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Strongly correlated electron systems and quantum critical phenomena (11 April 2003, Troitsk, Moscow Region)

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1. Introduction

The Russian seminar "Strongly Correlated Electron Systems and Quantum Critical Phenomena" has been convened at the Institute for High Pressure Physics of the Russian Academy of Sciences (IHPP RAS) for the first time in this country. The event is significant, because no conferences or seminars devoted exclusively to the physics of strongly correlated systems had been conducted in the past in Russia; problems belonging to this field were usually discussed at more general physics gatherings, for instance, at meetings devoted to low-temperature physics. The 'gem' of the seminar was undoubtedly the section on "Quantum Critical Phenomena," where research in this field had been presented for the first time.

The organizing committee of the seminar included L V Keldysh (chairman, full member of the Russian Academy of Sciences, P N Lebedev Physics Institute RAS), S M Stishov (corresponding member of the Russian Academy of Sciences, IHPP RAS), V V Brazhkin (DSc, IHPP RAS), S V Demishev (DSc, Institute of General Physics RAS), V N Ryzhov (DSc, IHPP RAS), T V Valyanskaya (PhD, IHPP RAS), V A Zayats (PhD, Division of Physical Sciences RAS), and L B Solodukhina (IHPP RAS).

The study of quantum critical phenomena is a powerful self-sufficient field of research in the modern physics of the condensed state; it is closely related to the physics of strongly correlated electron systems. Work in this field is conducted actively at the leading research centers of the United States, Europe, and Japan: suffice it to browse through the publications of the latest conferences on the physics of strongly correlated electron systems (SCES 2002 Krakow, Poland, July 2002) and on low-temperature physics (LT23, Hiroshima, Japan, August 2002). For instance, experimental observation of quantum critical behavior was reported at the SCES conference for a wide range of materials including $CeIn_3$, $CeIn_{3-x}Sn_x$, $CeMIn_5$ ($M = Rh$, Co), UGe_2, $UGa_{3-x}Ge_x$, MnSi, CeRhSn, $YbRh_2Si_2$, $CePd_2Si_2$, $La_{2/3}Ga_{1/3}Mn_{1-x}Ga_xO_3$, etc; a considerable number of purely theoretical papers dealing with the nature of quantum critical points and with the genesis of anomalous physical properties were also presented. All invited and plenary talks on heavy fermion problems at the LT23 conference were devoted to various aspects of quantum critical behavior in these materials. The European research program FERLIN (recently completed), supporting research in quantum critical phenomena, can be seen as evidence of the attention paid in the West to this branch of research.

It was no accident that IHPP RAS was chosen as the venue for conducting the first seminar on "Strongly Correlated Electron Systems and Quantum Critical Phenomena": the progress in the physics of quantum critical phenomena stems mainly from the fact that a number of groups joined forces to do experimental studies in the physics of low and ultralow temperatures and high-energy physics, in collaboration with groups working on the synthesis of new materials. It is a well-known fact that quantum phase transitions occur at temperatures very near zero and that the main parameters whose variation brings about a transition are pressure, magnetic field, and structural disorder. As a rule, it is pressure that is used to lower the temperature of continuous phase transition (typically between magnetic and nonmagnetic phases) practically to zero and to approach a quantum critical point. Although the pressures at which quantum critical phenomena are observed in the majority of materials known at present are not very high by modern standards (on the order of several dozen kilobars), experimental studies of these phenomena prove to be fairly time- and labor-consuming and require knowledge of special techniques for dealing with the equipment designed to produce high pressures. At the present moment active studies of strongly correlated systems undergoing quantum phase transitions under changing pressure are actively being pursued at the IHPP RAS; however, the scale of research into quantum critical behavior in Russia is on the whole falling behind the world level. A seminar on "Strongly Correlated Electron Systems and Quantum Critical Phenomena" in Russia may be regarded, on the one hand, as a challenge, a sort of 'trial of strength' and, on the other hand, as an unequivocal attempt at self-organization in the scientific community that is working on one of the hot research issues in the fundamental physics of the condensed state. Note that despite the one-day format of the seminar, 18 talks were delivered, covering both theoretical

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and experimental work, and more than 50 scientists took part. The seminar was organized into three sections: "Quantum critical phenomena" (chaired by L V Keldysh), "Strongly correlated and heavy fermion systems" (chaired by V B Timofeev), and "Bose condensation" (chaired by S M Stishov).

2. Quantum critical phenomena

Before we begin to analyze the scientific content of current research in quantum criticality, it must be remarked that most papers deal with quantum critical points caused by specific features of phase diagrams. Scenarios discussed from the theoretical point of view are those of possible quantum critical behavior, including various models of the ground state. As most of the subjects of study belong to heavy-fermion metals, discussions of the anomalies of the physical properties are done in terms of the non-Fermi-liquid state and of deviations from the Fermi-liquid pattern in the behavior of resistivity, heat capacity, and susceptibility. The feature that has acquired considerable significance is the universality of behavior of various materials in the neighborhood of the quantum critical point; this behavior is observed regardless of the specific microscopic mechanism that leads to the creation of a quantum phase transition.

A detailed introduction into this sort of problem was presented in Stishov's review paper (IHPP RAS) "Quantum phase transitions: Introduction." The talk clarified first of all the difference between the well-known classical continuous phase transitions and quantum transitions. By definition, quantum phase transitions are phase transitions occurring at $T = 0$ in response to changes in the variables determining the intensity of quantum fluctuations. Phase transitions occurring at $T > 0$ can always be described in terms of classical statistical mechanics. This is also true for such essentially quantum phenomena as superfluidity and superconductivity. The reason for this situation is that in the closest vicinity of T_c there always holds an inequality $\hbar\omega^* \ll k_B T$ corresponding to the classical behavior of critical fluctuations. Here, ω^* is the characteristic frequency of fluctuation. This does not mean, of course, that quantum mechanics does not play any role in this case. It is often said that quantum mechanics defines the very existence of the order parameter; however, classical thermal fluctuations determine its behavior at $T > 0$. On the other hand, we know that a quantum statistical problem in a d-dimensional space can be reduced to a classical problem with effective dimensionality $d + 1$. The additional coordinate here is the imaginary time within the interval $[0, -i\hbar\beta]$, where $\beta = 1/k_B T$. In the general case the coordinate space of this system is confined in the time direction, but as $T \to 0$, the time interval becomes unlimited and the system acquires all the features of a true classical system in a $(d + 1)$-dimensional space. However, as far as critical properties are concerned, the effective dimensionality of the system is found to be $(d + z)$, where z is the dynamical critical exponent. Therefore, the dimensionality of a quantum system in the critical region at $T = 0$ may become equal to, or even exceed, the upper critical dimensionality d_c^+ with all the ensuing consequences. The phase diagram of a material with a quantum critical point clearly displays regions of quantum fluctuations delimited by the lines $\xi_\tau = L_\tau$, where ξ_τ is the correlation or relaxation time, and $L_\tau = \hbar/kT$ is the extension of the space–time continuum in time. If $\xi_\tau < L_\tau$, a system cannot know that it is at a finite temperature and behaves as if it were in a $(d + 1)$-dimensional space. Obviously, a line $\xi_\tau = L_\tau$ corresponds to the quantum–classical crossover.

The results presented by V A Sidorov (IHPP RAS), "Quantum critical phenomena at high pressure", may serve as an experimental illustration of the above argument. This report was devoted to superconductivity arising close to pressure-induced quantum critical points in a number of ferromagnets with heavy fermions. The author of this paper studied the conductivity and magnetic susceptibility of quasi-two-dimensional compounds of the family $Ce_n M In_{3n+2}$ ($M = Rh, Ir, Co$) at low (down to 0.3 K) temperatures under high hydrostatic pressures (up to 50 kbar). It was found that a quasi-two-dimensional antiferromagnet Ce_2RhIn_8 under pressures close to the quantum critical point becomes superconducting with critical temperature $T_c \approx 2$ K and critical field $H_{c2}(0) = 53.6$ kOe. The coexistence of antiferromagnetism and superconductivity was also discovered in other members of the family, such as $CeRh_{1-x}Ir_xIn_5$ and Ce_2RhIn_8. It is interesting that the $p-T$ diagram of $CeCoIn_5$ (and of a related compound $CeRhIn_5$) is found to be similar to the $x-T$ diagram of high-temperature superconducting cuprates and reflects the presence of a quantum critical point, a pseudogap, and a region of non-Fermi-liquid behavior of transport properties. We can thus assume that specific physical properties of high-temperature conducting cuprates and superconductors with heavy fermions are determined by common physical mechanisms.

An alternative field of research into quantum critical behavior was described by S V Demishev (General Physics Institute RAS). His report, "Quantum critical behavior due to disorder," showed that quantum criticality in strongly correlated magnetic systems not only arises at singular points of $x-T$, $p-T$, and $H-T$ phase diagrams but can also be stimulated by disorder. If the random-potential amplitude exceeds a certain critical value, no long-range order is set down to $T = 0$, and the ground state of the system is the Griffiths phase. The physical properties of this phase are dictated by those clusters whose spins are correlated stronger than on average over volume; in the limit $T \to 0$ this leads to the temperature dependence of magnetic susceptibility and magnetic contribution to specific heat of the type $\chi \sim 1/T^\alpha$, $C_m \sim T^{1-\alpha}$; note that the power-law exponent is not universal and depends on the characteristics of the random field. It is interesting that the quantum critical behavior caused by disorder may arise both in the case of antiferromagnetic and ferromagnetic interactions. Furthermore, this theoretical result is valid for spin systems of different dimensionality, including quasi-one-dimensional and dimerized ones.

Demishev's report presented a review of the original experimental studies of the effect of doping with Fe and Co magnetic impurities on the magnetic properties and heat capacity of the low-dimensional magnet $CuGeO_3$. Magnetization of samples was studied using the method of high-frequency (60–360 GHz) electron paramagnetic resonance (EPR) which made it possible to unambiguously single out the contribution of quasi-one-dimensional antiferromagnetic chains of Cu^{2+} ($S = 1/2$) to the integrated magnetization of specimens. It was found that doping $CuGeO_3$ with 1% Fe or 2% Co results in total suppression of both spin-Peierls and antiferromagnetic transitions up to $T = 1.8$ K. In the absence of long-range magnetic ordering, the temperature dependence of magnetic susceptibility for $T < 30$ K follows a power law with exponents $\alpha = 0.35 \pm 0.02$ (1% Fe) and $\alpha = 0.93 \pm 0.03$ (2% Co). In the case of iron doping, an analysis of the magnetic contribution to specific heat gave a value $\alpha = 0.37 \pm 0.03$; this coincides within experimental errors with the value found from the temperature dependence $\chi(T)$. The data received indicate that doping with magnetic impurities Fe and Co results in a greatly disordered magnetic subsystem of $CuGeO_3$ and triggers a quantum critical mode, generating a Griffiths phase at $T < T_G = 30-40$ K. The author was able, based on the data of quantitative analysis of the shape of the EPR lines of Cu^{2+} chains, to show that magnetic interactions in the Griffiths phase of $CuGeO_3$ mostly retain a one-dimensional character.

Reports that followed in this section were theoretical, devoted to mechanisms of generation of quantum phase transitions and to properties of systems in the neighborhood of quantum critical points. The report of S V Maleev and V P Plakhtii (St. Petersburg, Nuclear Physics Institute RAS), "Magnetic-field-induced quantum transition in antiferromagnets," discussed the quantum phase transition from a noncollinear magnetic structure to a collinear phase in frustrated antiferromagnets R_2CuO_4, where $R =$ Nd, Pr, Sm, or Eu. Critical exponents of the order parameter and of the spin-wave gap were found in the molecular-field approximation. For nonfrustrated tetragonal antiferromagnets of the Y-123 type, a second-order phase transition is found only for the diagonal direction of the field. In the case of the $CuGeO_3$ family, a line of second-order phase transitions was found for all field directions except [100], on which a first-order transition occurs. This was shown experimentally in Pr_2CuO_4 and explained in terms of the molecular-field theory that takes into account the pseudodipole interaction of neighboring CuO_2 planes. However, direct measurements of the order parameter, which is proportional to the magnetic Bragg peak intensity (1/2 1/2 1), in Pr_2CuO_4 showed that this simple theory is invalid and quantum fluctuation have to be taken into account. The scaling analysis shows that these fluctuations must result in anomalously high heat capacity near the transition point.

The report by A N Kozlov and L A Maksimov (Russian Research Center 'Kurchatov Institute'), "Superconductivity in the neighborhood of the spin-density-type quantum critical point," discussed *d* pairing in the Van Hove scenario for a two-dimensional system triggered by the closeness to a spin-density-type quantum critical point. Under these conditions, the Fermi surface passes near the saddle points of the electron spectrum, and the polarization operator has a double-logarithmic singularity for scattering by the nesting vector. As a result, it is possible to write a closed ladder equation for the mass operator. The integral equation then reduces to a differential one, which permits simple numerical analysis; the analysis shows that a nonmonotonic dependence of the superconducting transition temperature on carrier concentration is observed in the neighborhood of optimum doping.

Finally, a short communication by A V Syromyatnikov (St. Petersburg Nuclear Physics Institute RAS), "Singlet dynamics in Heisenberg spin-1/2 kagomé antiferromagnets and low-temperature singularities in heat capacity of antiferromagnetic clusters," gave the physical picture of the low-energy spectrum of Heisenberg spin-1/2 kagomé antiferromagnets (KA). It was shown that the kagomé lattice can be represented by a set of blocks containing 12 spins arranged into star shapes and ordered into a triangular lattice. A star has a doubly degenerate singlet ground state which can be treated in terms of pseudospin 1/2. By using group theory, it was shown that the lower singlet sector of the KA is formed by a stripe of stars' ground states that arises as a result of the interstar interaction and that this stripe is described by an effective Hamiltonian of the magnet in a magnetic field. Group theory was also used to establish a generalized form of this Hamiltonian and to calculate its parameters in the third order of perturbation theory. This talk also discussed the possibility of experimentally verifying this physical picture and considered cases of kagomé antiferromagnets with high spin values. The nature of the two-peak structure of the specific heat of kagomé clusters was studied using, as a case study, a detailed analysis of the heat capacity of stars. Simple models were suggested, explaining the origin of low-temperature peaks at $T_1 < \varDelta$, where $\varDelta$ is the spin gap; it was shown that the factor leading to the emergence of this peak is the fast growth of state density above the gap. The origin of the weak dependence of the low-temperature peak on the magnetic field was also explained.

3. Strongly correlated and heavy-fermion systems

In contrast to the physics of quantum critical phenomena, the topics covered in this section of the seminar were more traditional for Russian physicists, many of whom are recognized leaders in this field of research. Obviously, the success of a specific direction of research largely depends on the availability of research subjects for the experimenter, and this in turn depends on the level achieved by the national technological base.

The talk "Synthesis of high-purity compounds of rare metals for fundamental physics research" by G S Burkhanov (A A Baikov Institute of Metallurgy and Materials Science, RAS) pointed out that the synthesis and analysis of high-purity metals and the development of materials based on them are among the strategically important fields of modern materials science; they are inseparable from progress in the priority branches of technology and in fundamental research in physics. The current trend is to constantly increase the purity requirements of materials: nowadays, this concept includes the upper limits on both the admissible content and type of impurities and their isotopic composition and crystal defects in synthesized materials.

It is on the basis of high-purity rare-earth metals (REM) purified by the vacuum distillation-sublimation technique that a number of multicomponent compounds were synthesized at the Institute of Metallurgy for conducting applications-oriented and basic research in the physics of strongly correlated electron systems.

Intermetallic REM compounds RNi, RNi$_2$, RNi$_5$, RAl$_3$, RCu$_5$, RInCu$_2$, and RMg$_3$ (where R is Ce, La, Nd, Pr, Tb, Ho, Er, Tm, Yb, or Y), and also $Ce(Cu_{1-x}Ni_x)_5$ and $(Ce, La)_2Ni_3Si_5$ were prepared in order to study specific features of their ground state using inelastic neutron scattering techniques. Heavy-fermion compounds based on cerium (Laves phase) of the Ce(La, Nd)M_2 type (where M is Al, Fe, Co, Ni, Ru, Rh, Ir, or Pt) were synthesized in order to study electrophysical, galvanomagnetic, and magnetooptical properties. It must be emphasized that a number of priority experimental results reported at the seminar were obtained with these very samples.

P A Alekseev (RRC 'Kurchatov Institute') showed in his talk "Neutron analysis of heavy-fermion systems" that neutron spectroscopy provides a unique quality of data for the detailed study of microscopic mechanisms of formation of strongly correlated electron states (SCES), including the heavy-fermion state (HFS). The specific features and advantages of inelastic neutron scattering technique stem, first of all, from the relatively low energy of neutrons and their high penetrative power, so that we can study the true (nonperturbed) ground state in the entire volume of a specimen. Second, studying SCESs is facilitated by the direct interaction of neutrons with localized electrons (typically f or d type) that participate in the formation of a hybridized state. Furthermore, we emphasize the possibility of using single-crystal specimens to study magnetic and lattice excitations in various directions of the wave vector in the Brillouin zone.

This technique, combined with thermodynamic and kinetic studies, as well as with other spectroscopic methods, makes it possible to extract important physical information on the nature of the unusual properties of SCES and thereby facilitates the solution of the problem of creating new functional materials. Neutron spectroscopy makes possible an evaluation of the scale of effects of hybridization of localized states and states in the conduction band with respect to interactions with a crystalline electric field or relative to exchange effects, and the determination of the hierarchy of these interactions of f electrons with their neighborhood; this hierarchy, in fact, prescribes the type of the ground state of the system. The report demonstrated these possibilities using a number of classical HF systems and systems with mixed valence, such as $CeAl_3$, $CePd_3$, SmB_6, and materials that belong to a very interesting class of Kondo insulators, such as YbB_6.

The detailed information on specific features of the spectrum of elementary excitations which is obtained in neutron-scattering experiments permits us to evaluate the applicability of the existing models and opens the way to new microscopic concepts of the nature of the strongly correlated state. For example, recent experiments with an HF system $CeAl_3$ detected renormalization of energies and intensities of paramagnetic excitations in a broad range of temperatures: from the Kondo temperature $T \sim T_K$ up to $T \sim \Delta_{CF}$ (where Δ_{CF} is the characteristic scale of splitting in the crystalline electric field). The results obtained indicate the need to take into account the interplay of crystalline electric field effects and hybridization of band and f electrons in realistic models.

Complex neutron studies of another classical compound with mixed valence, SmB_6, revealed impressive peculiarities in the spectrum of lattice and magnetic excitations in this compound. It was shown that the resonance violation of adiabaticity of the electron and phonon subsystems leads to the emergence of additional modes in the phonon spectrum; also found was a specific low-energy magnetic excitation with parameters that are directly connected with the degree of hybridization. As a result, a microscopic model was developed for the exciton-type ground state which is perhaps applicable to other systems that are characterized by a competition between two relatively unstable electronic configurations of the f shell.

Neutron experiments with poly- and single-crystalline specimens of a Kondo insulator YbB_{12} allowed the authors to uncover characteristic features of the spectrum of magnetic excitations of this compound and find their relation to processes of formation of a narrow gap at the Fermi level and of a singlet nonmagnetic ground state. It was found that the properties of this type of SCES are determined by both cooperative and local effects of electron – electron interaction.

The strongly correlated ground state manifests itself clearly in transport properties. The report "Anomalies of transport properties of Ce-based intermetallic compounds," presented by N I Sluchanko (General Physics Institute RAS), is a good illustration of this statement. Of special interest were the original results of studying the galvanomagnetic properties of the classical 'magnetic Kondo lattice' in $CeAl_2$ specimens rotated in a magnetic field. This approach allowed the experimenters to correctly separate the contributions to the Hall effect in the heavy-fermion metal $CeAl_2$ and for the first time to single out the anomalous temperature-dependent contribution with a distinct activation energy. The observation of dielectric behavior of electron concentration in a system with metallic-type conduction is an extraordinary effect, which is unlikely to be explainable in terms of the existing theoretical models. Among other things, this report analyzed in detail the applicability of the Kondo-lattice model to describing transport characteristics in various cerium-based metallic compounds.

No discussion of strongly correlated systems can avoid the field of high-temperature superconductors (HTSCs). Research in this area was presented in the talk by A A Gippius (M V Lomonosov Moscow State University), "Nuclear resonance in high-temperature superconductors $HgBa_2CuO_{4+\delta}$." We know that the nuclear spin-lattice relaxation in HTSCs is determined not by the Korringa interaction with conduction electrons as happens in conventional superconductors but by spin fluctuations of local magnetic moments of Cu^{2+} in CuO_2 planes. These fluctuations result in power-law decay (not exponential decay as in the BCS theory) of the relaxation rate below T_c and in the formation of a spin gap above T_c. The analysis of relaxation characteristics helps to clarify the nature of symmetry of the order parameter and to determine the value and anisotropy of the superconducting gap; a reliable determination of these parameters is required to understand the nature of the effect of high-temperature superconductivity.

A comparison of experimental data on the spin-lattice relaxation of the ^{199}Hg and ^{63}Cu nuclei with theoretical calculations showed that in mercury-based HTSC $HgBa_2CuO_{4+\delta}$ (Hg-1201) specimens with different oxygen content δ the formation of the superconducting state is in good agreement with the spin-fluctuation mechanism (with an order parameter symmetry of the $d_{x^2-y^2}$ type and with a superconducting gap $2\Delta/k_B T_c \approx 7$).

As in other HTSCs, superconductivity in the Hg-1201 system is achieved by doping the CuO_2 layers of the stoichiometric compound $HgBa_2CuO_4$ with holes, that is, by populating the O(3) positions of oxygen (stoichiometric $HgBa_2CuO_4$ is an insulator). Divalent copper ions Cu^{2+} in undoped original compounds have a $3d^9$ electron configuration and are bound to neighboring copper ions through the antiferromagnetic exchange interaction Cu – O – Cu. Measuring the spectra of nuclear quadrupole resonance of copper in $HgBa_2CuO_{4+\delta}$ as a function of the doping level revealed considerable and monotonic growth of the quadrupole frequency (from 17 to 27 MHz) as oxygen content δ increased. This signifies that doping with holes at the positions of copper atoms in the $HgBa_2CuO_{4+\delta}$ system has no saturation effect even at high values of δ ($\delta \geqslant 0.22$). Moreover, the doping level is a monotonic function of oxygen concentration and represents the main factor determining the growth of the quadrupole frequency in $HgBa_2CuO_{4+\delta}$.

It was shown, using an analysis of the temperature dependence of the spectral width of nuclear magnetic resonance (NMR) of ^{19}F nuclei in new single-phase fluorinated HTSC $HgBa_2CuO_{4+\delta}F_x$ compounds, that averaging of the local field profile in a specimen is most effective in the mode of melting of the vortex lattice, and the NMR data make it possible to evaluate the melting temperature: $T_{cr} = 35$ K. We can assume that the transition between the temperature-dependent motion of quasi-three-dimensional vortex elements ($T < T_{cr}$) and the melting mode ($T > T_{cr}$) occurs in the Hg-1201F compound at $T = 35$ K, with two-dimensional vortices having a constant correlation time.

A theoretical interpretation of experiments with strongly correlated systems requires a discussion of models in which the behavior of the system is mostly determined by a nontrivial combination of strong Coulomb interaction and low dimensionality of the system. Representative in this sense are two reports presented in this section: one by M Yu Kagan, D V Efremov, and A V Klaptsov (Institute of Physics Problems RAS), entitled "Superconductive pairing and spin-charge separation in strongly correlated two-dimensional and ladder systems," and the other by A À Barabanov, A M Belemuk, and L A Maksimov, entitled "Electrical resistance and the Hall effect in a two-dimensional doped antiferromagnet: the spin-polaron approach."

At the beginning of the former of the two reports its authors analyzed the possibility of superconductive pairing and spin – charge separation in strongly correlated one-dimensional and ladder systems. Among ladder systems, they considered the limit of strong bonding along steps, that is, when the antiferromagnetic (AFM) exchange between two spins on a step $J_\perp$ and hole hopping along the step $t_\perp$ are much larger than the counterpart parameters $J_{||}$ and $t_{||}$ for exchange and hopping along chains. In this limit the phase diagram of both 'bipedal' and 'tripedal' ladders contains extended segments of the Luther – Emery liquid, in addition to the Luttinger liquid which is standard for one-dimensional systems. In the Luther – Emery phase, two holes sit on the same step, which indicates that the local Cooper pairing arises in a natural manner (a biholon with a charge of $2e$). This phase also has a spin gap, which manifests itself in experiments measuring magnetic susceptibility $\chi(T)$. In the Luttinger liquid, there is no spin gap, and the main instability is the one with relation to the formation of spin-density waves. In this phase a nontrivial phenomenon of spin – charge separation takes place.

The authors then considered the possibility of superconductive pairing and spin – charge separation in two-dimensional systems. In HTSC materials, the Fermi – Bose mixture model was considered. The role of fermions in this model is played by spinons, and that of bosons by holons. In addition, the authors suggested a scenario of spinon and holon confinement at low temperatures and of deconfinement at higher temperatures. Confinement at low temperatures corresponds to the formation of a composite fermion (bound spinon – holon state), that is, practically of a physical hole. A superconducting pair is then formed by an attractive interaction between two composite fermions (two holes).

The scenario of spin – charge separation discussed here is in agreement with experiments on photoemission and with the results of numerical calculations for low-temperature situations. It is similar to Laughlin's theoretical ideas, which emphasize an analogy between a composite electron (hole) in HTSC systems and the quark bag in chromodynamics.

A F Barabanov, A M Belemuk (IHPP RAS), and L A Maksimov (RRC 'Kurchatov Institute') discussed the temperature dependence of resistance $\rho(T)$ and Hall coefficient $R(T)$ in the framework of the Kondo-lattice model for a two-dimensional doped antiferromagnet, with the real carrier band spectrum taken into account. This spectrum corresponds to photoemission experiments with angle-resolved photoemission spectroscopy (ARPES) and is described by the spin – polaron approach for the lower quasiparticle band of charge carriers. It is assumed in this approach that carriers are scattered on the AFM fluctuations in the system of localized spins; this system is treated in the spherically symmetric approximation in the absence of long-range order, taking into account spin frustration. It was found that for a realistic spectrum of carriers this scattering is determined by the low-lying spin excitations (with energies on the order of 100 – 500 K) with momenta close to the AFM vector $Q = (\pi, \pi)$ both at intermediate doping levels and in the limit of low doping; in this case, the spin excitation spectrum has a gap whose width is dictated by temperature and by the spin-frustration parameter. This fact, together with the quasi-nesting nature of the lower band (with parts of the Fermi surface close to the AFM boundary of the Brillouin zone), leads to a strong and very much temperature-dependent anisotropy of scattering. This report showed that, for different doping levels, this scattering mechanism explains both the linear $\rho(T)$ dependence (down to fairly low temperatures) and the nontrivial large increase in the Hall constant $R(T)$ when temperature decreases; this was experimentally observed in high-temperature superconductors in the normal state. The multimomentum approach developed here for the solution of the kinetic equation makes it possible to correctly describe the scattering anisotropy and the temperature-related restructuring of the nonequilibrium distribution function of charge carriers.

Ever since high-temperature superconductivity was discovered, discussion has continued unabated about the mechanism that is responsible for the transition to the superconducting state. Many different points of view have been advanced, beginning with the standard phonon mechanism of Cooper-pair formation in the strong-coupling approximation and ending with Laughlin's recent ideas on the 'gossamer' superconducting state as an extension of Anderson's model of 'resonating valence bonds.' A significant place in this spectrum of points of view is occupied by the model of superconductive pairing through the magnetic fluctuation interaction. The report by N M Plakida (Joint Institute for Nuclear Research), "Exchange and spin fluctuation mechanisms of superconductivity in cuprates," was devoted to discussing one of the possible models of this type that explains the appearance of high superconducting transition temperatures.

Plakida's report considered a microscopic theory of superconductivity in the framework of the p – d Hubbard model for the CuO_2 plane. Using the projection technique for the matrix Green's function of Hubbard operators, the Dyson equation was obtained in the approximation of nonoverlapping diagrams, and an equation was derived for the superconducting gap. Analytical estimates and a numerical solution to this equation show that the interband transitions result in antiferromagnetic exchange pairing for Hubbard subbands, as it occurs in the $t – J$ model, and that intraband transitions additionally generate spin-fluctuation pairing of the d-wave type. The most important for d-type superconductive pairing is the exchange interaction. Retardation effects for this mechanism are unimportant and it can therefore be approximated by an instantaneous exchange interaction, as is done in the $t-J$ model. The pairing of electrons (holes) in this mechanism is caused by a reduction of the kinetic energy of electrons in the presence of strong correlations (double occupation of quantum states is forbidden) at the expense of interband hopping in a lattice with short-range AFM ordering. The spin-fluctuation pairing due to scattering by spin fluctuations gives a certain contribution to increasing the transition temperature but plays its role efficiently only at a sufficiently high intensity of spin fluctuations. The results obtained confirm the calculations carried out in terms of the $t-J$ model. Both the dependence of T_c on the lattice parameter a and the isotopic effect are described via the dependence of the exchange interaction J on a and on zero oscillations of oxygen ions. The obtained superconducting temperature as a function of hole concentration in the singlet p – d subband and the gap width as a function of wave vector agree qualitatively with experimental results.

4. Bose condensation

The collective behavior of excitons and the possibility of forming a Bose-condensed ground state at low temperatures do not cease to attract researchers' interest. V B Timofeev (Institute of Solid State Physics RAS) presented a report "Bose condensation of interwell excitons in double quantum wells: A phase diagram" on the study of luminescence of interwell excitons in GaAs/AlGaAs quantum wells (n – i – n heterostructures) containing large-scale fluctuations of random potential in heterojunction planes. The properties of excitons were studied at low temperatures down to 0.5 K, and a special case was considered where an electron and a hole, excited by light, are mostly localized in two neighboring quantum wells separated by a barrier transparent to tunneling.

The work was carried out with domains of about 1 micron in size, which played the role of macroscopic lateral traps for interwell excitons. With this in view, the surface of the specimens was covered with a metal mask containing windows 1 micron or less in size, prepared using lift-off electron-beam lithography. Photoexcitation and observation using luminescence were carried out using the near-field optical technique. At low pumping and low temperatures, residual charged impurities cause strong localization of interwell excitons, while the corresponding luminescence line is nonuniformly broadened. As the excitation power increases, a narrow line of delocalized interwell excitons grows in a threshold manner (line width less than 300 μeV) which grows greatly in intensity as pumping is increased, while it is also shifted toward lower energies within its width, in correspondence with the accumulation of excitons at the lowest state of the domain. As temperature increases, this line disappears from the spectrum in a power-law manner, that is, in essentially a no-activation-energy fashion. This phenomenon can be connected with Bose condensation in a quasi-two-dimensional system of interwell excitons. Critical values of exciton density and temperature were found in the investigated temperature range of 0.3 – 3.6 K and a phase diagram was constructed, delimiting the domain of the exciton condensate. The talk also discussed coherent properties of the condensed phase of interwell excitons under conditions of resonance excitation by circularly polarized light.

The report by V D Kulakovskiĭ (Institute of Solid State Physics RAS) and A N Gippius and S G Tikhodeev (General Physics Institute RAS), "On the nonequilibrium condensation of excitonic polaritons in semiconductor microresonators," falls quite close to this range of problems. Mixed exciton – photon states, or polaritons, in planar semiconductor microresonators with quantum wells in the active layer are quasi-two-dimensional Bose particles with an effective mass several orders of magnitude smaller than the effective mass of excitons, and with a short lifetime (several ps). Because of the small effective mass, strong nonlinear effects develop in this electron – polariton system at densities that are substantially lower than the critical density for the Mott transition and lead to macroscopic filling of states with wave vectors $k < 3 \times 10^3\ \mathrm{cm}^{-1}$. The report also gave a detailed analysis of the nature of nonlinear effects and of the properties of the polariton system with macroscopically filled modes.

A theoretical analysis of this kind of problems was presented in the reports by L V Keldysh (P N Lebedev Physics Institute RAS), "On the Bose condensation of excitons," and by Yu E Lozovik (Institute of Spectroscopy RAS), "Coherent phases and quasi-condensates in low-dimensional systems."

The report by Yu E Lozovik analyzed multiparticle quantum effects in low-dimensional electron systems. In particular, it discussed the properties of two-component quasi-two-dimensional systems that are being intensely investigated experimentally at the moment: spatially separated electrons and holes in coupled quantum wells, specifically in high magnetic fields. Lozovik also discussed a similar one-dimensional system in coupled quantum filaments and a zero-dimensional system of coupled quantum dots.

In addition, he analyzed the behavior of a two-layer system of electrons in a magnetic field with a half-filled Landau level for each of the components. In the absence of interaction within each of these levels and with only small tunneling between them for quasiparticles (composite fermions consisting of electrons with two bound flux quanta), a two-dimensional Fermi surface is 'reconstructed' (it is identical in shape to the original one in the absence of a magnetic field). It was shown that both layers can independently be represented as compressible phases of marginal Fermi liquids of composite fermions. The report also discussed a 'disbalanced' equilibrium system of two identical coupled electron layers in a high magnetic field. The two layers become 'disbalanced' when a voltage is applied between them. In this situation there is a system of excess electrons on the first Landau level and an equal number of unoccupied sites — holes — at the zero Landau level on the second layer. In all the situations described above the BCS-type pairing of quasiparticles in these two subsystems, or the formation of a quasi-condensate of strongly coupled pairs, results in the formation of a coherent phase possessing superconductivity, some specific optical properties, and Josephson-type effects.

The report discussed the conditions of pairing of marginal Fermi liquids and analyzed optical effects that would confirm the observation of the coherent phase of excitons not only qualitatively but quantitatively as well, that is, in a more unambiguous fashion. As examples of such phenomena, one can consider the unusual stimulated two-photon emission and the Raman scattering of light by two-dimensional Bose-condensed excitons, accompanied by coherent recombination or creation of two (above-condensate) excitons with oppositely oriented momenta. The intensity of their lines depends on the anomalous averages. Therefore, these processes make it possible to directly investigate the off-diagonal order; they only occur if the system contains an excitonic Bose condensate. Therefore, they can be used as a method of detecting the Bose condensation of excitons (or 'quasi-condensate' in a two-dimensional system at $T \neq 0$). We can classify a number of new optical phenomena, such as the stimulated back-reflection of light at (oblique) incidence of a laser beam on a quasi-two-dimensional or semiinfinite exciton condensate, as other spectacular manifestations of the Bose condensation of excitons. This effect is caused by the photostimulated coherent recombination of two excitons from a Bose condensate, accompanied by the formation of two photons with oppositely oriented momenta. In the absence of an incident laser beam, the two-exciton recombination produces luminescence with correlation between photon states with opposite momenta; this luminescence can be detected in Hanbury–Brown–Twiss-type experiments with two detectors placed on opposite sides of the exciton system.

The experimental realization of Bose condensation in 1995 in vapors of alkali metals at ultralow temperatures (on the order of several hundred nanokelvin) in a magnetic trap was not only one of the most impressive achievements of experimental physics in the last decade but also one that opened unrivalled possibilities for studying quantum-statistical properties of matter. To date, hundreds of experimental and theoretical papers have been published in this field. We need to remark that serious advances in the theoretical understanding of the properties of Bose condensates in ultracold rarefied atomic gases were facilitated by the fact that a qualitative, and in many cases quantitative, description of this system can be obtained in terms of the relatively simple theory of rarefied Bose gas formulated by N N Bogolyubov, E P Gross, and L P Pitaevskiĭ. The range of problems in studying ultracold quantum gases has widened now and includes also the properties of degenerate Fermi gases (including the search for superconductivity), Bose–Fermi mixtures, and quantum phase transitions from the superfluid state to a localized state of the Mott insulator. In the framework of this seminar, these topics were represented in a theoretical work by Yu M Kagan and L A Maksimov (RRC 'Kurchatov Institute'), "Relaxation of oscillations in superfluid gas inside a cigar-shaped trap," on the dynamic properties of the superfluid Bose gas in a strongly anisotropic trap. A detailed experimental study of the evolution of oscillations in a trap whose longitudinal and transverse dimensions were in the 180:12 ratio demonstrated that these oscillations have quite a considerable lifetime (on the order of 1 second, at the Q factor of 2000). But the most interesting feature was that the relaxation of the 'breathing' mode at high amplitude shows nonmonotonic behavior. This points to a nonlinear character of the relaxation mechanism. In their previous publications these authors predicted a decay of oscillations of the Bose condensate in an elongated trap as a result of parametric resonance, which is the only mechanism of energy transfer from transverse gas oscillations to longitudinal excitation modes at zero temperature. This report suggested that the nonmonotonic decay of oscillations in the gas can be described in terms of hydrodynamic equations of the Landau–Khalatnikov quantum liquid. A complete set of nonlinear equations for the interacting discrete modes was constructed. Gas relaxation is described in the two-mode approximation that implements the mechanism of parametric resonance with energy transfer from the 'breathing' mode to the longitudinal mode at half-frequency, and a reverse process with energy returned from longitudinal oscillations to the 'breathing' mode; this is essentially a new application of the theory of dissipative structures.

On the whole, we would like to emphasize the high level of reports and the wide spectrum of problems discussed in connection with various aspects of the physics of strongly correlated systems and quantum critical points. We think that bringing theoreticians and experimenters working on similar problems together within one seminar was the most significant outcome of the meeting. This factor greatly raised the level and efficiency of discussions. In this connection, it appears desirable to turn the seminar "Strongly Correlated Electron Systems and Quantum Critical Phenomena" into a regularly convened event.