Landau Institute for Theoretical Physics

A. I. LARKIN MEMORIAL CONFERENCE

June 24–28, 2007
Chernogolovka, Russia

http://LarkinConf.itp.ac.ru

CONFERENCE PROGRAM

June 24, Sunday,
Morning session:

8:55 - 9:00	Conference Opening		

Phase transitions

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9:40 - 10:20	P. Coleman	Simply Symplectic: a new look at large N expansions for quantum matter	6
10:20 - 11:00	S. Kivelson	Myriad phases of the checkerboard hubbard model	7
11:00 - 11:20	**Coffee break**		
11:20 - 12:00	A. MacKenzie	Spontaneous resistive anisotropy at high fields in $Sr_3Ru_2O_7$	7
12:00 - 12:40	G. Biroli	Cooperativity, dynamic heterogeneity and the emergence of a growing length scale at the glass transition	7
12:40 - 13:20	S. Pikin	On the ac magnetic susceptibility of spin-chains: solitons in one-dimensional systems	7
13:20 - 14:30	**Lunch**		

June 24, Sunday,
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Nonequilibrium superconductivity

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15:10 - 15:50	S. Iordanskiy	The nucleation and relaxation of the order parameter in BCS model	9
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16:10 - 16:50	A. Kapitulnik	Search for Broken Time Reversal Symmetry State in Sr_2RuO_2 and other Unconventional Superconductors	10
16:50 - 17:30	Yu. Ovchinnikov	Multiparticle tunneling in Josephson junctions and hysteresis in the current-voltage characteristics near the threshold value	11
17:30 - 18:10	N. Kopnin	Nonequilibrium charge transport and current noise in quantum SINIS contacts	11

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Localization, mesoscopics and chaos

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12:00 - 12:40	L. Levitov	Polarization catastrophe and supercritical impurities in graphene	13
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June 25, Monday,
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12:00 - 12:40	M. Trunin	Peculiarities of the microwave conductivity of superconducting single crystals with different doping levels	22
12:40 - 13:20	A. Yazdani	Probing formation of cooper pairs on the atomic scale in the high T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$	23
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17:00 - 17:40	B. Spivak	Theory of the quantum metal to superconductor transition in highly conducting films	24
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June 28, Thursday,
Afternoon session:

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15:20 - 16:00	T. Giamarchi	Dynamics of disordered elastic systems	29
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16:20 - 17:00	A. Koshelev	Vortex lattices in tilted magnetic field	30
16:00 - 17:40	V. Mineev	Electrodynamics of Larkin-Ovchinnikov-Fulde-Ferrell superconducting state	30
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June 24, Sunday, Morning

Homage to Tolya Larkin
Larkin's contribution to the phase transition theory

Valery Pokrovsky[1,2]

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In his early years as a scientist Tolya Larkin has made several fundamental contributions to general theory of phase transitions. Together with V. Vaks he formulated the universality hypothesis (1966) assuming that the critical behavior depends only on symmetry of the system and the way of its violation and does not depend on microscopic details. In the pioneering work together with D. Khmelnitskii he applied the renormalization group technique to calculate the critical behavior of the scalar field with the ϕ^4 interaction in 4 dimensions. This work was the immediate precursor of the Wilson renormalization group approach in $4-\varepsilon$ dimensions. Larkin and Khmelnitskii proposed direct physical application of their theory to 3-dimensional systems with dipolar interaction supported by the experiment. Larkin and S. Pikin demonstrated that the shear elastic strains turn the second order Ising (magnetic) phase transition into the first order one. Larkin and Yu. Ovchinnikov discovered that spin wave fluctuations in isotropic magnets are strongly developed not only near phase transition point, but at any temperature below it providing corresponding singularity to the longitudinal magnetic susceptibility. This was the first indication of the critical behavior in a more dimensions than it was predicted by Landau mean-field theory. I discuss the further developments of these works.

May be not less important Tolyas contribution was his participation in discussions of works by other authors, including Berezinskii, Polyakov, Migdal and others including myself. In these discussions several new ideas were formulated with his help, though he was not a coauthor.

Simply Symplectic: a new look at large N expansions for quantum matter

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Over the years, large N and large S expansions have played an important role in the development of controlled approximations for statistical mechanics, particle and condensed matter physics. Particle physicists have embraced the SU(N) group, as a structure that preserves baryon and meson structure, but unfortunately for condensed matter physics the structure of the SU(N) group - which has no two-particle singlets and no well-defined time-reversal symmetry, has limited our ability to develop a controlled treatment of magnetism and superconductivity.

I'll explain how the use of symplectic groups provides a large N expansion that is more closely tailored to condensed matter, both magnetic and charged. Symplectic large N groups restore the proper time-reversal parity of spins: an essential element for the formation of Cooper pairs and spin valence bonds. Applications of this method to frustrated magnetism, where the approach correctly recovers the finite temperature Ising transition in the J1-J2 Heisenberg model that Larkin, Chandra and Coleman predicted many years ago. I'll also show how heavy fermion superconductivity can be treated using this approach.

Myriad Phases of the Checkerboard Hubbard Model

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The zero temperature phase diagram of the checkerboard Hubbard model is analyzed[2] in the *solvable* limit in which it consists of weakly coupled square plaquettes. As a function of the on-site Coulomb repulsion $U > 0$ and the density of electrons per site, $n_{el} \equiv 1 - x$, we demonstrate the existence of *at least* 16 distinct phases. For instance, for $0 < x \ll 1$, there is a d-wave superconducting phase which, depending on the magnitude of U, can have[1] a large pair-size and gapless "nodal quasiparticles" (d-BCS) or tightly bound pairs and no nodal quasiparticles (d-BEC). In the $x \to 0$ limit, these phases evolve into a novel d-wave Mott insulator. Other interesting phases include an insulating charge density wave (CDW), a spin-1/2 antiferromagnet (AF) which may, or may not exhibit coexisting nematic orbital or $\sqrt{5} \times \sqrt{5}$ CDW order, a spin-1/2 Fermi liquid (FL) with two bands, a spin-3/2 AF, and a spin 3/2 FL.

[1] W. F. Tsai and S. A. Kivelson, Phys. Rev. B **73**, 214510 (2006).
[2] H. Yao, Wei-Feng Tsai, and S.A.Kivelson, unpublished.

Spontaneous resistive anisotropy at high fields in $Sr_3Ru_2O_7$

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Recently, my research group presented evidence supporting the existence of a novel quantum phase in the vicinity of a metamagnetic quantum critical point in $Sr_3Ru_2O_7$ [1]. Here, I present a summary of an extensive follow-up project which shows that within this phase, the resistivity becomes highly anisotropic when a small in-plane field component is added to the large out-of-plane field that promotes the metamagnetic transition [2]. The characteristics of this anisotropy will be discussed, and compared with previous intriguing work on semiconductor 2DEGs [3].

[1] S.A. Grigera, P. Gegenwart, R. A. Borzi, F. Weickert, A. J. Schofield, R.S. Perry, T. Tayama, T. Sakakibara, Y. Maeno, A. G. Green and A. P. Mackenzie, Science 306, 1155 (2004) and references therein.
[2] R.A. Borzi, S.A. Grigera, J. Farrell, R.S. Perry, S. Lister, S.L. Lee, D.A. Tennant, Y. Maeno and A.P. Mackenzie, Science 315, 214 (2007).
[3] For example M. P. Lilly, K. B. Cooper, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. 82, 395 (1999).

Cooperativity, dynamic heterogeneity and the emergence of a growing length scale at the glass transition

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The glass transition is one of the longest standing unsolved puzzles in condensed matter physics. In spite of a great deal of theoretical effort over the past few decades, a real understanding of this and related phenomena is still lacking. Indeed, the most basic issues are still unresolved: Is the abrupt dynamical arrest merely a crossover with little or no universality? Or, instead, is it related to a true underlying phase transition, of a new kind? Recent experimental and numerical works, to a large extent triggered by new theoretical tools and concepts, unveiled that the dynamics becomes increasingly spatially correlated and heterogeneous on approaching the glass transition, thus strongly suggesting a positive answer to this last question. Concomitantly, theoretical predictions aimed to explain these dynamical correlations in terms of critical phenomena have been developed and started to be tested in detail. In this talk I shall discuss these new results focusing in particular on the theoretical findings and their comparison to experiments.

On the ac magnetic susceptibility of spin-chains: solitons in one-dimensional systems

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Single chain magnets [1, 2] (SCM) are attracting huge interest because of their unusual properties and behavior under the action of magnetic field and temperature. In such systems, slow magnetic relaxations were predicted by Glauber [3] who described the individual dynamics of the spin unit composing a chain and had shown that the relaxation time follows an activation law. This approach to SCM was definitely confirmed by the whole series of recent ac and dc measurements for various compounds [4, 5]. In the present paper, we apply the model of classical thermally activated solitons (kinks or domain walls), which was developed earlier [6], for the description of temperature and frequency dependences of the magnetic susceptibility of single chain magnets in alternating magnetic fields. We show that basic features of such a magnetic response admit the qualitative and even quantitative explanations at the mentioned phenomenological approach: the characteristic rapid decrease at temperature below its blocking value, this blocking value and maximum in the susceptibility, the shift of blocking temperature to higher values at the increase in frequency, the universal curve at high temperatures and any frequency. The comparison of experimental data and theoretical results allows to estimate the number of solitons and "weak" places in correlation regions of a sample.

[1] A. Caneschi, D. Gatteschi, N. Lalioti et al., Angew. Chem. 113, 1810 (2001).
[2] R. Clerac, H. Miyasaka, M. Yamashita et al., J. Am. Chem. Soc. 124, 12837 (2002).
[3] R.J. Glauber, J. Math. Phys. 4, 294 (1963).
[4] H. Miyasaka, R. Clerac, K. Mizushima et al., Inorg. Chem. 42, 8203 (2003).
[5] M. Balanda, M. Rams, S.K. Nayak, et al., Phys. Rev. B 74, 224421 (2006).
[6] E. Demikhov, S.A. Pikin, and E.S. Pikina, Phys. Rev. E 52, 6250 (1995).

The Ground State of Imbalanced Fermi Mixtures

Martin Zwierlein[1,2]

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Fermionic superfluidity, whether it occurs in superconductors, in helium-3 or inside a neutron star, requires pairing of fermions. In an equal mixture of "spin up" and "spin down" fermions, pairing can be complete and the entire system will become superfluid. When the two populations of fermions are unequal, however, not every particle can find a partner. Can superfluidity persist in response to such a population imbalance? If so, what would be the nature of this imbalanced superfluid state?

This question has been raised over forty years ago, at that time in the context of superconductors in a magnetic field. Chandrasekhar and, independently, Clogston found a limit of the upper critical field in superconductors, corresponding to an upper limit on the spin imbalance in Fermi mixtures, beyond which superfluidity breaks down. Sarma discussed a superfluid state supporting spin imbalance, but found it to be unstable. In 1964, Larkin and Ovchinnikov [1] and independently Fulde and Ferrell [2] proposed a novel superfluid state (LOFF-state), lower in energy than the BCS state, allowing for Fermi surface mismatch by forming Cooper pairs at finite momentum.

Forty years later, the debate surrounding the ground state of imbalanced superfluidity is still on-going. I will report on our studies of this intriguing question in a strongly interacting two-state mixture of trapped, ultracold fermionic atoms [3–6]. The observation of vortices established superfluidity for imbalanced spin populations. When the fraction of unpaired atoms increased beyond a critical value, we observed the breakdown of the superfluid state, the Chandrasekhar-Clogston limit of superfluidity. Very recently, we could show that this breakdown is not associated with pair breaking, but that the remaining Fermi mixture still contains pairs - pairs which do not condense even at zero temperature [6].

[1] A.J. Larkin and Y.N. Ovchinnikov, Zh. Eksp. Teor. Fiz. **47**, 1136 (1964), [Sov. Phys. JETP **20**, 762 (1965)].
[2] P. Fulde and R.A. Ferrell, Phys. Rev. **135**, A550 (1964).
[3] M.W. Zwierlein, A. Schirotzek, C.H. Schunck, and W. Ketterle. Science **311**, 492 (2006).
[4] M.W. Zwierlein, C.H. Schunck, A. Schirotzek, and W. Ketterle. Nature **442**, 54-58 (2006).
[5] Y. Shin, M.W. Zwierlein, C.H. Schunck, A. Schirotzek, and W. Ketterle. Phys. Rev. Lett. **97**, 030401 (2006).
[6] C.H. Schunck, Y. Shin, A. Schirotzek, M.W. Zwierlein, and W. Ketterle. Science **316**, 867 (2007).

The nucleation and relaxation of the order parameter in BCS model

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The formation and relaxation of the coherent order parameter is considered in a cooled below T_c Fermi gas of BCS model. The main difficulty is connected with the classical selfconsistency equation unambiguously defining the order parameter (the gap) and therefore it is not fulfilled for the order parameter values far from the equilibrium. This question was considered in the work [1] for the space uniform case. The present paper represent a generalization on the formation of order parameter by subsequent growth of certain superconducting nuclei in the volume of supercooled electron gas.

The physical base for the consideration of the non equilibrium values of the order parameter is given by Landau assumption of a large relaxation time in the vicinity of the critical temperature. Therefore it is possible to consider the states with the non-equilibrium value of order parameter as approximately stationary states using Lagrange method to find the minima of BCS hamiltonian at a given value of modulo square of the order parameter.It is possible to show that the appropriate Lagrange multiplier change the interaction BCS constant g_0 to the effective constant $g_{eff}(\Delta)$. That gives the possibility to satisfy the selfconsistency condition but with the new interaction constant. In the case of the nonuniform values of the order parameter $\Delta(\mathbf{r})$ the effective interaction constant will be also non uniform in space. The mean field theory of BCS model is asymptotically exact for a macroscopically large electron number. It is assumed that mean field theory is also valid for a smooth varying $\Delta(\mathbf{r})$.

The thermodynamic average of the modified BCS hamiltonian depends only on the function $\Delta(\mathbf{r})$ and can be found by the perturbation expansion near T_c and it's minimization in $\Delta(\mathbf{r})$. This problem is solved quite easily in the space uniform case [1], where the selfconsistency itself gives the minimum of the effective hamiltonian at $\Delta = const$.The relaxation process is connected with the annihilation and the scattering of the excitations leading to the change of the electron number in Cooper pairs N_s. One needs to take into account the change of Cooper pairs energy $\epsilon = \frac{\partial H^0_{BSC}}{\partial N_s}\delta N_s$ where δN_s is the change of the electron number in Cooper pairs in each specific collision. The relaxation equation valid for modulo square of the order parameter is close to the real part of TDGL equation obtained in [2] at a bit different assumptions.

In the nonuniform case the function $\Delta(\mathbf{r})$ is defined by some kind of the nonlinear Shrödinger equation with the boundary conditions on the surface of the domain where $\Delta(\mathbf{r}) \neq 0$. These boundary conditions require some small values of Δ and the effective pressure of the superconductive electrons in Cooper pairs. For the spherical symmetry one obtains a family of solutions depending on a real parameter λ which can be chosen either superconducting nuclei radius or the electron number N_s in Cooper pairs. The relaxation process is connected with the annihilation and scattering of excitations like in the uniform case. Calculating the total change in N_s due to the collisions inside superconducting nuclei for unit of time one get the evolution equation for N_s. The condition of large relaxation time is valid near T_c.

[1] S. V. Iordanskiy, R. B. Saptsov, E. A. Brener, JETP, in press.
[2] R. J. Watts-Tobin, Y. Kraehenduehl, L. Kramer, J. Low Temp. Phys.**42**, 459 (1981)

Search for Broken Time Reversal Symmetry State in Sr_2RuO_4 and other Unconventional Superconductors*

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We show results of polar Kerr effect (PKE) measurements on high quality single crystals of Sr_2RuO_4. In these measurements we are searching for an effect analogous to the magneto-optic Kerr effect (MOKE) which would cause a rotation of the direction of polarization of the reflected linearly polarized light normally incident to the superconducting planes. PKE is sensitive to TRS breaking since it measures the existence of an antisymmetric contribution to the real and imaginary parts of the frequency-dependent dielectric tensor. Such a contribution is necessarily absent if TRS is not broken in the material. Our results show unambiguously the emergence of a finite, PKE at $T_c \approx 1.5$ K [1]. The size of the effect increases with decreasing temperature down to 0.5 K and seems to saturate at ∼65 nanorad.

The broken-TRS is expected to have two possible chiralities. To choose between the two possible states, a TRS-breaking field such as a magnetic field, that couples to the order parameter can be applied. We observed that the size of the effect and its temperature dependence are the same as in zero-field cooled experiments indicate that the signal we observe is not due to trapped flux. Finally, we observed that measurements in which we cooled the sample in fields below ∼ 5 Oe gave random sign of the PKE, similar to zero field (with the same ∼ 65 nanorad magnitude), suggesting that ordering fields need to be larger than H_{c1} to affect the low temperature sense of chirality.

We will further discuss TRSB effects in other superconductors including high temperature superconductors.

* This work was supported by Center for Probing the Nanoscale, NSF NSEC Grant 0425897 and by the Department of Energy grant DEFG03-01ER45925.

[1] Jing Xia, Maeno Yoshiteru, Peter T. Beyersdorf, M. M. Fejer, Aharon Kapitulnik, Phys. Rev. Lett. 97 (2006),167002.

Multiparticle Tunneling in Josephson Junctions and Hysteresis in the Current-Voltage Characteristics near the Threshold Value

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The origin of hysteresis effect in the voltage region of the I-V curves of a superconducting junction near the threshould value $V = (E_1 + E_2)/e$ (where E_1, E_2 are energy gap values in superconductors) is discussed. It is shown how the actual structure of the I-V curve can be determined by multiparticle tunneling processes. This circumstance is related to the essential role played by a large parameter$(\delta/\Gamma)^{2/3}$ (Γ being the depairing factor, δ is the order parameter), which can compensate the low barrier transparency. As a consequence the perturbation theory in the transparency coefficient does not hold any longer in such a threshold region. Besides the underlying physical aspects of the phenomenon the actual structure of I-V characteristic is an issue of obvious interest for Josephson junctions based devices.

Nonequilibrium charge transport and current noise in quantum SINIS contacts

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Charge transport and the current noise in a high-transmission single-mode SINIS junction (S stands for superconductor, I is an insulator, and N is a normal metal) are considered in the limit of low bias voltages and low temperatures. The length of the normal conductor is assumed much larger than the superconducting coherence length, but shorter than the inelastic mean-free path. Both the dc current and the noise spectrum are sensitive to the population of the sub-gap states which is far from equilibrium even at low bias voltages. Nonequilibrium distribution establishes due to an interplay between voltage-driven inter-level Landau-Zener (LZ) transitions and intra-level inelastic relaxation. The kinetic equation for the quasiparticle distribution on the Andreev levels is derived taking into account both relaxation processes and the LZ transitions which are incoherent for low voltages. We show that, for a long junction when the number of levels is large, the LZ transitions enhance the action of each other and lead to a strong increase in the dc current far above the critical Josephson current of the junction [1]. The Fano factor is also enhanced drastically, being proportional to the number of times which particle can fly along the Andreev trajectory before it escapes from the level due to inelastic scattering.[2] Combining the dc current and noise measurements one can fully characterize the non-equilibrium kinetics in SINIS junctions.

[1] N. B. Kopnin and J. Voutilainen, Phys. Rev. B **75**, No. 17, (2007).
[2] N. B. Kopnin, Y.M. Galperin, and V. Vinokur, cond-mat/0703187.

Anderson localization and quantum chaos in works of A. I. Larkin (review talk)

D. Khmelnitskii
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Quantum Interference in Clean Chaotic Billiards

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A physical scenario of how quantum interference between classical trajectories leads to quantum chaos was suggested in Ref. [1] and this work has greately influenced development of the field. At the same time, this theory is based on introducing fictitious quantum impurities that are supposed to mimic quantum effects and therefore it remained phenomenological. We suggest a new scheme of calculations using expansion of Green functions in the number of scattering on the boundaries of the billiard. Using this technique we derive diffusons and cooperons for a clean chaotic billiard assuming only averaging over the energy. Calculating a weak localization correction it is demonstrated that a finite curvature of the boundaries does lead to the mixing of classical trajectories thus providing a finite value for the regularizer of Ref. [1]. This allows us to calculate the Ehrenfest time microscopically and justify the phenomenological approach although some important details are different. The developed method may become an useful tool in study of quantum chaotic systems.

[1] I.L. Aleiner and A.I. Larkin, Phys. Rev. B **54**, 14423 (1996)

Eigenfunction correlation in a multifractal metal and insulator

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The local in space overlap of two different (one particle) wavefunctions is studied in systems with quenched disorder characterized by a large localization/correlation length and a multifractal structure inside the localization/correlation radius. From this perspective we study numerically the 3D Anderson model and compare the results with those for certain random matrix models. So we identify the random matrix models that capture all the relevant features of the 3D Anderson model but have an advantage of being amendable for analytical treatment and less expensive for numerical simulations.

By combining analytical and numerical results for random matrix ensembles with direct numerical diagonalization of the 3D Anderson model we discuss a number of qualitative phenomena in the eigenfunction overlap. Among them are enhancement of correlations near the critical point of the Anderson localization transition, low-frequency enhancement of correlations in the Anderson insulator and the phenomenon of repulsion of eigenstates at large energy separations.

All those effects are relevant for the matrix elements of local interaction between particles.

Valleytronics in graphene

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Conduction and valence bands in graphene form conically shaped valleys, touching at a point called the Dirac point. There are two inequivalent Dirac points in the Brillouin zone, related by time-reversal symmetry. Intervalley scattering is suppressed in pure samples. The independence and degeneracy of the valley degree of freedom suggests that it might be used to control an electronic device, in much the same way as the electron spin is used in spintronics or quantum computing. We discuss three building blocks of this emerging field of "valleytronics".

The first building block provides a controllable way of occupying a single valley in graphene, thereby producing a valley polarization. Such a *valley filter* can be formed by a ballistic point contact with zigzag edges. The polarity can be inverted by local application of a gate voltage to the point contact region. Two valley filters in series may function as an electrostatically controlled *valley valve*. This second building block represents a zero-magnetic-field counterpart to the familiar spin valve. Thirdly, a *detector* of valley polarization can be created by reflecting electrons from one valley as holes from the other valley at the interface with a superconductor.

Based on research reported in:

- A. Rycerz, J. Tworzydło, and C. W. J. Beenakker, Nature Physics **3**, 172 (2007).
- A. R. Akhmerov and C. W. J. Beenakker, Phys. Rev. Lett. **98**, 157003 (2007).

Vacuum Polarization and Screening of Supercritical Impurities in Graphene

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Screening of Coulomb impurities in graphene is considered using the exact solution for vacuum polarization [1] obtained from the massless Dirac-Kepler problem. For the impurity charge below certain critical value no density perturbation is found away from the impurity, in agreement with the linear response theory result. For supercritical charge, however, the polarization charge is shown to have a power law profile, leading to screening of the excess charge at large distances. The Dirac-Kepler scattering states give rise to standing wave oscillations in the local density of states which appear and become prominent in the supercritical regime.

[1] A. V. Shytov, M. I. Katsnelson, L. S. Levitov, arXiv:0705.4663

Metal-insulator transition in a weakly interacting many-electron system with localized single-particle states

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We consider low-temperature behavior of weakly interacting electrons in disordered conductors in the regime when all single-particle eigenstates are localized by the quenched disorder. We prove that in the absence of coupling of the electrons to any external bath *dc* electrical conductivity exactly vanishes as long as the temperature T does not exceed some finite value T_c. At the same time, it can be also proven that at high enough T the conductivity is finite. These two statements imply that the system undergoes a finite temperature Metal to Insulator transition, which can be viewed as Anderson-like localization of many-body wave functions in the Fock space. Metallic and insulating states are not different from each other by any spatial or discrete symmetries.

We formulate the effective Hamiltonian description of the system at low energies (of the order of the level spacing in the single-particle localization volume). In the metallic phase quantum Boltzmann equation is valid, allowing to find the kinetic coefficients. In the insulating phase, $T < T_c$, we use Feynmann diagram technique to determine the probability distribution function for quantum-mechanical transition rates. The probability of an escape rate from a given quantum state to be finite turns out to vanish in every order of the perturbation theory in electron-electron interaction. Thus, electron-electron interaction alone is unable to cause the relaxation and establish the thermal equilibrium. As soon as some weak coupling to a bath is turned on, conductivity becomes finite even in the insulating phase. Moreover, in the vicinity of the transition temperature it is much larger than phonon-induced hopping conductivity of non-interacting electrons. The reason for this enhancement is that the stability of the insulating state is gradually decreasing as the transition point is approached. As a result, a single phonon can cause a whole cascade of electronic hops.

We show that even in the presence of a weak coupling to phonons the transition manifests itself (i) in the nonlinear conduction, leading to a bistable I-V curve, (ii) by a dramatic enhancement of the nonequilibrium current noise near the transition.

[1] D.M. Basko, I.L. Aleiner, B.L. Altshuler, Annals of Physics 321, 1126 (2006).
[2] D.M. Basko, I.L. Aleiner, B.L. Altshuler, cond-mat/0602510.
[3] D.M. Basko, I.L. Aleiner, B.L. Altshuler arXiv:0704.1479.

Asymmetric Zero-Bias Anomaly for Strongly Interacting Electrons in One Dimension

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[2]*Condensed Matter Theory Laboratory, RIKEN, Wako, Saitama 351-0198, Japan*
[3]*Theoretical Physics Institute, University of Minnesota, Minneapolis, Minnesota 55455, USA*

We study a system of one-dimensional electrons in the regime of strong repulsive interactions, where the spin exchange coupling J is small compared with the Fermi energy, and the conventional Tomonaga-Luttinger theory does not apply. We show that the tunneling density of states has a form of an asymmetric peak centered near the Fermi level. In the spin-incoherent regime, where the temperature is large compared to J, the density of states falls off as a power law of energy ε measured from the Fermi level, with the prefactor at positive energies being twice as large as that at the negative ones. In contrast, at temperatures below J the density of states forms a split peak with most of the weight shifted to negative ε [1].

[1] K. A. Matveev, A. Furusaki, and L. I. Glazman, Phys. Rev. Lett. **98**, 096403 (2007).

Coulomb effects in a mixed granular system near the percolation threshold

A. S. Ioselevich
Landau Institute for Theoretical Physics, Chernogolovka, Russia

We consider a granula system with two sorts of small grains (with good and with poor conductivity) near the threshold of percolation through well-conductive subsystem. Due to the Coulomb blockade effects the conduction is dominated by the largest (critical) well-conductive clusters. The Coulomb interactions affect the probability of hops between such clusters, and thus the global conductivity of the system, in the zero-bias anomaly manner. Due to the fractal structure of critical clusters, the temperature dependence of the Coulomb anomaly factor is described by stretched exponential with index expressed through known indices of percolation theory. In contrast with non-fractal systems, strong anomaly arises here not only in low dimesions, but also in 3D case.

Branch-cut singularities in thermodynamics of Fermi liquid systems

Alexander M. Finkel'stein and Arkady Shekhter
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The recently measured spin susceptibility of the two-dimensional electron gas [1] exhibits a strong dependence on temperature, which is incompatible with the standard Fermi liquid phenomenology. In this talk, I show that the observed temperature behavior is inherent to ballistic two-dimensional electrons. Besides the single-particle and collective excitations, the thermodynamics of Fermi liquid systems includes effects of the branch-cut singularities originating from the edges of the continuum of pairs of quasiparticles. In the presence of interactions, the branch-cut singularities generate non-analyticities in the thermodynamic potential that reveal themselves in anomalous temperature dependences. This analysis provides a natural explanation for the observed temperature dependence of the spin susceptibility, both in sign and in magnitude.

[1] O. Prus *et al* Phys. Rev. B 67, 205407 (2003)

Effects of Exchange Symmetry on Full Counting Statistics

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[2] *L.D. Landau Institute for Theoretical Physics RAS, 117940 Moscow, Russia*

We study the full counting statistics for the transmission of two identical particles with positive or negative symmetry under exchange for the situation where the scattering depends on energy. We find that, besides the expected sensitivity of the noise and higher cumulants, the exchange symmetry has a huge effect on the average transmitted charge; for equal-spin exchange-correlated electrons, the average transmitted charge can be orders of magnitude larger than the corresponding value for independent electrons. A similar, although smaller, effect is found in a four-lead geometry even for energy-independent scattering.

June 26, Tuesday, Morning

Bootstrap in Supersymmetric Liouville Field Theory

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Super-Liouville theory is important for its relation to Non-Critical Superstring theory. The 4-point correlation function of exponential fields is constructed in the N=1 Super-Liouville field theory . This construction involves the so-called Conformal Blocks, for which we suggest a recursion representation. Together with the explicit expression for Structure constants of Operator Product Expension(OPE) it allows to construct the 4-point function and to verify that the OPE algebra of LFT is associative.

Magnetic Frustration and Screening in the 3-Impurity Kondo Model: Exact Results on a Stable Non-Fermi-Liquid Phase

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An exotic ('Non-Fermi-Liquid') phase appears in the three-impurity Kondo model with frustrating antiferromagnetic interactions between half-integer impurity spins in the presence of triangular symmetry. This phase arises from an interplay between magnetic frustration and the Kondo effect, without fine-tuning of parameters. An exact description of this phase is found in terms of conformal field theory, verified using Wilson's numerical renormalization group, and used to compute exactly a variety of universal low-energy properties. This includes singular signatures in electrical transport.[1]

[1] I. Ingersent, A. W. W. Ludwig, I. Affleck, Phys. Rev. Lett. **95**, 257204 (2005).

Liouville Gravity and Nucleation in 2D

Alexander B. Zamolodchikov
NHETC, Department of Physics and Astronomy Rutgers University Piscataway, NJ 08855-0849, USA

Effect of fluctuations of geometry (quantum gravity) on nucleational decay of a metastable state is examined. We find that in 2D the effect is quite dramatic, changing standard exponential suppression to a power law. This clears a number of puzzles related to the first-order transitions on dynamical lattices (matrix models). The talk is based on my joint work with Alyocha Zamolodchikov (hep-th/0608196)

Instanton and superconductivity in supersymmetric CP(N-1)model

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We consider the supersymmetric CP(N-1)model as a phenomelogical model for the fluctuation of the quasi-two dimensional superconductor. The susy CP(N-1)model in two dimension has a striking similarity to the N=2 susy gauge theory in the four dimension, and there appear BPS mass spectrum and a curve of marginal stability. We show that such BPS mass and curve of marginal stability are derived also from a one-dimensional n-vector model in the large n-limit. This mapping is further investigated at the critical point. We discuss the relation to the pseudo gap phase, and examine the effect of the external magnetic field.

[1] Hikami S and Yoshimoto T, J.Phys.A 40 (2007) F369

Hele-Shaw problem: Random Matrices and hydrodynamic singularities

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A broad class of non-equilibrium growth processes in two dimensions have a common law: the velocity of the growing interface is determined by the gradient of a harmonic field (Laplacian growth). This kind of growth is unstable, giving rise to fractal singular patterns. Hele-Shaw problem is the most notable realization of the Laplacian growth.

Recently it has been recognized that the theory of Laplacian growth is related to a few modern branches of theoretical physics. One of them is a theory of Random Matrices. In the talk I plan to review this relation emphasizing a hydrodynamic interpretation of Random Matrix Theory and relation of growing patterns to distribution of zeros of orthogonal polynomials.

Dispersive shock waves in interacting one-dimensional systems and edge states of FQHE.

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The hydrodynamic description of many body systems in one spatial dimension is discussed. For simplest integrable models in one dimension, such as Calogero-Sutherland model, it is possible to find an exact quantum hydrodynamic description of the system [1]. The exact form of hydrodynamic equations is very specific to the integrable model under consideration. However, the hydrodynamic description itself is based on local conservation laws and is intrinsically universal. The presence of nonlinear and dispersive terms in hydrodynamic equations leads to the effects which are missed in the linearized hydrodynamic description (bosonization). I plan to describe one of such effects - the formation of dispersive shock waves. The relevance of this phenomenon to the dynamics of edge states in fractional Quantum Hall Effect will be discussed [2].

[1] A. G. Abanov and P. B. Wiegmann, Phys. Rev. Lett **95**, 076402 (2005).
Quantum Hydrodynamics, the Quantum Benjamin-Ono equation, and the Calogero Model.

[2] E. Bettelheim, A. G. Abanov, and P. Wiegmann, Phys. Rev. Lett. **97**, 246401 (2006).
Nonlinear Quantum Shock Waves in Fractional Quantum Hall Edge States.

Response Functions of 1D Interacting Fermions with a Generic Dispersion Relation

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[2] *Georgia Institute of Technology, Atlanta, GA 30332, USA*

We evaluate the dynamic structure factor and spectral density of interacting fermions with a nonlinear dispersion relation. The nonlinearity brings qualitative differences to the response functions, compared to the predictions of the Luttinger liquid theory.

The sharp peak characteristic for the dynamic structure factor in the Tomonaga-Luttinger model, broadens up; for a fixed wave vector q, the structure factor becomes finite at arbitrarily large frequency. The main spectral weight, however, is confined to a narrow frequency interval with the width of order $q^2/2m$; here mass m is determined by the curvature of the dispersion relation. At the lower boundary of this interval the structure factor exhibits a power-law singularity with exponent $\mu(q)$ depending on the interaction strength and on the wave vector [1]. The origin of this newly found non-analytical behavior of the structure factor is related to the physics of the Fermi-edge singularity.

In another striking departure from the Luttinger liquid theory, the curvature of the dispersion relation restores the main feature of the Fermi liquid for particle excitations. The spectral function of particles acquires the shape of a Lorentzian peak centered at the mass-shell [2]. At the same time, the spectral function of holes remains similar to that of the Luttinger liquid theory, displaying a power-law singularity on the corresponding mass-shell.

The constructed theory provides a link between the studied phenomena and the anomalies in the response functions of other one-dimensional systems, such as quantum magnets and interacting bosons.

[1] M. Pustilnik, M. Khodas, A. Kamenev, and L.I. Glazman, Phys. Rev. Lett. **96**, 196405 (2006).
[2] M. Khodas, M. Pustilnik, A. Kamenev, and L.I. Glazman, preprint cond-mat/0702505.

Theory of 1d Bose Liquids

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I shall present our recent calculations of the dynamic structure factor (DSF) of a 1d bose liquid. In a 3d Bose condensate the DSF is known to have a sharp peak at the Bogolubov mode. We found that the behavior of 1d system is markedly distinct: its DSF exhibits a broad power-law singularity at the so-called Lieb I mode and a power-law non-analyticity at the Lieb II mode. I shall discuss the corresponding exponents and other manifestations of the obtained results.

New Routes to Solitons in Quasi 1D Conductors

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We shall review a progress in experiments and theory, elucidating the role of microscopic solitons in quasi-1D electronic systems with a symmetry breaking. Here the solitons emerge as elementary excitations, and instantons appear as related transient processes. Recent interest to solitons in electronic processes rises from a discovery of the ferroelectric charge ordering in organic conductors [1], and from nano-scale tunneling experiments[2, 3] in Charge Density Wave materials. The charge ordering allows to observe several types of solitons in conductivity, and their bound pairs in optics. The observed internal tunneling [2] goes through the channel of amplitude solitons, which correspond to the long sought quasi-particle - the spinon. The same experiment gives an access to the reversible reconstruction of the junction via spontaneous creation of a lattice of embedded 2π solitons - a grid of dislocations

[3], and the tunneling is concentrated in their cores. The resolved spectra [3] in the normally forbidden, below the pair-breaking threshold, subgap region recovers collective quantum processes like coherent phase slips - 2π instantons [4]. On this solid basis we attempt to extend the theory of solitons in quasi-1D systems to arrive at a picture of combined topological excitations in general strongly correlated systems: from nearly antiferromagnetic oxides to high gap superconductors. E.g. the amplitude soliton becomes a building unit of the FFLO modulation. Probabilities for transforming electrons or their pairs into solitons are given by instantons. Transition rates are governed by a dissipative dynamics, originated internally by emission of gapless phase excitations in the course of the instanton process. On this basis, we calculate subgap transitions for photo-electron spectroscopy, optics and tunneling [4].

[1] P.Monceau, F.Ya. Nad, S.Brazovskii, Phys. Rev. Lett., **86**, 4080 (2001); *Review*: S. Brazovskii, cond-mat/0606009.
[2] Yu.I. Latyshev, P. Monceau, S. Brazovski, et al, Phys. Rev. Lett., **95**, 266402 (2005).
[3] Yu.I. Latyshev, P. Monceau, S. Brazovski, et al, Phys. Rev. Lett., **96**, 116402 (2006).
[4] S. I. Matveenko and S. Brazovskii, Phys. Rev. B **72**, 085120 (2005); cond-mat/ 0101278/0208121/0305498.

Thermodynamics of 1D systems – the role of renormalizations at intermediate scales.

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We re-visit the issue of the perturbative expansion for the specific heat $C(T)$ for interacting fermions in 1D. Earlier works have found that (i) the charge component $C_c(T)$ is linear in T, (ii) the spin component is reduced by the RG renormalization of the running backscattering amplitude $g_1^{-1}(l) = A - B\log l$, and (iii) the running $g_1(T)$ enters $C_s(T)$ only at order g_1^3, such that logarithms only appear at the fourth order in the bare g_1, and $C_s(T)$ eventually scales as $T/\log^3 T$. On the other hand, perturbatively, the backscattering amplitude appears in $C_s(T)$ already at the first-order in the interaction. We study in detail why this does not lead to a logarithmic renormalization of $C_s(T)$ before fourth order. For this, we consider the model with different fermionic and bosonic cutoffs, λ_f and λ_b (λ_f is the bandwidth, λ_b is set by the actual momentum-dependent interaction). We show that for $\lambda_f \gg \lambda_b$, $C_s(T) \propto g_1$ does contain a running $g_1(T)$, but only for $\lambda_b < T < \lambda_f$. At smaller T, g_1 in $C_s(T)$ freezes at the scale λ_b. We further show, in agreement with earlier works, that a new contribution to $C_s(T)$ emerges at the third order, and this one contains the running $g_1(T)$ down to the lowest T.

June 27, Wednesday, Morning

Theory of High Tc Superconductivity: where we are after 20 years? (review talk)

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Infra-Red Hall Effect in cuprates

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Measurements of the Hall Effect at infrared frequencies has been found to provide a sensitive probe of the electronic properties of strongly interacting electron metals. The results on electron and hole doped cuprates in the normal state will be reviewed. In both cases the results are consistent with antiferromagnetic (AF) correlation effects which inter into σ_{xy} differently than in σ_{xx}. In underdoped hole doped cuprates σ_{xy} is reduced more than σ_{xx} consistent with Fermi surface reconstruction in a spin density wave (SDW) ground state [1]. The absence of long range AF order suggests that the effects are due to AF fluctuations on the vertex corrections to σ_{xy}. In underdoped $Pr_{2-x}Ce_xCuO_4$ SDW gap like features are observed in σ_{xy} (more dramatically than in σ_{xx}) [2]. σ_{xy} is electron-like at low frequency and hole-like at high frequency consistent with the underlying band structure. In optimally doped $Bi_2Sr_2CaCu_2O_{8+\delta}$ σ_{xy} has a nearly simple Drude form with a smaller relaxation rate than in σ_{xx} [3]. In overdoped $Pr_{2-x}Ce_xCuO_4$ the relaxation rate is large. Partial sum rules (cut off frequency ≈ 0.4 eV) on σ_{xx} and σ_{xy} are compared for both over doped electron and optimally doped hole cuprates. We conclude that the IR Hall data imply a suppression of the sum rule on σ_{xy} approximately a factor of two greater than the suppression of the σ_{xx} sum rule suggesting different Mott renormalizations of the Hall and longitudinal conductivities.

[1] L.B. Rigal, *et al.*, Phys. Rev. Lett. **93**, 137002 (2004).
[2] A. Zimmers, *et al.*, cond-mat/0510085, submitted to Phys. Rev. B.
[3] D.C. Schamadel, *et al.*, Phys. Rev. **B75**, 140506 (2007).

The Nodal Metal in Cuprates

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The pseudogap in the cuprates is a novel phenomenon, and understanding its nature may resolve the issue of what interactions give rise to high temperature superconductivity. Angle resolved photoemission has revealed that the pseudogap phase is characterized by a partially truncated Fermi surface: a Fermi arc. We have found that the arc length is proportional to T/T*, where T* is the pseudogap temperature. This implies that in the zero temperature limit, the pseudogap phase has the same nodal structure as the d-wave superconducting phase. But, the arcs do not appear to be a thermal effect, as they abruptly collapse to zero below T_c. Implications of these results for various theories will be discussed.

Superconductivity in Doped Mott Insulators

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I will begin with a discussion of particle-hole asymmetry in doped Mott insulators and exact sum rules for one-particle spectroscopies. I will then turn to a variational approach to gain insight into the strongly correlated d-wave superconducting state of the high Tc cuprates. After a quick review of earlier work on the essential difference between pairing and phase coherence in doped Mott insulators, I will describe new results. These include: the notion of the "underlying" Fermi surface in the SC state; characterizing nodal quasiparticles; doping and temperature dependence of the superfluid density and the insensitivity of the strongly correlated SC state to disorder.

Peculiarities of the microwave conductivity of superconducting single crystals with different doping levels

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Results of recent investigations of the temperature dependences of the surface impedance $Z(T) = R(T) + iX(T)$ and microwave conductivity $\sigma(T) = \sigma'(T) - i\sigma''(T)$ in $YBa_2Cu_3O_{7-x}$, $Ba_{1-x}K_xBiO_3$, and $V_{3+x}Si_{1-x}$ single crystals are discussed.

In the superconducting state of $YBa_2Cu_3O_{7-x}$ with $x > 0.35$ the behavior of the superfluid density $n_s(T,x) \propto \sigma''_{ab}(T,x)$ can be treated in the framework of d-density wave scenario of pseudogap in underdoped HTSC. The observed peculiarities of the imaginary part $\sigma''_c(T,x)$ of the c-axis conductivity at $T \ll T_c$ are determined by a strong decrease of the interlayer coupling integral with an increase of x [1].

Measurements of the surface impedance $Z(T)$ in $Ba_{1-x}K_xBiO_3$ crystals with $T_c = 11$ K ($x \approx 0.5$) and $T_c = 30$ K ($x \approx 0.4$) allow one to establish that the former is a BCS-superconductor ($Z(T)$ saturates exponentially with lowering temperature at $T \ll T_c$) and the latter is not ($Z(T)$ is linear at $T \ll T_c$) [2]. In addition, it is found that the temperature dependences of the upper critical field $H_{c2}(T)$ of the crystals with $T_c > 20$ K are similar to those in HTSCs, both exhibiting strong positive curvature. On the contrary, $H_{c2}(T)$ curves of the crystals with $T_c < 15$ K are in complete agreement with the BCS theory. The transition from BCS-type to HTSC-like superconductivity in $Ba_{1-x}K_xBiO_3$ is interpreted within Abrikosov's extended saddle-point model [3].

The temperature dependences of the microwave complex conductivity of $V_{3+x}Si_{1-x}$ single crystals with different stoichiometry (silicon content) allowed us to observe a number of peculiarities of two-band superconductors, namely, a nonlinear metallic behavior of resistivity at $T > T_c$, a positive curvature of $\sigma''(T)$ curves close to T_c, and a coherence peak in $\sigma'(T)$ centered at $T \sim T_c/2$ [4].

[1] M.R. Trunin, Physics-Uspekhi **48**, 979 (2005).
[2] G.E. Tsydynzhapov, A.F. Shevchun, M.R. Trunin et al., JETP Letters **83**, 405 (2006).
[3] A.A. Abrikosov, International Journal of Modern Physics **13**, 3405 (1999).
[4] A.M. Shuvaev, M.R. Trunin, Yu.A. Nefyodov et al., unpublished.

Probing Formation of Cooper Pairs on the Atomic Scale in the High T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$

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Using a specially designed scanning tunneling microscope (STM), we have examined for the first time the evolution of local electronic states of a high-Tc superconductor as a function of temperature with atomic resolution. Systematic studies of the gap formation at specific atomic sites, as well as large area gap-maps, measured as a function of temperature and doping in $Bi_2Sr_2CaCu_2O_{8+\delta}$ samples, are used to examine when the formation of gaps in the tunneling spectra correspond to electron pairing. These measurements show that over a wide range of the phase diagram, pairing gaps nucleate in an inhomogeneous fashion in nanoscale regions well above the bulk transition temperature T_C. These regions proliferate as the temperature is lowered, resulting in a spatial distribution of gap sizes Δ in the superconducting state. Despite the inhomogeneity, we find that every pairing gap Δdevelops locally at a temperature T_P, following the relation $2\Delta/k_BT_P = 7.9 \pm 0.5$. This local pairing criteria is remarkably robust to strong variation of Δ , local disorder, and doping of the samples. At very low doping ($x0.14$), systematic changes in the DOS indicate the presence of another phenomenon, which is unrelated and perhaps competes with electron pairing. Our observation of nanometer-sized pairing regions provides the missing microscopic basis for understanding recent reports of fluctuating superconducting response above T_C in hole-doped high-Tc cuprate superconductors. Work done in collaboration with Kenjiro K. Gomes, Abhay Pasupathy, Aakash Pushp, Shimpei Ono (CREPI, Japan), Yoichi Ando (CREPI & Osaka University, Osaka, Japan)

[1] K.K. Gomes *et al., Nature (2007) in press.*

Theory of the Nernst effect near quantum phase transitions in condensed matter, and in dyonic black holes

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We present a general hydrodynamic theory of transport in the vicinity of superfluid-insulator transitions in two spatial dimensions described by Lorentz-invariant quantum critical points. We allow for a weak impurity scattering rate, a magnetic field B, and deviation in the density, ρ, from that of the insulator. We show that all the frequency-dependent, thermal and electric linear response functions, including the Nernst coefficient, are fully determined by a single universal electrical conductivity and a few thermodynamic state variables. With reasonable estimates for the parameters, our results predict a B and temperature dependence of the Nernst signal which closely resembles meaurements in the cuprates and in $Nb_{0.15}Si_{0.85}$ films, including the overall magnitude. Our theory predicts a "hydrodynamic cyclotron mode" of the Cooper pairs, which could be observable in ultrapure samples. We also present exact results for the zero frequency transport co-efficients of a supersymmetric conformal field theory (CFT), which is solvable by the AdS/CFT correspondence. This correspondence maps the ρ and B perturbations of the CFT to electric and magnetic charges of a black hole in the AdS space. These exact results are found to be in full agreement with the general predictions of our hydrodynamic analysis in the appropriate limiting regime. The mappings of the hydrodynamic and AdS/CFT results under particle-vortex duality is also described.

Fluctuation Phenomena in Tunnel Structures (review talk)

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Italian National Institute for the Physics of Matter, National Council for Research, Rome, Italy

The specifics of fluctuations in tunnel structures will be discussed. We start from the fluctuation renormalization of the density of states and its observability in the form of the pseudogap in differential resistance of tunnel junction above superconducting transition. Manifestation of this phenomenon in layered and granular superconductors, the special role of high order corrections will be discussed. The second part of review will be devoted to analysis of fluctuation phenomena in tunnel structures between a well cooled superconductor and a superconductor being in fluctuation regime. Finally will be discussed various fluctuation properties of the Josephson junctions: its radiation of electromagnetic waves at temperatures close to the critical, renormalization of the critical current due to fluctuations of the modulus and phase of the order parameter etc.

Superconducting fluctuations near a quantum critical point

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In this talk, I will discuss theoretical results on disordered films, which undergo a magnetic-field-tuned superconducting transition at low temperatures. I will focus on the role of quantum superconducting fluctuations near Hc2(0). It will be shown that in the dirty case the Aslamazov-Larkin, Maki-Thomson and density of states contributions are of the same order. At extremely low temperature, the total fluctuation correction to the normal conductivity is negative in the dirty limit and depends on the external magnetic field logarithmically [1]. This result explains the experimentally observed negative magneto-resistance in the vicinity of the magnetic-field-tuned superconducting transition. I will also discuss fluctuation contributions to various quantities in higher orders of perturbation theory and extract a family of most divergent diagrams [2].

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Theory of the quantum metal to superconductor transition in highly conducting films

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We derive the theory of the quantum superconductor to metal transition in disordered materials where the resistance at of the normal metal is small compared to the quantum of resistance $\hbar/e^2$. This occurs in situations in which "Anderson's theorem" does not apply, *e.g.* in a clean s-wave superconductor in the presence of a magnetic field , or in a low temperature d-wave or p-wave disordered superconductor. Near the point of the transition the spacial distribution of the superconducting order parameter is is highly inhomogeneous. Because of the sign-oscillations of the Josephson-coupling between superconducting "puddles", there are always at least three zero temperature phases - a metallic phase , a superconducting glass phase, and a superconducting phase. The glassy properties of the system are much more pronounces in the case of superconduting films of light materials in the magnetic field parallel to the films. As the system approaches the point of metal-superconducting glass transition the conductivity of the system diverges, and the Wiedeman-Franz law is violated.

Quantum phase transitions of "localized – delocalized electrons" type

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Two main theoretical approaches to description of metal-insulator transitions are compared. One [1–3] results in flow diagrams, the other [4–6] is expressed in traditional terms of thermodynamics and takes the form of "temperature T vs control parameter x" phase diagram where all the experimental data can be gathered and analyzed. These two approaches fit each other for 3D and 2D systems of noninteracting electrons, for spin-orbit interaction and for transitions between different states of Hall liquid. However, there is no consensus for the case of 2D superconductor-insulator transition. Here the temperature dependence of the resistance at different constant magnetic field values near the transition which follow from the general theory of quantum phase transitions [4–6] apparently contradict to microscopic calculations done by Galitskii and Larkin [7].

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Fluctuations in systems with superconducting islands (review talk)

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We discuss fluctuation phenomena in a system of superconducting islands embedded into a normal-metal matrix. Such a system can be realized in two different ways: the islands can be preformed artificially, or appear as a result of fluctuations in the vicinity of the superconducting transition. An array of superconducting islands take up an intermediate position between two classes of superconductive materials: homogeneuosly disordered superconductors and granular superconductors, sharing features of both. As in a granular system, each island can be described by the phase of the order parameter, while the coupling between the islands and the dynamics of a single island's phase are determined by coherent motion of Cooper pairs in the normal metal, subject to the Fermi-liquid renormalizations.

In an array of artificially-made superconducting islands coupled by the proximity effect in the normal metal, physics is determined by the interplay between the Josephson interaction, which favors superconducting state, and Coulomb blockade effects, which destroy phase coherence. For islands placed on a two-dimensional disordered film, we obtain that the macroscopic superconductive state is destroyed at the critical sheet resistance $R_{\square,c} \approx 1.5(h/e^2)/\ln^2(b/d)$, where b is the distance between the islands, and d is their size. This results is obtained in the absence of tunnel barriers between the islands and the film, when the bare Coulomb blockade effects are weak and become important only at suffiently large time scales [1].

If the proximity-coupled array is placed above the superconducting transition, Andreev reflection of an electron off the island with a fluctuating phase opens an additional channel of electron dephasing. We calculate the corresponding contribution to the decoherence rate and demonstrate that in a broad temperature range it strongly exceeds the rate of dephasing in normal disordered conductors due to electron-electron interaction [2].

Finally, we addres the issue of fluctuation appearance of the islands of superconducting phase close to the superconductive transition in a homogeneoulsy disordered superconductor. In disordered films with a large dimensionless conductance $g \gg 1$, the effects of mesoscopic fluctations are suppressed by the factor of $1/g$. As a consequence, fluctuation-induced islands fall into the region of strong thermal fluctuations and do not influence the nature of phase transition. We show that mesoscopic fluctuations are crucially enhanced near the critical conductance where superconductivity is destroyed at $T = 0$ due to Coulomb suppression of the Cooper attraction. This leads to strong spatial fluctuations of the local transition temperature and thus to the percolative nature of the thermal superconductive transition [3].

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Nernst signal as a probe of short-lived Cooper pairs

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The importance of Nernst effect as a probe of superconducting fluctuations rose enormously with the discovery of a sizeable Nernst signal in the normal state of high-T_c cuprates. Here, I will present a study of the Nernst signal generated by superconducting fluctuations in conventional superconductors. Above the critical temperature (T_c), amplitude fluctuations of the superconducting order parameter survive and lead to a number of well-established phenomena, such as paraconductivity : an excess of charge conductivity due to the presence of short-lived Cooper pairs in the normal state. According to a theoretical calculation in the Gaussian approximation[1], these pairs should generate a Nernst signal whose magnitude depends only on universal constants and the superconducting coherence length. Here, we present measurements of amorphous superconducting films of $Nb_{0.15}Si_{0.85}$. In this dirty superconductor, the lifetime of Cooper pairs exceeds the elastic scattering lifetime of quasiparticles in a wide temperature range above

T_c and, consequently, their Nernst response dominates that generated by the normal electrons. We resolved a Nernst signal, which persists deep inside the normal state, up to temperatures $T \sim 30 \times T_c$ and magnetic field $B \sim 4 \times B_{c2}$. In the zero-field limit and close to T_c, its magnitude is in excellent agreement with the theoretical prediction[2]. Futhermore, we found that a field scale set by the Ginzburg-Landau correlation length separates two distinct regimes in the field dependence of the Nernst coefficient. The latter can be described by a unique function $F(\xi)$ with the correlation length as its unique argument set either by the zero-field coherence length (in the low magnetic field limit) or by the magnetic length (in the opposite limit)[3]. An important feature of amorphous superconductors is the possibility for a superconductor-insulator quantum phase transition. I will present preliminary measurements of the Nernst signal in the vicinity of magnetic-field induced quantum phase transitions observed in Nb_xSi_{1-x}[4] and InO_x.

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Competition between Superconductivity and Localization across the Disorder-Driven Superconductor-Insulator Transition*

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The investigation of disordered superconducting films is of fundamental importance to understand the impact of electron-electron interaction and disorder on the ground state of many-body systems. While the superconducting ground state is characterized by long-range phase coherence and the possibility of nondissipative charge transport, disorder acts in opposite direction, as it favors the repulsive part of the electron-electron interaction and the localization of the electron wave function. Tuning disorder strength can cause a direct transition from superconducting to insulating state (SIT).

I present results of an experimental study of low-temperature transport properties of the disordered thin TiN superconducting films across the localization threshold [1]. The films exhibit an extremely sharp separation between the well-defined superconducting- and insulating phases, demonstrating thus unambiguously a direct disorder-driven superconductor-insulator transition. Although the films choose unequivocally between either the superconducting or insulating ground states, temperature- and magnetic-field behaviors of the resistance reveal an insulating trend in the superconducting films and a superconducting trend in insulating films. At zero and low magnetic fields the conductivity of the insulating films is thermally activated, with the activation temperature being nonmonotonic and magnetic-field dependent. In all samples, including the insulating films, magnetoresistance varies non-monotonously with B, starting a positive magnetoresistance at low fields, then reaching a maximum, followed first by a rapid drop and eventually saturating at higher magnetic fields [2], where the difference between insulating and superconducting samples is suppressed and all curves converge. A sharp depinning threshold voltage is observed in the current-voltage characteristics at very low temperatures. Our results and a comparison with other studies on InO_x[3, 4] clearly indicate that, in the vicinity of the disorder-driven SIT, the response to applied magnetic and/or electric fields, is the same irrespectively of whether the underlaying ground state is superconducting or insulating. The observed similarity allows for conjecture that in the critical region of the transition a peculiar highly inhomogeneous "superconducting insulator" forms. This inhomogeneity may be considered as self-induced granularity, coming from the strong mesoscopic fluctuations in disordered thin superconducting films [5] and/or the fractal character of the electronic wave functions near the localization threshold [6].

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Fractal superconductivity near superconductor-insulator transition

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Theory of superconductive pairing in strongly disordered conductors with electron-electron attraction is proposed. Globally superconducting state can be formed out of localized single-electron eigenfunctions, if their localization length is long enough. For shorter localization lengths, electron pairing leads to formation of localized Cooper pairs and Arrhenius behaviour of resistivity. Fractal nature of nearly-critical eigenfunctions determines unusual properties of "fractal superconductive state": extreme inhomogeneity in real space and existence of a pseudogap above transition temperature.

Magnetoresistance of granular superconductors at low temperatures

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We discuss the resistivity of granular superconductors in the presence of magnetic field at low temperatures. It is assumed that the tunneling between grains is large such that all conventional effects of localization can be neglected. We show that at low temperatures the superconducting fluctuations reduce the one-particle density of states but do not contribute to transport. As a result the resistivity in the transition region exceeds the normal state value leading to a negative magnetoresistance. We also analyze the possibility of the formation of a magnetic field induced insulating state in a two dimensional granular superconductors and show that such a state appears in a model with spatial variations of the single grain critical magnetic field. This model describes realistic granular samples with the dispersion in grain sizes and explains a mechanism leading to a giant peak in the magnetoresistance.

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June 28, Thursday, Afternoon

The fate of the vortex lattice (review talk)

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In 1970 A. I. Larkin "melted" vortex lattice by impurities. I will discuss the consequences of this work and another early papers of Anatolii Ivanovich for physics of Vortex Matter. I will try to overview, how far did we move and where we are in our present understanding of vortex physics.

Flux dendrites produced by avalanches in superconducting films

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We present review of our recent experimental and theoretical studies of magnetic flux penetration in thin superconducting films. Magneto-optical imaging reveals that below 10 K the penetration of magnetic flux in MgB_2 films is dominated by dendritic structures abruptly formed in response to an applied field. The dendrites show a temperature-dependent morphology ranging from quasi-1D at 4 K to large tree-like structures near 10 K. This behavior is responsible for the anomalous noise found in magnetization curves, and strongly suppresses the apparent critical current [1]. The instability is of thermo-magnetic origin, as supported by linear analysis of thermal diffusion and Maxwell equations [2], which allowed us to follow the development of the fingering instability in bulk samples [2] and thin films [3]. The theory also explains specific anisotropy in the flux penetration pattern in the films with anisotropic pinning [4].

In addition, we will discuss interaction of the vortices in a superconducting film with Bloch walls occurring in in-plane magnetized ferrite garnet films used for magneto-optical imaging. Our theory [5] explains how vortices are attracted to such walls, and excellent quantitative agreement is obtained for the resulting peaked flux profile determined experimentally in $NbSe_2$ using high-resolution magneto-optical imaging of vortices. In particular, this model, when generalized to include charged magnetic walls, explains the counterintuitive attraction observed between vortices and a Bloch wall of opposite polarity.

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Dynamics of disordered elastic systems

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The competition between disorder and elasticity leads to glassy physics. This physics manifests itself in the static properties, leading to phases such as the Bragg glass phase, but also in the dynamics. The disorder leads to pinning at zero temperature, while the divergent barriers of the glass lead to creep motion at finite temperature. Glassiness manifests itself in other ways, such as in the aging of various observables. I will examine these effects both for interfaces and periodic systems, and show how both analytical methods such as the functional renormalization group and numerical techniques allow to understand such physics.

Vortex lattices in tilted magnetic field

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I will overview physics of vortex state in strongly anisotropic layered superconductors in the magnetic field applied at a finite angle with respect to the layers. The key parameters which determines vortex configurations is the ratio of the London penetration depth, λ, and the Josephson length, λ_J, $\alpha = \lambda/\lambda_J$. Roughly, at $\alpha \gtrsim 0.7$ the tilted field always forms tilted vortex lines while $\alpha \lesssim 0.3$ such field penetrates in the form of crossing lattices composed of the Josephson vortices and stacks of the "pancake" vortices. Multiple intermediate lattice configurations are realized for $0.3 \lesssim \alpha \lesssim 0.7$, which occurs to be exactly the range realized in the most anisotropic high-T_c compound $Bi_2Sr_2CaCu_2O_x$.

At small c-axis field "pancake" vortices form two-dimensional chains oriented along the tilt direction. Even an isolated vortex chain has a surprisingly rich phase diagram, depending on the field components and α [1]. In particular, for $0.55 < \alpha < 0.7$ small c-axis field first penetrates in the form of kinks forming kinked/tilted chains. However, this state exists only at very small concentration of kinks. With increasing field it is transformed into the strongly deformed crossing chains via a first-order phase transition which is accompanied by a large jump of the "pancake"-vortex density. At further increase of the c-axis field, the chain structure smoothly transforms back into a simple tilted configuration via a second-order phase transition.

Rich vortex phase diagram also is realized at relatively large c-axis field forming dense "pancake"-vortex lattice. In this case small in-plane field penetrates inside the "pancake"-vortex lattice either in the form of the Josephson vortices ($\alpha \lesssim 0.5$) or solitons ($\alpha \gtrsim 0.5$).[2] In the latter case further increase of the in-plane field leads to the composite vortex lattice, built out of vortex lines with different orientations, which then transforms into a simple tilted lattice via a first-order phase transition.

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Electrodynamics of Larkin-Ovchinnikov-Fulde-Ferrell superconducting state

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It is developed the Ginzburg-Landau theory of the vortex lattice for clean isotropic three-dimensional superconductors including the space variation of currents and fields in the limit when the critical field mainly determined by paramagnetic depairing effect and the orbital effect is of minor importance. Then in addition to the Abrikosov vortex lattice the formation of Fulde-Ferrell-Larkin-Ovchinnikov state is favored. This case the diamagnetic superfluid currents mainly come from paramagnetic interaction of electron spins with local magnetic field, and not from kinetic energy response to the external field as usual. We find that the stable vortex lattice keeps its triangular structure as in habitual Abrikosov mixed state, while the internal magnetic field acquires components perpendicular to applied magnetic field. Experimental possibilities related to this prediction are discussed.

Larkin-Imry-Ma state of ^{3}He-A in aerogel

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Superfluid ^{3}He-A shares the properties of the spin nematic characterized by unit vector $\hat{\mathbf{d}}$ of spin anisotropy and the chiral orbital ferromagnet characterized by vector $\hat{\mathbf{l}}$ of the orbital angular momentum of Cooper pairs. This doubly anisotropic superfluid, when it is confined in aerogel, represents the most interesting example of a system with continuous symmetry in the presence of random anisotropy disorder, which is provided by aerogel strands.

Recent NMR experiments allow us to discuss the state of ^{3}He-A in aerogel in terms of the Larkin-Imry-Ma (LIM) state. The LIM state is characterized by the short-range orientational order of the vector $\hat{\mathbf{l}}$, while the long-range orientational order is destroyed by the collective action of the randomly oriented aerogel strings. Since ^{3}He-A is a chiral superfluid, the disordered LIM state can be represented as a system of randomly distributed skyrmions – vortices with continuous cores. The characteristic distance between the vortex-skyrmions and the size of their cores are determined by the LIM length $L_{\rm LIM} \sim \xi_a \xi_0^2/\delta^2$, where ξ_0 is the superfluid coherence length; ξ_a is the distance between the aerogel strands; and δ is their diameter. The estimation and the NMR data suggest that in the aerogel samples under investigation, the length scale $L_{\rm LIM}$ is of order of few microns, which is much bigger than the microscopic scales δ, ξ_a and ξ_0, but is smaller than the dipole length ξ_D characterizing the spin-orbit coupling between $\hat{\mathbf{l}}$ and $\hat{\mathbf{d}}$. The latter leads to anomalously small values of the observed transverse NMR frequency shift.

A regular anisotropy may destroy the LIM effect, and this does take place when one applies a uni-axial deformation to the aerogel sample. Even less than 1% deformation leads to the restoration of the uniform orientation of the $\hat{\mathbf{l}}$-vector in the sample. As a result the value of the transverse NMR frequency shift is enhanced by an order of magnitude compared to that in the LIM state. If the deformation leads to orientation of $\hat{\mathbf{l}}$ along the magnetic field $\mathbf{H}$, the transverse NMR frequency shift becomes negative. The arrangement with $\hat{\mathbf{l}} \parallel \mathbf{H}$ makes it possible to study novel phenomena which only occur under this arrangement and thus are not possible in bulk ^{3}He-A. One of these phenomena is the phase-coherent spin precession recently observed in ^{3}He-A in the deformed aerogel. This presents another realization of the Bose-Einstein condensation (BEC) of magnons, which is different from the magnon BEC found twenty years ago in ^{3}He-B and known as the homogeneously precessing domain (HPD). The $\hat{\mathbf{l}} \parallel \mathbf{H}$ geometry will also allow us to stabilize and observe Alice strings – half-quantum vortices – in rotating ^{3}He-A.

Open problems related to the disordered LIM state are also discussed, including the superfluid properties of the LIM state which could be rather unusual.

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