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REVIEWS

Neutron Spectroscopy: The Initial Steps of Development in Our Country and Several Achievements

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Abstract—Some questions related to the establishment, development, and prospects of physical studies using inelastic thermal-neutron scattering are briefly reviewed. The directions of these studies are determined by the unique possibilities of neutron technique for studying atomic-vibrational and magnetic excitations in condensed media.

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INTRODUCTION

To begin with, we will determine the difference between the scientific results obtained in diffraction and spectroscopic experiments, independent of the radiation type in use. Diffraction experiments produce data on the material structure (i.e., explain how the material is organized), whereas spectroscopic experiments provide data on the dynamics, i.e., information about the nature and character of forces and interactions, which determine the main properties of material (including its structure). This is fully valid for neutron methods of studying condensed matter: neutron diffraction and neutron spectroscopy (in other words, elastic and inelastic neutron scattering).

Currently, inelastic thermal-neutron scattering is the main universal method for studying atomic and magnetic dynamics of various materials. It was proposed in the middle of the last century and still continues evolving. Its competitiveness is based on the set of specific features inherent in thermal neutrons, which are important from the practical point of view for the problems of condensed-matter physics. These attractive advantages of neutron methods are as follows.

(i) In contrast to charged particles and electromagnetic radiation (including X rays), a neutron can relatively easily penetrate a material; i.e., neutron-based methods are bulk-sensitive.

(ii) An important feature is that neutron energy and momentum correspond to the characteristic values of the energy and momentum of quasiparticles in solids (phonons, magnons, and other excitations, which are necessary for understanding the laws of formation of condensed state of matter).

(iii) Since neutron has a spin ($S = 1/2$), it interacts not only with nuclei but also with magnetic moments in material; the scale of the nuclear and magnetic interaction forces (scattering cross sections) is approximately the same, which makes a neutron beam an efficient and unique tool for studying magnetism.

(iv) Nuclear-scattering amplitudes do not exhibit any systematic dependence on the nucleus charge or mass. This circumstance makes it possible to distinguish neighboring elements and even isotopes of one element in multicomponent systems and study systems with significantly different atomic numbers.

(v) Finally, typical parameters of thermal-neutron beams allow one to study excitations in solids with characteristic times of about 10^{-11}–10^{-13} s. It is radically important when studying systems with strong electron correlations (see below), which are characterized by rapid spin fluctuations.

All above features ensure that neutron scattering method will remain relevant in future for a long time.

1. HISTORIC MILESTONES OF ESTABLISHING NEUTRON SPECTROSCOPY IN OUR COUNTRY

A Russian reader is undoubtedly interested in the way the neutron-spectroscopy experiments were developed in the Soviet Union and then in the Russian Federation. Let us consider briefly the main milestones of establishing this direction of research without pretending to be exhaustive and objective, because this question deserves a more professional scientific and historical consideration.

Neutron spectroscopy in Russia started to be developed in the end of the 1950s–beginning of the 1960s, almost simultaneously at several institutes, where, obviously, a certain ground had been prepared. Those were the Kurchatov Institute of Atomic Energy (IAE) (Moscow), the Ioffe Physico-Technical Institute (Leningrad), the Mikheev Institute of Metal Physics (IMP) of the Academy of Sciences of the Soviet Union (Sverdlovsk), and the Joint Institute for Nuclear Research (JINR) (Dubna).

One can consider a forerunner of neutron spectroscopy to be the study of the neutron-moderation spectra (performed generally by the time-of-flight (TOF) method), aimed at optimizing nuclear reactors, in which conventional moderators were graphite and water (light and heavy); i.e., condensed media in modern terms. The evident idea that a change in neutron energy reflects to some extent the spectrum of excitations of the material from which the neutron is scattered gave rise (both in the United States and in the USSR) to an idea of using neutrons to study the atomic dynamics of solids.

The first who engaged themselves in the experimental development of this concept at the IAE were M.I. Pevzner and V.I. Mostovoy, colleagues of I.V. Kurchatov. Pevzner, with the aid of postgraduates M.G. Zemlyanov and N.A. Chernoplekov, and Mostovoy, in cooperation with young employees (involved previously in defense-related works) I.P. Sadikov and A.A. Chernyshov, began to develop prototypes of TOF spectrometers based on the MR and IRT-1000 reactors, respectively, which had been put into operation by that time at the IAE. Although the latter reactor was relatively low-power (with thermal power of 1 MW), it was intended for beam studies. At the beginning of the 1960s, these groups constructed operating prototypes of single-detector spectrometers (equipped with gas proportional neutron counters based on $^{10}BF_3$ and mechanical rotating choppers) with a vertical scattering plane on IRT-1000 beams. A chopper with curved slits was used in the spectrometer developed by Mostovoy's group, which made it possible to carry out simultaneously both time modulation and monochromatization of thermal-neutron beam. Due to the presence of a beryllium filter, neutrons with energy of less than 5 meV were used in the spectrometer developed by Pevzner's group. The first (published) measurements of vanadium and nickel phonon spectra were performed at the beginning of the 1960s on the latter device.

At the end of the 1960s, both methodical directions received their logical continuation. A thermal-neutron spectrometer was developed on the initiative of the researchers from IAE (I.P. Sadikov, A.A. Chernyshov, I.P. Eremeev) based on one of the highest power (10 MW) research reactors of that time (VVR-M, Kiev). It was constructed according to the combined scheme (chopper + monochromator crystal) in a multidetector version (range of scattering angles above 90°) based on ^{3}He counters. The instrument with a propane ($T \sim 80$ K) source of cold neutrons, cooled Be filter, and chopper (rotation speed up to 200 Hz) with curved slits was developed at the IAE based on the upgraded IRT-M reactor (N.A. Chernoplekov, M.G. Zemlyanov, A.E. Golovin, S.P. Mironov, Yu.L. Shitikov, G.F. Syrykh), which made it possible to obtain rather high resolution (~0.5 meV along the elastic line with $E = 5$ meV) in combination with a large beam size. The spectrometer was high-luminous, had a range of detection angles from 15° to 90° in the vertical scattering plane, and exhibited low background level. Both those devices met the world-level standards of the time, and the spectrometer at the IAE had been efficiently used until the 1990s. A number of interesting and significant physical results were obtained (some of which will be briefly presented below). Note that the basic studies by Yu.M. Kagan on the theory of inelastic neutron scattering in solids were performed at the same period.

At the end of the 1960s–beginning of the 1970s, other types of spectrometers were developed at the IAE: a three-axis spectrometer based on the IRT-M (later, the IR-8 reactor) and a TOF spectrometer with inverse geometry on the pulsed neutron source; the latter spectrometer was based on the "Fakel" electron accelerator.

The three-axis spectrometer "ATOS" (M.G. Zemlyanov, N.A. Chernoplekov, P.P. Parshin, A.Yu. Rumyantsev) was developed at the IAE at the design bureau (headed by I.V. Naumov) according to the classical cantilever scheme with planar monochromator and analyzer crystals; it satisfied advanced technical requirements of that time (uncertainty in angular positioning of 0.01°, possibility for scanning the scattering angles of both monochromator and analyzer). Note that this project was realized within bilateral cooperation with Hungarian physicists: the mechanical part was designed and manufactured in the Soviet Union, while the control system was produced in Hungary. Two identical devices were manufactured for the IR-8 reactor and for the VVR-M reactor in Budapest. They both were successfully launched at the first half of the 1970s and have been actively used to study many various problems (later on, the control systems were replaced with digital ones).

During the same period, a spectrometric complex was developed based the pulsed neutron source of the "Fakel" electron accelerator (power 25 kW) in inverse geometry with analyzers, based on a combination of a pyrolytic graphite crystal and a Be filter (I.P. Sadikov, A.A. Chernyshov, S.N. Ishmaev). The complex was designed for studying quantum and disordered systems and was equipped initially with a high-pressure system in combination with a helium cryostat, which made it possible to obtain data (unique for that time) on the influence of high pressure (up to 11 kbar) on the density of phonon states of molecular hydrogen in the solid phase.

Practically in the same way as in Moscow, Kurchatov stimulated the development of neutron studies in Leningrad. At the end of 1958 (one year before launching the VVR-M reactor in Gatchina), Kurchatov proposed A.F. Ioffe, who headed the newly organized Institute of Semiconductors at that time, to begin works on using neutron beams of nuclear reactors to study the dynamics of solids. Ioffe charged the laboratory headed by M.M. Bredov with this work. Bredov organized a group engaged in the development of a neutron spectrometer under the guidance of N.M. Okuneva. She was sent to the IAE to be trained under the guidance of Pevzner, where she gained an experience in neutron studies in cooperation with Zemlyanov and Chernoplekov.

The development of the TOF spectrometer Neutron-1 based on the VVR-M reactor was completed in the end of the 1960s, after which it had been successfully used for more than 10 years. The studies on this spectrometer made it possible to analyze successfully the density of phonon states in metals and alloys and, in particular, determine the role of short-range order in the formation of phonon spectrum. In 1975, Okuneva's group (organized later into a laboratory) at the design bureau of the Ioffe Institute developed a triaxial neutron spectrometer Neutron-3 (S.B. Vakhrushev, Ya.G. Gross, N.M. Okuneva, E.L. Plachenova, V.I. Pogrebnoi, R.F. Suramanov). The main line of research on this spectrometer was to analyze soft modes in ferroelectrics (primarily, relaxors).

TOF spectroscopy in inverse geometry had been developing at the Laboratory of Neutron Physics of JINR (Dubna) in the 1960s and 1970s: first, on the pulsed reactor IBR-30 and, later, on a new, much higher power reactor IBR-2 (peak power 1600 MW, pulse width 300 μs, frequency 5 Hz, average power 2 MW). A group headed for many years by Polish Professor I. Natkanets, developed a spectrometer-diffractometer KD-SOG (Krakow–Dubna spectrometer with inverse geometry), mounted on the 100-m path length of IBR-2. This system ensured satisfactory resolution and a broad energy-transfer range, which is important for investigations of the dynamics of high-molecular compounds and other studies of condensed-matter physics on this device. A group of physicists from the Leypunsky Institute of Physics and Power Engineering (Obninsk, Kaluga region), headed by V.P. Parfenov, developed a DIN-2PI spectrometer with direct geometry and a multidetector detection system on the same reactor. It was used mainly to study superfluid helium and the dynamics of metallic alloys.

The decision of the Soviet Government to organize a research center on the basis of the IVV-2 reactor (power 10 MW), which was built in Zarechnyi (Sverdlovsk region) in 1966, played an important role in the development of neutron studies in the USSR. Scientific studies (mainly of magnetism and radiation-induced defects) were performed on neutron beams by researchers of the Institute of Physics of Metals (IPM) under the quidance of S.K. Sidorov; two groups were involved, which were headed by B.N. Goshchitskii (experiments) and Yu.A. Izyumov (theory). The concept of neutron spectroscopy studies was implemented in the beginning of the 1970s, when a three-axis spectrometer was launched on the reactor (V.N. Goshchitskii, Yu.N. Ponosov, Yu.S. Mikhailov) with an equipment capable of cooling a single-crystal sample to helium temperatures, a possibility unique for the spectrometers operating in the USSR at that time. This system made it possible, e.g., to measure phonons in a lead single crystal in the superconducting state.

Later on, beginning with 1977, the second spectrometer Neutron-3, developed at the Ioffe Institute, was launched on the IVV-2 reactor. These instruments were equipped with double-crystal monochromators, which did not become popular in three-axis systems (despite some technical advantages of them).

One should note another important circumstance. A "neutron community" was formed in the Soviet Union in the 1970s, which consolidated researchers from several scientific centers of our country, where neutron scattering experiments were carried out. A special role in the informal establishment of neutron community was played by the all-Union conferences on applications of neutron scattering in solid-state physics. For almost 40 years, more than half of them were held in Zarechnyi (despite the difficulties of the end of the 1980s and the period of the 1990s).

2. DEVELOPMENT OF NEUTRON SPECTROSCOPY AT THE IAE

The coming into being and development of neutron spectroscopy in the world and our country made it possible to perform studies in the field of atomic and magnetic dynamics. New lines of experimental research emerged. Their complete review is a specific task, which goes far beyond the scope of a journal paper. As examples, we present below (briefly and omitting many details) some interesting and important (from our subjective point of view) results obtained with active participation of the researchers of the Kurchatov Institute.

2.1. Influence of Light and Heavy Impurities on the Phonon Spectrum of Metals

The formation of the phonon spectrum of a metal with impurities (both light and heavy) was considered as an interesting physical problem both from the viewpoint of the theory of solids and from the practical point of view, because phonon spectrum determines the thermodynamic and kinetic properties of metals. A deformation of phonon spectrum may also affect superconducting properties; note that, when solving this problem (formulated in the 1960s), an increase in the critical temperature of the superconducting transition by even 1 K was important. Neutron studies of the vibrational spectra were performed on the TOF spectrometer based on the IRT-M reactor. Systems based on vanadium with heavy W, Ta, and U impurities and on copper with Be impurity were investigated. Those studies showed to the full extent the validity of the concept about the relationship between the scattering law and phonon spectrum and allowed to establish the main effects in the lattice dynamics caused by impurity atoms [1–6]. Light and heavy impurities induce, respectively, the occurrence of local (above the boundary energy of the matrix vibrational spectrum) and quasi-local (in the region of acoustic vibrations) vibrational modes, reflecting the specific features of the bonding of impurity atoms with the matrix and also distort the matrix spectrum near the energy of these (quasi-local) modes. The corresponding effects are also observed in thermodynamics and other properties. All those phenomena were explained in the theoretical studies of Kagan's group.

2.2. Atomic Dynamics of Hydrogen in Metal Hydrides and in the Solid State under Pressure

The method of inelastic incoherent neutron scattering offers a unique opportunity to answer the questions of hydrogen localization and ordering in metals and some other aspects of the physics of hydrides. The atomic scattering power at incoherent inelastic neutron scattering is proportional to the σ/M ratio. The typical σ value for most of chemical elements is several barns, whereas this value for hydrogen (protium) is ~80 barn. Taking into account that the hydrogen atomic mass is minimum, its scattering power exceeds that of any metal by more than an order of magnitude. This means that one can obtain directly the partial spectrum of thermal atomic vibrations of hydrogen from experimental data. In the mid-1970s, these considerations stimulated the study of hydrides of transition and rare-earth metals on a TOF neutron spectrometer at the IAE.

An analysis of the obtained experimental data showed that the main factors that affect the formation of the oscillation spectrum of hydrogen atoms in hydrides of metals and intermetallic compounds and are related to the interaction of metal and hydrogen atoms are the number and symmetry of interstitial sites with different sizes, which are available for hydrogen incorporation. It was shown that the isotopic approximation, according to which the energy of deuterium atomic vibrations in deuterides of metals, $E_D = E_H/\sqrt{2}$ (E_H is the energy of hydrogen oscillations in the corresponding hydride), is also valid for the investigated materials [7–13].

The energy of the *para–ortho*-transition and density of phonon states of polycrystalline *para*-hydrogen were measured on the spectrometer with inverse geometry of the "Fakel" pulsed neutron source at pressures up to 11 kbar (in this case, the hydrogen crystal density increased by a factor of 2). It was found that the average squared amplitude of zero oscillations, determined based on the excitation for the *para–ortho*-transition, is related to the lattice parameter through the conventional Gruneisen coefficient of about 2 ± 0.1. At the same time, the energy of optical phonons of solid hydrogen increases significantly under pressure, which may indicate strong anharmonic effects [14] in this quantum system.

2.3. Electron–Phonon Interaction and Specific Features of the Fermi Surface in Nontransition Metals and Alloys

After putting the ATOS three-axis spectrometer into operation, the attention of researchers was focused on the electron–phonon interaction in metals, which manifests itself most strongly in anomalies in phonon dispersion curves, related to the specific features of screening of ion oscillations by conduction electrons (in particular, the Kohn anomalies). The wave vectors on which these anomalies are observed are related to sizes and topology of the two-dimensional interface between the occupied and free states of conduction electrons in the reciprocal space (Fermi surface). The experimental detection of new (theoretically predicted by Kagan and E.G. Brovman) threeparticle anomalies in the aluminum phonon spectrum [15] was especially important, because it confirmed experimentally the theory of simple metals developed by theoreticians. The study of the influence of conduction electrons on the formation of fine structure of phonon spectra was continued for a group of nontransition metals Mg, Zn, and Cd having a hexagonal lattice [16–18]. To carry out those studies, a large (even at that time) Cd single crystal was grown at the IAE from ^{110}Cd isotope, which does not absorb neutrons; its phonon-dispersion curves were recorded for the first time, and anomalies of the phonon group velocity were thoroughly studied. Those studies were performed in cooperation with the theoreticians from the department headed by Kagan, who developed an adequate theory of these phenomena and showed that the Fermi-surface topology can be studied using this technique.

Later on, with allowance for the accumulated knowledge, this field of research was developed for disordered metal alloys. The lifetime of free electrons in these systems is too short in comparison with pure ordered metals. Therefore, the Fermi surface cannot be studied using conventional electron methods. At the same time, the anomalies in the spectra of lattice vibrations remain quite strong. These studies were developed and gave grounds for a new approach to the study of the Fermi surface in metal alloys using the analysis of Kohn-type anomalies in phonon-dispersion curves [19].

2.4. Effects of Crystalline Electric Field in Rare-Earth Intermetallic Compounds

The studies of magnetic excitations in rare-earth intermetallic compounds (splitting of the states of *f* electrons in a crystalline electric field (CEF)) started at the beginning of the 1970s on the initiative of Sadikov. It was a new line of research, oriented to the spectroscopic study of the nature of low-temperature features of physical properties of strongly correlated electron systems [20–22], which called for a technique of low (helium) temperatures in neutron experiments. One should note that those were the pioneer studies not only in the USSR but in the whole world. In particular, it was shown that splitting of the levels of *f* electrons in a CEF in a metal is related unambiguously to the local symmetry of crystalline environment of a rare-earth ion and is determined quantitatively by both the charges of the ions of nearest environment and conduction electrons. Then those studies were actively developed at the IAE [23], JINR [24], and IPM [25] and laid a basis for further development of neutron studies of the heavy-fermion and intermediate-valence compounds.

2.5. Modern State and Prospects

Note that there was cooperation between research groups in the 1960s–1970s, both in the USSR and at foreign centers. As was noted above, physicists of the IAE discussed methodical questions with physicists of the Ioffe Institute (Leningrad) and physicists from Hungary. Beginning of physical studies on neutron beams also initiated scientific cooperation. For example, on the initiative of the IPM, the influence of a superconducting gap on the phonon lifetime was jointly studied. The effects of the crystalline field appeared as the base for joint studies of IAE, JINR, and IPM researchers.

In the second half of the 1970s, it became clear that the neutron center in the international Institute Laue–Langevin (ILL) in Grenoble (France), based on a 57-MW high-flux nuclear reactor, has the world's best methodical possibilities. This fact initiated the cooperation of several Soviet institutes with ILL physicists. For the Kurchatov Institute, this cooperation began with the studies of the electron–phonon interaction in nontransition metals and their alloys. Then, the cooperation was extended to studying magnetic and phonon spectra in strongly correlated rare-earth compounds. Later on, in the second half of the 1980s and in the 1990s, the cooperation had been rapidly developed and became a multilateral and multidimensional process, which involved the staff of the French Research Center in Saclay. The world-class results were obtained for quasicrystals and amorphous systems and then for new high-temperature superconductors (HTSCs) and the physics of various strongly correlated systems, with participation of all aforementioned Russian research centers and the scientists from leading European neutron centers (the United Kingdom, Switzerland, France, Germany). Let us review some results obtained at that stage.

3. MAIN RESULTS OF SOME COMPLEX SPECTROSCOPIC STUDIES

We will briefly review the main scientific results of some neutron-spectroscopic studies, which were characterized by a complex approach (magnetic and lattice dynamics) and aimed at solving urgent physical problems.

3.1. Magnetic and Phonon Spectra of Systems with Strong Electron Correlations

The most popular and striking manifestations of strong electron correlations are the heavy-fermion (HF) systems, systems with intermediate valence (IV), and Kondo insulators (KIs) (the latter are possibly the brightest in this series); cuprate HTSCs also belong to this class. Neutron spectroscopy provided a large amount of important and unique data on these systems. In fact, the studies of the spectra of *f*-electron excitations revealed the boundaries between the properties of the HF, IV, and KI types. This is related to the proximity of the scale of characteristic time of neutron–atom interaction (10^{-11}–10^{-13} s) to the characteristic times of spin fluctuations in the systems of this class. The main interactions inducing the formation of a particular ground-state type were studied using neutron spectroscopy. The manifestations of spin and charge fluctuations in the magnetic properties and lattice dynamics (in particular, the manifestation of resonance nonadiabaticity in the electron–phonon interaction in IV systems [26–29]) were studied for systems based on Ce, Sm, Eu, and Yb (including higher borides). The corresponding results were reported in [30–36].

The first measurements of the spectra of magnetic neutron scattering in HTSCs of both "2–1–4" (La_2CuO_4) and "1–2–3" ($YBa_2Cu_3O_7$) types suggested that the CEF effects in them are fairly strong, and the splitting reaches values of about 100 meV. The exchange interaction effects lead to dispersion of the corresponding excitations, and the temperature dependence of the width of one-site CEF excitations reflects the change in the density of electron states at the formation of a gap in their spectrum (later, these specific features were thoroughly investigated in [37]).

The study of the properties of HTSC systems showed that there may exist local charge discontinuities, induced by strong electron–electron and electron–phonon interaction. High sensitivity of CEF effects to local charge distribution, which was found in the first neutron studies (see, e.g., [38]), gives grounds to consider the neutron spectra of splitting in CEF as a good "probe" of the presence of these discontinuities in materials. In the $R\mathrm{Ba_2Cu_3O_{7-\delta}}$ compounds, a rare-earth ion R occupies a site between two CuO_2 planes; hence, CEF spectroscopy can be used as a tool for studying processes of doping and corresponding charge redistribution at the microscopic (cluster) level.

Neutron spectroscopy made it possible to observe directly and describe quantitatively the mechanism of charge transfer from CuO chains to CuO_2 planes and thus provided unique information about the formation of clusters, related to the occurrence of "frustrated phase separation." This concept was used by an international group of Russian and Swiss physicists for studying the problem of local charge discontinuities for different ways of HTSC doping by an example of the "1–2–3" systems (at a change in the oxygen concentration [39, 40] or substitution in the rare-earth site [41, 42]).

3.2. Lattice Excitations and Magnetic Dynamics of Some HTSCs

Almost immediately after the discovery of superconductivity in doped lanthanum cuprate, the following concept was suggested: many unusual properties of cuprate HTSCs are related to the features of both their crystal structure and dynamics of their lattice and magnetic moments. This idea stimulated intense studies of these compounds using inelastic neutron scattering. Practically at once after the discovery of HTSCs, the first data on softening of frequencies of some specific phonons upon a structural phase transition in $(LaSr)_2CuO_4$ were obtained at the Kurchatov Institute [43]. Within the established traditions, Kohn anomalies in this new compound were sought for [44]. Later on, fundamental studies were carried out in cooperation with some European neutron centers on high-flux neutron sources [45–47].

In particular, it was found that the phonon-dispersion curves of the group of new superconducting compounds with complex lattices ($La_{2-x}Sr_xCuO_4$, $YBa_2Cu_3O_{6+x}$, Nd_2CuO_4, Pr_2CuO_4) [48–50] are consistent to a great extent with the concepts about ion bonding with screening of polar vibrations upon introduction of mobile charges. Some anomalies were found in the vibrational spectrum, related to the electron–phonon interaction during introduction of free charges into cuprate and other new superconductors [51–53]. At the same time, the set of data and comparison with other superconducting or similar nonsuperconducting materials in the families of "conventional" and "unusual" superconductors indicated that the conventional electron–phonon pairing mechanism is insufficient to explain the high temperatures of superconducting transition.

When studying the atomic dynamics of HTSC cuprates on the level of the function of density of phonon states, a particular attention was paid to the vibrations of copper and oxygen atoms, which compose the CuO_2 planes responsible for the HTSC phenomenon. The studies [54, 55] were pioneer in this field. The partial vibrational spectra of copper and oxygen atoms were reconstructed experimentally using the isotopic-contrast method [56, 57]. The effects of electron–phonon interaction in the $YBa_2Cu_3O_{7-y}$ system were investigated in detail in [57–59]. For the homologous series of the HTSC bismuth-based cuprates $Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+4}$ ($n = 1, 2, 3$), the widespread concept about the block structure of these compounds was confirmed at the level of force interatomic interaction and the weakness of interblock interaction in cuprates in comparison with the intrablock interaction was evidenced [60–62].

The low-frequency dynamics of the subsystem of magnetic moments on copper ions was studied by an example of stoichiometric cuprates Nd_2CuO_4 and Pr_2CuO_4 [63–68]. It was shown that the presence of magnetic phase transitions in Nd_2CuO_4 and the difference in the spectra of low-energy magnetic excitations in these two compounds are determined by the specific features of magnetic behavior of the rare-earth ions, which were taken into account in the S.V. Maleev's model of the magnetic dynamics of this class of compounds, based on the exchange interactions of pseudo-dipole type [69, 70]. A phase transition depending on magnetic field (quantum critical point) was observed at zero temperature in Pr_2CuO_4 (which was predicted in this model) and the critical indices for the spectral weight and correlation length of quantum critical fluctuations were determined [71–73]. Then the study of the magnetic dynamics of cuprate superconductors was continued within the investigation of the peculiar magnetic excitation (resonance mode) found in these compounds [74].

CONCLUSIONS: PROSPECTS OF NEUTRON STUDIES

We attempted to formulate the characteristic features and advantages of neutron spectroscopy, show the development of this method and its application in real studies, and trace the main stages of the establishment of this line of research at the Kurchatov Institute (an important partner in the formation of the Russian segment of this technically unique and substantial platform for studying materials). There is no doubt that neutron scattering technologies will be in high demand in the coming decades (as a minimum foreseeable time period). What are the apparent prospects of this process?

From the very beginning, neutron scattering was considered as a specific, privileged method, providing a direct access to the interatomic adhesion forces in material. First of all, this method makes it possible to understand the fundamental principles of surrounding matter. In the next stage, the stored knowledge can be used to form new (absent in nature) materials with unique and required properties for industrial development in correspondence with the social requirements. For example, it is not coincidence that the fundamentals of atomic technologies in different countries were developed in the scientific centers having subdivisions with similar solid-state physics departments. The use of research nuclear reactors at these centers as sources of intense neutron beams was a natural consequence of these processes.

The massed study of lattice vibration spectra in the initial stage of development of neutron spectrometry and magnetic dynamics investigations (started somewhat later) played an important role, e.g., in the analysis of the unique phenomenon of superconductivity, which was initially observed at ultralow temperatures. The concept of interaction between different branches of excitation spectra (electrons and phonons) was extremely important for its understanding. Higher temperatures of superconducting transitions were found in a specific class of compounds, in which electron degrees of freedom are bound into unusual magnetic excitations. Neutron spectroscopy is the most important tool for gaining knowledge about these excitations, which gives us hope that the stored knowledge will lead soon to qualitative understanding of this phenomenon and make it possible to endow materials with "room-temperature" superconductivity (at conventional ambient temperatures) by changing, e.g., their magnetic properties.

Currently, neutron scattering analysis is mainly performed on new materials in order to study and understand the fundamental laws combining the components of these materials into integer and the relationship of the structure of materials with their properties and useful functions. The major part (more than half) of all studies are of fundamental character and devoted to the physics of the condensed state of matter (including both ordered and disordered crystalline materials, amorphous materials, quasicrystals, some liquids, etc.). The rest ones are almost equally divided between the investigations of the chemical properties of materials (and biological objects) and studies of the so-called soft matter. The latter includes easily deformed objects (e.g., polymers, gels, colloids, emulsions, etc.), which play an increasingly important role in industry and everyday life.

Obviously, the general structure of neutron studies will be mainly retained. However, the increasing demand in socially useful studies and results will certainly shift the focus of neutron investigations. One of the factors determining this shift is the high cost of the development of new neutron sources and instrumental stock, causing evident desire to obtain a clear answer on the questions: why and what for? At the same time, the human society is challenged by the need for renewable energy sources, environmental contamination, and other factors determining the human existence. The unique method of neutron scattering, which can be universally applied to various objects from atomic to microscopic level in a wide range of response times, is to play a certain role in solving the global problems important for maintaining economic growth. Let us outline some of them.

Modern technologies call for new materials with specified electronic and magnetic properties. Thus, semiconductors and superconductors, metals and alloys, and magnetic materials for data accumulation and storage will be studied using inelastic neutron scattering, and the correspondence of their properties with modern theoretical concepts about matter structure will be verified. In our opinion, it is a conventional and most efficient field of application of neutron spectroscopy, which is enriched by the use of modern computational capabilities. On the one hand, it is related to the development of neutron experiment, which provides increasingly comprehensive data on the material dynamics due to the increase in the number of detector systems and their "pixelization" (especially in modern TOF spectrometers). Therefore, a particular task is the standardization of computer methods for accumulating, storing, and processing large arrays of experimental data. On the other hand, the methods for calculating physical properties of materials are being constantly developed with an increase in their accuracy and reliability; therefore, a future neutron experiment can hardly be imagined without detailed theoretical and model calculations.

The importance of new construction and engineering materials with improved functional parameters, which require characterization of their properties, along with multiferroics, relaxors, and carbon materials, including dental cement, constantly increases. The study of geological objects and processes occurring in the Earth's crust requires the formation of close-to-extreme natural conditions (high temperature and pressure). In this case, neutron scattering has an undoubted potential, although it is currently used not in full measure.

A particular attention will be paid to the study of materials capable of accumulating large amount of hydrogen in order to design efficient non-contaminating engines. This line of research includes also investigations of various accumulating devices both of hydride type and energy storage systems (batteries), which can be studied in situ and in operando due to the high penetrating ability of neutron radiation. One should also note expected and even realized (partially) application of neutron nondestructive methods for gaining information about unique objects of cultural and historical heritage (archaeological artifacts, etc.).

With allowance for the peculiar sensitivity of neutrons to hydrogen (the main biologically active element), neutron studies of vital objects and processes (life sciences) will undoubtedly become more important in future. In this context, neutron spectroscopy is intended to solve problems that are seemingly atypical for this technique. The point is that the basis for understanding the functioning of living matter is the information about the arrangement of biologically active centers or molecules. At the same time, the extremely complex polyatomic structure of these materials hinders to a great extent their detection and localization. Spectroscopic data offer this possibility when comparing the data of neutron experiment with the results of atomic-dynamics calculations. Detailed data on the biological processes are necessary at all levels, from atomic to cellular, including both small lipid and peptide molecules and macromolecular complexes. One must understand in detail the role of water in biological enzymes and the role of biological macromolecules in the permittivity of cellular membranes. To date, the investigations of medicines, their active centers, and interaction with shells in dependence of the delivery path to a damaged organ can be performed using neutron scattering, and the importance of these data cannot but increase in the nearest future.

We hope that neutron-scattering studies will be attractive for the young generation of scientists and that this review of neutron applications will draw their attention and, maybe, involve in the development of this line of research. The details of the experimental technique and methods are considered in the subsequent publication [75].

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REFERENCES

1. Yu. Kagan and Ya. A. Iosilevskii, Zh. Eksp. Teor. Fiz. **44**, 1375 (1963).
2. M. G. Zemlyanov, V. A. Somenkov, and N. A. Chernoplekov, Zh. Eksp. Teor. Fiz. **52** (3), 665 (1967).
3. G. F. Syrykh, A. P. Zhernov, M. G. Zemlyanov, et al., Zh. Eksp. Teor. Fiz. **70**, 353 (1976).
4. G. F. Syrykh, M. G. Zemlyanov, N. A. Chernoplekov, and V. M. Koltygin, Zh. Eksp. Teor. Fiz. **73**, 313 (1977).
5. G. F. Syrykh, A. P. Zhernov, M. G. Zemlyanov, et al., Phys. Status Solidi B **79** (1), 105 (1977).
6. Yu. L. Shitikov, B. A. Vindryaevskii, M. G. Zemlyanov, and N. A. Chernoplekov, Zh. Eksp. Teor. Fiz. **80** (2), 729 (1981).
7. M. G. Zemlyanov, E. G. Brovman, N. A. Chernoplekov, and Yu. L. Shitikov, *Inelastic Scattering of Neutrons* (IAEA, Vienna, 1965), Vol. 2, p. 431.
8. P. P. Parshin, M. G. Zemlyanov, M. E. Kost, et al., Izv. Akad. Nauk SSSR, Neorg. Mater. **14** (9), 1653 (1978).
9. V. F. Petrunin, S. K. Dolukhanyan, M. G. Zemlyanov, et al., Fiz. Tverd. Tela **23** (7), 1926 (1981).
10. P. P. Parshin, M. G. Zemlyanov, A. S. Ivanov, et al., Fiz. Tverd. Tela **23** (9), 2634 (1981).
11. P. P. Parshin, M. G. Zemlyanov, A. V. Irodova, et al., Fiz. Tverd. Tela **26** (3), 672 (1984).
12. P. P. Parshin, M. G. Zemlyanov, and Yu. L. Shitikov, Fiz. Tverd. Tela **27** (9), 2766 (1985).
13. P. P. Parshin and M. G. Zemlyanov, Z. Physica Chem. Neue Folge **64**, 1095 (1989).
14. B. A. Vindryaevskii, S. N. Ishmaev, G. V. Kobelev, et al., Fiz. Nizk. Temp. (Kiev) **15** (5), 457 (1989).
15. A. Yu. Rumyantsev, V. V. Pushkarev, M. G. Zemlyanov, et al., Zh. Eksp. Teor. Fiz. **75**, 712 (1978).
16. A. A. Chernyshov, V. V. Pushkarev, A. Yu. Rumyantsev, et al., J. Phys. F **9** (10), 1983 (1979).
17. A. A. Chernyshov, B. Dorner, V. V. Pushkarev, and A. Yu. Rumyantsev, J. Phys. F **13** (1), 33 (1983).
18. A. S. Ivanov, N. L. Mitrofanov, V. V. Pushkarev, et al., Fiz. Tverd. Tela **28** (3), 767 (1986).
19. A. S. Ivanov, A. Yu. Rumiantsev, B. Dorner, et al., J. Phys. F **17** (9), 1925 (1987).
20. P. A. Alekseev, I. P. Sadikov, I. A. Markova, et al., Fiz. Tverd. Tela **18**, 676 (1976).
21. P. A. Alekseev, I. P. Sadikov, I. A. Markova, et al., Fiz. Tverd. Tela **18**, 2509 (1976).

22. P. A. Alekseev, A. Andreeff, I. P. Sadikov, et al., Phys. Status Solidi B **97**, 87 (1980).
23. P. A. Alekseev, V. N. Lazukov, I. P. Sadikov, and A. Yu. Rumyantsev, Pis'ma Zh. Eksp. Teor. Fiz. **43**, 586 (1986).
24. E. A. Goremychkin and E. Myule, Pis'ma Zh. Eksp. Teor. Fiz. **39** (10), 469 (1984).
25. P. A. Alekseev, I. P. Sadikov, V. P. Kolyadin, and A. V. Mirmel'shtein, Zh. Eksp. Teor. Fiz. **39** (10), 477 (1984).
26. H. A. Mook, R. M. Nicklow, T. Penney, et al., Phys. Rev. B **18**, 2925 (1978).
27. E. S. Clementyev, P. A. Alekseev, M. Braden, et al., Phys. Rev. B **57** (14), R8099 (1998).
28. V. N. Lazukov, N. N. Tiden, P. A. Alekseev, et al., Phys. Status Solidi C **1** (11), 3174 (2004).
29. P. A. Alekseev, A. S. Ivanov, B. Dorner, et al., Europhys. Lett. **10**, 457 (1989).
30. P. Fulde, *Handbook of Physics and Chemistry of Rare Earths,* Ed. by K. A. Gschneidner and L. Eyring (North-Holland, Amsterdam, 1978), Ch. 17, p. 295.
31. P. Fulde and M. Loewenhaupt, Adv. Phys. **34** (5), 589 (1985).
32. D. J. Newman and B. Ng, Rep. Prog. Phys. **52**, 699 (1989).
33. E. Holland-Moritz and G. H. Lander, *Handbook of Physics and Chemistry of Rare Earths,* Ed. by K. A. Gschneidner (Elsevier, 1994), Vol. 19, Ch. 1, p. 1.
34. A. Furrer and A. Podlesnyak, *Handbook of Applied Solid State Spectroscopy,* Ed. by D. R. Vij (Springer, 2006), Ch. 6, p. 259.
35. P. A. Alekseev, Phys.-Usp. **58** (4) 330 (2015).
36. P. A. Alekseev, Phys.-Usp. **60** (1) 58 (2017).
37. A. Furrer, J. Supercond. Novel Magn. **21**, 1 (2008).
38. A. Furrer, P. Allenspach, J. Mesot, et al., Eur. J. Solid State Inorg. Chem. **28**, 627 (1991).
39. U. Staub, J. Mesot, M. Guillaume, et al., Phys. Rev. B **50**, 4068 (1994).
40. J. Mesot and A. Furrer, J. Supercond. Novel Magn. **10**, 623 (1997).
41. A. Mirmelstein, A. Podlesnyak, V. Bobrovskii, and I. Zhdakhin, J. Phys.: Condens. Mater. **11**, 7155 (1999).
42. A. Mirmelstein, V. Bobrovskii, N. Golosova, et al., J. Supercond. Novel Magn. **15** (5), 2002 (2002).
43. A. S. Ivanov, N. L. Mitrofanov, A. Yu. Rumiantsev, et al., Physica B **156–157**, 910 (1989).
44. A. S. Ivanov, N. L. Mitrofanov, A. Yu. Rumyantsev, et al., Sverkhprovodimost: Fiz., Khim., Tekh. **4** (10), 1884 (1991).
45. L. Pintschovius, N. Pyka, W. Reichardt, et al., Prog. High Temp. Supercond. **21**, 36 (1990).
46. A. S. Ivanov, N. L. Mitrofanov, A. Yu. Rumyantsev, et al., Fiz. Nizk. Temp. (Kiev) **17** (10), 693 (1991).
47. N. Pyka, L. Pintschovius, and A. Yu. Rumiantsev, Z. Physica B: Condens. Matter **82**, 177 (1991).
48. L. Pintschovius, N. Pyka, W. Reichardt, et al., Physica B **174**, 323 (1991); Physica C **185**, 156 (1991).
49. N. Pyka, N. L. Mitrofanov, P. Bourges, et al., Europhys. Lett. **18** (8), 711 (1992).
50. W. Reichardt, L. Pintschovius, N. Pyka, et al., J. Supercond. **7** (2), 399 (1994).
51. M. Braden, W. Reichardt, A. S. Ivanov, and A. Yu. Rumiantsev, Physica C **235–240**, Pt II, 1167 (1994).
52. M. Braden, W. Reichardt, W. W. Schmidbauer, et al., J. Supercond. **8** (5), 595 (1995).
53. M. Braden, W. Reichardt, A. S. Ivanov, and A. Yu. Rumiantsev, Europhys. Lett. **34** (7), 531 (1996).
54. N. A. Chernoplekov, M. N. Khlopkin, G. Kh. Panova, et al., Physica C **153–155**, 1655 (1988).
55. P. P. Parshin, M. G. Zemlyanov, N. A. Chernoplekov, et al., Sverkhprovodimost: Fiz., Khim., Tekh. **1**, 30 (1988).
56. P. P. Parshin, M. G. Zemlyanov, and P. I. Soldatov, J. Exp. Theor. Phys. **74** (2), 400 (1992).
57. P. P. Parshin, M. G. Zemlyanov, O. E. Parfenov, and A. A. Chernyshov, JETP Lett. **51** (7), 434 (1990).
58. A. V. Chumachenko, M. G. Zemlyanov, A. Yu. Muzychka, et al., JETP **82** (1), 107 (1996).
59. P. P. Parshin, M. G. Zemlyanov, O. E. Parfenov, and A. A. Chernyshov, *Proc. Third Int. Conf. on Phonon Physics "Phonons 89"* (World Scientific, Singapore, 1989), Vol. 1, p. 310.
60. P. P. Parshin and M. G. Zemlyanov, Appl. Phys. A **74**, S1619 (2002).
61. P. P. Parshin, M. G. Zemlyanov, A. V. Irodova, et al., Fiz. Tverd. Tela **38** (6), 1665 (1996).
62. P. P. Parshin, M. G. Zemlyanov, and A. V. Irodova, Fiz. Nizk. Temp. (Kiev) **22** (5), 564 (1996).
63. A. S. Ivanov, Ph. Bourges, D. Petitgrand, and J. Rossat-Mignod, Physica B **213–214**, 60 (1995).
64. H. Casalta, Ph. Bourges, D. Petitgrand, and A. Ivanov, Solid. State Commun. **100** (10), 683 (1996).
65. A. Ivanov, D. Petitgrand, Ph. Bourges, and P. Alekseev, Physica B **234–236**, 717 (1997).
66. H. Casalta, Ph. Bourges, D. Petitgrand, et al., Physica B **234–236**, 803 (1997).
67. D. Petitgrand, H. Casalta, P. Bourges, and A. Ivanov, Physica B **234–236**, 806 (1997).
68. H. Casalta, Ph. Bourges, M. d'Astuto, et al., Phys. Rev. B **57**, 471 (1998-I).
69. D. Petitgrand, S. V. Maleyev, Ph. Bourges, and A. S. Ivanov, Phys. Rev. B **59**, 1079 (1999-II).
70. S. V. Maleyev, D. Petitgrand, Ph. Bourges, and A. S. Ivanov, Physica B **259–261**, 870 (1999).
71. A. S. Ivanov, Ph. Bourges, and D. Petitgrand, Physica B **259–261**, 879 (1999).
72. D. Petitgrand, A. S. Ivanov, and S. V. Maleyev, Appl. Phys. A **74**, S853 (2002).
73. A. Ivanov and D. Petitgrand, J. Magn. Magn. Mater. **272–276**, 220 (2004).
74. A. S. Ivanov, Doctoral Dissertation in Physics and Mathematics (Peter the Great Saint-Petersburg Polytechnic University, St. Petersburg, 2017).
75. A. S. Ivanov and P. A. Alekseev, Crystallogr. Rep. **66** (2021) (in press).

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