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CONFERENCES AND SYMPOSIA

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Seminar in the P L Kapitza Institute for Physical Problems of the Russian Academy of Science "Mesoscopic and strongly correlated systems" (23 and 25 April 1996)

On April 23 and 25, 1996, the seminar "Mesoscopic and strongly correlated systems" was held at the P L Kapitza Institute for Physical Problems Russian Academy of Sciences. The talks presented were the following:

(1) **V D Kulakovskiĭ** (Institute of Solid State Physics, Russian Academy of Sciences, Chernogolovka) "Correlation effects in an electron-hole quantum-well magnetoplasma";

(2) **Yu V Dubrovskiĭ, V G Popov, E E Vdovin, Yu N Khanin, I A Larkin** (Institute of Microelectronics Technology, Russian Academy of Sciences, Chernogolovka), **T G Andersson, J Tordson** (Chalmers University, Göteborg, Sweden), **J-C Portal, D K Maude** (High Magnetic Fields Laboratory, Grenoble, France) "Tunnelling resonances in a single-barrier heterostructure";

(3) **V E Kravtsov** (L D Landau Institute of Theoretical Physics, Russian Academy of Sciences) "Wave function multifractality and energy level statistics near the Anderson transition";

(4) **G B Lesovik** (Institute of Solid State Physics, Russian Academy of Sciences, Chernogolovka), **A L Fauchere, J Blatter** (Institute of Theoretical Physics at ETH) "Scattering matrix description of nonlinear transport in NS contacts";

(5) **A Yu Kitaev** (L D Landau Institute of Theoretical Physics, Russian Academy of Sciences) "Quantum calculations";

(6) **G Yu Logvenov, V A Oboznov, V V Ryazanov, A V Ustinov** (Institute of Solid State Physics, Russian Academy of Sciences, Chernogolovka) "Vortex dynamics in one- and two-dimensional discrete Josephson structures";

(7) **E S Soldatov, S P Gubin, A S Trifonov, V V Khanin, G B Khomutov S A Yakovenko** (Physics Department of M V Lomonosov Moscow State University) "Correlated electron tunnelling in a tunnelling cluster structure";

(8) **V F Gantmakher, M V Golubkov, V N Zverev** (Institute of Solid State Physics, Russian Academy of Sciences, Chernogolovka) "Superconducting response in highly resistive materials";

(9) **V F Gantmakher, V N Zverev, V M Teplinskiĭ** (Institute of Solid State Physics, Russian Academy of Sciences, Chernogolovka) "Scaling relations in three-dimensional disordered superconductors";

(10) **S A Gudoshnikov, O V Snigirev** (Physics Department of M V Lomonosov Moscow State University) " Scanning SQUID microscopes: design and applications"

(11) **S I Dorozhkin** (Institute of Solid State Physics, Russian Academy of Sciences, Chernogolovka) "Magnetotransport and magnetocapacitance of two-dimensional electronic systems in strong magnetic fields; the integer and fractional Hall effects, and the dielectric state";

(12) **L V Butov** (Institute of Solid State Physics, Russian Academy of Sciences, Chernogolovka) "Exciton condensation in double quantum wells";

(13) **A F Volkov** (Institute of Radio Engineering and Electronics, Russian Academy of Sciences) "Phase coherence effects in mesoscopic superconductor–normal metal structures";

(14) **V A Kashurnikov, A I Podlivaev** (Engineering-Physics Institute, Moscow), **N V Prokof'ev, B V Svistunov** (Russian Scientific Centre 'Kurchatov Institute') "Supercurrent states in finite one-dimensional rings";

(15) **M A Skvortsov, M V Feigel'man** (L D Landau Institute of Theoretical Physics, Russian Academy of Sciences) "Low-temperature vortex dynamics in layered superconductors: one more example of parametric level statistics";

(16) **L S Levitov, A V Shitov** (L D Landau Institute of Theoretical Physics, Russian Academy of Sciences) "Coulomb anomaly in tunnelling into a poor conductor";

(17) **D E Presnov, V A Krupenin, S V Lotkhov** (Physics Department of M V Lomonosov Moscow State University) "Single-electron structures of supersmall Al/AlO$_x$/Al tunnelling junctions: manufacturing techniques and experimental results";

(18) **D S Golubev** (P N Lebedev Physical Institute, Russian Academy of Sciences), **A D Zaikin** (P N Lebedev Physical Institute, Russian Academy of Sciences, and Karlsruhe University, Germany), **J von Delft, W Tichy** (Karlsruhe University, Germany) "The parity effect in small superconducting granules";

(19) **I M Suslov** (P L Kapitza Institute for Physical Problems, Russian Academy of Sciences) "Density of states near the localization threshold".

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Correlation effects in an electron-hole quantum-well magnetoplasma

V D Kulakovskiĭ

Photoluminescence and luminescence photoexcitation techniques are employed to study a photoexcited, neutral electron-hole (e–h) magnetoplasma in InGaAs/InP, CdTe/CdMnTe, and CdMnTe/CdMgTe quantum wells at low temperatures. The experimental data are compared with theoretical predictions obtained in a number of approximations.

It is found that at high temperatures ($T > 100$ K) a high-density e-h plasma is well described in terms of the plasma approximation with renormalized effective masses. At temperatures is lower of 50 – 30 K, exciton effects become important. The result in a suppressioin of the dependence of the transition energy on the e–h pair density for uppermost occupied ($j = N$) Landau levels at filling factors $N < \nu/2 < N + 1$.

For a half-integer filling factor, transitions between near-Fermi Landau levels are well described in terms of excitons and deexcitons. To describe the experimental results at arbitrary filling factors the screening effects have been taken into account.

A spin-aligned, electron-hole magnetoplasma has been experimentally realized in CdMnTe quantum-wells. It is found that the interaction of spin-aligned excitons is weakly repulsive and that Landau levels in a dense spin-aligned magnetoplasma are renormalized weaker as compared to the unpolarized plasma.

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Tunnelling resonances in a single-barrier heterostructure

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Yu N Khanin, I A Lurking, T G Andersson,
J Tordson, J-C Portal, D K Maude

Resonant features in the tunnelling current through a single barrier heterostructure are seen for a nonuniform doping of a thin near-barrier layer at 4.2 K.

In a heterostructure with a single 5-nm AlAs barrier and weakly doped symmetric spacers (60 nm, $n^- = 2 \times 10^{16}$ cm^{-3}, GaAs) separating the barrier from the highly doped contact region ($n^+ = 3 \times 10^{18}$ cm^{-3}, GaAs), resonant tunnelling of electrons through virtual states of a quantum quasi-well between the heterobarrier and the n^-/n^+ boundary has been observed. Experimentally, this effect manifests itself in an aperiodic, oscillatory current-voltage characteristic. In a magnetic field perpendicular to the current, the oscillation amplitude gradually decreases down to a certain minimum at $B \approx 2.5$ T, after which oscillations oppositely phased to the original ones, develop. All experimental results are in good quantitative agreement with the resonant tunnelling model [1].

At higher (> 400 mV) biases, the same samples exhibit resonances associated with tunnelling through the X-valley levels of the barrier. With the AlAs barrier region acting as a quantum well for the X-valley, electrons tunnel from the 2D states of the accumulation layer which was formed at the emitter side of the barrier as an external bias voltage is applied. Tunnelling through the X states is of resonance character when the lowest electrical subband in the accumulation layer coincides with the X-valley quantum levels in the AlAs barrier.

Further barrier doping gives rise to another type of resonance, in which accumulation 2D layers are formed on both sides of the barrier. In heterostructures with a single doped $Al_{0.4}Ga_{0.6}As$ barrier of 14 nm thickness (the equivalent 2D donor concentration being $n^+ = 3 \times 10^{12}$ cm^{-2}), the dependences of the differential conductivity on the external bias exhibit a ‘−8 mV’ peak due to the resonant tunnelling between the lowest electric subbands of the 2D enriched layers (0 – 0 transition); and a ‘+14 mV’ peak resulting from a transition between different subbands (0 – 1 transition). For magnetic fields $B > 9$ T along the current, in which case the 2D layers have only one Landau level filled ($\nu < 1$), an anomalous behaviour of the resonant peaks is observed. The peaks shift to lower voltages and splitting, the shifts being linear in the magnetic field and the splittings being of asymmetric character. Possible causes for the observed anomalies, in particular Coulomb correlations in a 2D electron gas, are discussed.

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Wave function multifractality and energy level statistics near the Anderson transition

V E Kravtsov

The energy level statistics in complex quantum systems reflects the nature of dynamics of the corresponding classical systems. For classically chaotic systems, the energy level distribution obeys the Wigner–Dyson statistics [1, 2]. Integrable systems are characterized by the Poisson spectral statistics. A system of free electrons in a random potential is the only example of a situation in which, depending on the energy and the amount of disorder, either statistics are possible. Below the mobility edge E_c all states are localized [3] and do not overlap. As a result, the energy levels prove to be uncorrelated and obey the Poisson statistics. Above the mobility edge, the wave functions are extended, and the spectral statistic is of the Wigner–Dyson type.

However, near the mobility edge E_c a narrow spectral region $|E - E_c| < \delta E(L)$ exists in which wave functions are neither localized nor extended. The corresponding critical wave functions are characterized by spatial multifractality [4, 5, 6] that is described by a spectrum of fractal dimensionalities

$d^* = d - \eta$. In the thermodynamic limit ($L \to \infty$) the number of states $N = \delta E(L)/\Delta(L)$ in the energy interval $\delta E(L)$ becomes infinite, bringing about a third type of a universal, critical spectral statistics [7, 8, 9].

Although, for the critical states, the repulsion of closely lying levels is the same as for extended ones, the tails of the two-level correlation function $R(w)$ [8, 9, 11] and the fluctuations in the number of levels in a given energy interval $\langle(\delta N)^2\rangle$ behave in an unusual way. In particular, $\langle(\delta N)^2\rangle = \alpha\langle N\rangle$ has a linear term characteristic of the Poisson statistics [10], which is shown to be due to the multifractality of the critical states. The relationship between the statistics of critical wave functions and that of energy levels [11, 12] is given by $\alpha = \eta/(2d)$, where $\eta = \eta(2)$ is the multifractality exponent, and d the space dimensionality. For delocalized wave functions in a metal the exponent $\eta = 0$, which is precisely the reason why the term linear in $\langle N\rangle$ is absent in $\langle(\delta N)^2\rangle$ in this (and also in the Wigner-Dyson) case.

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Scattering matrix description of nonlinear transport in NS contacts

G B Lesovik, A L Fauchere, J Blatter

Electron transport across a disordered conductor/superconductor (NS) contact is analysed within the framework of the scattering matrix approach similar to that of Landauer and Büttiker applied to normal contacts.

A general, finite-temperature finite-voltage current expression dependent on the scattering matrix elements in the normal part is obtained.

The authors' interest in the nonlinear regime is prompted by the experimental observation [1, 2] of zero- and finite-voltage peaks in the current-voltage characteristics, a phenomenon associated with a complex interplay of the Andreev NS boundary reflection and the coherent scattering from the complex potential in the normal conductor.

Disorder is described in terms of the elastic scattering matrix, which also accounts for possible normal scattering at the NS boundary.

The spectral conductance (which transforms to the total differential conductivity by setting the temperature to zero and neglecting the dependence of the scattering matrix on the applied voltage) is given by

$$G_s(\varepsilon) = \frac{2e^2}{h}\left(1 + |\Gamma(\varepsilon)|^2\right) \mathrm{Tr}\Big\{ t_{21}^{\dagger}(\varepsilon)\left[1 - \Gamma^*(\varepsilon)^2\, r_{22}^{\top}(-\varepsilon)\, r_{22}^{\dagger}\right]^{-1}$$
$$\times \left(1 - |\Gamma(\varepsilon)|^2\, r_{22}^{\top}(-\varepsilon)\, r_{22}^{*}(-\varepsilon)\right)$$
$$\times \left[1 - \Gamma(\varepsilon)^2\, r_{22}(\varepsilon)\, r_{22}^{*}(-\varepsilon)\right]^{-1} t_{21}(\varepsilon)\Big\}\,,$$

where $\Gamma(\varepsilon)$ is the Andreev reflection amplitude, and the occurrence of scattering matrix elements for two energy values is indicative of electron-hole correlations. This expression contains in it the previous Landauer–Büttiker [3] and Beenakker [4] results as limiting cases, and can serve as a starting point for a general analysis. Spectral conductance properties are qualitatively illustrated by considering the single barrier situation, and the development of Andreev resonances in NINS contacts is demonstrated.

Finally, the peaks in the current-voltage characteristics at zero or finite voltage [5] are explained in terms of the scattering matrix.

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Quantum calculations

A Yu Kitaev

An ordinary calculation may be thought of as a sequence of elementary operations on bits, with each operation involving no more than two bits. The computer at any instant is in one of 2^N states, N being the total number of bits.

Now suppose each bit is represented by spin or some other doubly degenerate quantum system. A current state of such a quantum computer is described by a wave function, or more precisely by a unit vector in a 2^N-dimensional space. At each stage, an arbitrary unitary operator may be applied to act on one or both spins, a quantum computer program being a sequence of such operators. We may apply such a program to the initial state $|x_1 \ldots x_n 0 \ldots 0\rangle$, where the sequence of zeros and units $x_1 \ldots x_n = x$ specifies the ‘particular problem’ (say, for a number addition program, x is the pair of numbers to be added). The calculation done, the projections of the first m spins onto the z axis (0 = spin up, 1 = spin down) must be measured, and it is this sequence of zeros and units which we call the ‘answer’. Clearly, for any given program the answer may, or may not, be meaningful. The program must be correct, i.e., it must correspond to the computation problem at hand.

Although the practical realization of the quantum computer idea is still some way off, it is quite clear that, for some problems, the quantum computer is by far faster than its ordinary counterpart. P Shor [1] developed a quantum algorithm which takes as little as about n^4 operations for prime factorization of an n-digit number, to be compared with $\exp(n^{1/2})$ operations for even the most effective ordinary computer algorithm. In the present report, a simpler example problem was considered: Given the relatively prime integer numbers q and a, to find $x > 0$ such that $a^x = 1 \pmod{q}$. The proposed method is also valid for some more general problems [2].

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Vortex dynamics in one- and two-dimensional discrete Josephson structures

G Yu Logvenov, V A Oboznov, V V Ryazanov, A V Ustinov

One- and two-dimensional Josephson arrays using underdamped tunnelling junctions have been a subject of extensive recent study in a number of European and American laboratories (see the references below).

One motivation for this interest is the modelling of nonlinear wave processes describable by a discrete analogue of the 'sinus-Gordon' equation. Another is the study of the vortex dynamics and the thermal and quantum fluctuations in the superconducting phase. In practical terms, such structures hold promise as generators and receivers for use in the millimetre and submillimetre (or 100 – 1000 GHz) radiation range.

It has been shown both experimentally [1, 2] and theoretically [3 – 5] that the primary dissipation mechanism for a current-carrying, two-dimensional tunnelling Josephson network involves the so- called 'row switching' processes due to an entire row of junctions simultaneously switching from the superconducting to a dissipative resistive state.

Our results indicate that two types of row switching processes exist: a flux-flow regime at high temperatures close to the critical value T_c, and a purely quasiparticle (gap) regime at low temperatures. The crossover between these two regimes occurs at the zero value of the effective mass of the fluxons which occur in underdamped Josephson arrays [6].

One further dissipation mechanism determining the viscosity of vortex motion on cooling is due to the radiation emitted by the superconducting phase plasma oscillations as the fluxon performs its motion in discrete Josephson structures.

A study co-authored by two of us [7] reports the observation of resonances in one-dimensional chains of tunnelling Josephson junctions when the frequency of the periodic motion of the fluxon is a multiple of the frequency of the linear modes it excites.

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Correlated electron tunnelling in a tunnelling cluster structure

E S Soldatov, A S Trifonov, V V Khanin,
S P Gubin, S A Yakovenko, G B Khomutov

The phenomenon of correlated electron tunnelling in a molecular system at room temperature has been investigated experimentally.

The system studied was a Langmuir mono- layer of stearic acid with metal-organic clusters incorporated in it. A scanning tunnelling microscope was used to study the sample surface profile and the electric characteristics of single-molecule tunnel structures.

A special technique for manufacturing stable, reproducible Langmuir monolayers of carboran clusters rigidly fixed at the substrate was developed, which enabled to examine tunnelling electron transport in stable single-molecular structures.

At room temperature, such two-junction 'STM tip-cluster molecule-substrate' tunnel structures exhibit current-voltage characteristics with sharply distinct blockade and 'Coulomb scale' features indicative of the correlated nature of electron tunnelling in the structure [1].

To investigate a 'three-electrode' single-cluster transistor system, before cluster monolayer deposition an array of nanoelectrodes was formed on the substrate using an electron lithography technique.

The study of electron transport in a such a system brought out the possibility that the tunnelling current through a cluster molecule can be controlled by changing the voltage on a nanoelectrode next to the molecule, i.e., for the first time a single-electron molecular transistor capable of operating at room temperature, was formed. Its signal characteristic (the variation of the tunnelling current through the 'STM tip-cluster-substrate' system with the control electrode voltage) was periodic in character, the period being 700 mV, and its slope indicated a high electrometric sensitivity of the system (7×10^{-4} e Hz$^{-1/2}$).

The measured characteristics agree with the predictions of the 'orthodox' single-electronics theory, which fact justifies the analogy between a molecular cluster and a metal nanogranule as well as showing that the orthodox theory is valid for describing electron tunnelling in structures prepared from such inherently quantum entities as a single molecule.

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Superconducting response in highly resistive materials

V F Gantmakher, M V Golubkov, V N Zverev

Spatial inhomogeneities in materials undergoing the superconductor-insulator transition are of crucial importance. An inhomogeneous material can be described by the granular superconductor model. As grains become superconductive below the transition temperature T_c, the energy spectrum develops a gap Δ at the Fermi level, quasiparticles in the granules freeze out, and the one-particle tunnelling current decreases. When the resistance across intergranular junctions is high, the Josephson current is suppressed by quantum fluctuations, and the resistance acquires an exponential factor $R(T) \propto \exp(\Delta/T)$. A magnetic field, destroying the gap in a grain, gives rise to a considerable increase in conductivity thus providing one possible mechanism of giant negative magnetoresistance. We have studied this phenomenon in metastable quenched Cd–Sb, Ga–Sb, and Zn–Sb alloys, which underwent the metal-insulator transition upon increasing temperature. From the ratio of $R(T)$ in zero and strong magnetic fields, the value of Δ was obtained.

A similar magnetotransport behaviour was observed in thin amorphous indium oxide films with varying degree of oxidation, i.e., with different density of states near the Fermi level. There is much experimental evidence from various groups that these films may be uniformly disordered over a wide range of states from the extremely insulating to the superconducting one. A high negative magnetoresistance was observed for films in an insulator state. The field derivative of the resistance, $\partial R/\partial H$, was negative up to 20 T, the highest field available. For films in the superconducting state, it took much smaller magnetic fields to suppress superconductivity — and hence to increase the resistance. For intermediate film states, both features, i.e., the small positive derivative in weak fields and the large negative derivative in high fields, were observed.

Magnetoresistance in insulator states is described in terms of a magnetic-field-dependent gap located at the Fermi level. The magnitude of the gap was found to be 0.3 – 0.4 K in zero field and decreased as $1/H$ in high fields. The similarity in the behaviour of amorphous indium oxide films and highly resistive inhomogeneous superconductors suggests that the gap in the energy spectrum is due to the Cooper interaction.

There are two schemes in which the superconducting interaction may be invoked to account for the negative magnetoresistance observed in our inhomogeneous insulator, namely: (a) films may become effectively granulated and acquire fluctuation-induced superconducting clusters, and (b) the gap in the density of state is due to the Cooper interaction between electrons localized in shallow states whose binding energies are smaller than the energies of virtual phonons. For either model, further experimental and theoretical verification is needed.

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Scaling relations in three-dimensional disordered superconductors

V N Zverev, V F Gantmakher, V M Teplinskiĭ

Disordered, three-dimensional Josephson systems based on high-resistance metastable Ga–Sb, Zn–Sb, and Cd–Sb alloys have been investigated. The three alloys are superconductors, with transition temperatures of about 10 K. At 140 – 300 K they gradually transform into amorphous insulator, in which process inhomogeneity and various types of weak bonds, such as tunnelling junctions, thin conducting channels, etc., develop. The density and scale of these elements change in the transformation process as, accordingly, does the superconducting response of the system. To investigate the response, the sample resistance and the acsusceptibility signal were measured.

It is established that the temperature dependence of the critical current in Zn–Sb samples is nonmonotonic. As the temperature is lowered below the superconducting transition temperature T_c, the critical current increases, reaches a maximum at $0.7T_c$, and then declines, approaching saturation at low temperatures. This limiting value varies with normal sample resistance as R^{-2}, whereas the critical current at the maximum scales with $R^{-3/2}$. For Ga-Sb and Cd–Sb samples, the critical current increases monotonically with decreasing temperature, but well below T_c is also found to scale with R^{-2}. This kind of scaling relation being known for small-size high-resistivity Josephson junctions, the analogy between inhomogeneous superconductors and a single Josephson junction is emphasized.

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Magnetotransport and magnetocapacitance of two-dimensional electronic systems in strong magnetic fields; the integer and fractional quantum Hall effects, and the insulating state

S I Dorozhkin

A survey is given of the author's recent work on two-dimensional electronic systems in silicon-based (e and p channels) field transistors, in single GaAs/AlGaAs heterojunctions, and in Si/SiGe heterostructures.

1. By comparing the chemical potential discontinuity with the quasiparticle excitation energy we have determined the fractional charge of the quasiparticles in the 1/3-fractional-quantum-Hall-effect state which was found to be close to 1/3 of the electron charge [1]. The chemical potential discontinuity was measured by the magnetocapacitance technique and the quasiparticle energy gap was determined from the activation energy of the dissipative conductivity.

2. By the use of the capacitance spectroscopy and tilted-field magnetotransport techniques, the spin polarization of a two- dimensional electronic system in the ultraquantum ($\nu < 1$) limit with $\nu = 1/3$ and $\nu = 2/3$ FQHE states is studied by measuring the chemical potential changes due to changes in the Zeeman energy [2]. In the magnetic field range studied, it is found that the amount of spin polarization changes only for $\nu \gtrsim 2/3$. The results obtained: (a) indicate the absence of $\nu = 1/3$ skyrmion excitations which should reduce drastically the system's spin polarization for ν departing from 1/3, and (b) correspond to quasihole excitations with field-aligned spins and to quasielectron excitations with spin-reversal, in the $\nu = 2/3$ FQHE state.

3. Magnetic-field induced transitions from a metal to a Hall insulator (i. e., to a state with an unboundedly increasing magnetoresistance and a finite Hall resistance) are examined for GaAs/AlGaAs [3] and Si/SiGe [4] heterojunctions. In the latter case, a strong enhancement of the magnetoresistance in a tilted magnetic field is observed. In GaAs/AlGaAs field-effect transistors in strong magnetic fields, the transition is observed at a fixed value $\nu = 0.28$ (in which case also the $\nu = 1/3$ FQHE state is seen). Decreasing the field removes the $\nu = 1/3$ FQHE state as well as shifts the transition to $\nu = 0.5$. In Si/SiGe structures the dielectric state occurs in the interval $1 < \nu < 3$, going over to the $\nu = 1$ state of the integer quantum Hall effect (IQHE) as the magnetic field is increased. A model is proposed to account for transitions between IQHE and insulating states in terms of the chemical potential oscillating relative to the energy of delocalized one-electron states in the presence of a long-range nonuniform potential in the sample [5].

4. In resistive states corresponding to half-integer-filled magnetic levels, resistance (rather than resistivity) is found to be a size-independent characteristic, its value being equal to the difference of the Hall resistance from a quantized state. Nondissipative edge currents are invoked to account for the effect [6].

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Exciton condensation in double quantum wells

L V Butov

The electron-hole (e-h) interaction in a neutral e-h system may lead to the condensation of e-h pairs (excitons) which is analogous to the Bose-Einstein condensation of bosons in the low exciton concentration limit. Double quantum well (DQW) semiconductor heterostructures are good candidates for the realization and experimental investigation of the exciton condensate, due to the large lifetime of indirect excitons involving electrons from one QW and holes from the other. A magnetic field perpendicular to the QW plane improves dramatically the critical conditions for the exciton condensation, mainly due to the complete quantization of the electron and hole energy spectra [1].

In investigating the neutral e-h system in AlAs/GaAs DQWs in strong ($H \leqslant 14$ T) magnetic fields at low ($T \geqslant 350$ mK) temperatures, the following anomalies in the transport and optical properties of indirect excitons are found, which are indicative of the exciton condensation effect: (a) a substantial increase in the exciton diffusivity in strong ($H > 8$ T) magnetic fields and at low ($T < 4$ K) temperatures, interpreted as the onset of exciton superfluidity [2]; (b) an anomalously strong exciton radiative lifetime reduction in the same field-temperature range as the fast exciton transport, interpreted in terms of the large oscillation strength of the exciton condensate; (c) anomalously strong noise in the integrated exciton photoluminescence intensity observed in magnetic fields below those for the fast exciton transport, interpreted as critical fluctuations near the phase transition [3].

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Phase coherence effects in mesoscopic superconductor–normal metal structures

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Phase coherence effects discovered in a study of charge transfer processes in mesoscopic superconductor-normal metal (SN) structures are discussed. One effect is the low-temperature ($T < 100$ mK) intragap conductance in tunnelling superconductor-insulator-normal metal (SIN) structures. The system under experiment consisted of an Nb superconductor and a highly doped semiconductor, with an insulating Schottky barrier at the SN interface. The phenomenon is believed to be associated with the anomalous proximity effect (the condensate function due to this effect being not small at low energies) and with the current component corresponding to the so-called interference current in the Josephson junction. A second effect is the oscillatory conductivity of mesoscopic SN structures with more than one SN contact. This is again associated with the proximity effect and the nonlocality of the condensate functions of the normal and superconducting films. It is shown that phase coherence in kinetic properties persists over a large number of normal-film coherence lengths. In particular, Shapiro steps in an SNS junction with no Josephson effect are possible.

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Supercurrent states in finite one-dimensional rings

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Topological supercurrent (SC) excitations in one-dimensional mesoscopic rings are considered. In the superfluid phase such excitations are well-defined up to

(a) tunnelling (of amplitude Δ) between clockwise- and counterclockwise-current resonant states;

(b) SC decay via phonon emission into the substrate; both effects being macroscopically small.

The present approach, involving the hydrodynamical phase field action and its effective Hamiltonian extension, enables a direct description of transitions between states with different topological numbers and proves very convenient not only for estimating Δ and the SC decay width, but also for a unified description of all one-dimensional superconductor-insulator transitions currently known.

Particular emphasis is made to find the macroscopic scaling of Δ (the main superfluid characteristic of a mesoscopic system) in various situations, namely, the commensurable case, a single-impurity system, and a disordered system. The results obtained agree very well with the exact diagonalization spectra of boson Hubbard models.

In addition to true one-dimensional electronic conductors, two further important experimental situations, a two-dimensional electron gas in a fractional quantum Hall state, and quasi-one-dimensional superconducting rings, are discussed. Some experimental schemes for SC studies, such as measuring equilibrium current, the absorption of resonant electromagnetic radiation, and the relaxation of metastable current states, are suggested.

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Low-temperature vortex dynamics in layered superconductors: one more example of parametric level statistics

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The dynamics of vortex motion in layered superconductors are analysed in the flow regime and at low temperatures $T \leqslant \omega_0$, where $\omega_0 \approx \Delta^2/E_{\mathrm{F}}$ is the energy separation between core-localized electronic states. Under these conditions, the inelastic level width $\Gamma \ll \omega_0$, which invalidates the quasi-classical picture [1] usually employed in the theory of superconductivity with its continuous spectrum assumption. We assume the elastic free path time to be not too long, $\Delta^{-1} \ll \tau \ll \omega_0^{-1}$, so that the position of each electronic level E_n changes dramatically (by more than ω_0) as the vortex feels various random potential realizations in its motion. The energy dissipation during the vortex motion occurs via nonadiabatic (Zener) electron transitions between neighbouring localized states. For low vortex velocities $v \ll \Delta/(p_{\mathrm{F}}\sqrt{k_{\mathrm{F}} l}\,)$, Zener transitions occur in relatively rare situations in which levels come within a distance $\ll \omega_0$ of one another, so that the probability of such processes is determined by the statistics of the energy levels E_n and their 'velocities' $\mathrm{d}E_n/\,\mathrm{d}X$. The corresponding statistical ensemble is identical to none of Dyson's (even though being very close to the unitary ensemble), and was recently described in Ref. [2]. The dissipation is evaluated in a manner similar to [3], yielding the vortex friction coefficient η (i.e., the flow-regime longitudinal conductivity σ_{xx}) of the same order obtained quasi-classically in Ref. [1]. However, unlike quasi-classical theory, η shows a slow growth with vortex velocity.

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Coulomb anomaly of tunnelling into a poor conductor

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The Coulomb tunnelling current anomaly is discussed using the effective action method. The method is applied to the 'strong coupling' problem which arises when the driving voltage is low and perturbation theory diverges. Using the quasi-classical approach, we describe the process by means of imaginary time electrodynamics, and express the anomaly in terms of the exact conductivity $\sigma(\omega, q)$ and exact interaction potential. The calculation is compared with the familiar perturbation theory result for the diffusion anomaly. With the same method, the anomaly enhancement by an external magnetic field, and the electrode screening effect are investigated.

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Single-electron structures of supersmall Al/AlO$_x$/Al tunnelling junctions: manufacturing techniques and experimental results

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Structures showing potential for digital applications [1] are of particular interest in applied research on single-electron devices. The 'trap' device [1], for example, may be considered as a prototype of a simplest memory cell. In order to be able to manufacture single-electron structures, an experimental nanotechnique [2, 3] for producing closely (100 – 150 nm) spaced supersmall ($S \leqslant 80 \times 80$ nm^2) Al/AlO$_x$/Al tunnelling junctions was developed in our laboratory. The tunnelling junction arrays which are currently being produced have an electric parameter spread of 10 – 20% within a sample and 30 – 40% from one sample to another. The principal problem in the design of complex single-electron devices is the low-frequency noise from the effective background charge of the metallic islands in the structure used.

Our study of the noise characteristics of single-electron transistors seem to locate the noise sources in the substrate, within 50 – 100 nm from a transistor island [2 – 4]. A trap-type single-electron device with a charged state lifetime of over five hours at working temperature $T = 35$ mK, was manufactured [5, 6]. It is demonstrated that among other factors limiting the state lifetime at activation-suppressing temperatures ($\leqslant 100$ mK) are the distributed nature and drift of the effective background charge of the metallic islands [5, 6], and the back action of the transistor on the trap. Thus, a transistor current increase from 5 to 300 pA is equivalent to raising the working temperature up to 250 mK [5 – 8].

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The parity effect in small superconducting granules

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The properties of a small superconducting granule depend on the parity of the number N of the electrons involved in Cooper pairing. This is the so-called 'parity effect' whose analogue has long been known in nuclear physics. In 1992, experiments on small aluminium granules showed this effect.

For N even, the ground state has all the electrons Cooper paired and the excitation spectrum has a gap 2Δ (excitations may only appear in pairs due to the conservation of the number of electrons on the granule). The specific heat of a granule at low temperatures has the form

$$c_e = 16\pi\left[N(0)V\Delta\right]^2 \frac{\Delta}{T} \exp\left(-\frac{2\Delta}{T}\right),$$

where $N(0)$ is the one-electron density of states at the Fermi level, and V is the granule volume. For N odd, even in the ground state, one electron remains unpaired and accordingly a single excited quasiparticle exists. In this case the excitation spectrum has no gap, and the specific heat behaves as

$$c_0 = \frac{1}{2} + \frac{16\pi}{3}\left[N(0)V\Delta\right]^2 \frac{\Delta}{T} \exp\left(-\frac{2\Delta}{T}\right).$$

The parity effect can be observed only at low temperatures:

$$T < T^* \simeq \frac{\Delta}{\ln\left[N(0)V\Delta\right]}\,.$$

The meaning of this condition is simple: for $T < T^*$ the number of extra excited quasiparticles becomes less than unity.

The parity effect is particularly marked in supersmall granules less than 10 A in diameter, which have only recently become amenable to experimental study. For such granules, the one-electron level separation δ becomes comparable to the macroscopic gap Δ^0. As the granule size is decreased, the superconductivity property is suppressed and ultimately disappears completely, much later for an even than for an odd number of electrons on the granule. For example, assuming a one-electron spectrum to be equidistant and restricting ourselves to the average field approximation, the following critical values of δ are obtained:

$$\frac{\delta^e_{\text{cr}}}{\Delta^0} = 2\exp C \simeq 3.56 \quad \text{for} \quad \text{even } N,$$
$$\frac{\delta^0_{\text{cr}}}{\Delta^0} = \frac{\exp C}{2} \simeq 0.89 \quad \text{for} \quad \text{odd } N,$$

where $C = 0.5772...$ is Euler's constant.

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Density of states near the localization threshold

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The calculation of the density of states for the Scrödinger equation with a Gaussian random potential reduces to the second-order phase transition problem with a 'wrong' sign of the coefficient of the fourth-power term in the Ginzburg-Landau Hamiltonian. For such a Hamiltonian, average field theory in its usual sense does not work and in each case fluctuations must be included. Space dimensionality $d = 4$ again plays a special role and has to do with the renormalization property of the theory, namely: for $d > 4$, the theory does not renormalize and requires that a lattice model be used; for $d < 4$, a single subtraction renormalization is possible; and for $d = 4$, a logarithmic situation admitting of both renormalizable and nonrenormalizable models, occurs. For $d > 4$, asymptotically exact weak-order results are obtained from the self-energy perturbation expansion by retaining the first term and the sum of far-off terms, with being the latter calculated by the Lipatov method and, owing to the factorial divergence of the series, yielding a qualitatively important nonperturbative contribution [1]. Four-dimensional nonrenormalized terms include parquet terms, which correspond to the higher powers of large logarithms, and the terms most rapidly growing in N (N being the order of perturbation theory), which correspond to the zero- and one-logarithmic contributions [2]. Four-dimensional renormalizable models are restricted to the leading powers of the logarithms at small N, and include all powers at large N; the coefficients for the latter are evaluated in the leading N asymptotics from the Callan – Symanzik renormalization condition taking the Lipatov asymptotics for the boundary conditions. The theory for $d = 4 - \varepsilon$ is constructed in a similar way, retaining only the leading powers of N for small $1/\varepsilon$’s and all powers for large N’s, and using the leading N asymptotics of the expansion coefficients in the latter case [3]. For all cases considered, the results are qualitatively the same: the phase transition point shifts from the real axis to the complex plane, thus bypassing the spurious pole and rendering the density of states regular for all energies including the mobility edge vicinity.

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