t^{-3/2}$. We analyze the homogeneity and isotropy of the vortex tangle during the turbulent decay and compare the simulation data with the Manchester experiments[2]. Our simulations also indicate that the presence of the AB phase boundary causes the motion of vortices to become turbulent, in accordance with the Helsinki experiments. In general, the lower the temperature, the smaller a perturbation is needed for turning laminar vortex flow turbulent, but the central question whether laminar spin down in the bulk volume can be stable in the limit $T \to 0$ is still unanswered.

1. V.B. Eltsov *et al.*, arXiv:1005.0546. 2. P.M. Walmsley *et al.* Phys. Rev. Lett. **99**, 265302 (2007).

Keywords: superfluid helium, vortex, spin down, rotation

Search for a link between pair-breaking and turbulence in superfluid ^{3}He-B

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We study the force velocity response of a 4.5μm wire in superfluid ^{3}He-B at low temperatures. At low velocities, superfluid flow around the vibrating wires is laminar exhibiting pure potential flow and the corresponding dependence of the velocity on force is linear. The linear damping term arises from the intrinsic losses in the vibrating wire and the exchange of momentum with ambient quasiparticles. When the velocity of the cylindrical wire reaches one third of the Landau velocity, pair-breaking starts to occur and becomes the dominating damping term. However, detailed investigation of the linear regime shows that, even below the pair-breaking limit, the damping force acting on a wire increases with a series of plateaus and discontinuities. These features are reproducible and are independent of temperature and magnetic field strength. On closer inspection, the plateaus appear to contain oscillations. It has been previously suggested that these oscillatory events are due to vortex-loop creation at protuberances on the wire.[1] From the amplitude of these oscillations, the size of emitted vortex loops can be estimated. We are able to alter the onset of the plateaus as well as the size of the oscillations by immersing the wire in vorticity produced by a neighbouring wire. Our data indicates that extra damping is observed once the plateau has been crossed, whether oscillations are present or not and hints to pair-breaking; suggesting a possible link with vortex production.

1. D.I. Bradley, *Phys Rev Lett*. **84**, 1252 (2000)

Keywords: Quantum Turbulence, Vortex Rings, Superfluid ^{3}He-B

Numerical study of the inhomogeneous vortex tangle at zero temperature

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We present the results of direct numerical simulations of the evolution of the nonuniform vortex tangle, originally concentrated in the restricted domain, at zero temperature. The numerical simulation is performed with the use of both full Biot-Savart law and localized induction approximation. An algorithm, which is based on consideration of crossing lines, is used for vortex reconnection processes. The calculations are carried out both in an infinite volume and in a cubic box with solid walls. We properly studied the change of the total vortex length in the initial domain. In particular we were carefully monitoring all mechanisms leading to the loss of the length, such as the change of length owing to reconnection processes, the eliminations of very small loos below the space resolution, the change of length due insertion and removing of points to supply numerical algorithm stability, etc. We found that the main mechanism of decrease of the vortex length inside the initial volume is related to the escaping of vortex loops, with is realized probably in the diffusion like manner, and the other mechanisms listed above do not affect appreciably on the spreading of the vortex tangle. We compared results of our numerical simulations with the theory of diffusion of the vortex tangle, elaborated early by one of the authors. We obtained, that the evolution of the length in the initial domain is satisfactory described by the diffusion equation: $\partial L/\partial t = D\nabla^2 L$, with the diffusion constant D equal to 2.2 κ where κ is the quantum of circulation. The good agreement with the experimental data and numerical simulation enables us to conclude that the diffusion process plays a dominant role in the free decay of the vortex tangle in the absence of the normal component. This work was supported by the RFBR (grants Nos 10-08-00369 and 10-02-00514).

Keywords: numerical simulation, superfluid helium, vortex tangle decay

Geometric symmetries in superfluid vortex dynamics

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The zero-point dynamics of a quantized vortex line in a superfluid feature symmetries associated with the geometric character of the complex-valued field, $w(z) = x(z)+iy(z)$, describing the instant shape of the line. Along with a natural set of Noether's constants of motion that—apart from their rather specific expressions in terms of $w(z)$—are nothing but components of the total linear and angular momenta of the fluid, the geometric symmetry brings about crucial consequences for kinetics of distortion waves on the vortex lines—the Kelvin waves. In combination with analysis of dimensions, the symmetry implies the locality of the Kelvin-wave cascade, and provides parametric estimates for non-local sub-leading contributions. Similar considerations apply to other systems with purely geometric degrees of freedom.

Keywords: quantized vortex dynamics, Kelvin wave cascade

Laminar vortex motion in rotating superfluid ^{3}He-B at $0.2\,T_\mathrm{c}$

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One of the central interests in superfluid helium studies at present is dissipation in vortex motion on approaching the zero temperature limit, $T \to 0$, particularly the mechanism of the excess dissipation beyond mutual friction in Fermi systems. The dynamic properties of vortices in ^{3}He-B have been studied to below $0.2\,T_\mathrm{c}$ by recording the decay time of vortex tangles [1], by measuring the propagation velocity of the precessing vortex front while it moves along a long rotating cylinder [2], and by monitoring vortex motions in rotating flow during the spin up or spin down of the superfluid component [3]. A large temperature independent excess dissipation is observed in the presence of turbulent vortex flow [1,2]. However, also laminar vortex flow in the bulk volume has been found possible to below $0.2\,T_\mathrm{c}$, with no measurable dissipation losses beyond mutual friction [3].

Here we examine examples of laminar flow. Transient vortex states in rotation are distinguished by high polarization of order $\sim 90\,\%$ along the rotation axis, causing laminar vortex flow in the bulk to be quite robust with respect to perturbations from axially symmetric rotating flow. The disorder from vortex formation and annihilation is limited to a narrow turbulent boundary layer coating the cylindrical container surface. This boundary layer is seen in vortex filament calculations, where it increases in width with decreasing temperature to about one inter-vortex distance at $0.2\,T_\mathrm{c}$. It contains the reconnections of the vortices within the outermost ring with the cylinder surface and with neighboring vortices.

1. D.I. Bradley *et al.*, Phys. Rev. Lett. **96**, 035301 (2006). — 2. V.B. Eltsov *et al.*, Phys. Rev. Lett. **99**,265301 (2007). — 3. V.B. Eltsov *et al.*, preprint arXiv:1005.0546.

Keywords: superfluid ^{3}He-B, rotating flow, vortices, turbulence, laminar vortex flow, mutual friction

Energy spectra of homogeneous isotropic turbulence in superfluids

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I will present *Minimal Model of Quantum Turbulence* (MinMod) aimed to describe as simple as possible homogeneous, isotropic turbulence of superfluids in zero temperature limit with energy pumping at scales $\mathcal{L}$ much above the intervortex distance ℓ. ***In classical hydrodynamic (HD) interval of scales,*** $\mathcal{L} > r > \ell$, MinMod reproduces Kolmogorov-41 spectrum $E(k) \simeq \varepsilon^{2/3}k^{-5/3}$ (in k-space) with constant energy flux ε, and, for $\varepsilon = 0$, a thermodynamic equilibrium with HD energy equipartition $E(k) \propto k^2$.

In quantum Kelvin wave (KW) region, $\ell > r > a$ (a – vortex core radius) MinMod is based on the explicit calculations of full 6-KW interaction coefficients [1] and L'vov-Nazarenko [2] KW-spectrum $E(k) \simeq \Lambda\,\varepsilon^{1/3}\kappa\,\ell^{-4/3}k^{-5/3}$ ($\Lambda = \ln \ell/a\,,$ κ-circulation quantum). This spectrum results from step-by-step energy cascade caused by 4-KW interactions in a system of quantized vortex filaments with random large-scale curvature. MinMod reproduces also thermodynamic equilibrium in the KW system with the energy equipartition, $E(k)$ =const. ***At crossover scales*** $k\ell \sim 1$ MinMod considers superfluid turbulence as a mixture of HD and KW motions [3] with fractions that depend on $k\ell$.

Resulting energy spectrum for $\Lambda \gg 1$ consists of: 1) Kolmogorov-41 part, $E(k) \propto k^{-5/3}$ for $k\ell \ll 1$;
2) the energy accumulation with HD equilibrium, $E(k) \propto k^2$ at $k\ell \lesssim 1$; 3) followed by the KW equilibrium, $E(k)$ $\sim$const. at $k\ell \gtrsim 1$; 4) and by the L'vov-Nazarenko KW spectrum $E(k) \propto k^{-5/3}$ for $k\ell \gg 1$.

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Keywords: Hydrodynamic turbulence, bottleneck energy accumulation, Kelvin-wave turbulence.

Time-of-flight measurements of vortex rings in superfluid ^{4}He at high temperatures

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We report the time-of-flight measurements of quantized vortex rings generated by a vibrating wire in superfluid ^{4}He at high temperatures where normal fluid component exists. It is considered that quantum turbulence consists of a tangle of quantized vortices and nucleates vortex rings, which propagate in superfluid and can attach to boundaries. In previous works at 30 mK,[1,2] the transition to turbulence triggered by free vortex rings and then propagation of trigger vortex rings were studied using two vibrating wires: a generator wire and a detector wire of vortices. At high temperatures, motions of vortices are expected to be greatly different from those at 30 mK because of the normal fluid component: mutual friction with the normal fluid component disturbs propagating vortex rings. In this work, we measured the time-of-flights of vortices propagating in a distance of 0.88 mm above 1.25K, corresponding to normal fluid fraction of helium of more than 4%, using a generator wire and a detector wire. We find that the time-of-flights distribute from 0.06 s to 27.4 s, much larger than the time-of-flight of vortex rings at 30 mK,[2] which is order of 10 ms. Circular vortex rings limited in the size of a generator amplitude will be dissipated due to mutual friction with the normal fluid component. Therefore the present results imply that non-circular vortex rings or vortex tangles are generated by the generator, propagating slowly and colliding to the detector before complete dissipation.

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Keywords: superfluid ^{4}He, quantized vortex, turbulence transition, oscillating structures

Motions of vortex lines attached to oscillating objects in turbulent state of superfluid ^{4}He

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Oscillating objects can generate turbulence in superfluids even at very low temperature. In many cases, vortex lines are attached initially to oscillating objects, resulting in causing turbulence. Recently, we have successfully obtained a vibrating wire effectively free of vortices,[1] enabling the study of vortex dynamics in turbulence without concerning initially attached vortices. The vortex-free vibrating wire can generate turbulence only when vortex rings are applied from a vortex ring source to the wire.[2] In a previous study,[3] we reported that the lifetimes of a turbulent state distribute exponentially at a low driving force and that the mean lifetime decreases exponentially with decreasing driving force but decreases considerably below a critical driving force.
The present concern is the critical behaviors of vortex dynamics near the turbulent-to-laminar transition. We find that the critical velocity of a turbulent state is proportional to the square root of vibrating frequency. We estimate a velocity at which an oscillating object can extend half-circular vortex loops and find that it is proportional to the square root of frequency, which is consistent with the experimental results observed here. We also find that the resonance frequency of the vibrating wire increases in a turbulent state, implying that vortex loops large enough to vibrate at the same frequency affect the motion of the wire.

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3. Yano, H., Nago, Y., *et al.*, Phys. Rev. B **81**, (2010) in press.

Keywords: superfluid ^{4}He, turbulence transition, oscillating structures

Dynamics of inhomogeneous vortex tangles in quantum systems

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We present a series of analytical and numerical studies of chaotic dynamics of vortices in quantum systems in inhomogeneous conditions. Vortex loops composing the vortex tangle can move as a whole with some drift velocity depending on their structure and length. The flux of length, energy, momentum etc., executed by the moving vortex loops takes place. Supposing that vortex loops have a Brownian structure we calculated the (size dependent) drift velocity and free path of the loops. Based on this calculation we obtained that the evolution of the vortex line density obeys a diffusion type equation with the diffusion constant equal to 2κ (where κ is the quantum of circulation). The mathematical details are exposed in previous works by the author [1]. As an application we used the diffusion equation to describe the decay of the vortex tangle at very low temperatures. We compared the solution with recent experiments on the decay of superfluid turbulence. The good agreement with the experimental data and numerical simulation enables us to conclude that the diffusion process plays a dominant role in the free decay of the vortex tangle in the absence of the normal component. Another application considered in presentation is the problem of motion of turbulent front. The key supposition is that the motion of front is executed in the diffusion like manner with the strong source of vortex line density behind the vortex front. This work was supported by grants 10-08-00369 and 10-02-00514 from the RFBR.

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Keywords: inhomogeneous vortex tangle, vortex loops diffusion, decay of superfluid turbulence

Thermal detection of quantum turbulent decay in superfluid ^{3}He-B at ultralow temperatures

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Previous experiments undertaken at Lancaster have measured the decay of quantum turbulence in superfluid ^{3}He-B generated by a vibrating wire grid at ultralow temperatures.[1] The decay was found to be consistent with a classical Kolmogorov-type energy cascade. At these low temperatures, the normal fluid component is essentially negligible and decoupled from the superfluid component. The decay of quantum turbulence cannot therefore be explained in terms of a classical decay mechanism of mutual friction due to the normal fluid viscosity.
To further our investigations into the decay of quantum turbulence, an experimental cell has been constructed consisting of a superfluid ^{3}He-B quasiparticle "black body" radiator housing two vibrating grids as well as a selection of thermometry wires which allow temperatures to be measured both inside and outside the radiator. This is mounted on a Lancaster style nuclear refrigerator capable of cooling ^{3}He to $\sim 110\,\mu$K. We present a set of preliminary data derived from attempts to thermally detect the energy produced by the decay of quantum turbulence. We hope that this will further our insight into the microscopic mechanism responsible for the dissipation of quantum turbulence.

1. S.N. Fisher et al, Decay of Pure Quantum Turbulence in Superfluid ^{3}He-B, Phys. Rev. Lett. **96**, 035301 (2006)

Keywords: ^{3}He-B, black body radiator, quantum turbulent decay, vibrating wire grid

Quantum turbulence within the Gross-Pitaevskii model

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We will discuss some results in the field of quantum turbulence with special attention to turbulent cascades. In particular we will focus on the dynamics of Bose-Einstein condensates which are modeled via the Gross-Pitaevskii equation in the forced and dissipated case. The nonlinearity of such equation is responsible for the energy and particles transfers in Fourier space: in certain conditions constant fluxes - similar to Richardson's cascades in classical Navier-Stokes turbulence - can develop.
After giving a sketch on mathematical theories able to predict such turbulent states, we will present recent numerical results on different regimes observed in the three-dimensional case. Depending on the way the large scales are dissipated, we observed either power-law spectra that are consistent with the weak turbulence theory prediction or steeper one which can be explained in terms of the critical balance argument.[1]

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Keywords: Bose-Eistein condensation, wave turbulence, Kolmogorov-Zakharov spectra, nonlinear phenomena

Superfluid high Reynolds number von Kármán experiment

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This facility will exploit the capacities of a high cooling power refrigerator ($400\,W$ @ $1.8\,K$) for implementing a large dimension von Karman flow (inner diameter 80 cm), working as well with He-I or gaseous helium, as with He-II down to 1.65 K. A Von Karman flow is produced between two parallel contrarotating or co-rotating impellers. Depending on the location inside the flow, it presents either a reasonable example of homogeneous isotropic turbulence, or the interesting case of strong anisotropy. Realisation of a large scale experiment permits to address either the high Reynolds numbers limit ($Re \simeq 10^7 - 10^8$) or resolve the dissipative scales of superfluid turbulence at lower Re. Concerning the facility itself, challenges concern heat extraction, mechanism associated with the turbines operating in subcooled superfluid helium and safety issues. Design of the experiments, choice of solutions related to the keypoints mentioned above and photos of components are presented.

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Keywords: Cryogenic helium, Superfluid, Von Karman flow, Quantum turbulence, Large scale facility

Velocity spectra in turbulent He II

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Velocity fluctuation measurements in a superfluid turbulent flow were reported more than a decade ago [EPL 43 p29, 1998]: the power spectrum scaling, compatible with a $f^{-5/3}$ scaling was the first experimental evidence that superfluid can undergo a Kolmogorov-like turbulent cascade.
We present the first experimental confirmation of this result and extend it to different flow geometries using stagnation pressure anemometers both in He I and He II within three cryogenic liquid $^4\mathrm{He}$ steady flows: grid and wake flows in a pressurized wind tunnel capable of achieving mean velocities up to 5 m/s at temperatures above and below the superfluid transition, down to 1.7 K, and a "chunk" turbulence flow at 1.55 K, able to sustain mean superfluid velocities up to 1.3 m/s.
Depending on the flows, our velocity probes are resolving from one to two decades of the inertial regime of the turbulent cascade, which allows quantitative measurement of some flow properties, such as the integral length scale and the turbulence intensity, which have been found to match their classical values.

Acknowledgments: ANR (grant ANR-05-BLAN-0316, "TSF") and Région Rhône-Alpes

Keywords: Superfluid, Cryogenic helium, Quantum turbulence, Velocity spectrum

Saturation of counterflow turbulence in He II

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One of the most important problems of classical fluid dynamics is the decay of homogeneous isotropic turbulence. We are interested in this problem in the context of helium II. Here the turbulence can be easily generated by a heat flux which induces a relative velocity (counterflow) between the normal fluid and the superfluid, hence, if the heat flux exceeds a critical value, the formation of a tangle of quantised vortex lines of density L. When the heat flux is stopped the tangle decays, but there are puzzling features. Direct application of Vinen's equation yields the scaling $L \sim t^{-1}$ where t is time. Schwarz and Rozen [1] observed a faster decay followed by a slower decay. Skrbek et al. [2] found an initial transient followed by the same classical $t^{-3/2}$ scaling observed in grid-generated turbulence [3]. We present a model which accounts for these apparently contradictory results.

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3. M.R. Smith, R.J. Donnelly, N. Goldenfeld, and W. F. Vinen, Phys. Rev. Lett. **71**, 2583 (1993).

Keywords: vortices, turbulence, decay, counterflow, helium II

Interactions of thermal quasiparticles with turbulent structures in ^{3}He-B

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We discuss theoretical and numerical aspects of Andreev scattering technique [1] which is used to detect vortex filaments in turbulent ^{3}He-B. Earlier, using a 2D vortex point model, we found [2] that the Andreev shadow caused by systems of vortices is not necessarily the sum of shadows of individual vortices. We discuss implications of such a 'partial screening' for interpretation of experiments. We also develop our 2D model to compute the average Andreev reflection coefficient of a flux of thermal quasiparticles incident upon a random system of vortex points modelling a 3D vortex tangle, and a system of vortex-antivortex pairs modelling a 3D gas of vortex rings. Of particular interest is the change of the reflection coefficient with the transition between these two configurations of point vortices. Our study is motivated by observation [3] of the transition from a gas of vortex rings to a dense tangle. We argue that such a transition should be associated with the several-fold increase of the average reflection coefficient.

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Keywords: vortices, turbulence, thermal quasiparticle excitations, ^{3}He-B

Quantum turbulence produced by vibrating grids in superfluid ^{3}He-B

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Quantum turbulence consists of a tangle of quantized vortex lines which interact via their self induced flow. At very low temperatures there is no normal fluid component and no associated viscosity, and the effect of the mutual friction on evolution of turbulence is negligible. In ^{3}He-B at low temperatures we have developed noninvasive but sensitive methods to study turbulent tangles using existing ambient excitations.
We have investigated quantum turbulence generated by two different vibrating grids and find that quantum turbulence produced is qualitatively similar in both cases. At low velocities vibrating grids produce many ballistic vortex rings that propagate independently. Our detection techniques suggest that properties of the ballistic rings generated are determined by frequencies of grid oscillations rather than a grid mesh size. A formation of the vortex tangle from ballistic vortex rings at grid's critical velocity is clearly observed by a cross-correlation technique utilizing several turbulence detectors. Improved measurements on steady-state production of vorticity permit us to compare and analyze energy spectra for various types of vorticity generated by grid. Results of steady-state measurements are consistent with studies of decay and onset of turbulence.

Keywords: quantum turbulence, superfluid helium, vortex rings, vortex tangle

Studies of turbulence generated by vibrating wire in He-I and He-II

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For many decades quantum turbulence has been subject of investigations in superfluid ^{4}He at high temperatures. Strength of helium-4 for turbulent studies is that by changing temperature less than three times from 4.2K down to 1.5K it is possible to contrast classical and quantum turbulence. Recently various vibrating objects: spheres, grids, wires and forks became popular tools to generate and probe turbulence in helium. We have initiated studies of superfluid turbulence in ^{4}He using two 13.5 micron diameter vibrating wire resonators placed in the box with small orifice.
We have studied force-velocity characteristics of the wires in normal and superfluid helium in velocity range up to several meters. We can clearly identify transitions from laminar to turbulent behavior by increased damping experienced by the wire in normal fluid as well as observation of hysteresis in superfluid. Unexpectedly, our results in superfluid helium show that in certain conditions transition to turbulence in superfluid component does not result in full coupling of normal and superfluid fractions as usually anticipated in that velocity and temperature range. The observed damping of the wire is much smaller than observed in normal turbulence or a superfluid turbulence when normal and superfluid components are interlocked. Critical velocities for several cooldowns are contrasted by plotting drag coefficients for the wires against wire velocities. Several scenarios are considered to explain observed results.

Keywords: quantum turbulence, superfluid helium 4, vibrating wires, normal turbulence

Simulation of counterflow turbulence by vortex filaments *Statistics of vortex reconnections*

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By using the vortex filament model with the full Biot-Savart law, we have succeeded for the first time in generating the statistically steady state of counterflow turbulence in superfluid ^{4}He under periodic boundary conditions [1]. This state exhibits the characteristic relation $L = \gamma^2 v_{ns}^2$ between the line-length density L and the counterflow relative velocity v_{ns} and there is quantitative agreement between the coefficient γ and some measured values. Since we obtained the realistic state of quantum turbulence, we will use the numerical data to study the statistical property of turbulence as the next step. We focus on the statistical property of reconnection dynamics from about 350 reconnection events in our steady counterflow turbulence simulation, and characterize the dynamics by the minimum separation distance $\delta(t)$ between the two reconnecting vortices. For a statistical understanding, the separation distance $\delta(t)$ is fitted by a correction-factor expression $\delta(t) = A(\kappa|t-t_0|)^{1/2}(1+c|t-t_0|)$, which was performed in the visualization experiments using the solid hydrogen tracer particles by Paoletti *et al.*[2] The statistics of our data shows that the separation distance typically follows an asymptotic relation $\delta = A(\kappa|t-t_0|)^{1/2}$, which indicates that the quantized circulation κ is the dominant controlling feature.

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Keywords: superfluid ^{4}He, quantized vortices, counterflow

Vortex dynamics in a two-phase sample of superfluid ^{3}He

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At $0.2\,T_c$ mutual friction dissipation is two orders of magnitude larger in ^{3}He-A phase than in ^{3}He-B. The slower vortex dynamics in ^{3}He-B leads to new phenomena when the vortices are partly in the A and partly in the B phase. The static vortex configurations have been studied previously in a long rotating cylinder which is divided with a magnetic-field-stabilized A-phase barrier layer in two long B-phase sections [1]. Here NMR measurement is used to monitor the spin-up and spin-down vortex flow responses in the B-phase to rapid changes in rotation. Spin up is started from zero rotation, while spin down is started from the equilibrium vortex state where the vortices in the two B-phase sections are interconnected across the A-phase barrier layer. Compared to measurements in the absence of the A-phase barrier layer [2], spin up is unusually slow, owing to almost complete absence of remanent vortices, while spin down is found to be much faster, indicating turbulent response. In agreement with vortex filament calculations, two novel phenomena emerge from spin down measurements: (i) Because of rapid radial motion the vortices in the A phase are pulled to the cylinder wall and a vortex-free hollow is created in the B phase at the AB interface. (ii) Differences in azimuthal motion between the two phases cause the vortices around the hollow dome to become helically twisted around the cylinder axis. The inhomogeneous twist introduces reconnections and turbulence among the vortices, which is observed as rapid spin down.

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2. V.B. Eltsov *et al.*, preprint arXiv:1005.0546.

Keywords: superfluid ^{3}He, rotating flow, vortices, AB interface, turbulence, mutual friction

Dynamics of polarized quantum turbulence in rotating superfluid ^{4}He

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Turbulence in superfluid ^{4}He at low temperatures was studied in a cube-shaped container that was rotating continuously. This allows the dynamics of polarized tangles of quantized vortex lines to be probed. In one experiment, an AC component of rotation of variable frequency and amplitude was superimposed on the DC angular velocity of rotation. The extent of the disturbance was monitored through motion of negative ions travelling along vortex lines in the axial direction and also by measurements of the vortex line density deduced from the attenuation of a pulse of charged vortex rings travelling in the transverse direction. Frequency-dependent resonances were observed along with the amplitude-dependent crossover from a weakly perturbed array of rectilinear vortex lines (highly polarized quantum turbulence) to nearly isotropic 3d turbulence. In another experiment, the vortex array was perturbed by injecting a charged vortex tangle across it. The density and polarisation of the resulting turbulent state was characterized by the amplitude and time of flight of a subsequent probe pulse of negative ions.

Keywords: quantized vortex, quantum turbulence, superfluid turbulence,polarized vortex tangle, rotating turbulence

Transition to quantum turbulence and the propagation of vortex loops at finite temperature

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We performed numerical simulation of the transition to quantum turbulence and the propagation of vortex loops at finite temperatures in order to understand the experiments using vibrating wires in superfluid ^{4}He by Yano $et\ al$. We injected vortex rings to a finite volume in order to simulate emission of vortices from the wire. When the injected vortices are dilute, they should decay by mutual friction. When they are dense, however, vortex tangles are generated through vortex reconnections and emit large vortex loops. The large vortex loops can travel a long distance before disappearing, which is much different from the dilute case. The numerical results are consistent with the experimental results.

Keywords: Quantized vortex, SUperfluid ^{4}He

6 Reduced dimensionality, quantum fluids and solids

Excitation spectra of two-dimensional hard-core bosons in the superfluid phase

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The spectra of elementary excitations of the hard-core bosons on square and triangular lattices in the superfluid phase are investigated using the second order spin-wave theory. The nearest-neighbor repulsion and next-nearest-neighbor interaction (repulsive or attractive) are taken into account. The behavior of the spectra along different directions in the Brillouin zone at fixed particle density is analyzed in detail at various ratios between the parameters of the system. Special attention is devoted to the investigation of the spectrum peculiarities, in particular the roton minima. In the case of the triangular lattice with the next-nearest-neighbor repulsion, next to the known minima on the zone boundary, a true roton minimum inside the Brillouin zone is found. Expressions for the spin-wave velocity are obtained in an explicit form for both types of lattices. Our analytical results, found with account for the second order corrections to the spin-wave spectrum, are in very good agreement with the corresponding data known from literature.[1,2]

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Keywords: hard-core bosons, excitation spectra, superfluid, roton minima

Tuning surface roughness to momentum-couple highly confined normal ^{3}He

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In a previous experiment[1] we observed the inertia of liquid ^{3}He confined to a 650 nm thick slab (defined by highly polished silicon and glass surfaces) to decouple below 100 mK. This can be understood in terms of surface roughness where the characteristic parameters of height l and autocorrelation length R dictate the phenomenological scattering rate τ^{-1}. We describe our efforts to roughen the confining surfaces, so that the liquid remains coupled down to the superfluid transition temperature, but without compromising the confinement length scale. New experimental arrangements capable of resolving the coupled inertia and dissipation will also be described. This research was supported by the NSF under DMR-0806629 (Materials World Network at Cornell) and the EPSRC under EP/E054129/1 and EP/C522877/1 (at Royal Holloway).

1. S.G. Dimov *et al* “Decoupling of confined normal ^{3}He”. J. Low Temp Phys **158** 155, 2010.

Keywords: Surface Roughness, Confined ^{3}He

Superfluid ^{3}He-B spinwaves in cylinder of one millimeter in diameter at low pressures

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One can expect spinwaves in the superfluid ^{3}He-B if the liquid is restricted by its geometry. The orientation of the order parameter of the superfluid is determined by the surface field-, bulk field- and bulk bending free energy, and gradually changes over a typical size equal to the magnetic coherence length. The profile of the order parameter functions as a potential, which determines how many spinwaves modes can be formed into the container. Spinwaves in restricted geometry, such as slabs and cylinders, were already found in the 70ths. In both geometries it was found that the intensities of higher modes reduces. This is in agreement with theory for slab geometries, but one should be able to find equal intensities for all modes, if one is able to create a quadratic potential into a cylindrical geometry.

As cooled, the orientation of the order parameter in our cylinder starts to grow into a flare out configuration, but is expected to undergo a transition at lower temperatures as the magnetic coherence length is then several times larger then the cylinders diameter. However, such transition is not observed, and the system seems to be 'stuck' into the flare out configuration. The advance of this meta-stable configuration is that it forms a nearly quadratic potential. Here the observed spinwave modes have nearly equal intensities. Also the amount of the spinwaves grow with increasing pressure, which is in agreement by theory as the energy difference per mode is a function of the dipole coherence length.

Finally, the expected (based on energetic arguments) order parameter configuration (uniform texture) can be realized if a heat pulse is absorbed into the meta-stable configuration. After the liquid has become normal its cools rapidly to the uniform texture, which is dominated by the surface field free energy.

Keywords: Superfluid 3He, Spinwaves, Restricted geometry, NMR

Features of magnetoresistance and magnetothermopower in $Bi_{1-x}Sb_x$ wires near the gapless state

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We have found a significant increase in the magnetoresistance accompanied by an anomalous dependence of magnetothermopower in single crystals, micro- and nanowires of $Bi_{1-x}Sb_x$ obtained by liquid phase casting.[1] The effect is interpreted in terms of the occurrence of a "gapless state" in Bi-Sb wires at a certain concentration of Sb, which was theoretically considered in the work of Abrikosov and Falkowskiy.[2]

This work was supported by SCOPES IZ73ZO_ 127968 "Functional Nanowires" and Ukrainian project 10.820.05.08.UF.

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Keywords: quantum wires, gapless state, giant magnetoresistance

Hard-core bosons on a square lattice in the random phase approximation

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Using random phase approximation (RPA) we calculate thermodynamic functions of a square lattice hard-core boson (HCB) model with nearest (nn) V_1 and next-nearest (nnn) V_2 neighbor interactions in terms of an equvalent anisotropic spin-1/2 XXZ model in a magnetic field. The system undergoes liquid-solid phase transitions that can be either of the first or second order. Depending on the hopping value t and the ratio $\alpha = V_1/V_2$ between nn and nnn interactions, the system displays two types of critical behavior. The line of the first order transitions terminates in a bicritical endpoint inside the solid phase or ends in a tricritical point continuously giving way to the second order phase transition line. The connection of the hopping term t and the ratio α with criticality of the system is investigated. We have built the $\alpha - 1/\Delta$ diagram ($\Delta = V_1/(2t)$), the locus of critical points where bi- and tricritical regimes change into each other. It turned out that over the interval $1/(1+\alpha) < \Delta < \Delta_0 \simeq 1.38$ only the tricritical regime is possible. At fixed $\Delta > \Delta_0$ two points $\alpha_{c1}(\Delta)$ and $\alpha_{c2}(\Delta)$ appear in the $\alpha - 1/\Delta$ plane, so that inside and outside the interval $\alpha_{c1} < \alpha < \alpha_{c2}$ the system displays the bi- and tricritical behavior, respectively. If $\Delta \to \infty$ then $\alpha_{c1} \to 0$ and $\alpha_{c2} \to 0.6$ in full agreement with known mean-field results. For the anisotropic 1/2-spin XXZ model in a magnetic field we have derived the exact expression connecting the internal energy with the transverse Green function. The heat capacity $C(T)$ and magnetic susceptibility $\chi(T)$ calculated within RPA exhibit λ-point kind irregularities at phase transition temperature. In the paramagnetic phase a temperature run $\chi(T)$ depends significantly on whether the magnetic field h is lower or higher than the critical value h_c which is a function of both α and Δ. The quantity h_c is the critical field that determines the phase transition between spin-flop and paramagnetic states at $T = 0$.

Keywords: hard-core bosons, phase diagram, random phase approximation, susceptibility, heat capacity

Novel phases of quantum fluids near solid surfaces

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Keywords: Surfaces

INVITED PAPER

Giant coupling effects in confined ^{4}He

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Coupling between two superconductors or superfluids can be thought of as resulting from wave function overlap. In suitable weak-link geometries this leads to Josephson effects that are well known in superconductors, and are of more recent vintage in superfluids. We report on measurements of superfluid density and heat capacity for ^{4}He confined between two bonded silicon wafers. These data are informative both about the nature of the weak links and the regions which they couple. The confinement consists of lithographically-defined boxes of helium linked through a uniform film or a shallow channel. These data show coupling and collective effects that can extend to distances of over 100 times the bulk correlation length.[1] This is clearly beyond distances expected on the basis of wave function overlap. It seems likely that these large effects are due to the role that critical fluctuations play in ^{4}He, but not in the low temperature superconductors. In the case of the high T_c superconductors, giant proximity effects have also been reported.[2] It has been suggested that these are due to the existence of superconducting phase fluctuations in the normal layer of a superconductor-normal-superconductor junction[3].

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Keywords: phase transition, proximity effects, fluctuations, reduced dimensionality

INVITED PAPER

Quantum gases on graphene

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The phase diagrams of the first layer of ^{4}He and H_2 on top of a single graphene sheet have been calculated by means of a series of Diffusion Monte Carlo calculations and compared to the same diagrams for graphite. The results indicate that the main difference is the binding energy of the quantum gases to the absorbent, lower in the graphene case. In both cases, the ground state of the adsorbate is a $\sqrt{3} \times \sqrt{3}$ structure, that transforms, upon pressure, into a triangular solid. No other stable phases were found for ^{4}He, but a stripped α phase appears between the registered and the triangular solids in the case of H_2.

Keywords: phase diagram, graphene

INVITED PAPER

Fluid helium in a narrow pore at zero temperature

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The zero temperature adsorption isotherm of ^{4}He in a rigid cylindrical pore with alkaline walls is computed within finite-range density functional theory, with the radius of the tube as a parameter. It is shown that starting from narrow pores and increasing the radius, the adsorbed helium first becomes bound in a quasi-onedimensional phase, and finally condenses into a quasi-twodimensional configuration by going through an almost filling situation. The results are in agreement with recent calculations for carbon nanotubes based on thermodynamical approaches.

Keywords: helium condensation, varying pore radius, transition

Adsorption of helium in a deformed pore

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The adsorption potential in the interior of an infinite nanopore along the z–axis, with varying radius $R(z)$, is derived as a function of a deformation parameter. Detailed calculations for a carbon nanotube indicate that according to the magnitude of the deformation the potential landscape can be substantially modified, giving rise to regions of weakened confining strength, and even changing the nature of the minima. This modified field may induce thermodynamic instabilities in the adsorbed fluid. A similar situation takes place for other materials, and is illustrated for helium in an alkaline pore with variable cross–section.

Keywords: deformed pore,adsorption potential,instabilities

Path Integral calculation of ^{4}He in quasi-one-dimensional channels

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We have carried out a series of torsional oscillator measurements for liquid ^{4}He confined in a one-dimensional (1D) channel (FSM16). It was found that the temperature below which a rapid increase of the superfluid fraction in the 1D channel is observed, is strongly suppressed from the bulk superfluid transition temperature. For 2.8-nm channel, this temperature $T_{\rm o}$ takes place at 0.9 K under low pressure, and is strongly suppressed by pressurization. Moreover, for 2.2-nm channel the rapid increase was not observed clearly.[1] To clarify these properties of ^{4}He in 1D channel, we have performed a numerical calculation of path integral Monte Carlo. We calculated the energy of ^{4}He confined in cylindrical containers in the range of liquid density. $T_{\rm onset}$, at which the energy drops due to particle exchanges, does not depend strongly on diameter down to 1.7-nm, and then shifts to lower temperature with further narrowing. Below 0.48-nm channel, $T_{\rm onset}$ disappears. The diameter dependence of $T_{\rm onset}$ is similar to the behavior of $T_{\rm o}$ observed by the torsional oscillator.

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Keywords: superfluidity, quasi one-dimension

Superfluid transition in ^{4}He films adsorbed on thin porous golds submicronmeter thick

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The superfluid transition of ^{4}He films on planar substrate, purely 2D substrate, shows the Kosterlitz-Thouless (KT) transition. However, in multiple-connected porous substrates, a dimensional crossover from a 2D-XY (KT transition) to a 3D-XY system is expected when the correlation length $\xi \propto (1 - T/T_{\rm c})^{-0.67}$ grows near $T_{\rm c}$ and exceeds a length scale of the pore connection [1]. We present superfluid density measurements by 20 MHz quartz crystal microbalance (QCM) for the three different porous gold substrates with the thickness $L = 410$, 840, and 1290 nm (diameter of gold strands $d_{\rm gold} = 29$, 38, and 40 nm respectively) in the temperature range of $0.7 \sim 1.0$ K. Our results are fully explained by the scenario of the 2D-3D crossover even at the high frequency, and we find a 3D critical region when ξ exceeds ~ 150 nm, which is approximately 5 times larger than $d_{\rm gold}$. We also suggest a possibility that a finite size effect occurs when ξ exceeds the substrate thickness L.

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Keywords: ^{4}He film, superfluid transition, finite size effect

Quantum interference in bismuth nanowires: evidence for surface charges

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We report the results of magnetoresistance (MR) studies of single crystal Bi nanowires with diameter $d < 80$ nm. The single crystal nanowire samples were prepared by Tailor-Ulitovsky technique. Due to semimetal-to-semiconductor transformation and big density of surface states with strong spinorbit interactions the charge carriers are confined to the conducting tube made of surface states. The Aharonov-Bohm oscillations, extracted from the longitudinal MR, with two periods ΔB proportional to h/e and h/2e were observed, the manifestation of Berry phase was found in h/2e oscillations [1,2]. But even in the case of transverse magnetic field, the equidistant oscillations of MR exist at certain rotation angles and the period of oscillations depends on the wire diameter d as for the case of longitudinal MR. An interpretation of transverse MR oscillations is presented.
This work was supported by the STCU Grant N 5050.

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Keywords: bismuth nanowire, magnetoresistance, Aharonov-Bohm oscillations, Berry phase, semimetal-to-semiconductor transformations, surfase states

Quantum Monte Carlo simulations of the Kosterlitz-Thouless transition for two-dimensional disordered Bose-Hubbard model

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A lot of interest has been paid to the nature of disordered Bose systems. These systems can be realized by ^{4}He in porous glasses or atomic gases in optical trap potentials. Our study is devoted to numerical simulations for two-dimensional (2D) disordered Bose systems using quantum Monte Carlo method. In this report, the chemical potential was assumed to depend on the site randomly and its distribution was given by a Gaussian distribution. In 2D pure Bose systems, it is well-known that the Koterlitz-Thouless (KT) transition occcurs. Our motivation is to study effects of the randomness on KT transition. By changing the dispersion of the Gaussian distribution, we found that the transition temperature decreases as the dispersion increases. The phase diagram was obtained to show the superfluid and the disordered phases. We try to understand our results by using the concept of ”percolation”.

Keywords: Kosterlitz-Thouless transition, superfluid, quantum Monte Carlo

Low-temperature properties of quantum Heisenberg antiferromagnet and Hubbard model on one dimensional lattices containing equilateral triangles

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We study the quantum Heisenberg antiferromagnet and the Hubbard model on two one-dimensional lattices containing equilateral triangles, namely, i) a chain of corner-sharing double tetrahedra [1,2] and ii) a frustrated three-leg ladder [3]. These lattices support localized one-particle (one-magnon or one-electron) states which are located on triangular traps. Each of these states is two-fold degenerate due to chirality of the triangle and becomes the lowest-energy state for sufficiently strong antiferromagnetic interaction or (positive) hopping integral along the triangle sides. Using the localized-state picture we construct many-body states, count their number, and calculate their contribution to the thermodynamic quantities. In strong magnetic fields around the saturation field h_0 (Heisenberg antiferromagnet) or around a particular value of the chemical potential μ_0 (Hubbard model) the constructed states dominate the low-temperature thermodynamics of the systems. Additional interspin interactions or intersite hoppings in the model Hamiltonians may lift the degeneracy with respect to chirality. We compare analytical predictions with exact diagonalization data for finite quantum systems.

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Keywords: frustration, localized states, flat bands, Heisenberg antiferromagnet, Hubbard model

Helium fluid in extremely narrow 1D channels 1.5 nm in diameter

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Recently we have studied 1D states of He fluid adsorbed in a silica-based nanoporous material FSM with straight uniform 1D channels of various diameters 1.8-4.7 nm[1]. While narrower channels are basically favorable to realize the 1D states of adsorbed He, the stronger adsorption potential and its corrugation from the substrate disturb motion of He adatoms critical for the quantum behavior. To find the optimum channels for 1D He quantum fluid close to the narrowest limit, we have measured heat capacities of ^{4}He and ^{3}He adsorbed in channels 1.5 nm in diameter, which are narrower than those used in previous studies. From the heat of desorption for ^{4}He adatoms, the coverage n_f, up to which ^{4}He film grows uniformly, is determined to be 15 μmol/m^2 using the Frenkel-Halsey-Hill model. At coverages sufficiently below n_f, the temperature dependence of the ^{4}He heat capacity has a shoulder, above which adsorbed ^{4}He is delocalized from the substrate. However, the depression indicating quantum behavior has not been observed up to n_f, which suggests that ^{4}He film remains amorphous-like normal fluid until n_f. In contrast, dilute ^{3}He, which was adsorbed additionally on ^{4}He film slightly below n_f, has a large temperature-independent specific heat comparable to the gas constant. It is likely to indicate that ^{3}He atoms behave like gas even in the extremely narrow channels, because of smoothing and weakening of the substrate potential by preplating with ^{4}He.

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Keywords: ^{4}He film, 1D state, quantum fluid, nano-scale 1D channel

Third sound in superfluid ^{4}He films adsorbed on packed multiwall carbon nanotubes

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We are studying the propagation of third sound in thin ^{4}He films adsorbed on multiwall carbon nanotubes. The nanotubes of average diameter 15 nm are lightly packed into a cylindrical resonator, with a resistor bolometer at the cylinder end to detect the temperature oscillations accompanying the waves. The lowest standing-wave mode is excited by mechanical vibrations, with FFT analysis allowing measurement of both the sound speed and dissipation. We observe the KT onset transition, and then at higher thicknesses capillary condensation becomes important. At 1.3 K we do not observe layering effects, and it may be necessary to make lower-temperature measurements for this. We also do not see any effects attributable to helium adsorbed on the inner surface of the nanotubes.

Keywords: helium films, adsorption on nanotubes, third sound

Impurity gel samples in superfluid He-II – results of neutron studies

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A few years ago we proposed the idea to use massive deuterium or heavy water gel samples in He-II cooled down to a few mK for production and storage of ultra cold neutrons (UNC) due to inelastic scattering of very cold neutrons on the cluster backbone of the gel. Results of the first measurements performed in ILL at temperatures above 1.6 K had witnessed in support of the idea: propagating through the D2O gel sample cold neutrons showed strongly anisotropic scattering at energies E above 5K whereas decrease of their energy to E below 0.5K had resulted in near isotropic s-scattering. From the SANS measurements it followed that characteristic dimensions of clusters in freshly prepared D2O gel samples were below 15nm, and in D2 gel samples their sizes were distributed between 3 and 150 nm. Heating of the sample from 1.6 to 2.13 K had resulted in a significant increase of content of small diameter clusters. Based upon these results we proposed the second idea – the rate of production of UCN in a newly built UCN source on pure He-II could be increased significantly by filling the helium vessel with a gel at high gel densities. Whether the effective mean free path of the injected 0.9 nm neutrons was restricted by their elastic scattering on impurity nanoclusters, and it was less than the vessel size, cold neutrons should diffuse through the sample , and the propagation time of cold neutrons between two their collisions with the vessel walls should increase strongly. It should result in a strong rise of the UCN density inside the vessel. The work is supported by the RFBR grants No 07-02-12136-o and 10-02-00906-a.

Keywords: quantum gels, superfluid helium, neutron scattering

Phase diagram of ^{4}He film in 3D nanopores of ZTC

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Previously we have studied superfluidity of ^{4}He film in HMM-2 of which pores 2.7 nm in diameter are connected in three-dimension (3D) with the period 5.5 nm[1]. The superfluidity of the film has an onset characteristic of the 3D superfluid transition with a sharp peak in the heat capacities. It suggest that the 3D pore connection cause the superfluid transition. To investigate three dimensionality of superfluid ^{4}He film, recently we have studied on ^{4}He film adsorbed in new 3D nanoporous material ZTC, of which 3D period is shorter than HMM-2. The nanopores have the pore diameter 1.2 nm, the 3D period 1.4 nm, and the porosity 78% . From the heat of vaporization, the uniform ^{4}He layers are observed to be formed up to about 1.4 atomic layers. At low coverages below the first adsorbed layer completion, the heat capacity rapidly decreases below a temperature $T_{\rm L}$. It suggests a localized state of ^{4}He at temperatures below $T_{\rm L}$. Heat capacity isotherms show maxima around 1.1 layer, similarly to the cusps of ^{4}He isotherms observed in HMM-2. At 1.2-1.3 layer above the coverage, dilute ^{3}He additionally adsorbed on the film has specific heats comparable to the gas constant, which indicates that the ^{4}He film is quantum (Bose) fluid between 1.1 and 1.4 layer. Thus, the phase diagram of ^{4}He film in ZTC is determined, together with results of the superfluid onset by a torsional oscillator.

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Keywords: restricted geometry, superfluid ^{4}He film, phase diagram, 3D nanopores

Ground-state properties of electron-electron quantum bilayers

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The ground-state behaviour of electron-electron quantum bilayer systems within the neutralizing background and zero magnetic field is studied by including unequal density of layers. The quantum self-consistent mean-field approximation of Singwi, Tosi, Land and Sjölander (qSTLS) is used to study the intra- and inter layer properties, such as the static pair-correlation functions, the static structure factors, the static density susceptibility and the static local-field correction factors over a wide range of layer density parameter r_s and layer spacing d. We find that the inclusion of unequal density brings a phase transition from charge density wave (CDW) to coupled Wigner crystal (WC) ground state at the close proximity of the layers. We also find that inclusion of unequal density markedly reduce critical r_s for the onset of Wigner crystallization. The results are compared with recent findings of the equal density effects in electron-electron quantum bilayer systems.

Keywords: Quantum Well, Wigner Crystal, Electron-electron correlation

Features of the magnetothermopower and magnetoresistivity of Bi nanowires in weak and strong magnetic fields

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In single-crystal Bi nanowires obtained by the Ulitovsky method, we study the effect of weak and strong magnetic fields on the thermopower, which has a positive value in absence of a magnetic field and reverses sign due to the quantum size effect [1]. It is shown that weak and strong magnetic fields lead to an increase in the positive contribution to the thermopower, which, in turn, results in an increase in Power factor = $\alpha^2\sigma$ at 30-50 K. A strong magnetic field $\mu H > 1$ leads to a shift of the thermopower sign reversal to the region of higher temperatures in magnetic fields, the thermopower remains positive in the entire temperature range. Bi nanowires are promising materials for thermoelectric applications.

This work was supported by SCOPES IZ73ZO_ 127968 "Functional Nanowires".

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Keywords: bismuth nanowires, quantum size effect, thermopower, power factor, thermoelectric applications

QCM study of 2D superfluid in ^{3}He-^{4}He mixture films on gold

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There have been a number of experiments exploring the nature of 2D superfluidity and configuration of ^{3}He-^{4}He mixture films on various substrates. It is found that the superfluidity is strongly affected by ^{3}He concentration. At T = 0, ^{3}He tends to float on top of ^{4}He due to the different zero point energies and configuration of the mixture films can be viewed as "superfluid sandwich model". In the mixture films with thick ^{3}He overlayer, an extra temperature dependence of the superfluid density and suppression of the superfluid transition temperature are observed [1], yet details of these behavior have not been revealed. We present the results of QCM (quartz crystal microbalance) measurements on flat gold substrate to study an effect of ^{3}He on the superfluidity of the mixture films. Our measurements are done by keeping a constant ^{3}He coverage (0, 1.7, or 19.0 μmol/m^2) and then adding ^{4}He. For the mixture films with $n_3 \sim 1.7$ μmol/m^2, the temperature dependence of the superfluid density shows no difference from pure ^{4}He film. However, for $n_3 \sim 19.0$ μmol/m^2, the temperature dependence is dramatically changed. Reduction of the superfluid transition temperature is observed. These observations suggest that localization of ^{4}He induced by overlayer ^{3}He is enhanced by increasing temperature. In the torsional oscillator experiment on Mylar [1], the similar behavior is observed in the mixture films with much thicker overlayer of ^{3}He, $n_3 \sim 136$ μmol/m^2 (~ 13 bulk-density layers). A threshold coverage of ^{3}He contribution to the temperature dependence is suggested between 1.7 and 19.0 μmol/m^2.

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Keywords: KT transition, ^{3}He-^{4}He mixture film

Ground-state properties of 2D hard-core bosons in superfluid phase within second-order spin wave theory

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Using the second order spin-wave theory we derive an analytical expression for zero-temperature thermodynamic potential of the hard-core bosons on a square and triangular lattices in the superfluid phase. The model takes into account the hopping of the particles, the nearest neighbor repulsion, and next nearest neighbor interaction which can be of any sign. The internal energy, superfluid density, boson density and compressibility are calculated for different sets of the system parameters. We found the Kosterlitz-Thouless transition temperature using the universal jump condition. It is shown that even at small particle density the second order corrections to the linear spin-wave approximation are significant at high enough interparticle interactions.
We compare our results for the internal energy, boson density, and superfluid density with a number of numerical data for hard-core bosons on square[1] and triangular[2,3] lattices. In all the cases quite good agreement is obtained.

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Keywords: hard-core bosons, superfluid density, thermodynamic potential, second order spin-wave theory

Finite temperature phase diagrams of hard-core bosons on a square lattice

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A hard-core boson model on a square lattice is known to exemplify liquid, solid and superfluid phases. Using two-time Green-function formalism with the decoupling on the first step we build finite temperature phase diagrams for the quantum square lattice hard-core boson model with nearest (nn) and next nearest (nnn) neighbor interactions. The nn interaction is assumed to be repulsive while nnn interaction can be either attractive or moderately repulsive. The behavior of the system has been investigated at different magnitudes of the hopping and ratio between the nn and nnn interactions. It turned out that for hard-core bosons with only nn interaction even arbitrary small hopping leads to the appearance of the first order phase transitions in the low temperature region. The analysis shows a significant distinction in the behavior of the system at high and small hopping. Namely, at small hopping with decrease in temperature neither solid nor liquid can exist as stable homogeneous phases, so that below a definite temperature the system is necessarily separated into two-phase mixture. In this respect the hard-core bosons with small hopping display behavior similar to that found for the Ising model. In the case of high enough hopping the properties of the system are quite different. Due to the high kinetic energy there exists a density region where a stable homogeneous liquid phase occurs up to zero temperature. Furthermore, if the nnn interaction is repulsive then the density region of absolute instability at zero temperature extends until some density, above which a homogeneous solid phase can exist up to zero temperature at least as metastable.
Our investigations indicated conclusively the possibility of reentrant phase transitions in a square lattice of hard-core bosons with nn and nnn interactions.

Keywords: hard-core bosons, finite temperature phase diagrams, reentrant phase transition

Multiple-spin exchange in strongly correlated fermion systems

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The concept of Multiple-Spin Exchange is reviewed from the pioneering paper of P.A.M Dirac (1926), to recent experimental observation in two-dimensional highly correlated fermion systems. Special emphasis is put on two-dimensional ^{3}He: a model system with tunable magnetic frustration, exhibiting exotic magnetic states (like spin-liquid) and Mott-Hubbard transition from liquid to commensurate solid.

Keywords: quantum solid, magnetism, spin liquid
INVITED PAPER

Quantum phase transition of ^{4}He confined in a regular nanoporous structure

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^{4}He confined in porous media provides a unique model for the study of strongly correlated Bosons in external potentials. We observed a pressure - induced quantum phase transition (QPT) for liquid ^{4}He confined in a porous Gelsil glass (pore size: 2.5 nm)[1]. The pore structure provided by Gelsil is a random network of nonuniform-sized pores, and the pore wall is atomically rough. So the QPT might be related to the emergence of a Bose glass state[2]. In order to elucidate the effect of the randomness and disorder in the porous structure, we have examined superfluidity of ^{4}He confined in Hybrid Mesoporous Material (HMM-3) [3]. HMM-3 has a *regular* three - dimensional array of spherical spaces of 5.1 nm in diameter, which are connected each other by thin apertures of 2.5 nm in diameter[5]. The spherical spaces and the apertures provide a well - defined periodic potential for the confined helium. We have succeeded to detect the ^{4}He superfluid transition in powder samples above the bulk freezing pressure 2.5 MPa by ultrasound technique. The superfluid transition temperature T_c decreases abruptly at pressure $P > 2.8$ MPa, and approaches 0 K at $P \sim 3.4$ MPa. This result shows that nanoscale confinement is most essential for the emergence of QPT, and disorder in porous structure has a secondary effect.

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Keywords: quantum phase transition, quantum critical phenomena, superfluid, porous media

Elements of transport theory on the ground of one-dimensional model of quantum stat. hydrodynamics.

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We want to construct a theory of transport phenomena in nearly perfect fluids. Nowadays the consecutive quantum statistical hydrodynamics, suitable for the description of nearly perfect fluidity in various mediums, does not exist. Such a theory can be useful, even if it does not go into the details of the processes which take place. The non-equilibrium theory that we propose can be considered as a generalization of the equilibrium (h,k)-dynamics formulated by us earlier. In it a new macroparameter, named the effective action, is introduced and the coefficients of transport phenomena, including diffusion coefficient and shear viscosity, are expressed through it. We construct it from two equations with temperature-dependent parameters. The first one is a modified continuity equation for probability density (F-P equation) and the second one is a motion equation like the H-J equation. We start from the Lagrangian form of quantum mechanics but introduce a generalized Lagrangian density which considers a stochastic influence of cold and thermal vacua. This generates a process of self-diffusion. Therefore, in the corresponding formula drift and diffusion velocities are taken into account and an additional term in the form of diffusion pressure appears. We construct an one-dimensional model of quantum statistical hydrodynamics at finite temperature. As a result we get a system of Lagrange-Euler equations. Its solution with respect to probability density and phase allows us to obtain nonequilibrium wave functions of thermal vacuum, describing the approach to a thermal equilibrium, without the direct manipulation with the Schroedinger equation. This has some applications for the description of a new matter state - nearly perfect fluids.

Keywords: nearly perfect fluids, one-dimensional model, quantum statistical hydrodynamics, self-diffusion

Unusual monolayer superfluidity of ^{4}He on lithium

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We have investigated the phase diagram of ^4He on Li using a quartz crystal microbalance (QCM), which measures the normal coverage, and ellipsometry, which measures the total coverage. The Lithium films are formed in situ on a QCM at low temperature using a laser ablation technique. Above 0.76K, the He coverage is a continuous smooth function of the chemical potential with no layering transition. In this regime, the conventional features of a Kosterlitz-Thouless(KT) transition are observed , but they abruptly disappear below this temperature. This and other features of the isotherms lead us to a 2D phase diagram which is distinctly different from both previous experiments on adsorbates such as plated graphite and also computer simulations of 2D helium. In particular, on lithium, the KT transition meets the 2D liquid-vapor critical point to form a tricritical point, and at sufficiently low temperatures, essentially all of the helium participates in superflow, i.e. there is no ”dead layer”.

Keywords: Kosterlitz-Thouless, alkali metal, tricritical point

Phase diagram of ^{4}He confined in 1D nano-porous material FSM16 with 2.8-nm channel

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We have carried out a series of torsional oscillator measurements for liquid ^{4}He confined in a nano-porous material FSM16 which possesses a one-dimensional 2.8-nm straight channel. It was found that the superfluid onset temperature T_o is strongly suppressed as 0.9 K at 0.01 MPa, and is suppressed further under the application of pressure. This onset continuously approaches zero at around 2.1 MPa at absolute zero. In order to search the property of ^{4}He in 2.8-nm channel, we have performed the freezing pressure and heat capacity measurements. It was made clear that the freezing does not occur up to 3.75 MPa, which means that the disapprance of superfluid onset at around 2.1 MPa is a qunatum phase transition between superfluid and non-superfluid liquid states. The heat capacity shows no anomaly at T_o, while it has a broad bump at the higher temperature than T_o. In the pressure region where superfluid disappears, the bump lowers. The heat capacity behavior indicates that ^{4}He in the channel falls into a low entropy state before the superfluid is observed.

Keywords: superfluidity, quasi one-dimension

Dynamic probes of quantum phase transition in quantum spin chain with three-site interactions

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We consider spin-1/2 XX chain with three-site interaction of $XZY - YZX$ type[1−3]. This model is known to exhibit two different spin liquid phases which are separated by a quantum phase transition point[2,3]. In our study we wish to clarify how the quantum phase transition point manifests itself in dynamic properties of the spin model. For this purpose we study several dynamic structure factors which are built on different local operators. Some of them, which are governed by a two-fermion excitation continuum[4], have been found in the closed form. We discuss general and specific properties (boundaries on the plane wavevector–frequency, van Hove singularities, soft modes etc.) of the two-fermion dynamic structure factors. We compare the obtained results with the corresponding ones obtained earlier for the spin-1/2 XX chain with three-site interaction of $XZX + YZY$ type[5].

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Keywords: quantum phase transition, spin liquid, dynamic properties

Bose Hubbard model confined in the restricted geometry

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Recently, a lot of experiments for ^{4}He confined in various porous media have been performed and the results depend on the dimensionality and pore sizes of the media. Above all, a powder medium FSM that consists of one-dimensional pores attracts a great deal of interest. The present work is motivated by the experiments for FSM.
We investigated the Bose system confined in one-dimensional channel by using quantum Monte Carlo simulations. We observed temperature dependences of the superfluid density and two correlation functions of the tubal and the circumferential direction of the channel. We found that the correlation of the system developed along the circumference as temperature is lowered, and then the Kosterlitz-Thouless(KT) phase appears at a temperature depending on the confining potential and on the ratio of the circumferential length to the length of the channel.

Keywords: superfluid, ^{4}He, restricted geometry

Adsorption of atoms on a single carbon nanotube

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We present results from physical adsorption experiments on individual carbon nanotubes. A suspended closed-end single-wall nanotube driven at its resonance frequency, f_{res}, serves as a pristine substrate and an ultrasensitive mass balance. Adsorption changes the suspended mass and $f_{res} \propto [M_{nt} + M_{ads}]^{-1/2}$, where M_{nt} and M_{ads} are respectively the masses of the bare nanotube and the adsorbates. We operate our balances following the technique of Sazonova et al.[1]. The nanotube is grown as the last step in the fabrication, suspended across μm-wide trenches on a substrate with evaporated Pt conducting pads. The current through, and charge and tension on the nanotube are controlled via three electrodes (source, drain and gate). The nanotube is driven to vibrate using a modulated (1 kHz) AC current in the 1 MHz to 1 GHz range. Usually several resonances are detected and tracked as a function of gate voltage. To measure an isotherm, a chosen resonance is followed at constant temperature as a function of pressure of gas in equilibrium with the adsorbate. Simultaneous conductance measurements can be performed. With these devices we have studied the adsorption of Ar and Kr above 68 K. We observe two-dimensional vapor (V), fluid, commensurate solid (CS) and incommensurate solid phases, and the transitions between them[2]. We observe a change in the conductivity of the nanotube at a V-CS transition. We will compare adsorption on individual nanotubes with adsorption on nanotube bundles and exfoliated graphite. Our research is supported by the NSF, grant 09807690.

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Keywords: resonators, adsorbed gases, phase transitions, electrical conductivity
INVITED PAPER

Superfluidity in one-dimensional state of ^{4}He fluid nanotubes

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We have realized ^{4}He fluid nanotubes in one-dimensional (1D) nanopores, 1.8-4.7 nm in diameter and about 300 nm in length, of which pore walls are preplated with ^{4}He inert layer about 0.5 nm in thickness[1]. The fluid nanotubes set into the 1D phonon state at low temperatures where the thermal phonon wavelength is longer than the nanotube diameter. In the torsional oscillator experiment, the frequency shift Δf due to the superfluidity was observed for the nanotubes in the 1D state. The smallest diameter of the superfluid tube is 0.8 nm formed in the 1.8 nm 1D pores preplated with the ^{4}He inert layers. The small diameter fluid tubes formed in 1.8-2.4 nm pores show the temperature dependence that the superfluid Δf slowly increases with decreasing temperature. This dependence is quite different from that of the large pore diameters which is similar to the universal jump of the 2D Kosterlitz-Thouless transition. The tube diameter dependence of the observed superfluid shift Δf is qualitatively well reproduced by the Monte Carlo calculation for a classical XY spin system modeled on the present ^{4}He nanotubes[2]. The 1D state is known to be the normal fluid state at any finite temperatures, where the correlation function decreases as $\exp[-r/\xi^{1\mathrm{D}}]$. Even in the 1D state, the superfluid shift Δf can be observed when the correlation length $\xi^{1\mathrm{D}}$ becomes longer than the nanotube length about 300 nm.

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Keywords: supefluidity, ^{4}He fluid nanotubes, one-dimensional state
INVITED PAPER

Vortices in superconducting lead nanowires

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We study the nucleation of vortices in lead superconducting nanowires as a function of applied magnetic field and temperature.. Bulk lead is a Type-I superconductor and exhibits the Meissner effect. However, at small scales the magnetisation properties of lead may exhibit unusual behaviour. Experiments by Simon Bending [1] showed that Pb nanowires show typical Type-II characteristics in a decreasing applied magnetic field at temperatures $T < 5.2K$, but not for $T > 5.2K$. We use the 3D Ginzburg-Landau equations to model the nanowires and the simulations show that the magentisation curve of wires *do* show hysteresis for temperatures $T < 5.2K$, in agreement with the experimental results. We also study the stable vortex configurations of the nanowires.

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Keywords: nanowires, vortices, magnetization, hysteresis

Bose condensation and superfluidity of ^{4}He in nanopores

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Using a torsional oscillator, Taniguchi and Suzuki measured superfluid fraction of liquid ^{4}He in one-dimensional nanopores [1]. In their experiments, they used samples which are immersed in liquid ^{4}He. They found a frequency shift at $T = T_\lambda$, which shows a transition to superfluid state of the bulk liquid, but also found an additional shift at a lower temperature, which they ascribed to the onset of superfluidity in the 1D part. In this work, we study the superfluid behavior of 1D ^{4}He filling nanopores. We consider a classical *XY* model, defined on a 3D lattice whose size is $L_x \times L_x \times L_z$ with $L_z \gg L_x$. There are two quantities that are relevant for superfluidity: the amplitude of the Bose-Einstein condensation $\langle m^2 \rangle$, which is ordering of spin vector in the *XY* plane, and helicity modulus Υ, which is the coefficient of the increase in the free energy under a twisted boundary condition. In numerical results, we find that $\langle m^2 \rangle$ starts to increase at the bulk transition temperature, $T = T_\lambda \simeq 2.20J$ even when $L_z \gg L_x$. On the other hand, the onset temperature of the helicity modulus is strongly suppressed due to the phase slippage [2] as the bar becomes narrow, *i.e.* $L_z \gg L_x$. Clearly, in one-dimensional systems, the onset temperature of these two quantities are different. It is now crucial to determine precisely the onset temperature of superfluidity in the 1D part. This would give us important information on 1D superfluid behavior.

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Keywords: ^{4}He, nanopores, XY model, helicity modulus, bose condensation

7 Charges and quantum fluids

A new model for the density-dependence of electron mobility and cavity formation in supercritical and liquid helium

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Electron mobilities in supercritical and liquid helium were investigated as a function of the density. The mobilities were derived from I(V) curves measured in a high-pressure cryogenic cell using a corona discharge in point-plane electrode geometry for charge generation. The presented data spans over a wide P, T range due to the versatility of our experimental set-up. Where data from previous investigation is available very good agreement is found. We present a new model to calculate electron mobilities both in the liquid and supercritical phase. This model requires the electron-helium scattering length and thermodynamic state equations as the only input and circumvents the employment of the surface tension. Our model reproduces experimental data very well, in particular towards lower densities where transitions from localised to delocalised electron states are observed.

Keywords: quantum fluid, electron mobility

Electron transport on liquid helium in confined geometry

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We present an investigation on the transport of electrons on liquid helium films through narrow channels using suitable substrate structures, micro-fabricated on a silicon wafer which resembles Field Effect Transistors. The sample has Source and Drain regions, separated by a Gate structure, which consists of two gold electrodes with a narrow gap (channel) through which the electron transport takes place. The electron densities on both source and drain are determined by an optical measurement of the underlying helium film, where the surface charge density depends on the thickness of this film. For time-resolved measurements, a pulse of electrons from a small filament is first collected on the source area, and then the passage of this pulse through the channel of the split gate towards the drain is monitored. This allows determining the electron transport of surface state electrons in channels of various dimensions and for a wide range of electron densities. We also present investigations on the potential distribution across the silicon wafer. Pulsing the gate for a short time can be used for a determination of the mobility of the electrons through the channel. Results for a wide range of electron densities are reported.

Keywords: Surface state Electrons, Electron transport

Ripplonic Lamb shift for electrons on helium surface

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Electrons on helium surface is an ideal system for studying many-body phenomena, as it is free from disorder. I will discuss some recently found phenomena related to the electron coupling to capillary waves on the helium surface, ripplons, and to the electron-electron interaction. I will show that two-ripplon processes lead to the Lamb-like shift of the energy levels of quantized electron motion normal to the surface. The shift is free from the strong divergence that appears if, following conventional wisdom, one disregards the 3D character of the electron motion. It displays a characteristic temperature dependence, which is in quantitative agreement with the experiment. I will also show that two-ripplon processes play a significantly smaller role in the electron energy relaxation than previously assumed. This leads to a long coherence time of qubits based on quantized lateral states in quantum dots on helium surface placed into a microwave cavity.[1] I will also discuss a long-sought effect, the onset of intrinsic resonant bistability of the response of a quasi-2D electron system to a microwave field, which has been recently seen in the experiment on electrons on helium and which is due to the electron correlations.[2]

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2. Konstantinov, D. *et al.* (2009). "Resonant Correlation-Induced Optical Bistability in an Electron System on Liquid Helium", Phys. Rev. Lett. **103**, 096801.

Keywords: two-dimensional systems, electron scattering, many-electron effects
INVITED PAPER

Transport measurements of electrons on liquid ^{4}He in the 1.6 μm channel

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Electrons floating on the surface of liquid ^{4}He form the two-dimensional Wigner crystal at low temperatures. Because of the fluctuation caused by the long-wavelength thermal phonons, the crystal in the two-dimension has the quasi-long-range positional order rather than the true long-range order at any finite temperatures. The effect of the thermal fluctuation is more significant in a lower dimensional system, and no long-range order is expected for the one-dimensional crystal. Here we have investigated by means of transport measurements whether electrons form a crystal in the quasi-one-dimensional geometry with a few electrons in the confined direction. For this purpose, we have developed the device to measure the conductance of electrons confined in the channel 1.6 μm in width, and investigated the transport properties associated with the formation of the Wigner crystal.
The transport is found to be nonlinear below about 1 K; the current shows a clear plateau with increasing excitation voltage. The plateau is associated with the resonant scattering of ripplons by the Bragg-Cherenkov mechanism[1,2]. As the Bragg-Cherenkov scattering occurs only when the electrons form a lattice accompanying the commensurate deformation of the the helium surface, the observed plateau strongly suggests that the electrons form a crystal-like structure in the channel. Judging from the magnitude of the current at the plateau, only a few electrons are present in the confined direction, forming the crystal-like structure.

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Keywords: electrons on helium, Wigner crystal, low dimensionality, mesoscopic system

Radiation-induced zero-resistance states in surface electrons on He

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We report a novel transport phenomenon realized by optical pumping in an ultraclean quasi-2D system of nondegenerate electrons subjected to perpendicular magnetic fields. When exposed to resonant millimeter microwaves, which excite the transition of electrons between surface-state subbands, the system exhibits novel quantum oscillations of the magnetotransport.[1] The oscillations are periodic in the inverse magnetic field and originate from the scattering-mediated transitions of the excited electrons between the Landau levels of the occupied subbands. At sufficientely low temperatures and high radiation intensities, we observe vanishing longitudinal resistivity, $\rho_{xx} \to 0$, at the minima of the resistance oscillations. The zero-resistance states exhibit strong hysteresis in varying magnetic fields. We suggest possible connection of the observed phenomenon with microwave-induced zero-resistance states recently discovered in a quantum degenerate electron gas in ultrahigh-mobility GaAs/AlGaAs heterostructures.[2,3]

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Keywords: electrons on helium, zero-resistance states, microwave absorption

INVITED PAPER

Mixed scenario of the charged helium surface reconstruction

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One of the instabilities studied in classical hydrodynamics is the Frenkel-Tonks (FT) instability [1, 2] occurring in a threshold manner at the charged liquid surface and resulting in its deformation. A distinctive feature of the FT instability compared with other decay processes (Rayleigh instability of the cylindrical jet [3], Karman trace behind the moving cylinder (sphere) [4], instability of the interface between two liquid media moving relative to each other [5], Taylor vortex instability of viscous liquids between two rotating coaxial cylinders [5], etc.) is the possibility of stopping the decay process after which a new metastable state with a finite corrugation amplitude is formed (i.e., a reconstruction occurs). Discussed in the paper is the mixed scenario of charged liquid surface reconstruction when the surface 2D charge density is close to the saturation. The basic building block of arising honeycomb structure is shown to be a modified multielectron dimple.

This work was partly supported by the RFBR grant 09-02-00894.

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Keywords: liquid helium, charged surface, reconstruction

Dynamic melting of 2D electron crystal over liquid helium induced by damaging electric field

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The complex conductivity of 2D electron crystal over liquid helium is studied in the region of the coupled plasmon-ripplon resonance with two AC driving voltage of different frequency. The low voltage is used for measurements and high one destroys the crystal. It is found that resonance spectrum deforms with increase of the damage voltage and the resonance disappears at a critical value of damage signal. That shows a possibility of disordered state of surface state electrons over liquid helium. The sharp change of both components of the layer conductivity versus damage voltage is observed. That change is similar to the conductivity behavior at equilibrium phase transition crystal-to-liquid. The mobility and effective mass of electrons are calculated from the data obtained. The values calculated are compared with mobility and effective mass at both dynamical low temperature transition and thermodynamic equilibrium melting. The probable reason of the phenomena observed is the dynamic melting of 2D electron crystal.

Keywords: 2D electron crystal, liquid helium, nonlinear properties, dynamic melting

Ripplon-limited nonlinear mobility of surface electrons over liquid helium

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We study, both theoretically and experimentally, the non-equilibrium mobility of surface electrons localized over liquid helium surface. The experiments are carried out in the temperature range where electron mobility is limited by electron scattering at surface excitations of liquid helium (ripplons). Holding and driving electric fields of wide ranges are used in measurements. It is shown that electron momentum relaxation is provided by one-ripplon processes of carrier scattering by long-wavelength excitations. At the same time the main channel for energy relaxation is two-ripplon processes of emission of short-wavelength quanta of helium capillary waves. Special attention is paid to the condition of strong holding fields under which hot electrons are confined to the ground surface level. Depending on the relation between the momentum relaxation rate and electron-electron collision frequency, different theoretical approaches are used to describe the nonlinear mobility of surface electrons. The results obtained allow to estimate the range of physical parameters where experimental data can be described by the theory of nonlinear electron transport within the ground surface level.

Keywords: surface electrons in helium, electron-ripplon scattering, non-linear mobility

Transport through a point constriction of an electron liquid on the surface of superfluid ^{4}He

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We present transport measurements of a two-dimensional electron liquid on the surface of superfluid ^{4}He in a novel microchannel device[1]. In the device, a point constriction between two electron reservoirs is formed by a nano-fabricated split-gate electrode. The surface electron current passing between the reservoirs may be suppressed as the split-gate voltage is swept negative, closing the constriction. We demonstrate that the current threshold depends not only on the applied potentials but also on the surface electron density, in good agreement with a simple model of the device developed with the aid of finite element analysis. Weak step-like decreases in the current are observed as the constriction is closed which may be due to ordering effects arising from the Coulomb repulsion between electrons[2]. The detailed understanding of the characteristics of such a device is an important step in the development of mesoscopic experiments with surface electrons on liquid helium[3].

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Keywords: electrons on helium, point-contact, nano-constriction, Coulomb interaction

Ripplon-phonon interaction in liquid helium governs the mobility of surface state Electrons

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We have shown that, in the τ approximation, the mobility of the 2D electron system localized above the surface of superfluid helium is limited by the longitudinal momentum transfer from ripplons to phonons of liquid helium and rapidly increases at low temperatures as $\mu \approx 8.4 \times 10^{-11} n_e T^{-20/3}$ cm^{4}K$^{20/3}$/(V·s), where n_e is the surface electron density, if the pressing electric field $E_\perp$ (kV/cm), temperature T (K) and driving-field frequency ω satisfy the relations $T^{20/3} E_\perp^{-3} \ll 2 \times 10^{-7}$ and $\omega \leq 10^8 \cdot T^5$ K^{-5}s^{-1}. These conditions imply that the driving frequency must be smaller than the ripplon-to-phonon momentum relaxation rate τ_{RP}^{-1} and, on the other hand, the electron-to-ripplon relaxation time be much shorter than τ_{RP} multiplied by the effective mass ratio of electrons and ripplons. In particular, $E_\perp \simeq 1$ kV/cm corresponds to $T \leq 70$ mK and $\omega/2\pi \leq 30$ Hz. Thus, the mobility measurement via the damping of hybrid phonon-ripplon modes of a Wigner solid[2] is inapplicable for observing the effect, since the frequencies of these modes lie in the megahertz range. Measuring the low-frequency longitudinal conductivity of the 2D electron system in the Corbino geometry[3] seems more promising.

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Keywords: surface-state electrons, superfluid helium, mobility, ripplons, phonons

Mobility of the electrons over liquid helium and possible formation of autolocalized state of electron in dense gas

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We present the results of experimental study of the mobility of surface electrons over liquid helium, localized in quasi-one-dimensional conducting channels over profiled substrate. The mobility is measured in temperature range of electron scattering by helium atoms in vapor phase. It is shown that, under temperature increase, the monotonous decrease of mobility, proportional to helium vapor concentration, is changed by abrupt drop which we attributed to a possible formation of a surface anion - bubble electron polaron state in dense helium gas [1]. Temperature of formation of an electron bubble for one-dimensional system seems lower than that for two-dimensional system. It is experimentally shown that at gradual transition from quasi one-dimensional system to quasi-two-dimensional the temperature of formation of a bubble moves to higher value. The results obtained are compared with those on mobility of two-dimensional and three-dimensional electron systems in helium vapor.

1. V.Shikin, Journal of Low Temperature Physics, Vol. 139, Nos. 5/6, June 2005

Keywords: surface electron, liquid helium, electron bubbles

Phase transitions in 2D electron system over liquid helium

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Electrons over liquid helium form a 2D classical system with Coulomb interaction. They can be spatially ordered, forming electron or Wigner crystal. A possible way to study the system is to measure the complex conductivity of the electron layer, which is different in the ordered and disordered states. One can observe the melting-crystallization transitions changing the temperature or surface electron density. Besides the equilibrium melting, a phase transitions induced by electric field in the electron layer plane (dynamic phase transitions) can be observed. In the present work a transition to a new state in the electron layer over liquid helium is found. The transition is observed at temperature $T \approx 0.1$ K, which is much lower than the electron crystal melting temperature ($T_{melt} \sim 0.6 - 0.7$ K), as a sharp increasing the real part of the complex inverse conductivity of the electron layer when the holding electric field is decreasing. The new state can be destroyed with the high driving field. Probably, the observed state is the 2D electron glass.

Keywords: phase transition, Wigner crystal, liquid helium

INVITED PAPER

8 Normal liquid ^3He, ^4He and mixtures

Mass coupling and Q^{-1} of impurity-limited normal ^{3}He in a torsion pendulum

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We present results of the Q^{-1} and period shift, ΔP, for ^{3}He confined in a 98% nominal open aerogel on a torsion pendulum. The aerogel is compressed uniaxially by 20% along a direction aligned to the torsion pendulum axis and was grown within a 400 μm tall pancake similar to an Andronikashvili geometry. The result is a high Q empty-pendulum able to resolve dissipation and mass coupling of the impurity-limited ^{3}He over the whole temperature range. After measuring the empty cell background, we filled the cell above the critical point and observe a temperature dependent period shift, ΔP, between 100 mK and 3 mK that is 2.9 % of the period shift (after filling) at 100 mK. The Q^{-1} due to the ^{3}He decreases monotonically by more than an order of magnitude between 100 mK and 3 mK at a pressure of 0.1 Bar, in contrast to measurements that show smaller changes in sound attenuation[1] over a similar temperature range. We plan to carry out measurements over the whole pressure range in the normal and superfluid phases. This research was supported by the NSF under DMR-0806629 (Materials World Network at Cornell) and under DMR-0703656 (at Northwestern).

1. R. Nomura *et al* “High-Frequency Acoustics of ^{3}He in Aerogel”. Physical Review Letters **85** 4325, 2000.

Keywords: Impurity limited transport, normal ^{3}He

Condensation of ^{4}He in Vycor : new hints for the origin of hysteresis

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Despite numerous experiments, the influence of confinement on the liquid-gas phase transition has not yet been fully elucidated. While the disappearance of the hysteresis loop between condensation and evaporation below the bulk critical point has often been interpreted as due to a confinement induced shift of the critical point, recent investigations point to the role of nucleation.
We have used our setup, built for studying helium in aerogel, to study the condensation and evaporation of helium in Vycor for 17 temperatures from 3 to 5.2 K (T_c), with a particular interest in the closure of hysteresis which is found to occur near 4.6 K (10% below T_c). We will describe our results, which take advantage of high resolution isotherms and optical measurements, and put them in the context of capillary condensation.
We will discuss the competition between nucleation and percolation as evaporation mechanisms. Although relaxation effects along the hysteresis loop indicate the presence of activated processes, optical measurements at low temperature (T < 4 K), together with the temperature dependence of the pressure threshold for evaporation suggest that cavitation does not occur in Vycor. We further compare our isotherms with the theoretical model developed by Saam and Cole and show that they are best fitted by a surface tension which vanishes at the closure of the hysteresis loop, suggesting that this closure results from the displacement of the critical point by the confinement. These conclusions are at variance with those recently reached by experiments using usual fluids confined in other silica porous glasses.

Keywords: phase transition, capillary condensation, confinement

Mass flux and solid growth in solid ^{4}He: 60 mK - 700 mK

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Keywords: Solid ^{4}He
INVITED PAPER

NMR studies of ^{3}He droplets in dilute ^{3}He-^{4}He solid solutions

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We have performed measurements of the temperature dependence of the nuclear magnetic resonance relaxation times for a wide range of ^{3}He concentrations for dilute mixtures of ^{3}He in solid ^{4}He. The temperatures for phase separation are determined for ^{3}He concentrations $500 < x_3 < 2000$ ppm for a molar volume V_M = 20.7 cm^3. We also report the temperature dependence of the nuclear spin-lattice relaxation times for ^{3}He in the droplets formed after phase separation at low temperatures. The temperature dependence suggests that the interface ^{3}He atoms responsible for the relaxation are degenerate, not solid-like.

Keywords: magnetic resonance, phase separation, Fermi droplets

The ground state energy of ^{3}He droplet in the LOCV framework

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We use the lowest order constrained variational (LOCV) method to calculate the ground state energy of liquid ^{3}He droplet at zero temperature. Different types of density distribution profiles, such as the Gaussian, the quasi-Gaussian, and the Woods-Saxon are used. It is shown that at least around 69 ^{3}He atoms are needed to get the bound state for the droplet. Depending on the choice of the density profiles and on the atomic radius of ^{3}He, the above estimate can increase up to 396 atoms. Our calculated ground state energy, the radius of liquid ^{3}He droplet, as well as the optimized input profiles, are compared with those of variational Monte Carlo and parameterized Jastrow correlation function methods, and a resonable agreement is found.

Keywords: ^{3}He liquid droplet, quantum liquid, variational method

Mechanical response of ^{4}He films adsorbed on graphite with a quartz tuning fork

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We carried out 5 MHz AT-cut quartz-crystal microbalance (QCM) experiments for ^{4}He films adsorbed on Grafoil (^{4}He/Gr) [1], and found that its sliding friction is significantly small. It is interesting to clarify the mechanical response of ^{4}He/Gr when the external force acting on the films is small. Recently, in order to reduce this force, we have started a QCM experiment for ^{4}He/Gr with a 32 kHz quartz tuning fork, and have measured the temperature dependence of the resonance frequency for various surface densities. It was found that the frequency does not decrease monotonously with the surface density, which means that the film still undergoes partial decoupling. Above 22.9 atoms/nm^2, the frequency increases at a certain temperature T_C *in cooling*, which corresponds to the superfluid transition temperature measured by a torsional oscillator by Crowell and Reppy [2]. Between 22.9 and 26.7 atoms/nm^2, it was found that the frequency exhibits hysteresis between warming and cooling and that a part of the film remains decoupled above T_C *in warming*. This suggests that superfluidity changes solidlike layers underneath the superfluid film. This hysteresis smears out when the surface density increases.

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Keywords: ^{4}He film, superfluidity, sliding friction

Density matrix of the system "Bose-liquids + impurities" in the approximation of pair correlations

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In the work we consider the movement of a ^{3}He impurity atom in the Bose-liquid of ^{4}He. The aim of this study is to explain and predict experimental results for ^{3}He–^{4}He mixtures based on the expression for the density matrix in the approximation of pair correlations:

$$R(x|x') = R_0(\mathbf{r}_1, \ldots, \mathbf{r}_N|\mathbf{r}'_1, \ldots, \mathbf{r}'_N)R_i(\mathbf{R}|\mathbf{R}')e^{\lambda_0}$$
$$\times \exp \sum_{\mathbf{k}\neq 0} \left\{ \lambda_1 \rho'_{\mathbf{k}}\rho_{-\mathbf{k}} - \frac{1}{2}\lambda_2(\rho_{\mathbf{k}}\rho_{-\mathbf{k}} + \rho'_{\mathbf{k}}\rho'_{-\mathbf{k}}) + \lambda_i(\rho_{\mathbf{k}}e^{i\mathbf{k}\mathbf{R}} + \rho'_{\mathbf{k}}e^{i\mathbf{k}\mathbf{R}'}) + \bar{\lambda}_i(\rho'_{\mathbf{k}}e^{i\mathbf{k}\mathbf{R}} + \rho_{\mathbf{k}}e^{i\mathbf{k}\mathbf{R}'}) \right\},$$

here R_0 is the density matrix of ideal Bose-particles, R_i is that of an impurity atom, and the remaining factor takes interaction into account; coefficients $\lambda_1, \lambda_2, \lambda_i, \bar{\lambda}_i$ depend on the absolute value of the wave-vector. The collective variables $\rho_{\mathbf{k}}$ are the Fourier coefficients of the density fluctuations. To obtain the matrix we use an approach from [1]. The diagonal element of the density matrix integrated over all the variables is the partition function of the system. This gives a possibility to find the thermodynamic functions of the studied system in the whole temperature domain.

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Keywords: density matrix, the collective variables, ^{3}He–^{4}He mixtures

The momentum distribution of liquid ^{3}He in the extended lowest order constrained variational framework

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We obtain the one-body momentum distribution and the density matrix of normal liquid ^{3}He at zero and finite temperatures from the occupation probability within the Ristig–Clark formalism. We use correlation functions at zero and finite temperatures derived from the lowest order constrained variational (LOCV) and the extended LOCV (ELOCV) methods. We analyze the momentum distribution $n(k)$ with respect to the discontinuity Z, as well as the singular behavior of $n(k)$ at the Fermi surface. In particular, the gap in $n(k)$ at the Fermi surface is found to be about 0.41 and 0.30 comparing to 1.0 (0.72) for the noninteracting (dilute hard-sphere) Fermi gas model at zero temperature, and it decreases by increasing the temperature. We also compare our results with other approaches such as Diffusion and Green's function Monte Carlo methods, and we show, that the use of ELOCV correlation functions improves our results.

Keywords: normal liquid ^{3}He, momentum distribution, occupation factor, Fermi surface

Acoustic resonances excited by quartz tuning forks in helium fluids

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Ordinary quartz tuning fork resonators, operated at about 30 or 200 kHz frequency, couple to acoustic first and second sound resonances in helium fluids under certain conditions. We have studied acoustic resonances in supercritical ^{4}He, normal and superfluid ^{4}He, and in isotopic mixtures of helium. Suggestive temperature, pressure, and concentration dependencies are given. Furthermore, we propose a thermometric reference point device based on second sound resonances in helium mixtures, and indicate possible differences in the nature of second sound resonances in superfluid ^{4}He and helium mixtures.

Keywords: Quartz tuning fork, Normal ^{4}He, Superfluid ^{4}He, Helium mixtures, First sound, Second sound

Transport in mesoscopic ^{3}He films on rough surfaces

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High precision torsional oscillator measurements of the flow of ^{3}He films on a highly polished silver surface have found decoupling of the film from the oscillator in the normal state[1]. The relaxation rate at low temperatures varies linearly with temperature. This result is explained by a theory that includes the surface roughness as a disorder potential [2]. AFM scans of the silver surface used as a direct characterization of the surface roughness are incorporated as a disorder potential to calculate the relaxation rate with good agreement to the experimentally observed rate. The anomalous temperature dependence of the relaxation rate is accounted for by interference between bulk inelastic scattering and weak elastic scattering off the rough surface. Decorating the substrate with large scatterers restores film-substrate coupling, also consistent with the theory. Surfaces with theoretically designed roughness are proposed that can be fabricated to enable coupling. These predictions are especially useful in the context of future experiments of confined ^{3}He in torsional oscillators in the superfluid state. The results on the nature of quasiparticle scattering at rough surfaces may also have implications in the understanding of the effects of confinement on superfluid ^{3}He. This is also a realization of a mesoscopic system in which the disorder potential is fully characterised, measurable and tunable.

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Keywords: surface roughness, confined ^{3}He, wall scattering

High energy study of the roton-like mode in liquid ^{3}He films

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We report on new inelastic neutron scattering studies of the elementary excitations of a liquid ^{3}He monolayer adsorbed on a ^{4}He plated exfoliated graphite substrate. The measurements have been made using higher energies than in our previous work. The neutron scattering experiments show that the high energy and wavevector collective excitation branch which reappears at the edge of the lower energy limit of the continuum, remains well defined at high energies, confirming the existence of this collective "roton-like" mode. The results agree well with theoretical calculations presented in this conference.

Keywords: Fermi liquid, ^{3}He, two-dimensional, zero sound, plasmon, excitations, collective modes

Neutron scattering from cryogenic ^{3}He: in critical opalescence and from surface layers adsorbed on He II

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Ongoing neutron scattering experiments from cryogenic ^{3}He are described. The first set of experiments involves small-angle neutron reflection from the liquid surface, opening up new opportunities for studying surface excitations and interface properties. Neutron scattering from the free surface of a 0.5% solution of ^{3}He in ^{4}He mixtures was measured at 80mK, 300mK, 600mK and 1.9K. The results are compared to a model that fits well with diffusive interface between the well-known top layer of pure ^{3}He and bulk ^{4}He liquid below. Secondly, a new experimental method for the investigation of critical collective excitations in neutron critical opalescence is described. Transmission data through the ^{3}He gas/vapour phase of pure ^{3}He in the temperature range 1.45 – 50 K yielded information about ^{3}He gas density. The data demonstrate some quite unexpected behavior: near the critical temperature ($\sim$3K) we observed higher neutron transmission than would be expected based on the average density of ^{3}He atoms. The data are compared with results obtained by the use of conventional methods. Neutron opalescence provides a promising technique for studying of quantum fluids under critical conditions.

Keywords: neutron scattering, neutron critical opalescence, quantum gases

9 Cold atoms and molecules, Quantum gases

Monte Carlo study of quantum phase diagram of Rydberg atoms with repulsive $1/r^6$ interaction

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We study the quantum phase diagram of bosons interacting via repulsive $1/r^6$ potential. The critical density for zero temperature gas-crystal phase transition is obtained from diffusion Monte Carlo calculations. If effective mass entering in the kinetic energy were taken to be of the order of the mass of a Rb atom, then the typical experimental conditions would correspond to being deeply in the phase of a classical crystal. Effects of the temperature are studied in the classical crystal using classical Monte Carlo method.

Keywords: Rydberg atoms, gas-solid phase transition

Single-site and single-atom resolved imaging of correlated quantum states in optical lattices

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Keywords: Quantum gases

INVITED PAPER

Thermodynamics of strongly interacting Fermi gases

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Our understanding of most condensed matter phenomena in based on two paradigm: first BCS theory which explains the onset of superconductivity by the pairing of electrons in weakly bound Cooper pairs, and, second, Landau's Fermi liquid theory which describes normal compounds as a nearly ideal Fermi gas of weakly interacting quasi-particles with renormalized masses.
In this talk, we will demonstrate how the recent study of thermodynamic properties of ultra-cold Fermi gases has provided a new experimental realization of these two pillars of contemporary physics and we will in particular show that they provide a comprehensive and quantitatively accurate description of these systems when interactions, temperature or spin imbalance are varied.

Keywords: cold atoms, quantum gas, Fermi liquid theory, BEC-BCS crossover

INVITED PAPER

On a dynamical self-consistent approach to quantum phase transitions based on the functional integral formalism.

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Phase transitions in one dimensional systems display complex mechanisms dominated by quantum fluctuations. Recent progress on theoretical approaches to quantum phase transitions has led to a better understanding of the role played by the competition between various energy scales responsible for classical and quantum fluctuations. However, most of these efforts are actually limited to account only qualitatively for the onset of quantum criticality. In particular, the mechanism by which quantum critical points are stabilized in composite materials, like electron-phonon systems and binary Bose-Bose or Bose-Fermi liquids, involves several distinct fluctuating order parameters, interactions of various natures, and distinct competing phases. Here the classical, self-consistent mean-field approach to Gaussian fluctuations in Ginzburg-Landau theory for second-order phase transitions is revisited and improved by a full account of the dynamics of the order parameter(s). The approach is based on a dynamical functional integral formalism that offers means for exactly evaluating microscopic parameters of the Hubbard-Stratonovich-bearing Ginzburg-Landau-Wilson energy functional, beyond the most commonly assumed local approximation. Interestingly, this leads to a dynamical self-consistent mean-field problem from which a Tc-g phase diagram is derived, suggesting a smooth onset of the quantum critical point by tuning the quantum critical parameter g.

1. A. M. Dikande, (2009) J. Phys. Soc. Japn. Vol. **78**, 094007

Keywords: Quantum fluctuations, functional integral formalism, Holstein model, Charge-density-wave instability

Useful quantum states in the presence of classical noise in a Bose Josephson junction

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We study the dynamical production of quantum states useful for interferometry in a Bose Josephson junction, in the presence of noise. After a sudden quench, the dynamics is driven by the interatomic interactions, which lead to the formation of useful entangled states (e.g. squeezed states at short times, macroscopic superpositions at larger times). Such states can be employed in interferometric applications to overcome classical limits of precision [1-3]. The presence of noise degrades these useful quantum correlations. In particular, we consider the effect induced by stochastic fluctuations of the energy of the two-modes [4]. We study such effect on squeezed states. Then, we address the decoherence of macroscopic superpositions and show that these latter are quite robust with respect to the noise considered, as the decoherence rate does not depend on the total number of particles. Finally, we identify the regime of parameters and the optimum time for the production of useful quantum states by calculating the squeezing and the quantum Fisher information.

1. D.J. Wineland *et al.*, Phys. Rev. A **50**, 67 (1994).

2. L. Pezzé and A. Smerzi, Phys. Rev. Lett. **102**, 100401 (2009).

3. C. Gross *et al.*, Nature **464**, 1165 (2010).

4. G. Ferrini *et al.*, arXiv:0911.0655.

Keywords: Bose Josephson, interferometry, macroscopic superpositions, decoherence

Coexistence of positional and superfluid orders in imbalanced Fermi condensates

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The so-called Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state is a possible state with coupled positional and superfluid orders in population-imbalanced two-component Fermi gas systems. Here, we present another example of fermionic supersolids in the case with a large population-imbalance. In a Fermi gas with a short-ranged repulsive interaction, a positional order corresponding to the antiferromagnetic (or SDW) order can occur in general, while it tends to be suppressed by a Fermi superfluid in population-balanced two component Fermi systems. However, we show that the coexistence between this ”SDW” order and the FFLO superfluid with s-wave pairing is favored by the population-imbalance. This coexisting phase is the s-wave analog of the coupled SDW and FFLO orders detected in the d-wave paired superconductor $CeCoIn_5$ [1,2].

1. A. D. Bianchi et al., Phys. Rev. Lett. 91, 187004 (2003).
2. R. Ikeda, Y. Hatakeyama, K. Aoyama, arXiv: 1003.0309.

Keywords: FFLO, imbalanced Fermi gas, supersolid

Particle currents in a fluid–dynamical description of two trapped fermion species

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A recent generalization of the fluid–dynamical scheme of nuclear physics that includes the pair density and current of superfluids, when applied to two trapped fermion species with pairing interactions, permits to examine the dynamical coupling between the normal and the anomalous densities, currents, and their fluctuations. In this work we concentrate on the particle transition currents of an unpolarized fermion system in a harmonic trap and establish the velocity portraits of either species for the lowest multipolar excitations. These current fluctuations are driven by the equilibrium density and gap and by the oscillations in the particle densities. We analize the velocity patterns according to different choices of the equation of state of the unperturbed fluids in order to establish the role of the equilibrium gap, in contrast to standard hydrodynamics. We also discuss the contribution of the density fluctuations to the velocity potential and flow of the superfluid gap.

Keywords: superfluid fermions,fluid–dynamics,particle currents

Extended fluid–dynamics and collective motion of two trapped fermion species with pairing interactions

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We extend our earlier fluid–dynamical description of fermion superfluids incorporating the particle energy flow together with the equation of motion for the internal kinetic energy of the pairs. The formal scheme combines a set of equations similar to those of classical hydrodynamics with the equations of motion for the anomalous density and for its related momentum density and kinetic energy density. This dynamical frame represents a second order truncation of an infinite hierarchy of equations of motion isomorphic to the full time dependent Hartree–Fock–Bogoliubov equations in coordinate representation. We analyze the equilibrium solutions and fluctuations for a homogeneous, unpolarized fermion system of two species, and show that the collective spectrum presents the well–known Anderson–Bogoliubov low energy mode of homogeneous superfluids and a pairing vibration phonon near the gap energy. We anticipate some results for a harmonically trapped fermion system.

Keywords: superfluid fermions,collective spectrum,gapped mode

Stability of a layer of dipolar bosons

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We present calculations of properties of dipolar Bose gases that are confined in one direction by a harmonic potential and translationally invariant in the other directions. The dipoles are all polarized in the confinement direction. This system is of particular interest since the dipole–dipole interaction is not only long–ranged, but also anisotropic, which leads to phenomena not found for simple contact interactions. In order to stabilize the system against collapse the dipoles additionally interact via a short ranged repulsive potential. We use both mean–field and many–body methods to calculate the properties of these systems and to investigate correlation effects. For the mean–field results we solve the Gross–Pitaevskii equation; the many–body results are obtained by the hypernetted–chain Euler Lagrange method which is not limited to weakly interacting or dilute systems but also works for strongly correlated systems. Under certain conditions we find instabilities of the system. These instabilities lead to a roton–maxon like excitation spectrum. We use the correlated basis function Brioullin-Wigner method to calculate the dynamic structure function $S(k, \omega)$ based on the many–body ground state results, and compare with the excitations obtained in mean-field approximation. Close to instability $S(k, \omega)$ exhibits a roton–maxon spectrum for energies smaller than twice the roton energy, and strong damping, i.e. excitations with finite lifetime, above that energy. From the many–body calculations we get strong evidence that the instability is caused by dimer formation, where two dipoles bind together.

Keywords: dipolar quantum gas, strongly correlated quantum gas, quantum phase transition

Counterflow quantum turbulence and the instability in two-component Bose-Einstein condensates

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We study the nonlinear dynamics of counter-superflow of two miscible Bose-Einstein condensates (BECs) and obtain two-component quantum turbulence for the first time. We solve theoretically and numerically the Gross-Pitaevskii equation in 1D, 2D, and 3D systems subject to the periodic boundary condition and in 1D trapped systems. The counter-superflow is unstable with a sufficient relative velocity. The instability excites the waves with some characteristic wave number. The waves grow up to become dark solitons through the nonlinearity. The dark solitons decay into quantized vortices in 2D and 3D cases. The vortices become tangled in 3D cases; this is quantum turbulence of two-component BECs. We investigate the dynamics in a trapped system to confirm that it shows the similar behavior to uniform systems.

Keywords: counter-superflow, quantum turbulence, soliton, Bose-Einstein Condensates

Two-superfluid model of two-component Bose-Einstein condensates; first sound and second sound

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Superfluid ^{4}He has been thoroughly studied theoretically and experimentally in the field of low temperature physics since Kapitsa discovered superfluidity of ^{4}He below the transition temperature[1]. Superfluid ^{4}He at a finite temperature is described by the two-fluid model with the normal fluid component and the superfluid component. We formulate the two-fluid model for two-component BECs, namely two-superfluid model, starting from the coupled Gross-Pitaevskii equations. The two-superfluid model well corresponds to the two-fluid model in superfluid ^{4}He. In a special condition, the two sound modes in the two-superfluid model behave like the first and second sounds in the two-fluid model of superfluid ^{4}He.

1. P. L. Kapitza, Nature **141**, 74 (1937).

Keywords: two-fluid model, Bose-Einstein Condensates, superfluid ^{4}He

Analogue of D-branes in Bose-Einstein condensates

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String theory is the most promising candidate for producing a unified theory of the four fundamental forces of nature. Dirichlet (D-) branes were found as non-perturbative solitonic states of string theory. They are characterized as hypersurfaces on which open fundamental strings can terminate with the Dirichlet boundary condition[1]. D-branes have been the most fundamental tool for studying non-perturbative dynamics in string theory. However, they are only a theoretical hypothesis. In this study, we demonstrate theoretically that analogues of D-branes in string theory can be realized in rotating, phase-separated, two-component Bose–Einstein condensates and that they are observable using existing experimental techniques[2]. The domain wall of the two condensates can be identified as a D-brane whose low energy dynamics is described by the Dirac-Born-Infeld action, where vortex lines identified as fundamental strings are attached to it. This study raises the possibility of simulating D-branes in the laboratory.

1. J. Polchinski, (1995). Dirichlet Branes and Ramond-Ramond Charges. Phys. Rev. Lett. **75**, 4724
2. K. Kasamatsu, H. Takeuchi, M. Nitta, and M. Tsubota, (2010) D-branes in Bose-Einstein condensates, arXiv:1002.4265.

Keywords: Bose-Einstein condensates, topological defects, solitons, multicomponent condensates

Soliton and vortex generation in Bose-Einstein condensates under oscillatory excitations

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We find novel mechanism of soliton and vortex formation in trapped Bose-Einstein condensates under the effects of oscillatory excitations consists of the rotating and the center-of-mass motion of the trapping potential, which has been recently demonstrated experimentally as a route to a realization of quantum turbulence[1,2]. We explore the numerical simulation of the dissipative Gross-Pitaevskii equation to reveal the dynamics of the condensate in an oscillating potential. When the velocity of the condensate exceeds some critical value at the trap center, the density ripple is excited due to the thermodynamic instability. In the two-dimensional case, this density ripple develop into the solitonic waves, which subsequently decays into vortices via snake instability. This is a possible explanation of the vortex creation mechanism observed by Henn *et al.*[1,2].

1. E. A. L. Henn, et al. (2009). Phys. Rev. A **79**, 043618.
2. E. A. L. Henn, et al. (2009). Phys. Rev. Lett. **103**, 045301 (2009).

Keywords: Bose-Einstein condensates, quantized vortices, solitons

Towards quantum magnetism with ultracold atoms

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Over the last 20 years, science with ultracold atoms has focused on motion: slowing down motion, population of a single motional state (Bose-Einstein condensation, atom lasers), superfluid motion of bosons and fermion pairs. In my talk, I will address the next challenge when motion is frozen out: Spin ordering. A two-component boson or fermion mixture can form magnetic phases such as ferromagnetic, antiferromagnetic ordering and a spin liquid. The challenge is to reach the low temperature and entropy required to observe these phenomena. I will describe our current efforts and progress towards this goal. This includes the study of fermions with strong repulsive interactions where we obtained evidence for a phase transition to itinerant ferromagnetism, and a new adiabatic gradient demagnetization cooling scheme which has enabled us to realize spin temperatures of less than 50 picokelvin in optical lattices. These are the lowest temperatures ever measured in any physical system.

Keywords: phase transition, quantum gas, magnetism

INVITED PAPER

Phase diagrams and collective modes of an imbalanced Fermi gas in 2D

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We have studied phase diagrams and the spectra of collective excitations for a trapped imbalanced Fermi gas in 2D with the s-wave pairing at finite temperatures. The treatment of collective modes is performed within the hydrodynamic approach using Euler and continuity equations. The equations of state for different phases are simulated by a polytropic law with parameters obtained using a fit to microscopic equilibrium distributions of the pressure and density. The latter ones are determined within the whole range of the BCS-BEC crossover using a path-integral description and taking into account fluctuations about the saddle point [1]. We focus on the case of imbalanced gases: when the number of 'spin-up' and 'spin-down' fermions that form the pair is no longer equal. The superfluid-to-normal transition in the trapped Fermi gas is governed by the Berezinskii-Kosterlitz-Thouless (BKT) mechanism. The collective modes at finite temperatures behave drastically differently from those in the zero-temperature case. This work was supported by FWO-V projects G.0356.06, G.0370.09N, G.0180.09N, G.0365.08.

1. J. Tempere, S. N. Klimin, and J. T. Devreese, Phys. Rev. A 79, 053637 (2009)

Keywords: imbalanced Fermi gas, BEC/BCS crossover, Kosterlitz-Thouless transition

Non-abelian vortices in spinor Bose-Einstein condensates

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We investigate collision dynamics of two non-Abelian vortices and find that unlike Abelian vortices, they do neither reconnect themselves nor pass through each other but create a rung vortex between them. This affords direct evidence of networking structures among non-Abelian vortices. Our prediction can be substantiated using the model of the cyclic phase of a spin-2 spinor Bose-Einstein condensate.

Keywords: non-Abelian vortex, spinor Bose-Einstein condensate, cyclic phase

INVITED PAPER

Phase transition from Bose-Einstein condensate (BEC) to Wigner crystal in two dimensional anisotropic trap

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We have investigated the behaviour of strongly-coupled charged bosonic atoms (Rubidium), moving in two dimensions, and interacting through a repulsive K0(r) potential [1] and held together by an anisotropic harmonic potential within the variational approximation. We show that the increase of the anisotropy of the confinement potential can drive the system from a two-dimensional (2D) to a one-dimensional (1D) configuration. Firstly, we obtain the density profiles [2] and compare with recent experiments [3] and theorical results [4]. Furthermore, we analyze the stability of the ground state configurations using the functional form of the inter-particle interaction potential. Secondly, we have found two different analytical expressions for the coupling constant above the transition from BEC to Wigner Crystal, and shown that they depend on the anisotropy parameter and particle numbers.

1. Nelson D R and Seung H S, Phys. Rev. B, 39 9153, 1989
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3. S. S. Jean and C Guthmann, J. Phys.: Condens. Matter 14 ,13653, 2002
4. S. W. S. Apolinario, B. Partoens, and F. M. Peeters, Physical Review E 72, 046122, 2005

Keywords: Phase transition, Wigner Crystal, Anisotropic Trap

Exact solution of strongly interacting quasi-onedimensional mixture of Bose and Fermi gases

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The ground state of a mixture of bosons and spin-polarized fermions in a tight atomic waveguide with point hard-core boson-boson and boson-fermion repulsions has a large degeneracy due to the arbitrariness in fixing the sign of the many-body wavefunction under exchange of bosons with fermions. Using a generalized Bose-Fermi mapping we find an exact basis set spanning the degeneracy manifold, the corresponding density profiles and momentum distributions. The symmetry of the ground state with large but finite interactions is finally discussed.

Keywords: Bose-Fermi mixtures

Interference effects in Bose-Einstein condensates at a beam splitter

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We describe a simple experiment in which two beams of Bose condensates (each described by a Fock state) impinge on a single beam-splitter. We find surprisingly rich non-classical interference patterns ("population oscillations") in the detectors following the beam splitter. These are the generalizations of the two-photon Hong-Ou-Mandel effect, but here involving much larger numbers of particles. The distributions of particles at detectors can be understood as resulting from the combination of two effects, the spontaneous phase appearing during quantum measurement, and the interference between different values of the phase described by a non-classical variable, the "quantum angle". It is the quantum angle that is responsible for the "population oscillations" in the detectors.

Keywords: Bose-Einstein Condensates, cold atoms, interference, phase coherence

Creation of NOON states by double Fock-state Bose-Einstein condensates

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NOON states (states of the form $|N>_a|0>_b + |0>_a|N>_b$ where a and b are single particle states) have been used for predicting violations of hidden-variable theories (Greenberger-Horne-Zeilinger violations) and are valuable in metrology for precision measurements of phase at the Heisenberg limit. We show theoretically how the use of two Fock state Bose-Einstein condensates as sources in a modified Mach Zender interferometer can lead to the creation of the NOON state in which a and b refer to arms of the interferometer and N is the total number of particles in the two condensates. The modification of the interferometer involves making "side" measurements of a few particles near the sources. These measurements put the remaining particles in a superposition of two phase states which are converted into NOON states by a beam splitter. The result is equivalent to the quantum experiment in which a large molecule passes through two slits. The NOON states are combined in a final beam splitter and show interference. Attempts to detect through which "slit" the condensates passed destroys the interference.

Keywords: Bose-Einstein Condensates, cold atoms, interference, NOON states

Quantum interference of Bose Einstein condensates

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Spontaneous phase symmetry breaking provides a classical field description of Bose-Einstein condensates (BEC), founded on a diagonal representation in phase states or coherent states. This leads to a description of classical interference phenomena, but remains unable to depict quantum effects associated with off-diagonal phase terms BEC in cold gases are more naturally represented by Fock states, having definite particle numbers, which express the full range of classical and quantum interference phenomena. We outline several thought experiments involving interferometers that show macroscopic quantum interference. The Hong-Ou-Mandel effect in a simple beam splitter is generalized to N particles; "population oscillations" demonstrate the results of interference of phase-state pairs (Schrödinger cats); phase cats impinging on a beam splitter can form the maximally entangled NOON state; interferometers with two pairs of separated detectors can demonstrate non-local effects including the violation of Bell inequalities.

Keywords: Bose-Einstein Condensates, cold atoms, interference, phase coherence, Schrödinger cats

INVITED PAPER

Clock shift and interstate coherence of multi-level atoms

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We consider a collisional shift of the transition between the internal states $|1\rangle$ and $|2\rangle$ in a cold homogeneous gas in the presence of $|3\rangle$-state atoms. In contrast to two-level atoms, the interstate coherence of both bosons and fermions enters the expression for the contact shift and thus can be probed by spatially homogeneous excitation. In particular, the measured contact shift in fully incoherent 3D atomic hydrogen[1] yields the difference $a_\mathrm{T} - a_\mathrm{S} = 30(5)$ pm between the triplet and singlet s-wave scattering lengths,[2] which is a factor of 2 smaller than the previous result[1] and somewhat lower than the theoretical values. We also discuss the nature of incoherence and potential effects of inelastic processes and derive the formula for the collisional relaxation rate. We further suggest that a small yet finite frequency shift of the $b \to c$ hyperfine transition in pure b-state 2D hydrogen[3] is caused by (i) the interaction with residual atoms in the state a not involved in the transition and (ii) the density-dependent wall shift of the hyperfine constant due to the interaction of adsorbed atoms with each other.[4] A related effect, the dynamic shift of the $|1\rangle - |2\rangle$ resonance under the CW excitation of another $|1\rangle \to |3\rangle$ transition can also explain the observed ENDOR spectra of 2D hydrogen.[3]

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4. A. I. Safonov, I. I. Safonova and I. S. Yasnikov, JETP Lett. **90**, 8 (2009).

Keywords: quantum gas, clock shift, cold collisions, coherence, atomic hydrogen

Dynamical properties of strongly repulsive Fermi gases

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We consider a two-component ultracold Fermi gas with repulsive interactions subjected to an external harmonic confinement. This system is predicted to undergo a ferromagnetic transition if the interaction strength exceeds a critical value.[1] We investigate its dynamical properties within the Random-Phase approximations using a functional-integral formulation.[2,3]

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Keywords: Itinerant ferromagnetism, Fermi gases

One-dimensional Bose fluid stirred on a ring trap

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We consider an interacting quasi-1D Bose fluid confined on a ring trap. We study the dynamical properties of the fluid induced by a moving barrier-potential as a probe of imperfect superfluid behavior of the 1D Bose system [1]. We consider a delta-function barrier, and focus first on noninteracting bosons. We provide an exact solution for the dynamical evolution for any state at all times and for arbitrary velocity of the barrier. Using a proper fermionization scheme, these results are generalized in order to address the Tonks-Girardeau limit of impenetrable bosons.

[1] R. Citro, A. Minguzzi, and F.W.J. Hekking, Phys. Rev. B 79, 172505 (2009).

Keywords: 1D-systems, quantum fluids, Tonks Girardeau

Ground-state properties of small mixed helium and spin-polarized tritium clusters

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We report the results on the ground-state energy and structural properties of small $^4\mathrm{He}_m(\mathrm{T}{\downarrow})_n$ clusters consisting of up to 4 T↓ and 8 ^{4}He atoms. Their small mass and weak attractive parts of interaction potentials makes them very weakly bound, with some at the limits of stability. The smallest bound clusters can be classified as quantum halos, as a consequence of their large spatial extent.
Our results have been obtained using very well know ^{4}He-^{4}He and T↓-T↓ interaction potentials. Since several ^{4}He-T↓ interatomic potentials appear in the literature, the effects of the chosen form on both energy and structural properties have been thoroughly investigated. All calculations have been performed using variational and diffusion Monte Carlo methods.
Present calculations for $^4\mathrm{He}_m(\mathrm{T}{\downarrow})_n$ are compared with existing results for $^4\mathrm{He}_m{}^3\mathrm{He}_n$ because both types of clusters have essentially the same mass, but differ in the interaction potentials and the statistics.

Keywords: small mixed clusters, ground-state energy, structural properties, helium, spin-polarized tritium

Vortex formations from domain wall annihilations in two-component Bose-Einstein condensates

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Topological defects or solitons appear not only in condensed matter physics but also in cosmology and high-energy physics. It is interesting to connect the physical phenomena of topological defects in the former systems to those in cosmology or high-energy physics[1,2]. Atomic-gas Bose-Einstein condensates (BEC) are ideal systems for testing the physics of topological defects in theoretical and experimental aspects. In this work, we theoretically study the vortex formation from the collision of the domain walls in phase-separated two-component Bose-Einstein condensates. The collision process can mimic the tachyon condensation for the annihilation of D-brane and anti-D-brane in string theory[3]. The vortices can be nucleated by the snake instability, which occurs when the domain wall and anti-domain wall are close to each other. A pair annihilation leaves the quantized vortices with superflow along their core, namely *superflowing cosmic strings*.

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3. Ashoke Sen, Int. J. Mod. Phys. A **20**, 5513 (2005).

Keywords: D-brane, QFS model systems for Astrophysics

Probing polaron physics with impurities in a condensate

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The generic problem of a particle coupled to a bath of bosons is known as a polaron in the context of an electron coupled to lattice vibrations. Ever since the pioneering work of Landau it has been studied in great detail, but nevertheless a full analytical solution (for eg. response properties) remains elusive in the nonperturbative regime. Moreover, no material has thusfar been found in which this strong coupling regime is realized for the electron-phonon system. In this contribution, we investigate whether impurities in a condensate can be used as an experimental testbed for polaron theory. We show that the system can be mapped onto a polaron Hamiltonian where the Bogoliubov excitations take on the role of the phonons. The Jensen-Feynman variational path-integral method is used to calculate static thermodynamic properties for the "impurity-BEC" polaron [1]. We identify a dimensionless coupling parameter as a function of which the system undergoes a transition to a strong coupling regime, characterized by a large effective mass and a strong self-induced potential. Experimental conditions necessary to reach this regime are discussed and applied to the case of a lithium impurity in a sodium condensate. This work was supported by FWO-V projects G.0356.06, G.0370.09N, G.0180.09N, G.0365.08.

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Keywords: Bose condensate, polarons, impurity in a condensate, strong coupling physics

Magnetic resonance study of high density atomic hydrogen gas

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We report on experimental study of high density atomic hydrogen gas at T<0.5 K in a strong magnetic field of 4.6 T by means of magnetic resonance methods: ESR, NMR, and double resonance. The gas is hydraulically compressed to densities in the range $10^{15} - 5 \times 10^{18}$ cm^{-3}, covering the collisionless and hydrodynamic regimes. We present new data on the clock shift in both regimes. Our results for the interstate shift caused by the atoms of the third hyperfine state agree qualitatively with the theory[1]. The intrastate shift, for the H gas consisting of only one hyperfine state, is vanishingly small in the hydrodynamic regime, which was explained by the coherent properties of colliding atoms[1]. In the low density collisionless regime and found that the shift increased considerably due to the loss of coherence in collisions with the walls. At densities exceeding 5×10^{16} cm^{-3} ESR spectra are strongly distorted by the electron spin waves, which at certain values of magnetic field gradient collapse into a very sharp and intensive peak. We consider a possibility of macroscopic occupation of the ground state of magnons ("magnons BEC") in the trap created by the magnetic field and the walls of the container. In double resonance experiments we realized coherent two-photon electron and nuclear spin transitions, and observed an electromagnetically induced transparency effect, when the ESR absorption is fully suppressed under the resonant NMR excitation.

1. J. Ahokas, J. Järvinen, G. V. Shlyapnikov, and S. Vasiliev, Phys. Rev. Lett., **101**, 263003 (2008), and **104**, 099302 (2010).

Keywords: clock shift, BEC, Electron-Spin Resonance, magnons

Magnetic field dependence of internal Josephson effects in spinor dipolar Bose–Einstein condensates

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We numerically study internal Josephson effects in spinor dipolar Bose–Einstein condensates by calculating Josephson equations derived by spin-1 Gross–Pitaevskii equations with magnetic dipole-dipole interactions. Considering analogy with dynamics of interacting two nonrigid pendulums, we obtain the several modes of the Josephson currents [1]. In this study, especially, magnetic field dependence is investigated on the Josephson effects. The magnetic field mimics external voltage in Josephson junctions, affecting the frequency and amplitude of the Josephson oscillations. Moreover, the dynamics represents chaotic properties under oscillational magnetic fields. We will report details of the study in our poster.

1. Yasunaga, M. and Tsubota, M., *Phys. Rev. A* **81**, 023624 (2010).

Keywords: Josephson effects, quantum gases

Dipolar Bose gas in 2D with tilted polarization

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Dipolar Bose gases confined to two dimensions have been proposed be used to generate a self-assembled lattice. Here we study a 2D dipolar Bose gas in the regime of strong correlations and where the polarization direction is tilted with respect to the confinement plane. Tilting the polarization direction leads to a weakening of the dipolar repulsion in the tilt direction, hence to an anisotropic, homogeneous quantum gas. We use the hyper-netted chain Euler-Lagrange method and diffusion Monte Carlo simulations to study ground state energy and the anisotropic pair distribution. We find a tendency of the quantum gas to establish long-range order in the strongly interacing direction at high density, and we discuss the consequences of this anisotropy for crystalization.

Keywords: dipolar quantum gas, strongly correlated quantum gas, quantum phase transition

10 BEC of excitations

Superfluidity and vortices in exciton-polariton condensates

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Keywords: Exciton polaritons, superfluidity
INVITED PAPER

Exciton polaritons in semiconductors: toward new frontiers of Bose quantum degeneracy

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Keywords: Exciton polaritons, BEC
INVITED PAPER

The quest for Bose-Einstein condensation in solid ^{4}He

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Ever since the seminal torsional oscillator (T-O) measurements [1,2] of Kim and Chan which suggested the existence of a phase transition in solid ^{4}He, from normal to a 'supersolid' state below a critical temperature $T_c = 200$ meV, there has been an unprecedented amount of excitement and research activity aimed at better understanding this putative phase of matter. Despite much work, this remarkable phase has yet to be independently and unquestionably verified by conventional scattering techniques, such as neutron or X-ray scattering, as is commonly the case in phase transition characterizations. We have carried out a series of neutron scattering measurements, which we here review, aimed at directly observing Bose-Einstein condensation (BEC) in solid ^{4}He at temperatures below T_c. In bulk liquid ^{4}He, the appearance of BEC below T_λ signals the onset of superfluidity. Assuming that superflow in the solid is of the same nature as in superfluid ^{4}He, the observation of a condensate fraction in the solid would provide an unambiguous confirmation for 'supersolidity'. Although our measurements (to date) have not yet revealed a non-zero condensate fraction or algebraic off diagonal long-range order n_0 in solid helium down to 65 mK, we have established a lower limit for n_0, $n_0 \leq 0.3\%$. Our search for BEC in solid helium continues with improved instrumentation.

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2. E. Kim and M.H.W. Chan, Science **305**, 5692, (2004).

Keywords: Neutron scattering, Bose-Einstein condensation

Bose-Einstein condensation of magnons in rotating superfluid ^{3}He B

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At ultra low temperatures (below 0.4 T_c), it is possible to create a Bose-Einstein condensate of magnons in superfluid ^{3}He-B[1]. Due to the attractive interaction between magnons, the BEC can only exist in a trap, which in our case is provided by the texture of the orbital part of superfluid helium order parameter and a minimum in the polarizing magnetic field. Both features of the trap can be controlled, either by rotating the cryostat or tuning the magnetic field. In this way, the spectrum $\omega_{mn} = \omega_{\text{Larmor}} + \omega_r(m+1) + \omega_z(n+\frac{1}{2})$ can be traced out and investigated. Using continuous wave NMR, it is possible to create a magnon BEC in the ground state of the trap. In this state, the number of excitations in the trap depends only on the excitation frequency which is the exact equivalent of the chemical potential for a BEC of real particles. After switching off the pumping, this state precesses coherently for about one second. Using the proper frequency, it is also possible to create a magnon BEC in any of the excited states. In particular, the influence of the texture on the excitation spectrum can be studied. The sensitivity of the magnon BEC to textural effects suggests it could be used as a new ultra low temperature probe for vortices in superfluid ^{3}He-B. We also studied the relaxation of the excited states to the ground state, with and without external pumping.

1. Bunkov, Yu. M. and Volovik, G. E. (2010) *J. Phys.: Condens. Matter* **22** 164210; arXiv:1003.4889.

Keywords: superfluid ^{3}He, BEC of excitations, NMR

Bose-Einstein condensation of rotons revisited

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Possibility for the Bose-Einstein condensation of rotons in helium was first considered[1] 30 years ago. It was shown that the relative velocity of the normal motion ($v_n - v_s$) in this state must be equal to the Landau critical velocity. We investigate if the condensation can be attained at lower velocity and find the conditions of this transition.

1. S.V. Iordanski and L.P. Pitaevski, "Bose condensation of moving rotons" *Sov. Phys. Usp.* **23** 317 (1980).

Keywords: superfluid helium 4, rotons, BEC

Magnetic Bose glass in model magnets with static doping

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We theoretically investigate the effect of geometric disorder on a paradigmatic quantum phase transition in magnetic systems, namely the antiferromagnetic transition induced in spin-gap antiferromagnetic insulators by the application of a magnetic field. This transition is equivalent to Bose-Einstein condensation (BEC) of a grand-canonical gas of interacting magnetic quasiparticles, induced in the ground state by the applied field.[1] Doping the magnetic insulators leads to disorder either in the magnetic lattice (site dilution) or in the magnetic couplings (bond disorder), and it allows to investigate the insulator-to-superfluid transition of strongly interacting bosons in presence of controlled disorder in the grand-canonical ensemble. We will present our recent progresses in the simulation of the magnetic Hamiltonian of Nickel-Tetrakis thiourea (DTN), a model $S = 1$ compound which represents a paradigmatic example of magnetic BEC.[2] We will consider both the case of site dilution and bond disorder, showing how a novel quantum paramagnetic phase, the magnetic *Bose glass*, emerges in both cases over a broad field and temperature range, and discussing its main signatures on the magnetic behavior at finite temperatures.[3] Finally we will present a direct comparison with the first experimental results on Cd- and Br-doped DTN.

1. T. Giamarchi et al, Nature Phys. 4, 198 (2008); 2. L. Yin et al., Phys. Rev. Lett., 101, 187205 (2008); 3. R. Yu, S. Haas, and T. Roscilde. Europhys. Lett. 89, 10009 (2010); R. Yu, S. Haas, and T. Roscilde, in preparation.

Keywords: quantum phase transitions, Bose glass, Anderson localization

Bose-Einstein condensates of magnons in superfluid ^{3}He-B and symmetry breaking fields

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Keywords: BEC, ^{3}He
INVITED PAPER

BEC of non-equilibrium quasiparticles in ^{3}He and beyond

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Bose-Einstein condensation (BEC) of excitations (or quasiparticles) whose number is not conserved is presently one of the debated phenomena of condensed matter physics. In thermal equilibrium the chemical potential of excitations (phonons, excitons, polaritons, magnons, etc.) vanishes and, as a result, their condensate cannot not form as an equilibrium state. BEC of excitations may exist only as a dynamic non-equilibrium phenomenon, when the condensate is either decaying with time, or persists as a steady state in which the decay of excitations is compensated by continuous pumping of new excitations. For magnetic excitations – magnons – the dynamic BEC is manifested as the spontaneous phase-coherent precession of spins. The magnon BEC was first discovered in 1984 in superfluid ^{3}He-B and later observed in other systems. Magnon BEC is accompanied by superfluidity of magnons, and since each magnon carries spin $s_z = -1$, this is spin superfluidity. We discuss different phases of magnon BEC (including those formed in magnetic traps), the observed signatures of spin superfluidity: (i) spin supercurrent, which transports the magnetization over a macroscopic distance more than 1 cm long; (ii) spin current Josephson effect which shows interference between two condensates; (iii) spin current vortex – a topological defect which is an analog of a quantized vortex in superfluids and an Abrikosov vortex in superconductors; (iv) Goldstone modes related to the broken $U(1)$ symmetry, which are analogous to sound waves in atomic BEC; etc., and specific properties of BEC of excitations which have no analogs in atomic BEC.

Yu.M. Bunkov & G.E. Volovik, Spin superfluidity & magnon Bose-Einstein condensation, arXiv:1003.4889.

Keywords: BEC of quasiparticles, magnon BEC, spin superfluidity, coherent precession
INVITED PAPER

11 Quantum vortices

Excitations and characterization of quantum turbulence in an atomic superfluid

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(Work done in collaboration with the following students and PD: E. Henn, J. Seman, P. Castilho, G. Roati, K. Magalhaes, R. Shiozaki, E. Ramos, M. Caracanhas, C. Castelo-Branco, P. Tavares , G. Bagnato, F. Jackson, F. Poveda, G. Telles, and the participation of external collaborators: A. Fetter, V. Yukalov , V. Romero-Rochin, M. Kobayashi, K. Kasamatsu and M. Tsubota)

In this work we review our technique to generate turbulence in a BEC, where a perturbation in the trapping potential produces displacement, rotation and deformation of the atomic cloud. The generation of quantized vortices is investigated as a function of the amplitude of oscillation as well as time of excitation. The results allow the construction of a diagram for stable structures justified based on numerical simulations using the Gross-Pitaevskii equation. The necessity of having the presence of dissipation is obtained during the numerical simulation. Hydrodynamic considerations allow us to understand the occurrence of an anomalous expansion behavior for the cloud within the urbulent regime. Concepts of thermodynamic are applied to understand the variation of pressure during the occurrence of turbulence in the condensate. The existence of a critical number of vortices as a threshold for turbulence is also discussed. (Experimental part with Financial support from FAPESP and CNPq – Brazilian agencies) .

Keywords: phase transition, quantum gas, magnetism

INVITED PAPER

Decay of vortex monopoles and dipoles in trapped finite temperature Bose-Einstein condensates

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Quantitive modeling of dissipative motion for quantum vortices in Bose-Einstein condensates has remained challenging, despite the relative simplicity of the theoretical framework for the system. Nonlinearity, dissipation, and thermal fluctuations all have a vital role to play in determining the vortex motion. We apply the stochastic projected Gross-Pitaevskii equation[1] (SPGPE) to the problem of dissipation of both lone vortices[2] and vortex-antivortex pairs[3] (vortex dipoles) in trapped, finite temperature, Bose-Einstein condensates. The SPGPE theory is shown to give a significantly faster damping rate for a lone vortex than either the damped GPE, or the PGPE. We also carry out quantitative simulations of the decay of a metastable vortex dipole, and our results are in good agreement with recent observations.

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3. T. W. Neely, E. C. Samson, A. S. Bradley, M. J. Davis, B. P. Anderson, "Observation of Vortex Dipoles in an Oblate Bose-Einstein Condensate ", Phys. Rev. A **81** 023630 (2010).

Keywords: quantum vortex, dissipation, stochastic Gross-Pitaevskii, finite temperature

Dissipation in vortex dynamics in superfluid ^{3}He-B at low temperatures

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In superfluid ^{3}He the dynamics of quantized vortices is closely related to the structure of their cores. This is because in Fermi systems mutual friction between the normal and superfluid components results from the interaction of thermal quasiparticles in the bulk with those bound to vortex cores. We review the structure of quantized vortices in the B phase of superfluid ^{3}He and the origin of the strongly temperature-dependent mutual friction, which leads to the laminar vortex dynamics at higher temperatures and to the turbulent dynamics at low temperatures. Even in the turbulent regime with vanishing mutual friction the core-bound quasiparticles are expected to play an important role in the termination of the Kelvin-wave energy cascade and in the loss of energy due to vortex reconnections — the two suggested mechanisms for zero-temperature dissipation in superfluids.

We report on the first experimental observation of the quasiparticles generated as a result of dissipation in turbulent vortex motion in ^{3}He-B at $0.2\,T_c$. We study the spin-up of the initially vortex-free and thus stationary superfluid component in a rotating cylindrical sample of ^{3}He-B through the propagation of turbulent vortex front along the axis of the cylinder. The axial motion and the azimuthal precession of the front are observed using NMR techniques. For thermal measurements the sample is embedded in a black-body radiator with a pinhole of 0.3 mm diameter. Two quartz tuning forks are used as detector of quasiparticle density and as heater for calibration purposes. The sensitivity of the measurements is better than 0.1 pW. We find that the total heat release is close to the kinetic energy stored in the original metastable state. Observation of time-resolved features is also possible.

Keywords: superfluid ^{3}He-B, core-bound quasiparticles, quantum turbulence, dissipation in zero-temperature limit

INVITED PAPER

Experiments on quantum vortices in superfluid ^{3}He-B in the T$\simeq$0 limit

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Keywords: Vortices

INVITED PAPER

Visualization of quantized vortex dynamics using ice nanoparticles

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We study the dynamics of quantized vortices and quantum turbulence utilizing a particle tracking visualization technique. This is accomplished using sub-micron and micron-sized hydrogen or atmospheric ice particles [1] injected into He^4 flows. Using this technique we have observed and characterized the reconnection of quantized vortices, thermal counterflows, and have observed a clear distinction between classical and quantum turbulence. We present the latest developments of this technique: the production and use of nano-particle ice. These sub-micron particles are superior to larger particles in a number of ways. In particular, being less affected by Stokes drag, they stay trapped on faster moving vortices and remain trapped closer to the lambda transition. Using these, we have made preliminary observations of counterflows that could shed light on the particle-vortex interaction mechanism and the dynamics of vortex arrays close to solid body rotation.

1. References can be found at http://complex.umd.edu

Keywords: quantum vortices, quantum turbulence, counterflow, reconnection, visualization

Dynamics of vortices and solitons in Bose-Einstein condensates by an oscillating potential

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We study hydrodynamic instability by an oscillating potential in a trapped Bose-Einstein condensate. Our numerical calculations of the two-dimensional Gross-Pitaevskii model show the phenomena characteristic of the oscillation, not observed in a uniform motion of potential. The oscillating potential makes the topological defects, namely quantized vortices and solitons, which interchange with each other through direct and inverse sneak instability. This research opens a new field of synergy dynamics between vortices and solitons. We also discuss vortex nucleation by an oscillating potential.

Keywords: Bose-Einstein condensate, an oscillating potential, sneak instability, topological defect

Vortex-induced dissipation in current-biased superconducting nanowires

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We present results on dissipation from vortex motion in current-biased superconducting thin-film nanowires. Our studies extend the theory of transition rates between metastable states in superconductors, first described in the seminal papers by Langer and Ambegaokar [1] and McCumber and Halperin [2], from quasi-1D to quasi-2D wires. We find for nanowires of thickness d and width w with Pearl length $\Lambda = 2\lambda^2/d$ much larger than coherence length ξ and penetration depth λ ($\Lambda \gg w \gg \xi \sim d$) that every crossing of a vortex results in a detectable voltage pulse. We account for the renormaliztion of the vortex crossing rate by superconducting fluctuations and estimate the amplitude of voltage pulses and their respective I-V characteristics. Our results show that fluctuations in quasi-2D superconducting nanowires are the dominant process for a significant increase in vortex crossings across the wire and responsible for increased dissipation. Finally, we discuss the impact of vortex-induced dissipation on dark counts in superconducting nanowire single-photon detectors, where unwanted dark counts limit the performance of detection.

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Keywords: vortex motion, dissipation, fluctuations, dark counts, single photon detector

Slow vortex rings

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It has been known since the times of Lord Kelvin [1] that a vortex ring is subject to wavy distortions called Kelvin waves. Few years ago, using the Local Induction Approximation [2] and the Biot-Savart law [3], it became apparent that Kelvin waves of finite amplitude A slow down the translational velocity of a vortex ring of radius R. In this work [4] we generalise previous results [3]. Using Gross-Pitaevskii's Non Linear Schrödinger Equation, we determine the speed of a vortex ring disturbed by Kelvin waves of azimuthal wavenumber m and relative amplitude A/R. We find that at increasing values of A/R the velocity of the vortex ring slows down, until A/R is so large that the ring stops and even moves backward. We also find that the effect depends on the perturbations being helical rather than planer.

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Keywords: vortex ring, Kelvin waves, Gross Pitaevskii equation

Andreev reflection from rectilinear vortices in rotating ^{3}He-B

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At very low temperatures, in the ballistic regime of transport, the collisions between the elementary excitations of ^{3}He-B, quasiparticles and quasiholes, can be neglected. The rotatory flow associated with quantized vortices, however, can constrain their trajectories. In the condensate rest frame the dispersion curve of excitations is symmetrical. In the presence of superfluid flow with velocity $\mathbf{v}$ excitations with momentum $\mathbf{p}$ undergo the Galilean transformation $E \to E + \mathbf{p} \cdot \mathbf{v}$. Thus, an excitation propagating through the superfluid flow field may not find a forward-propagating state and therefore retraces its trajectory and changes flavor from quasiparticle to quasihole. This mechanism is called Andreev reflection.[1]

We have measured Andreev reflection of quasiparticles from a cluster of rectilinear vortex lines in the rotating state using quartz tuning fork oscillators. These are the first direct measurements of Andreev scattering from a well-defined vortex configuration with a known density and spatial extent. Our measurements at $T = 0.20T_c$ with rotation velocities up to $\Omega = 17$ rad/s show that the fraction of the retro-reflected quasiparticles decreases linearly as a function of Ω or the density of vortices in the cluster. The results can be compared to direct analytic calculations,[2] in order to refine quasiparticle beam techniques for the visualization of different vortex configurations and measuring their densities.

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Keywords: superfluid ^{3}He-B, Andreev reflection, rotating flow, vortices

Classification of topological excitations with influence of vortices

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Classification of topological excitations is helpfull to understand what kind of topological excitations exist in ordered systems. In many cases, topological excitations are classified by homotopy theory, i.e., topological excitations are distinguished by mapping of n-dimensional sphere in real space to order parameter space[1].
However, monopoles in a nematic liquid crystal cannot be classified by the conventional homotopy theory in the presence of vortices[1], because the topological invariants defined by the conventional homotopy theory to the influence of a vortex. In this work, we propose the new invariants to describe the influence of two types of topological excitations by using Abe homotopy[2] and Fox homotopy[3], in which we consider a mapping of n-dimensional pinched torus.

We show a few applications of these homotopy groups in some ordered systems and explain the systematic method to calculate the influence on topological excitations.

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Keywords: topological excitations, quantum vortices, topology

Cold atoms trapping via helical interference patterns of the phase-conjugated Laguerre-Gaussian beams.

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The macroscopic wavefunction for ultracold atoms Ψ trapped in the interference pattern composed of the counter-propagating Laguerre-Gaussian beams (LG) with amplitudes $\mathbf{E}_{(f,b)}$ detuned by $\delta\omega = (\omega_f - \omega_b)$ is considered. In contrast to conventional quasi-1D optical lattices [1] the helical geometry of trapping is essentially three-dimensional. It is known that a sinusoidal optical lattice of the period $\lambda/2$ composed of a two contradirectional zeroth-order Gaussian modes [1] is transformed into the sequence of equispaced toroids for the pair of colliding LG [2,3]. When the opposite LG is reflected from a phase-conjugating mirror (PCM), the interference pattern is transformed into the pair of collocated helices each having λ pitch [2,3]. For the sufficiently large number of trapped atoms and low temperature atomic ensemble $T \approx 0$ the Gross-Pitaevskii equation is solved in the Thomas-Fermi approximation. The maxima of the atomic density $\rho(z, r, \theta, t) = |\Psi|^2$ are collocated with optical helices. The possible experimental implementation is described [2,3] using the $time - reversal$ property of PCM and photon's orbital angular momentum conservation [3,4].

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Keywords: optical dipole traps, quantum gases, optical vortices, superfluids, quantum vortices

Vortices in superconducting lead nanowires

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We study the nucleation of vortices in lead superconducting nanowires as a function of applied magnetic field and temperature. Bulk lead is a Type-I superconductor and exhibits the Meissner effect. However, at small scales the magnetisation properties of lead may exhibit unusual behaviour. Experiments by Simon Bending [1] showed that Pb nanowires show typical Type-II characteristics in a decreasing applied magnetic field at temperatures $T < 5.2K$, but not for $T > 5.2K$. We use the 3D Ginzburg-Landau equations to model the nanowires and the simulations show that the magentisation curve of wires *do* show hysteresis for temperatures $T < 5.2K$, in agreement with the experimental results. We also study the stable vortex configurations of the nanowires.

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Keywords: nanowires, vortices, magnetization, hysteresis

Modelling the evolution of topological defects in quasi-2d superfluid ^{3}He-A

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We modelled the order parameter of ^{3}He-A in a thick slab by three-dimensional unit vectors $\hat{\mathbf{m}}$, $\hat{\mathbf{n}}$ and $\hat{\mathbf{d}}$ on a discrete two-dimensional lattice. The vectors interact via gradient energy, dipole energy and anisotropy energy (mimicking the boundary conditions for $\hat{\mathbf{m}}$ and $\hat{\mathbf{n}}$ vectors in a slab). Initially, the vectors are chosen randomly and then allowed to evolve towards the local equilibrium at a rate limited by the orbital viscosity. Various topological defects of the order parameter are observed: quantized vortices, three types of domain walls (d-, l- and dl-walls), three-way and four-way-junctions of different walls, kinks on domain walls. Slabs of two different thicknesses were modelled. For any type of walls their total length was found to decrease with time t as $t^{-1/2}$, although with different prefactors for different types.

Keywords: superfluid ^{3}He-A, restricted geometry, topological defects

12 Quantum solids: growth, transport, dynamics

Hydrodynamic instability during non-uniform growth of a helium crystal

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The Rayleigh-Taylor instability[1] is an instability of the interface which can be realized when the lighter fluid is propelling the heavier one. We analyze an analog of the hydrodynamic Rayleigh-Taylor instability for the superfluid-solid ^{4}He interface under non-uniform growth rate of the solid phase. The development of the interface instability starts with an accelerated interface growth rate and provided that the magnitude of interface acceleration exceeds some critical value independent of the surface stiffness. The plane and spherical shapes of the liquid-solid interface are considered. For the Richtmyer-Meshkov[2] limiting case of an impulsively accelerated interface, the onset of instability does not depend on the sign of the interface acceleration. The investigation of the surface instability can explain the features observed in the experiment[3] where the crystal ^{4}He nucleation is triggered by focusing an ultrasonic wave of the large amplitude. The onset and development of the instability is expected at the surface of helium crystals in the course of their abnormal fast growth under large magnitudes of overpressures[4].

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Keywords: hydrodynamic instability , superfluid-solid ^{4}He interface, crystal non-uniform growth

Instability of a crystal ^{4}He facet in the field of gravity

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We analyze here the analog of the Rayleigh instability in the field of gravity for the superfluid-crystal ^{4}He interface provided that the heavier ^{4}He crystal phase occupies the space over the lighter superfluid phase. We find that the conditions and onset of the gravitational instability are different in kind above and below the roughening transition temperature when the crystal ^{4}He surface is in the rough or in the smooth faceted state, respectively. In the rough state of the surface the gravitational instability is fully analogous to the classical case of the fluid-fluid interface. In contrast, in the case of the crystal faceted surface the onset of the gravitational instability is associated with surmounting some potential barrier. The potential barrier results from nonzero magnitude of the facet step energy. The size and the tilting angle of the crystal facet are also important parameters for developing the instability. The initial stage of the instability can be described as a generation of crystallization waves at the superfluid-crystal interface.
In particular, we discuss the experiments[1,2] which may concern the gravitational instability of the superfluid-crystal ^{4}He interface.

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Keywords: ^{4}He crystal, liquid-crystal ^{4}interface, gravitational instability

Layering transitions in solid ^{4}He growth on graphite

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The quantum nature of solid ^{4}He results in many unusual phenomena, including the roughening of ^{4}He crystals. The epitaxial growth of solid ^{4}He on a graphite substrate occurs from the superfluid phase at pressures well below the bulk solidification point due to the large Van der Waals potential of the substrate[1]. The thickness of the adsorbed solid is known to increase with the pressure of the superfluid[2−4]. Below a critical temperature, this epitaxial growth becomes discontinuous and one whole layer forms before the next begins. These layering transitions, which have been shown to be related to the roughening phenomenon[5], have been observed for the ^{4}He-graphite system using differential adsorption[2] and fourth sound[3−4] methods. In this study, we have performed torsional oscillator measurements for the growth of solid ^{4}He on an exfoliated graphite sample, grafoil. We have observed shifts in the oscillation frequency that we believe are indicative of layering transitions. In addition, we have observed slight suppression of the superfluid transition temperature with the increase of the adsorbed solid thickness in the tortuous grafoil structure. Efforts are currently underway to search for supersolidity in the layer-by-layer grown solid ^{4}He.

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Keywords: Layering transition, Crystal growth, Solid ^{4}He

Dynamical transition of ^{4}He crystallization in a very high porosity aerogel

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Crystallization of ^{4}He in aerogels of 90 and 96% porosities shows a dynamical phase transition at around 600 mK due to the competition between thermal fluctuation and disorder: crystals grow via creep at high temperatures and via avalanche at low temperatures[1]. In a very high porosity aerogel of 99.5%, however, the transition had not been observed. We improved the spatial resolution of the video image and found that the 99.5% aerogel had have the transition at 200 mK which is much lower than those of the lower porosities. The avalanche size is significantly smaller in the 99.5% aerogel. We also report the temperature dependence of the growth velocity of ^{4}He in the aerogels. In the creep region, crystal growth is faster at higher temperature and becomes slower with cooling. This temperature dependence is opposite to the bulk crystal growth. Growth velocity is the lowest at the transition temperature. In the avalanche region, it slightly increases with cooling and saturates at lower temperature. This temperature independent growth is presumably the result of the macroscopic quantum tunneling through the disorder. The avalanche size distributes over a large scale and follows a power law. The system is in a scale invariant critical state without any fine-tuning of the experimental parameters. It can be concluded that the low temperature avalanche region is in the self-organized critical state.

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Keywords: quantum solids, aerogel, avalanche, self-organized criticality

Resonant Raman scattering features in the charge-density-wave phase

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The total electronic Raman scattering of light for a system with a charge density wave (CDW) on an infinite-dimensional hypercubic lattice is calculated. Within the dynamical mean-field theory (DMFT) the nonresonant, mixed, and resonant contributions into response function are determined for the spinless Falicov-Kimball model. Investigation is performed in three common experimental symmetries, which define the polarization of incident and scattered light. The complicated shape of the Raman spectrum and its strong reconstruction with the change of the incident photon energy is caused by the presence of the thermally activated subbands. The results for the resonance effects give information about the many-body charge dynamics of the CDW-ordered phase. All the calculations are performed for the dirty metal and for the Mott-insulator with developed gap.

Keywords: Electronic Raman scattering, charge-density-wave phase, dynamical mean-field theory

The effect of the crystal quality on hcp phase nucleation in bcc ^{4}He overcooled

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Pure ^{4}He bcc crystals are studied by precise pressure measurement technique under constant overcooling ΔT. The bcc-hcp phase transition is accompanied by both a sharp pressure decrease ΔP under constant volume condition and a simultaneous appreciable heat release in the sample up to few mK. Depending on ΔT, the measured lifetime τ of the metastable bcc phase was from several seconds to several hours. The dependence of nucleation frequency J $\sim \tau^{-1}$ on overpressure ΔP for the bcc-hcp phase transition in good annealed ^{4}He crystals demonstrates both homo- and heterogeneous nucleation mechanisms under different values of ΔP. It is shown that homogeneous nucleation is not realized in unannealed crystals as well as in crystals undergone the bcc-hcp phase transition even under maximal available ΔT $\simeq$ 0.08 K and ΔP $\simeq$ 1 bar. A contribution of possible different centers of nucleation to heterogeneous nucleation kinetics is discussed.

Keywords: solid ^{4}He, bcc-hcp phase transition, nucleation, overcooling

Spectroscopy of vibronic wavepackets in condensed ^{4}He generated by oscillating atomic bubbles

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Metal atoms embedded in liquid or solid helium form nanometer-sized cavities called atomic bubbles. Their structure and properties are well established via optical and magnetic-resonance spectroscopy of the embedded atoms (recently reviewed in [1]). Calculations show that the characteristic frequencies of the bubble surface oscillations (breathing, quadrupole, etc.) lie in the range of $10^{11} - 10^{12}$ Hz ($\sim$1 meV). However, no associated vibrational structure has been observed in the experimental spectra.

Here we present results of a new laser-spectroscopic study of transition-metal (Cu, Au) atoms in liquid and solid ^{4}He. In particular we observe transitions of inner shell electrons that have not been studied before. Such transitions are weakly perturbed by the interaction with the bubble and display a characteristic structure composed of a sharp zero-phonon line and a relatively broad phonon wing.

Based on these and earlier results we suggest a new way of looking at atomic bubble vibrations. The bubble interface motion is treated as a strongly localized wavepacket of lattice oscillations (phonons) with a broad continuous spectrum. The wavepacket is created at the instant of the electronic transition (absorption or fluorescence emission) in the embedded metal atom and quickly spreads out leaving the bubble in a new equilibrium configuration.

Laser spectroscopy of the dopants can thus be used as a tool for the investigation of elementary excitations in quantum fluids and solids.

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Keywords: impurities, matrix-isolation spectroscopy, phonons

Investigating metastable solid helium below its melting pressure

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We report a first attempt to produce metastable hcp solid helium below its melting pressure. An intense pulsed sound wave is emitted along the c-axis of a monodomain hcp helium-4 crystal starting from a static pressure just above the melting pressure. The sound pulse is made as simple as possible with a negative and a positive swing only. Density at focus is monitored by an optical interferometric method. It is found that the sound wave anisotropy splits the focussed wave into two separate pulses, corresponding to a longitudinal wave along the c-axis and a radial one perpendicular to it. This causes the amplification factor due to focusing to be less than for an isotropic medium. Nevertheless negative pressure swings up to 0.7 bar have been produced, crossing the static melting pressure limit. Improvements in the detection method and in the focussing amplification are proposed.

Keywords: metastable solid, vacancy, sound wave

Solid-liquid interface magnetic ordering

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We have observed, for the first time, several different states of the basic facets on ^{3}He crystal surface. Below the nuclear ordering transition temperature, $T_N = 0.93\,\mathrm{mK}$, the [100] facet shows three different growth modes, and the [100] facet shows two modes. We explain our results with the model of the ferromagnetic polaron which is formed near the elementary step on the facet, and show that the corresponding magnetic energy of the step is large and depends greately on the orientation of the underlying antiferromagnetic domain. We give the qualitative description of all growth modes observed in the antiferromagnetic phase and in the paramagnetic phase. The approach of the magnetic step is also shown to explain the great increase of mobility of basic facets in high magnetic fields observed earlier in Leiden. The connection of the polaron model with the present theories of roughening is discussed.

Keywords: surface magnetism, crystal growth

INVITED PAPER

Vacancy nature of the bcc phase in solid helium

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We analyze the problem of bcc phase existence in solid helium using identification of contributions of phonons and vacancies to thermodynamic properties. Phonons are considered within the classical Debye theory and vacancies are treated as wide-band quasi-particles according to Hetherington's approach.[1] The analysis of Debye temperature, Θ_D, and vacancy activation energy, Q_V, was performed in wide molar volume range for hcp ^{4}He and bcc ^{3}He.[2] Using dependence $Q_V(V_m)$,[2] we estimate vacancy concentration x_v on the bcc-hcp pressure-temperature line and on the melting curve for the both helium isotopes according to equation obtained in Ref.[1]. It results in almost the same dependence of $x_v(V_m)$ for ^{3}He and ^{4}He under condition of V_m increasing by 9% in ^{4}He. It means that in high temperature range, where vacancy contribution is essential, the hcp lattice is destabilized by high values of x_v. We establish that wide-band vacancies destabilize the hcp lattice and tend it to the hcp-bcc phase transition under raising their concentration with temperature near the melting curve for both helium isotopes. The criterion for hcp phase destabilization is found.

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Keywords: solid helium, hcp-bcc transition, vacancies

13 Supersolids, glasses and defects

The anomalous softening of helium-4 crystals

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Keywords: Supersolid
INVITED PAPER

Elastic properties of solid helium: Is there a phase transition? Is there a critical velocity?

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Keywords: Supersolid
INVITED PAPER

Review of experimental results on supersolidity

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Although the observation of non-classical rotational inertia in solid helium was first reported in 2004, the microscopic origin and physical interpretation of the observed phenomena is still a subject of considerable intrigue.[1] In this talk I will review and correlate recent experimental results to provide an up to date picture of what we do and still do not understand. I will also take the opportunity to highlight some of the most exciting and unpublished experimental results.

Work supported by NSF in collaborations with E. Kim, A.C. Clark, X. Lin, J.T. West, Zhigang Cheng, N. Mulders, L. Lurio, C. Burns, J. Beamish, O. Syshchenko, X. Rojas A. Haziot and S. Balibar

1. S. Balibar, *The enigma of supersolidity* , Nature 464, 176 (2010)

Keywords: supersolid, dc rotation, vortex

INVITED PAPER

Supersolid under slow rotation

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Despite relentless efforts to uncover the mechanism of supersolidity since its discovery in 2004[1], there is no well-established consensus in the community. In fact, similarities seen in shear modulus of solid helium[2] and torsional oscillator experiments along with lack of similarity to a conventional superfluid have generated a cloud of doubt about the superfluid nature of solid helium[3]. However, ac nature of the previous measurement techniques is partially responsible for the various complicated interpretations. To avoid the complication, we impose dc rotation on top of ac oscillation of torsional oscillator and piezo-transducers for shear modulus measurement. The dc rotation clearly affects one, torsional oscillation, but not the other, shear modulus, indicating that mechanisms for two apparently similar behaviors are in fact different. We provide clear evidence of vortices in supersolid for the first time with suppression of nonclassical rotational inertia under dc rotation.

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Keywords: supersolid, dc rotation, vortex

Non-equilibrium quantum systems – Glasses at ultra-low temperatures

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At low temperatures the elastic, dielectric and thermal properties of amorphous materials are dominated by atomic tunneling systems. Due to the irregular structure of glasses the parameters of these tunneling systems are widely distributed, leading to the well known very broad spectrum of relaxation times. Taking this wide spectrum of relaxation times into account, the elastic response of glasses as a function of temperature can be at least qualitatively descripted. Recently, it has been discovered, that the nuclear moments of the atoms involved in the tunnelig motion play an important role. In particular, at ultralow temperatures many new phenomena can be observed in connections with the nuclear properties of the tunneling atoms. We will review the thermal and elastic properties of glasses at ultra-low temperatures and point out possible relations to experimental observations made with supersolids.

Keywords: glasses, atomic tunneling systems, elastic properties

INVITED PAPER

A high temperature disorder-induced mobile phase in solid ^{4}He

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We report torsional oscillator (TO) experiments on solid ^{4}He at temperatures between 1.3K and 1.9K. Initially, our samples are singe crystals, grown at constant temperature and pressure on the melting curve. With the cell full of solid, we disorder the crystal by applying stress. Simultaneously with the appearance of disorder, the TO shows phenomena similar to those referred to as supersolidity[1]. These include a partial decoupling of the solid helium from the TO, a change of the dissipation, and a velocity dependence of the decoupled mass. The effect does not depend strongly on the crystalline symmetry (hcp or bcc) or on the temperature. From our neutron scattering experiments[2], we know that the disorder prevalent in our samples is low angle grain boundaries. The apparent mobility of the solid inside the TO can therefore be associated with the ability of the grain boundaries to move. The grain boundaries can be annealed out in the presence of fluid, which restores the ”perfect rigid body” behaviour of the solid.

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2. O. Pelleg *et. al.*, Phys. Rev. B 73, 024301 (2006)

Keywords: solid Helium, supersolid, disorder

Unifying the relaxational, rotational and shear dynamics of solid ^{4}He

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Solid ^{4}He may become a supersolid when its temperature T and mass-flow velocity V fall below their critical values T_c and V_c. Indeed, torsional oscillator (TO) studies of this solid show that, below $T \sim 250$ mK and rim-velocity $V \sim 10^{-4}$ ms^{-1}, the TO resonant angular frequency ω_0 increases rapidly consistent with superfluid inertia decoupling. However, an alternative explanation could be that solid ^{4}He contains inertially active crystal excitations whose relaxation time τ lengthens smoothly with falling T and V so as to alter the TO dynamics in the observed fashion whenever $\omega_0\tau$ passes through 1. To distinguish between these scenarios, we map the solid ^{4}He rotational and relaxational dynamics throughout the $V - T$ plane. These data demonstrate that the rotational dynamics of solid ^{4}He must be due to the generation (probably by inertial shearing) of precisely the same type of excitations which are generated by direct shearing.

Keywords: solid helium, supersolidity

The glassy response of double torsion oscillators in solid ^{4}He

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Single and double torsion oscillators have been used successfully to measure the anomalous change in resonant frequency and accompanying dissipation in solid ^{4}He. We present a glass description of the mechanical anomalies found in torsion oscillator measurements. Our results show that it is not necessary to invoke a supersolid interpretation to explain these mechanical anomalies. Previously, we demonstrated that the back-action of a glassy subsystem present in solid ^{4}He can account for frequency change and dissipation peak in many single torsion oscillator experiments [1,2]. Here, we show that the same glassy back-action can explain the experimental results of the composite torsion oscillator developed by the Rutgers group, which measures the response of solid ^{4}He at the in-phase mode $f_1 = 496$ Hz and out-of-phase mode $f_2 = 1173$ Hz [3].

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2. M. J. Graf, Z. Nussinov, A. V. Balatsky, J. Low Temp. Phys. **158**, 550 (2010). "The glassy response of solid ^{4}He to torsional oscillations".
3. M. J. Graf, J.-J. Su, D.P. Dahal, I. Grigorenko, Z. Nussinov, arXiv:1007.1999. "The glassy response of double torsion oscillators in solid ^{4}He".

Keywords: solid helium, glass, supersolid, defects, torsion oscillator

Search for “direct” evidence of glassy behavior in solid ^{4}He

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We have carried out a series of torsional oscillator (TO) experiments to search for clear evidence for glassy behavior by searching for ”ageing” effects in a solid ^{4}He (nominal $\sim$ 0.3 ppm ^{3}He impurity concentration) sample. We measured the dynamic response of solid ^{4}He by stepping down the external drive level applied to the TO at various waiting times (from several minutes up to 24 hours) and temperatures (10 mK - 100 mK) as follows. The sample is cooled from a high temperature ($\sim$ 400 mK) to a low target temperature while oscillating at a given drive level. After the TO reached the target temperature, the sample is aged for a given waiting time when the drive level is quickly reduced in half. The TO oscillation amplitude subsequent to the reduction in drive level is characterized by an initial undershoot and a subsequent exponential short time recovery followed by a logarithmic long time behavior. Both the exponential and logarithmic behaviors depend on the ageing time and the target temperature indicating ”glassiness.” The maximum temperature at which the relaxation effects can be observed coincides with the temperature below which a hysteresis in the TO frequency shift sets in. More measurements for ultra-pure ^{4}He samples are under way to see how these behaviors are affected by the ^{3}He-impurity concentration.

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Keywords: supersolid, helium-4, glassiness, torsional oscillator

Superfluid glass stabilized by elasticity of bose solid with quenched disorder

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Imperfections, such as dislocations, in solid ^{4}He play roles of nucleation sites of superfluid local order or quenched disorder destroying its long ranged positional order at low temperatures. With no underlying solid order, a glass ordering due to uncorrelated quenched disorder provided by, say, a porous material does not overwhelm the ordinary superfluid ordering. We examine here a system describing a bose superfluid ordering coupled with an elasticity of the bose solid including quenched disorder. It is shown that, reflecting that the elasticity makes the quenched disorder a correlated one, the resulting glass ordering overwhelms the ordinary superfluid ordering in most of the parameter range. In other words, the static superfluidity in the bose solid is destabilized by the quenched disorder. Based on this picture, some experimental observations on the so-called supersolidity in ^{4}He will be discussed.

Keywords: phase transition, superfluid glass, supersolid

NCRI and shear modulus of solid helium at low temperatures

E. Kim
KAIST

Keywords: Supersolid
INVITED PAPER

Supersolid behaviors in thin solid ^{4}He films adsorbed on nanoporous media

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Thin ^{4}He films adsorbed on solid surfaces are a unique model system of two-dimensional (2D) Bosons. One may expect a true supersolid state caused by intrinsic zero-point vacancies peculiar to this 2D bosonic system. We have searched for the possible supersolid state in 2D solid ^{4}He films formed on a nanoporous Gelsil glass (pore size: 2.5 nm) by studying the dynamics using a torsional oscillator (TO).
We have clearly observed a supersolid-like behavior in the solid ^{4}He films thinner than approximately two atomic layers. As the film is cooled, the TO frequency starts to increase at a certain temperature, and the dissipation shows a peak at around the midpoint of the frequency shift. The overall behavior shifts to lower temperature as the coverage n decreases and disappear at a "critical coverage" n_{c}. Above n_{c}, an ordinary superfluid transition occur with a linearly increasing transition temperature with n.
The supersolid-like response may be related to the formation of a gapped localized solid below n_{c} and an emergence of mobility edge at n_{c}, which were proposed from heat capacity studies by Crowell *e*t al.[1]. We propose that the crossover between the supersolid-like and superfluid states is a manifestation of a quantum critical phenomenon around n_{c} and 0 K tuned by the ^{4}He particle (or hole) density. The supersolid-like response also bears a striking resemblance to ultrasound results for ^{4}He and ^{3}He adsorbed on a different substrate [2].

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Keywords: two-dimensional helium, supersolid, quantum critical phenomenon

On the lattice dynamics of solid helium, supersolidity and glassy states

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In quest of possible explanation of the recently revealed phenomena in solid ^{4}He, which are presumably relevant to 'supersolidity', we reconsider the work of Nosanow and Shaw (1962) where within a Hartree approach the ground state of solid He is analyzed. We eliminated two main assumptions, which obviously affect the obtained results. Namely we apply no cutoff procedure for larger interatomic distances and do not require a wave function to be monotone from a lattice site to ∞. We calculate the ground-state energy, the self-consistent potentials and the Debye temperatures as functions of density. Our spherically symmetric wave functions found by means of a variational procedure with respect to their parameters were revealed to be not exactly localized at lattice sites but shifted aside by $\sim$ 0.2 Å at lowest densities for solid ^{4}He. These shifts disappear for increasing densities, which correspond to $\sim$ 3500 bar. This fact implies that He atoms are allowed not only oscillate but also move around the lattice sites. These movements may not be characterized as a pure rotation. But random atomic shifts in a crystal lattice may result in a glassy like behavior of ^{4}He at low temperatures while random movements along nearly equipotential surfaces around the crystal sites may produce effects characteristic of two-level systems. Besides such movements can facilitate delocalization e.g. via sliding as it was proposed in our recent work[1] by means of a flexible accommodation with respect to a potential relief in a crystal. The calculated ground-state energy was found to be very close to the experimental meaning and noticeably lower (by $\sim$ 0.4 K) as compared with a value obtained for a wave function localized at a lattice site.

1. N. Krainyukova, JLTP **158**, 602 (2010)

Keywords: lattice dynamics, quantum solid, supersolidity, glassy behavior

Transition into the supersolid(SS) state, supersolid density ρ_{ss} and the critical velocity V_c to destroy the SS state

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We have reported the onset of the vortex fluid(VF) state in hcp solid He below an onset temperature T_o[1]. Here we describe the transition from the VF state into the supersolid(SS) state, which is characterized by supersolid density and macroscopic coherence as well as a critical velocity to destroy, below a transition[2] at T_c. We demonstrate the inter-relation between the vortex core size derived from the minimum of the phase coherence length and the critical velocity to destroy the SS state. The large ratio between T_o and T_c may indicate the large fluctuations of the system and it gives a basis for the vortex state[3], as seen in the new type of superconductors, and for a new kind of phase transition, namely weak first order phase transition[4],[5], for the one from the VF state into the SS state. We would also like to discuss the vortex dynamics[6] in the VF state and the SS state properties[7].

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Keywords: phase transition, quantum solid, supersolid, vortex fluid, supersolid density, critical velocity

Quantum dislocations in solid ^{4}He

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Quantum crystals provide unique opportunity for studying quantum mechanics of extended objects – dislocations. Their glide and climb under finite external stress σ, variation of chemical potential $\Delta\mu$ and bias (geometrical slanting) in Peierls potential are studied by Monte Carlo simulations of the effective string models[1,2]. We treat on unified ground quantum effects at finite temperatures T. Climb at low T is assisted by superflow along dislocation core found in *ab initio* Monte Carlo simulations[2] in solid ^{4}He. For small σ and bias, gliding dislocation undergoes thermally assisted crossover from quantum smooth to classically roughened state[1] where Peierls potential becomes irrelevant. A typical temperature of such roughening T_r is determined by the pinning gap Δ. At larger σ avalanche-type creation of kinks is found. Two responses $R_1 = u/\sigma$ and $R_2 = du/d\sigma$, where u is string deformation, exhibit qualitatively different behaviors. We also determine two isochoric compressibilities $\chi_2(T) = dN/d\mu$ (as discussed in Ref.[2]) and $\chi_1(T) = \Delta N/\Delta\mu$, where ΔN is the amount of matter accumulated in (edge) dislocation half-plane. At low-T both quantities show reduction predicted in Ref.[2]. Increasing T, while superfluidity is not strongly affected, leads to recovery of $\chi_{1,2}$ to a plateau characterized by giant values in accordance with the observations[3]. This crossover is accompanied by changing nature of the dislocation core superfluidity – from the standard Luttinger type at low T to free-particle-like (non-Luttinger) one at higher T.

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3. M.W. Ray and R.B. Hallock, PRL **100**, 235301 (2008); PRB **79**, 224302(2009); arXiv:0908.2591

Keywords: quantum dislocations, roughening, superclimb
INVITED PAPER

Josephson effects in one-dimensional supersolids

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We demonstrate that superfluidity past an obstacle is possible in a solid phase in the one-dimensional Gross-Pitaevskii equation with a finite-range two-body interaction. The phenomenon we find is analogous to the DC Josephson effect in superconductors and we deduce the "Josephson relation " between the current and the phase difference of the condensates separated by the obstacle. Within our model, we also discuss the current-driven solid phase, which is realized above the Landau roton critical velocity of the liquid phase[L. P. Pitaevskii, JETP Lett. **39**, 511 (1984)]. The phase diagram in the plane of the current and the interaction strength is given.

1. Kunimi, M., Nagai, Y. and Kato, Y. (2010). "Josephson effects in one-dimensional supersolids" arXiv:1005.3936.

Keywords: Supersolid, Josephson effect, Landau critical velocity

Study of the stability of small vacancy clusters in solid ^{4}He

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We study numerically pair correlation of vacancies in solid ^{4}He at zero temperature with diffusion Monte Carlo method. Up to four vacancies were introduced into the solid through incommensuration between the number of available lattice sites and the actual number of atoms. No bound four-vacancy clusters were observed. Instead, while the vacancy-vacancy correlation function increases at small distances indicating vacancy attraction, the decay of the pair correlation function at large distances is compatible with only weak binding of four-vacancy clusters.

Keywords: Vacancy, vacancy clusters, solid helium

Deformation of helium crystal in the supersolid region and formation of a glassy phase

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A method has been developed to generate disorder in ^{4}He crystals by deformation in the course of the experiment. A special two-chamber cell was used which contained measuring and control chambers with a beryllium bronze membrane between them. In the experiment the temperature dependence of pressure was measured in carefully annealed crystals before and after deformation. It is shown that at low temperatures (in the supersolid region) the pressure consists of two parts: a phonon contribution proportional to T^4 and an additional contribution proportional to T^2. Naturally, the latter can be attributed to the contribution of a glassy phase which forms in the helium crystal owing to deformation. It is found that the glassy phase contribution disappears after annealing the crystal near the melting temperature. The annealing-induced relaxation of pressure in the deformed crystal is very slow process in contrast to a crystal with growth defects where a large pressure drop is observed. The results obtained are analyzed in the framework of the model of two-level tunneling systems in solid helium.

Keywords: solid ^{4}He, glassy phase, supersolid

Thermal conductivity of glasses induced by nuclear quadrupole interaction at ultra low temperatures

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Recently the influence of nuclear quadrupole interaction (NQI) on the properties of amorphous solids is widely investigated both experimentally and theoretically. In particular, in Ref.[1] thermal conductivity was investigated down to 6 mK. However no nuclear quadrupole effect was found. At the same time, in our previous publications [2] it was shown that below approximately 5 mK in certain glasses the NQI breaks down the coherent tunneling and strongly affects its dielectric permittivity. In this contribution we predict that the NQI can affect the thermal conductivity deeply. We found that resonant phonon absorption by the tunneling system is strongly suppressed and thus the thermal conductivity is **much larger** compared with that predicted by the standard tunneling model. We found that that application of a strong magnetic field decreases the thermal conductivity and the standard behavior is restored.

1.Daniel Rothfuß, Üta Kuhn, Andreas Fleischmann, and Christian Enss Thermal conductivity of superconducting bulk metallic glasses at very low temperatures.In: Phonons 2010, 13 International Conference on Phonon Scattering in Condensed Matter. Book of Abstracts .Taipei, Taiwan, April 18-23,2010, p. 201.
2. see, e.g., A.L. Burin, I.Ya. Polishchuk, P. Fulde, Yu. Sereda, Low-temperature breakdown of coherent tunneling in amorphous solids induced by the nuclear quadrupole interaction, Phys. Rev. Lett. 96 (2006) 025505.

Keywords: coherent and noncoherent tunneling, glasses, thermal conductivity

Isochoric compressibility of solid ^{4}He

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We have performed experiments in which we inject atoms into hcp solid ^{4}He at pressures greater than the bulk melting pressure. We measure the change in pressure of the solid in response to the injection, which gives a measure of the isochoric compressibility. It is peredicted that the isochoric compressibility of solid ^{4}He occurs by the climb of edge dislocations fed by superfluid dislocation cores[1] and that the compressibility should be zero at high temperature, become finite at some intermediate temperature where the dislocation cores become superfluid, and finally fall to zero again at low temperature where the dislocations become smooth[1]. We have obtained data[2] that show at $T > 700$ mK the compressibility is zero, rises sharply with falling temperature, saturates at $T \approx 500$ mK, and at lower temperature appears to fall. This behavior is generally consistent with the predictions of Solyer et al [1]. Supported by NSF DMR 07-57701 and 08-55954.

1. Soyler, S.G. *et al.* Phys. Rev. Lett. **103**, 175301 (2009).
2. M.W. Ray and R.B. Hallock, arXiv:0908.2591

Keywords: Supersolid, solid helium, dislocations, compressibility

Mass flux through a cell filled with solid ^{4}He induced by the thermo-mechanical effect

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We have induced a mass flow through a sample cell filled with hcp solid ^{4}He by the imposition of a temperature difference between two reservoirs filled with liquid helium connected to each other by porous Vycor glass rods in series with the bulk solid ^{4}He. The Vycor rods allow us to perform this experiment at pressures greater than the bulk melting pressure. The imposition of a change in the temperature difference between the reservoirs results in a rate-limited flux that creates a change in the pressure difference[1]. The equilibrium pressure and temperature differences are in accord with predictions based on the fountain effect. We show that the flow rate is limited by the solid, and not by the Vycor. Supported by the NSF DMR 08-55954.

1. M.W. Ray and R.B. Hallock, arXiv:1005.1022

Keywords: Supersolid, solid helium, fountain effect

New experiments bearing on the nature of the supersolid state of solid ^{4}He

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Keywords: Supersolid
INVITED PAPER

Path integral Monte Carlo calculation of momentum distribution in solid ^{4}He

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In this work, we perform microscopic simulations of ^{4}He commensurate and incommensurate hcp crystals by means of Path Integral Monte Carlo methods, both at zero and at finite temperature. Our main objective is to study the momentum distribution $n(k)$, through the calculation of its Fourier transform, the one-body density matrix $\rho_1(r)$. Using the worm algorithm[1], we are able to compute the properly normalized $\rho_1(r)$ and so to avoid the systematical uncertainties introduced by a posteriori normalization factor. The function $n(k)$ we get is comparable with the one obtained in neutron scattering experiments[2]. We see that, at densities close to the melting, $n(k)$ differs significantly from the Gaussian shape typical of classic solids, while these differences decrease at higher densities. Furthermore, we see that $n(k)$ in crystals presenting vacancies shows an additional peak at zero-momentum below a critical temperature: this suggests that, only at very low temperature ($T < 0.75\,\mathrm{K}$), the defects are able to allow a larger occupation of the low momentum states.

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Keywords: solid ^{4}He, supersolid, Path Integral Monte Carlo, momentum distribution, Bose-Einstein condensation

Observation of non-classical rotational inertia in two-dimensional ^{4}He solid on graphite surface

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^{4}He on graphite is an interesting system for study of a two-dimensional (2D) correlated Bose system. In torsional oscillator (TO) studies Crowell and Reppy (CR) observed an anomalous mass decoupling in ^{4}He bilayer films on graphite, and they mentioned the possibility that the decoupling originated from the non-classical rotational inertia (NCRI) of a commensurate 2D ^{4}He solid doped with zero-point vacancies due to zero-point motion of the quantum solid.[1] This is interesting in the context of the supersolid phase of a quantum solid. On the other hand, a recent numerical simulation claims the absence of the commensurate solid in the second layer.[2] In this work, in order to study the origin of the peculiar mass decoupling in the 2D ^{4}He films, we reexamined TO studies of ^{4}He films on Grafoil. A finite NCRI is observed at the coverage between 18.19 and 19.50 atoms/nm^2, which is in the vicinity of the second layer completion. This is basically in agreement with the results of CR. The size of NCRI is suppressed at a TO rim velocity over 500 μm/s, while the TO response of ordinary superfluid films appearing over 20.08 atoms/nm^2 does not depend on the TO velocity. These suggest the NCRI emerging in the range 18.19–19.50 atoms/nm^2 can be originated from the solid ^{4}He films. Our observation seems to be in conflict with the result of the numerical simulation. We will discuss the possible phase diagram suggested from our observation.

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Keywords: two-dimensional ^{4}He, supersolid, torsional oscillator

Coexistence of supersolidity and superfluidity in ^{4}He confined in porous Gelsil and Vycor

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Supersolid behaviors of solid ^{4}He have been observed even when solid ^{4}He is formed in nanometer-sized pores of Vycor and Gelsil[1,2]. This fact suggests that the possible supersolidity has a genuine microscopic origin, such as amorphous-like disorder. We have reexamined the torsional oscillator responses of ^{4}He confined in a porous Gelsil (2.5 nm pore size) and in a Vycor sample (7 nm pore size). At pressures just above the bulk freezing pressure P_f = 2.5 MPa, the supersolid response (reduction of rotational inertia accompanied with excess dissipation below about 0.15 K) *coexists* with ordinary superfluidity that is originated from the confined liquid. The superfluid transition temperature T_c becomes sensitive to the pressure. This suggests that just above P_f a new solid ^{4}He layer is grown from the so-called "inert" solid layer that is always tightly bound to the pore wall. The solid layer decreases the effective pore size for liquid ^{4}He, and sensitively suppresses the superfluidity. We therefore conclude that the supersolid signal comes from the thin solid layer(s) adjacent to the inert layer. Superfluid liquid is located at the center of the pores, and is *surrounded by* the supersolid layers. Our observation proposes for the first time that thin solid ^{4}He films of a few atomic layers exhibit supersolid behaviors. The layering of supersolid-like ^{4}He is consistent with the predictions of path-integral Monte Carlo simulation studies[3].

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Keywords: supersolid, porous media, glass

The glass description to the anomalies in solid ^{4}He

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I present our glass description to the anomalies found in specific heat and in shear modulus measurement.
We model the low-temperature specific heat of solid ^{4}He by invoking two-level tunneling states in addition to the contribution of a Debye crystal for temperatures far below the Debye temperature, $T < \Theta_D/50$. By introducing a cutoff energy in the two-level tunneling density of states, we can describe the excess specific heat observedin solid hcp ^{4}He, as well as the low-temperature linear term in the specific heat. Agreement is found with recent measurements of the temperature behavior of both specific heat and pressure. These results suggest the presence of a fraction at the parts-per-million (ppm) level of two-level tunneling systems in solid ^{4}He.
For shear modulus, we propose that the stiffening with decreasing temperature can be described with a glass susceptibility assuming a temperature dependent relaxation time $\tau(T)$. The glass susceptibility captures the freezing out of glassy degrees of freedom below a characteristic crossover temperature T_X. There the dynamic response of the solid satisfies $\omega\tau(T_X) \sim 1$, thus leading to an increase in the shear modulus. We predict that the maximum change of the amplitude of the shear modulus and the height of the dissipation peak are independent of the applied frequency ω. Our calculations also show a qualitative difference in behavior of the shear modulus depending on the temperature behavior of the glass relaxation time $\tau(T)$. These predictions can be tested by comparing the complex shear modulus with experiments at different frequencies.

Keywords: Solid Helium, glass

Simultaneous measurement of torsional oscillator and NMR in solid ^{4}He with 10 ppm of ^{3}He

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Recently, 'supersolid' behavior in solid ^{4}He attracts the interest of many people. One of the peculiar observation is that the period shift of the torsional oscillator (TO), which is called as NCRI fraction, depends strongly on very tiny amount of ^{3}He impurities.[1] NMR study of dilute ^{3}He in supersolid ^{4}He may provide useful information in order to understand the role of ^{3}He. We have done a simultaneous measurement of the TO and NMR of solid ^{4}He and found that there are three different states of ^{3}He below the phase separation temperature (T_{PS}).[2] In this report, we describe our latest results with 10 ppm of ^{3}He at 3.6 MPa. The NCRI response appears below about 500 mK. Simultaneously, we investigated the NMR signal of ^{3}He in solid ^{4}He. Below T_{PS}, signal intensity increases as a function of time after cooling through T_{PS}. It corresponds to the growth of ^{3}He cluster made by the phase separation since ^{3}He atoms outside of the cluster have much longer T_1 than the measurement interval. When we warm the solid above T_{PS}, signal intensity decreases gradually. It corresponds to the disappearance of the ^{3}He cluster. Below and above T_{PS}, the distribution of ^{3}He atoms changes significantly. However, we did not observe any systematic changes in the TO response. This result suggests that the phase separation and related changes of the distribution of ^{3}He is not directly related to the NCRI response.

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2. R. Toda *et al.*, Phys. Rev. B **81**, 214515 (2010).

Keywords: supersolid, 3He impurity, NMR

Observation of quantized vortex lines in solid He under DC rotation

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We report how one can detect quantized vortices in superfluids contained in cylindrical vessels in well designed torsional oscillator (TO) experiments under DC rotation. We show the case for the artificial 3D superfluid[1], which is made of Kosterlits-Thouless 2D He films condensed on porous glass substrates with well controlled pore size. We can understand the experimental results in terms of extra energy dissipation under DC rotation by considering the circular quantized superflow around each of vortex lines and interaction of the thermally excited 2D vortices with the superflow field caused by the quantized circulation as discussed in Ref.[1]. We show the case with hcp solid He and discuss the observation of the vortexline penetration below the supersolid transition temperature[2], T_c, where macroscopic phase coherence is realized. For hcp solid He we have reported the vortex fluid state onset temperature[3] T_o by detailed study using TO technique. TO response of the hcp He is characterized by the energy dissipation similar as in KT transition around 100 mK. The real supersolid (SS) state occurs at T_c much lower than T_o. We observe the evidence of the vortex line penetration below T_c. This may indicate some common features as in recently found new type of superconductors, where vortex state has been discussed[4].

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Keywords: quantum solid, supersolid state, vortex lines penetration, vortex fluid state, macroscopic coherence

Measurements of dielectric constant of solid helium 4

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Careful measurements of the dielectric constant of solid ^{4}He have been carried out down to temperatures as low as 35 mK, considerably lower than previous studies[1]. The samples were prepared from high purity gas with ^{3}He concentrations of the order of 200 ppb and were formed by the blocked capillary at constant temperature. The molar volume of the samples was 20.24 cm^3/mol. The dielectric constant of the samples were found to increase continuously below 120 mK and tend to saturate at lower temperature. This feature for the temperature dependence is very similar to the increase in the resonant frequency found in the torsional oscillator studies[2] and also the increase found in the shear modulus measurements[3]. The increase in shear modulus was interpreted to be associated with the stiffening of the dislocation network due to the condensation of ^{3}He impurities.

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Keywords: solid Helium 4, dielectric constant

Simultaneous measurements of the torsional oscillator anomaly and thermal conductivity in solid ^{4}He

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We report measurements of the AC rotational susceptibility of samples of solid ^{4}He grown in an annular cell under different conditions. The quality of the samples was characterized by measuring the thermal conductivity below 300 mK, where it is controlled by phonon scattering off dislocations and grain boundaries. Samples with two different ^{3}He impurity concentrations have been studied so far.

Keywords: solid helium, thermal conductivity, torsional oscillator

14 Magnetic properties of ^{3}He, nuclear magnetism

Bilayer Hubbard model for ^{3}He: a cluster dynamical mean-field calculation

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Inspired by recent experiments on bilayer ^{3}He,[1] we consider a bilayer Hubbard model on a triangular lattice. For appropriate model parameters we observe an enhancement of the effective mass as the first layer approaches integer filling while the second remains partially filled. At finite temperatures this raise of the effective mass – or equivalently the decrease of the coherence temperature – leads to a crossover to a state where the first layer fermions localize, drop out of the Luttinger volume, and generate essentially free local moments. This finite temperature behavior is shown to be robust against the cluster size. On the other hand, the zero temperature phase diagram depends on the cluster topology. In particular for clusters with an even number of unit cells, the growth of the effective mass is cut off by a first order orbital selective Mott transition. These results are obtained from a cluster dynamical mean-field calculation on an eight-site cluster with a quantum Monte Carlo cluster solver. Part of the results appear in ref. 2.

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Keywords: Bilayer ^{3}He

INVITED PAPER

Magnetic phase transitions in bcc solid ^{3}He

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Bcc solid ^{3}He is known to exhibit the uudd and the cnaf magnetic orders at low temperatures. The phase transition between the uudd and the paramagnetic phases and that between the uudd and the cnaf phases are established to be discontinuous. However, the phase transtion between the cnaf and the paramagnetic phases seems to be not well understood. While the transition at a high magnetic field is known to be continuous, it was reported to be discontinuous at a low magnetic field close to the triple point.[1] Therefore the existence of a tricritical point is expected on the boundary between the cnaf and the paramagnetic phases. Though some theoretical works supporting this experimental results have appeared,[2] the understanding of the phase transition is still not quite firm.
We studied this problem by making use of Monte Carlo simulations of a classical spin model on the bcc lattice. We studied the character of the phase transition by examinimng the energy histograms. For a parameter set of the three-spin and the planar and the folded four-spin exchanges, we found that the energy histogram shows two peaks near the pahse transition at a low magnetic field while it has only one peak at a high magnetic field. This implies that the phase transtion changes from a discontinuous to a continuous one by increasing the magnetic field. We will report the results for other set of parameters and compare them with experimental results.

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2. Sun, et.al. J. Low Temp. Phys. **86** (1992) 303; Dubois, J. et. al., J. Low Temp. Phys. **98** (1995) 37.

Keywords: Magnetism, phase transition, quantum solid

Spin kinetics of ^{3}He in contact with synthesized PrF_3 nanoparticles

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The resonance magnetic coupling between the nuclei of liquid ^{3}He and the ^{141}Pr nuclei of a finely dispersed van Vleck paramagnet PrF_3 powder with the grain size below 45μm has been discovered at a temperature of 1.5 K with the use of a pulsed NMR technique[1]. Using of nanosized PrF_3 powder would create a highly-coupled ^{3}He - ^{141}Pr spin system and could show new aspects of discovered earlier effect. The nanosized PrF_3 sample was synthesized using methods, described in [2]. The X-ray and HRTEM experiments showed high crystallinity of synthesized sample. Comparison of enhanced ^{141}Pr NMR spectra in microsized[1] (45 μm) and nanocrystalline PrF_3 powder is represented. Experimental data on spin kinetics of ^{3}He in contact with PrF_3 nanoparticles are reported.

This work was partly supported by the Ministry of Education and Science of the Russian Federation Federal Program Research and Research Pedagogical Staff of Innovative Russia

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2. L. Ma et al., (2007), Materials Letters, Vol. 61, 2765

Keywords: He-3, surface, surface effect, cross-relaxation, magnetic coupling, van Vleck

The study of the system "aerogel-^{3}He" by radiospectroscopy methods

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This work is an reveiw of our experimental data on the study of an aerogel (powder and bulk) in contact with ^{3}He at temperatures above Fermi temperature. Intrinsic and X-ray induced paramagnetic centers have been studied by EPR methods. The spin kinetics of normal ^{3}He in adsorbed, gaseous and liquid phases has been studied by pulse NMR. It has been shown dominating role of nuclear magnetic relaxation processes in adsorbed layer for relaxation of whole ^{3}He spin system in contact with an aerogel. The processes of a physical adsorption of ^{3}He molecules on an aerogel surface and its influence on nuclear magnetic relaxation are being discussed. Significant influence of ^{3}He adsorbed layer preparation routine on adsorbed ^{3}He nuclear magnetic relaxation found out. The HRTEM images of the aerogel samples are presented.

This work is supported by Russian Fund for Basic Research (grant N 09-02-01253).

Keywords: Aerogel, NMR, EPR, He-3, surface, surface effect

15 MEMS, NEMS: resonators, cavities, devices

Suppression of amplitude noise in cavity-driven oscillations of a nanomechanical resonator

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We analyze the dynamics of a nanomechanical resonator parametrically coupled to a microwave or optical cavity when the latter is driven at a frequency above resonance. For sufficiently strong coupling, the resonator undergoes limit-cycle oscillations[1]. Using an approach based on the truncated Wigner function we investigate the noise properties of the resonator within the limit-cycle states[2]. We find that at a given temperature the limit-cycle oscillations have lower amplitude noise than states of the same average amplitude excited by a pure harmonic drive; for sufficiently low thermal noise a sub-Poissonian resonator state can be produced. Comparison with a numerical solution of the quantum master equation of the system shows that the truncated Wigner function provides a good description of the resonator's behaviour within the limit-cycle states though it is noticeably less reliable in the vicinity of the onset of the oscillations.

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2. D. A. Rodrigues and A. D. Armour, Phys. Rev. Lett. **104**, 053601 (2010).

Keywords: nanomechanical resonator, optomechanics, quantum dynamics

Scheme to probe the quantum dynamics of a mesoscopic mechanical resonator

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We describe experimental and theoretical progress towards realising a circuit QED based scheme to generate and detect decohering quantum superpositions of a mesoscale mechanical resonator. The scheme involves driving the mechanical resonator into oscillation such that a Cooper pair box qubit initially prepared in a superposition of charge-degenerate states rapidly becomes entangled with separated position states of the resonator. The state of the qubit-resonator system is probed through its affect on the microwave mode of a superconducting coplanar waveguide (CPW) resonator to which the qubit electromagnetically couples.

An unusual feature of our circuit QED-mechanical resonator scheme is the application of a DC voltage bias to the centre conductor of the CPW via an inductor bias 'tee'. The latter ensures the necessary strong coupling between the qubit and mechanical resonator, without significantly affecting the quality factor of the probed several GHz microwave mode. As an intermediate stage, we also show how the simpler DC biased circuit QED setup without the mechanical resonator affords the possibility to investigate the quantum-versus-classical dynamics of a low noise, strongly nonlinear self-oscillating system that is distinct from the usually considered Duffing oscillator.

Keywords: Nanoelectromechanical systems, superconducting qubits, microwave resonators, decoherence, nonlinear dynamics

INVITED PAPER

Graphene membranes for cryogenic NEMS

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Graphene is a very promising material for implemeting nano- electromechanical resonators as it combines extremly low mass, very high young modulus (1TPa) and tunable charge density with excellent mobilities. We present experimental study of graphene membrane resonators obtained by the controlled underetching of Graphene transistors. Actuation is realized by RF irradiation on the gate while measurement of the mechanical motion is obtained by heterodyne frequency mixing followed by lock-in detection. The observed resonances for micron-scale doubly clamped membranes is of several tens of MHz with a quality factor of 500 at room temperature. A DC voltage applied on the gate induces a tension within the membrane which allows to continously tune the resonant frequency on a wide range (typically 50-100 MHz). Perspective to use these devices at low temperature and within the quantum regime will be presented.

Keywords: Graphene, high-frequency mechanics, cryogenics evironment

Putting the mechanics into quantum mechanics

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This talk will describe a recent experiment demonstrating the operation of a mechanical resonator in its quantum ground state, and further showing that single phonons can be swapped into and out of the resonator[1,2]. The experiment relies on the use of a microwave-frequency mechanical resonator, whose fundamental dilatational mechanical mode, at above 6 GHz, is sufficiently high to permit cooling this mechanical mode to its ground state using a conventional dilution refrigerator. The resonator state is measured using a superconducting qubit, which we have developed for quantum computation. We show by using the qubit as a quantum thermometer that the resonator is indeed in its quantum ground state, and further use the qubit to swap single phonons between the qubit and resonator. We use this ability to measure the resonator's single phonon energy relaxation time (T_1), and further create a mechanical superposition state, allowing us to estimate the resonator's phase coherence time (T_2).

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2. O'Connell, A. D. et al. (2010). "Quantum ground state and single phonon control of a mechanical resonator". Nature **464**, 697-703.

Keywords: mechanical resonator, quantum ground state, phonon, qubit

INVITED PAPER

A tunable hybrid electro-magnetomotive NEMS device for low temperature physics

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Microfabrication techniques have made possible the realization of mechanical devices with dimensions in the micro- and nano-scale domain. At low temperatures, one can operate and study these devices in well-controlled conditions, namely low electrical noise and cryogenic vacuum, with the ability to use high magnetic fields and superconducting coating metals[1]. Moreover, the temperature turns out to be a control parameter in the experimental study of mechanical dissipation processes, with the cryogenic environment ensuring that only low energy states are thermally populated. Immersed in a quantum fluid, these MEMS and NEMS devices (micro and nano elecro-mechanical systems) can probe the excitations of the liquid at a smaller scale, with higher frequencies and better resolution than ”classical” techniques[2]. We present experimental results obtained in vacuum on cantilever NEMS structures which can be both magnetomotive and electrostatically driven. The device is extremely sensitive with resolved displacements down to 1 Å using conventional room-temperature electronics. It is calibrated *in-situ*, and frequency/non-linearity can be tuned electrostatically. The design allows parametric amplification to be used.

1. E. Collin et al., *J. of Low Temp. Phys.* **150**, p. 739 (2008). 2. S. Triqueneaux et al., Physica B **284**, p. 2141 (2000).

Keywords: mechanics, NEMS, device, non-linearity

Detecting phonon blockade with photons

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By proper designing the coupling between a Cooper pair box and a nano-mechanical resonator, it is possible to reach a sufficient level on non-linearity as to make the experimental observation of phonon blockade possible. We show that phonon blockade can be observed by measuring the statistics of the light in a microwave superconducting resonator capacitively coupled to the mechanical mode. The underlying reason is the formation of an entangled state between the two resonators, ensuring a perfect match between the phonon dynamics and the photon statistics. Our scheme does also offer a way to prepare and detect entangled states between phonons and photons.

Keywords: Nano electromechanical systems, circuit quantum electrodynamics, entanglement

Characterization of MEMS devices for the study of superfluid helium films

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Measurements on the mechanical properties of MEMS resonators were performed to characterize such devices from room down to low temperatures. Using state-of-the-art silicon integrated circuit technology, we have designed, fabricated, and manufactured resonators consisting of pairs of parallel plates with a well-defined gap whose size can be controlled with high accuracy down to the sub-micron range. A full study of resonance properties at various temperatures and pressures were performed. We will discuss the details of design, fabrication, and operation. These studies open up a window of opportunities to look for novel phenomena in quantum fluids such as in superfluid ^{3}He films.

Keywords: superfluid films, MEMS, low-temperature devices

Quantum opto-mechanics: how to use micromechanics in quantum experiments

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Micro- and nanomechanical resonators are gradually becoming available as new quantum systems. Their size and mass allow access to a completely new parameter regime for macroscopic quantum experiments, and quantum optics provides a well-developed toolbox to achieve this. We report our latest results on laser cooling micromechanical resonators, both in the weak and in the strong coupling regime. We also discuss the possibility to generate opto-mechanical quantum entanglement, which is at the heart of Schrödinger's cat paradox.

Keywords: quantum mechanics, optics, mechanics
INVITED PAPER

Nanomechanical measurements of a superconducting qubit

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There is a rapidly growing effort to integrate quantum technologies with mechanical systems in order to manipulate and measure quantum states of mechanics for applications ranging from quantum computing to sensing of weak forces to the study of foundational questions in quantum mechanics. In this talk, I will report on our measurements of a novel nanoelectromechanical system, in which the flexural motion of a mechanical structure is coupled to the charge degree of freedom of a superconducting charge qubit, also known as a Cooper-pair box (CPB). I will discuss how the interaction with the CPB produces a CPB-state-dependent shift in the frequency of a flexural mode of the mechanics, which is similar to the single-atom phase shifts experienced by electromagnetic resonators in the dispersive limit of cavity quantum electrodynamics (CQED). Results will be shown that demonstrate the use of this dispersive shift for performing spectroscopy and read-out of quantum interference effects in the CPB and for parametric amplification of mechanical motion. In the end, I will discuss the prospects of utilizing the CPB-coupled nanoresonator for probing the quantum regime of nanomechanics.

Keywords: NEMS, superconducting qubits, quantum measurement
INVITED PAPER

Dissipation in high-stress silicon nitride nanomechanical resonators at low temperatures

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The understanding of dissipation in nanomechanical resonators is important for device applications and to study quantum mechanical effects in such systems. However, despite a range of experiments on semiconducting[1] and metallic[2] devices, dissipation in nanomechanical resonators at low temperatures is not yet well understood. Here we present measurements of dissipation in high-stress silicon nitride nanomechanical resonators at low temperatures. The resonators were fabricated as doubly-clamped beams with a layer of gold on top using a combination of optical lithography, electron-beam lithography and dry etching. The motion of the resonators was actuated and detected using the magnetomotive technique[3]. Four beams with frequencies ranging from 4 to 60 MHz were measured at low temperatures obtaining quality factors in the range of $10^5 - 10^6$.

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2. A. Venkatesan et al., Phys. Rev. B 81, 073410 (2010); F. Hoehne et al., Phys. Rev. B 81, 184112 (2010).

3. A. Cleland and M. L. Roukes, Sensors and Actuators A 72, 256 (1999).

Keywords: dissipation, silicon nitride, magnetomotive

Resonant magneto-conductance through a vibrating nanotube

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We address the electronic resonant transport in presence of a transverse magnetic field through the single level of a suspended carbon nanotube acting as a quantum oscillator. We predict a negative magneto-conductance with a magnetic-field induced narrowing of the resonance line and a reduction of the conductance peak when the nanotube is asymmetrically contacted to the leads. At finite bias voltage we study the threshold for phonon-assisted transport.

1. G. Rastelli, M. Houzet, and F. Pistolesi, Europhys. Lett., **89**, 57003 (2010).

Keywords: NEMS, quantum transport, Aharanov-Bohm effect, theory

Noncontact nanoscale friction probed by low temperature lateral force spectroscopy

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Nanotribology, namely, friction on nanoscale, has been of great interest both in basic physics and in N(M)EMS-based nanotechnology. On nanoscale, friction is observed even if two bodies are not in atomically contact. This "noncontact friction" has been observed using ultrasoft cantilevers as a moving body. Although the observed friction coefficient Γ is small ($\sim 10^{-12}$ kg/s)[1], it is 7 or 8 orders of magnitude larger than any theoretical predictions.

We have measured a noncontact friction down to 4 K by our low-T frequency-modulation atomic force microscope employing a quartz tuning fork cantilever with a PtIr tip[2]. $NbSe_2$ and $SrTiO_3$ are employed as the opposite bodies, which are chosen as typical metallic (superconducting) and insulating surfaces. Γ's are $\sim 10^{-4}$ kg/s, which is 8 orders of magnitude larger than the previous soft cantilever studies. Surprisingly, Γ at low temperatures shows a *maximum* when the tip-sample distance d is about 5 nm. The maximum in Γ is observed on both $NbSe_2$ and $SrTiO_3$, so it seems a universal phenomenon. Moreover, the Γ maximum is accompanied with an increase in the effective spring constant k of the tuning fork cantilever. The overall behavior of Γ and k bears a striking resemblance to the Debye-like relaxation response. A phenomenological model in terms of d-dependent relaxation time is proposed. Our finding suggests a novel, yet unknown, mechanism in the noncontact friction.

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Keywords: Nanotribology, noncontact friction, Scanning Probe Microscopy

Strong gate coupling of high-Q nanomechanical beam resonators

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The detection of mechanical vibrations near the quantum limit is a formidable challenge since the displacement becomes vanishingly small when the number of phonon quanta tends towards zero. An interesting setup for on-chip nanomechanical resonators is that of coupling them to electrical microwave cavities for detection and manipulation. In this work we show how to achieve a large cavity coupling energy of up to 1 MHz/nm for metallic beam resonators at high mechanical frequencies of 30-120 MHz. We used focused ion beam (FIB) cutting to produce uniform slits down to 10 nm, separating patterned resonators from their gate electrodes, in suspended aluminum films. We measured the thermomechanical vibrations down to a temperature of 25 mK, and we obtained a low number of about twenty phonons at the equilibrium bath temperature. The mechanical properties of Al were excellent after FIB cutting and we recorded a quality factor of $Q \sim 3 \times 10^5$ for a 67 MHz resonator at a temperature of 25 mK. Between 0.2K and 2K we find that the dissipation (Q^{-1}), is linearly proportional to the temperature. Below 0.2 K, both the dissipation and resonant frequency show only a weak temperature dependence, with thermal decoupling being ruled out as an explanation. Different mechanisms that produce a linear T dependence are discussed.
This research was supported jointly by the NSF under DMR-0908634 (Materials World Network) and by the Academy of Finland.

Keywords: nanomechanics, quantum limit, dissipation, focused ion beam

16 Magnetism, superconductivity, quantum coherence

Ac susceptibility and magnetization hysteresis loops of a thin current-carrying superconducting disk with B-dependent J_c

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In this paper, in the framework of the critical state model (CSM), the real and imaginary parts of ac susceptibility and also the magnetization hysteresis loops of a thin current-carrying superconducting disk for the Bean, Kim, and Exponential models of the local field-dependent critical current density $J_c(B)$ are calculated. The results are also compared with one another and also with those obtained in the absence of a radial transport current to search for the changes.

Keywords: Magnetization, Hysteresis loops, superconductivity

Low temperature spin wave excitations in $(Nd_xY_{1-x})_{2/3}Ca_{1/3}MnO_3$ $(x = 0, 0.1)$ CMR compounds

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We have studied the low temperature specific heat of the colossal magnetoresistance compounds (CMR) $(Nd_xY_{1-x})_{2/3}Ca_{1/3}MnO_3$ $(x = 0, 0.1)$ for $0.4 \le T < 2$ K in magnetic field. Applied magnetic fields lead to the drop of the low temperature specific heat by more than two orders, which implies a large magnetic contribution. Experimental data were successfully fitted by the sum $C\,(H,T) = C_{hyp} + C_{SG} + C_{fsw}$, where $C_{hyp} = D\,(H) \cdot T^{-2}$ is the hyperfine contribution, $C_{SG} = \gamma(H) \cdot T$ is a linear T - dependent term , and $C_{fsw} = a\,(H) \cdot T^{3/2} \cdot \exp\left(-\frac{\Delta(H)}{T}\right)$ is the ferromagnetic spin waves contribution caused by the magnetic ordering of Nd ions in the effective magnetic field of Mn subsystem, ($\Delta\,(H) -$ is a spin-wave gap in K). The linear term $\gamma(0) = 20$ JK^{-2}mol^{-1} attributed to the magnetic glass state of the insulating compounds studied in [1] rapidly decreases with H increasing up to 5 T: $\gamma\,(H) = \gamma\,(0) \cdot \exp\left(-\frac{H}{H_C}\right)$. The C_{fsw} contribution provides the best fitting of experimental data. It has been attributed to the ferromagnetic ordering with the anisotropy induced gap in the spin-wave spectrum which is similar to the gap induced by the applied magnetic field. The value of $\Delta\,(0)$ is approximately the same $(0.8K)$ for both studied compounds and Δ then increases with increase of H: $\frac{d}{dH}\Delta\,(H) = 0.2$ KT^{-1}.

1. E. Fertman, et al., J. Magn. Magn. Mater. **321**, 316 (2009).

Keywords: specific heat, spin-wave excitations, magnetic glass

Neutron scattering experiments with the unconventional superconductor UPt_3

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The superconductor UPt_3 has long been thought to have an unconventional order parameter (OP). Most of the experimental and theoretical evidence points to a triplet state with E_{2u} symmetry and strong spin-orbit coupling[1]. However, there are discrepancies with this conclusion. As a notable example, measurements of the anisotropy of the upper critical field H_{c2}, and the OP they suggest, are in conflict with measured NMR Knight shifts. Because of the unconventional nature of UPt_3, all surface scattering is pair breaking and can potentially complicate experimental measurements and thus their theoretical interpretations. Measurements that minimize interactions with a sample's surface are an extremely important tool for studying the superconducting state. Neutron scattering is one such technique and can help to illuminate the bulk properties of UPt_3. Preliminary small angle neutron scattering results to test time-reversal symmetry breaking predictions in the superconducting B-phase will be presented along with other areas of interest – such as the interplay between magnetism and superconductivity and the pseudo-spin portion of the OP – that will be examined using neutron scattering. Support for this work from the DOE, grant DE-FG02-05ER46248, is gratefully acknowledged.

1. J. D. Strand *et. al.*, "The Transition Between Real and Complex Superconducting Order Parameter Phases in UPt_3," Science, **328**, 1368 (2010).

Keywords: superconductivity, unconventional pairing, neutron scattering

Diagrammatic Monte Carlo for correlated fermions

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We show that Monte Carlo sampling of the Feynman diagrammatic series (DiagMC) can be used for tackling hard fermionic quantum many-body problems in the thermodynamic limit by presenting accurate results for the repulsive Hubbard model in the correlated Fermi liquid regime. Sampling Feynman's diagrammatic series for the single-particle self-energy we can study moderate values of the on-site repulsion ($U/t \sim 4$) and temperatures down to $T/t = 1/40$. We compare our results with high temperature series expansion and with single-site and cluster dynamical mean-field theory.

Keywords: correlated systems, Hubbard model, quantum Monte Carlo

Probing photon coupling strengths in one-dimensional arrays of Josephson junctions at microwave frequencies

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In this work experiments were done on probing photon coupling strength in one-dimensional(1D) arrays of Josephson junctions at microwave frequencies. For better coupled to the microwave photons, the 1D arrays were placed in a broad-band waveguide on the substrate. Two methods were used to investigate this problem: The first one is the dc response, namely the photoresistance of 1D arrays under a microwave irradiation, and the second one is the transmission of microwave photons after device-photon interaction. Both methods provide the photon coupling strength when the 1D array undergoes a magnetic-field tuned superconductor-insulator transition.

Keywords: phase transition, Josephson junctions, microwave

Generalized BCS equations for composite superconductors obtained via a Bethe-Salpeter equation: an overview

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We recall that: (1) While all agree that superconductivity occurs due to the formation of Cooper pairs (CPs), the pairing-mechanism for composite supercoductors (CSs) remains an enigma. (2) Pairing interaction in the BCS theory is fixed by appealing to either the equation for T_c, or the equation for $\Delta(0)$ *(and not by first principles)*, an approach that can also be followed for CSs via the generalized-BCS equations[1] (GBCSEs); these are obtained via a Bethe-Salpeter equation with a kernel that resembles a superpropagator, and the equality:$|W(0)|$ =$|\Delta(0)|$, where W is the binding energy , and Δ the gap. (3) GBCSEs seem to yield sensible results[2,3] for various CSs, and that (4) An extension of this framework,[4] incorporating Landau quantization, sheds new light on de-Haas van-Alphen oscillations and re-entrant superconductivity. We propose to present here a further extension of GBCSEs to deal with the CPs that have non-zero c.m. momentum, aimed at *calculating* critical currents.

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4. G.P. Malik, On Landau quantization of Cooper pairs in a heat bath, Physica B, 2010 (DOI No. 10.1016/j.physb.2010.05.026).

Keywords: Generalized BCS equations, composite superconductors

Quantum Processes in superconducting-magnetic Josephson junctions

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I discuss the theory of nonequilibrium transport in Superconductor-Ferromagnet-Superconductor (SFS) Josephson point contacts and weak links. Andreev bound states, multiple Andreev reflection and Spin Mixing (unitary spin dynamics induced by the SF interface) lead to unique signatures in the transport of charge, energy and spin in these devices. I illustrate these processes with three examples: (i) resonant heat transport, (ii) resonant spin transport in SFS junctions and (iii) long-range spin-transfer torques in coupled SFNFS devices. The latter could provide the basic element for constructing a new class of spintronic devices with quantum control.

Keywords: Superconductivity, Josephson Junction, Josephson Weak Link, Quantum Device, Nonequilibrium Transport, Andreev Bound State, Branch Conversion

INVITED PAPER

Magnetic resonance in spin-liquid and ordered phases of spin-1/2 antiferromagnet on the anisotropic triangular lattice

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The spin system of Cs_2CuCl_4 is formed by localized S=1/2 spins coupled antiferromagnetically within 2D layers with distorted triangular lattice. This magnet remains in a quantum spin-liquid state at temperatures far below Curie-Weiss temperature 4 K and exhibits a transition with a spiral ordering only at T_N=0.6 K.[1]. We studied spin excitations in Cs_2CuCl_4 by means of electron spin resonance at temperatures down to 0.05 K in the range 9-140 GHz. An unexpected energy gap of about 10 GHz and a splitting of spin excitation mode were found for the spin-liquid phase. This differs drastically from a conventional antiferromagnet, having a single gapless mode above T_N. The observed gap is presumably due to Dzyaloshinsky-Morya (DM) interaction, analogous to a gap in 1D S=1/2 spin-chains with DM interaction.[2] The nature of the observed splitting is not clear. Below T_N we have found a multibranch spectrum, coexisting with a mode at the paramagnetic resonance frequency. This unusual mode is proposed to be a "spinon"-type spin resonance of excitations within the spin-liquid continuum, which is known to remain below T_N. Other modes of spin excitations of the ordered phase may be well described by a macroscopic approach for a spiral magnet in a low field range. Excitations observed in high field phases remain unclassified.

1. R. Coldea, D. A. Tennant, Z. Tylchinsky, Phys. Rev. B 68, 134424 (2003).
2. M. Oshikawa, I. Affleck, Phys. Rev. B **60**, 1038 (1999).

Keywords: quantum spin liquids, 2D spin systems, frustrated antiferromagnet

17 Techniques: sensors, detectors, methods

CMN1000: a fast, accurate and easy to use thermometer for the range 10 mK - 2 K

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A CMN1000 magnetic susceptibility thermometer was developed to support thermometry alongside the SRD1000, a superconductive reference device for transferring the PLTS-2000. The physical dimensions and electrical signals of the CMN1000 sensor integrate well with those of the SRD1000. The parameters of the thermometer are easy to calibrate using the points of the reference device. We report on recent measurements of the sensitivity, reproducibility and response time of the thermometer in the range from 10 mK to 2 K. The results show that the CMN1000 is sufficiently fast and accurate to support precision thermometry.

Keywords: Thermometry, PLTS-2000, SRD1000

Research capabilities in quantum fluids and solids at the Spallation Neutron Source

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The Spallation Neutron Source (SNS) is an accelerator-based neutron source located in Oak Ridge, TN at the site of Oak Ridge National Laboratory. SNS is a unique facility that is providing the neutron scattering community world-wide with unprecedented research opportunities, to carry-out experiments in almost every scientific field. The capabilities of SNS allow for measurements of greater sensitivity and higher resolution, or in more complex sample environments than have been possible at existing neutron facilities. SNS has a world-class suite of 25 instruments either being planned, under construction, or in operation. We here briefly review selected instruments at SNS that are suitable for the studies of quantum fluids and solids (QFS), such as the ARCS wide-angle spectrometer, the high resolution BASIS silicon backscattering spectrometer and the CNCS cold-neutron instrument. In order to facilitate and diversify the experimental capabilities at SNS, the sample environment team, in collaboration with instrument staff, has initiated a program to design and build unique equipments dedicated to QFS studies. In particular, a large volume (100-150 cc) bridgman-type helium cell that can be taken to 100 bars has recently been constructed. Such a large volume is desirable in view of the relatively low ^{4}He scattering cross-section and moderate neutron flux. A cryostat large enough to accomodate the cell that has a base (empty cell) temperature of 30 mK is also being commissioned. Investigations of Bose-Einstein condensate and the elementary excitations in ^{4}He and ^{3}He-^{4}He mixtures are being planned.

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Keywords: Neutron scattering, Elementary Excitations, BEC

Quantum rotation sensors: relative merits of devices using photons, cold atoms and superfluid helium

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Quantum interferometers have been used to measure rotation by virtue of the Sagnac effect, which couples a rotation field to the phase of the effective wavefunction. Gyroscopes using coherent light, cold atoms or superfluid helium have been made and tested, with varying strengths and weaknesses. In this poster, we give a brief survey of quantum gyroscopy with an emphasis on the fundamental differences between these three approaches.

Keywords: superfluid, helium, cold atoms, laser gyro, gyroscope, interferometer

Magnetization measurements and surface observation of Grafoil substrate

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^{3}He films adsorbed on graphite substrates have been vigorously investigated. However, heat transfer mechanisms between ^{3}He films and graphite substrate have not understood yet. Results of thermal conductivity measurements have revealed that heat flows along the ^{3}He solid films over a long distance and then flows into the graphite substrate at some local spots [1]. Plausible candidate of these local spots is impurity clusters in graphite substrate. Diameter of impurity clusters must be larger than several-hundreds-nm so as to exchange heat with ^{3}He films as magnon or phonon at sub-mK temperature range. However, existence of such large clusters is quite questionable. Although contents of some impurities have been reported from the ash analysis for the actual graphite substrate, Grafoil [2], configuration of impurities has not been clarified. In this report, results of surface observations of Grafoil by a scanning electron microscope (SEM), analyses by energy dispersive X-ray spectroscopy (EDS), and magnetization measurements are shown. Impurity clusters with diameter of 1-10 μm containing Al, Ca, Si, Fe, etc. are observed at exfoliated surfaces of Grafoil. Ferromagnetism is also observed after subtraction of a diamagnetic contribution. The saturation magnetization is several times larger than that of HOPG [3], and coincides with the amount of magnetic impurities reported from the ash analysis [2].

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2. The data sheets of Grafoil by Union Carbide Corporation.
3. P. Esquinazi et al., *Phys. Rev. B* **66**, 024429 (2002).

Keywords: Grafoil, magnetization, scanning electron microscope, energy dispersive X-ray spectroscopy

On sound emission of quartz tuning forks in liquid helium

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Commercially produced quartz tuning forks have recently become a widely used tool in quantum fluids research. By measuring the resonance characteristics of these sensitive devices valuable information on the kinematic viscosity, cavitation, transition to classical and quantum turbulence has been obtained for ^{4}He, ^{3}He and ^{4}He - ^{3}He mixtures. While for tuning forks oscillating at relatively low frequencies (in many cases for the most common 32 kHz ones as well, except at very low temperatures), the losses due to acoustic emission of first sound could usually be neglected, however, for higher frequency forks (e.g., 77 kHz and 100 kHz forks available to us), acoustic emission becomes the dominant dissipative process. We present a systematic experimental study over a wide temperature range including the zero temperature limit in gaseous, normal liquid and superfluid ^{4}He as well as in ^{4}He - ^{3}He mixtures backed up by theoretical considerations, demonstrating clearly the relative importance of acoustic emission and laminar viscous/ballistic drag for various types of tuning forks in ^{4}He. Moreover, experimental evidence is presented that in superfluids forks affect each other via their acoustic velocity fields.

Keywords: quartz tuning fork, sound emission, cryogenic helium

Development of a ^{3}He refrigerator for possible experiments of solid ^{4}He on a small jet plane

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So far the gravity on the Earth(g_{E}) has not been taken seriously to mask the fundamental phenomena on quantum solids and liquids, except for some critical phenomena of superfluid ^{4}He. We are planning to investigate the effect of gravity on the equilibrium shape of solid ^{4}He, which has never been considered. Motivated by this idea, we got started to construct a cryostat which produced as low as 500 mK and met the severe restrictions of a jet plane.
The refrigerator was a usual ^{3}He-evaporator pumped by a scroll pump. A small GM refrigerator was installed to provide 4K stage. 1K pot was put in which was also pumped by another scroll pump to condense ^{3}He gas and sample ^{4}He. The cryostat was designed to have two optical windows to be able to observe solid ^{4}He under microgravity.
In the test flight for the cryostat, the minimum temperature of 690mK was kept during the entire flight of two hours. About 20 seconds microgravity and also 20 seconds 1.5-2.0g_{E} period before and after the microgravity did not affect the cooling parformance. We did some preliminary experiments with *bcc* solid ^{4}He under microgravity. The crystal was remained stuck to the bottom of the sample cell even in the 20 seconds microgravity condition. At the conference we would present a further progress together with cryogenics details and some pictures of solid ^{4}He.

Keywords: microgravity, jet plane, parabolic flight, ^{4}He

Magnetically driven cold shutters for measuring the influence of 300 K radiation on an optical cryostat

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We describe a simple and compact magnetic system to move metallic shutters inside an optical cryostat, based on a large permanent magnet located outside the cryostat. We use this system to probe the effect of 300 K thermal radiation transmitted through the observation windows on the temperature of our sample. We conclude that, as predicted from the separately measured IR transmission of our windows, the corresponding heat load is less than 1 μW. We discuss the relevance of this result to the operation of optical dilution refrigerators.

Keywords: Aerogels, optical cryostat, infrared radiation, infrared filters, low temperature shutters

Torsional oscillator experiments under DC rotation with reduced vibration

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A brief description of a stable rotating cryostat designed for torsional oscillator experiments under DC rotation is given, where vortex line penetration observations have been studied for 3D superfluid made of monolayer He filmst[2] as well as for hcp 4HeThe torsional oscillator performance gives often better data under steady rotation at moderate speeds than under still condition. The article[1] describes briefly the two of our rotating cryostats at ISSP, u-tokyo, and the present paper describes the torsional oscillator experiments using one of them, namely high speed rotating cryostat with much higher mass and stability of the frame.

1]. M. Kubota, et al., Physica B 329-333 (2003) 1577-1588.
2]. M. Fukuda, et al., Phys. Rev. B 71, 212502 (2005)
3]. M. Yagi, et al., This QFS meeting at SS session.See also M. Kubota et al., at SS session.

Keywords: quantum solid, supersolid state, vortex lines penetration, vortex fluid state, macroscopic coherence

An operation circuit of micro-SQUID magnetometer in a dilution refrigerator

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We have been developing a micro SQUID (μ-SQUID) magnetometer, to investigate quantum effects in μm- or nm-sized magnetic materials[1]. In the μ-SQUID magnetometer, the sample is placed on the SQUID loop directly and the flux is detected by the loop itself. The close proximity between the sample and the SQUID loop is great advantage for high sensitive detection of magnetization from the tiny magnets. The heat release during the operation of the SQUID, however, became a great problem in experiments below 1 K because of the close proximity. Here we report a digital circuit for the μ-SQUID magnetometer which can reduce the heat release in the low temperature operation and whose parts are commercially available. The circuit consists of a FPGA-digital board with AD-DA converters and a pre-amplifier. The FPGA board is controlled by the LABVIEW software. The magnetization measurement of a crystal of the single molecule magnets is demonstrated.

1. K. Takeda, H. Mori, A. Yamaguchi, et al., Rev. Sci. Instrum., 79, 033909(2008).

Keywords: Macroscopic Quantum Tunneling in Magnetization, Low Temperature Technique

18 Other topics

Application of quantum ensembles to linguistic analysis

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We propose a thermodynamical approach (based on the grand canonical ensemble) to the analysis of frequency distributions in texts. Energy levels are identified with word frequencies (the number of occurrences in a given text) and the level occupation corresponds to the number of different words with the same frequency. The fugacity z is defined by $N_{\rm hapax} = z/(1-z)$, where $N_{\rm hapax}$ is the number of *hapax legomena*, i.e., words occurring only once in a given text sample. This number is known to be the largest of all the occupation numbers, and thus the entire distribution is more likely to resemble the Bose-distribution. Temperature of the system is found by fitting the occupation of higher levels. Due to the nature of the frequency distribution is seems that a simple model of very weak log-of-log growth is appropriate for the energy spectrum $\varepsilon_n \propto \ln(1 + \ln n)$. This requires, in particular, that the spectrum is bounded from above by some $n_{\max}$. One should note that a different approach to define the temperature of texts was applied in [1] using the classical Boltzmann function and the frequency behavior of the most frequent words. Interestingly, the temperature parameter used in our work exhibits an insignificant variation with the size of the text sample. This makes it a good variable for comparative linguistic studies. So far, we have performed analysis of some texts written in Ukrainian, English, as well as Guinean Maninka (in the Nko script). The calculated temperatures are about two orders of magnitude smaller than the Bose-condensation temperature defined in a standard way.

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Keywords: Bose-distribution, word frequency, text parameters

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