Anniversary session of the Scientific Council on the Problem of the Physics of Magnetic Phenomena of the Academy of Sciences of the USSR, (Moscow, 9–10 December 1982)

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The annual plenary session of the Scientific Council on the Problem of the Physics of Magnetic Phenomena, of the Division of General Physics and Astronomy of the USSR Academy of Sciences, was held in Moscow on December 9 and 10, 1982. The first session, on December 9, was devoted entirely to general questions of the annual plenary sessions of the Council: an account of the work of the Council and its sections in 1982, a discussion of the work planned for the Council in 1983, and some questions of current interest.

The second session, on December 10, was an anniversary session, devoted to the 60th anniversary of the formation of the Soviet Union. Its agenda was as follows:

1. An opening speech by the president of the Scientific Council on the Current State of Research on the Physics of Magnetic Phenomena in the Various Union Republics of the Soviet Union and on the Coordination of This Research.

2. A scientific report by professor V. A. Ignatchenko, doctor of physicomathematical sciences (L. V. Kirenskiĭ Institute of Physics, Siberian Branch, USSR Academy of Sciences, Krasnoyarsk), on "Stochastic characteristics of amorphous magnetic materials."

3. A scientific report by professor A. A. Samokhvalov, doctor of physicomathematical sciences, and his junior scientific colleague V. V. Osipov (Institute of the Physics of Metals, Ural Scientific Center, USSR Academy of Sciences, Sverdlovsk) on "The active electron–magnon interaction in magnetic semiconductors."

4. A scientific review report by professor R. Z. Levitin, doctor of physicomathematical sciences (Physics Department, M. V. Lomonosov Moscow State University, Moscow), on "The magnetism of actinide compounds."

In the first report, the speaker reviewed the results of some of the most important research on magnetism in prerevolutionary Russia and in the Soviet Union, drawing a picture of the present state of this research in the Union republics.

The first studies in Russia were carried out in the mid-18th century by Academician F. U. T. Epinus of the Russian Academy of Sciences. In the first half of the 19th century, the Russian Academician H. F. E. Lenz also formulated his famous law regarding the magnetic field of an induction current. In the second half of the 19th century, A. G. Stoletov, a professor at Moscow University, recorded the first actual magnetization curve of a ferromagnet in a closed magnetic circuit. The idea of a "molecular field" in ferromagnets was advanced by the Russian physicist B. L. Rozing (1892). Research by V. K. Arkad'ev dealt with the magnetic properties of ferromagnets in alternating magnetic fields and served as the foundation of magnetodynamics. During the Soviet years, some brillant studies were carried out by Ya. G. Dorfman. He explained the temperature-independent paramagnetism of the alkali metals, predicted electron paramagnetic resonance and cyclotron (diamagnetic) resonance, and proved the nonmagnetic nature of the molecular field in ferromagnets. In a famous study, L. D. Landau derived a quantum theory of the diamagnetism of an electron gas in a metal (Landau levels). N. S. Akulov derived a theory for the magnetic anisotropy and magnetostriction of ferromagnetic single crystals, thereby laying the foundation for the modern theory of the technical magnetization curve of ferromagnets. He was the first to suggest that there are two types of magnetization processes: rotation and displacement processes. Ya. G. Dorfman and Ya. I. Frenkel' were the first to estimate the size of single-domain ferromagnetic particles. In a famous study, L. S. Landau and E. M. Lifshitz (1935) furnished a definitive theoretical basis for P. Weiss's hypothesis regarding magnetic domains and proposed the first concrete model of a domain structure. A corresponding structure was subsequently found experimentally by N. S. Akulov and others. Research by Akulov, E. I. Kondorskiĭ, R. I. Yanus, Ya. S. Shur, and others laid the foundation for the modern theory of the hysteresis of ferromagnets. L. D. Landau and E. M. Lifshitz (1935) also proposed an equation describing the dynamics of the magnetization of ferromagnets (the Landau-Lifshitz equation), which underlies the entire modern theory of ferromagnetic resonance. Ya. P. Terletskiĭ generalized the Bohr–Van Leeuwen theorem, which states that a steady-state magnetization is impossible in a solid from the standpoint of classical electrodynamics and classical statistical mechanics. In some fundamental studies by the school of I. M. Lifshitz, a band theory of crystals with an arbitrary dispersion law was developed and used to derive rigorous theories for the magnetic and galvanomagnetic properties of weakly magnetic metals and semiconductors. A quantum-

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mechanical theory of ferromagnetism was first formulated by Ya. I. Frankel' (1928) on the basis of a model of collectivized electrons. The theory was pursued in studies by S. P. Shubin and S. V. Vonsovskiĭ, N. N. Bogolyubov, and S. V. Tyablikov, who developed a many-electron polar-exciton model which synthesized the band model and the Heisenberg localized model. A particular version of this model is presently used widely throughout the scientific world (the Hubbard model). Shubin and Vonsovskiĭ also proposed an *s–d*- (or *s–f*)-exchange model of transition metals, which has now been generally accepted and is used widely to explain various physical properties, including magnetic properties, of the transition metals and their metallic and semiconducting compounds. The *s–f*-exchange model has been used successfully to explain several magnetic and electrical properties of metallic and semiconducting rare-earth compounds (I. E. Dzyaloshinskiĭ, K. P. Belov, E. I. Kodorskiĭ, Yu. P. Irkhin, A. A. Samokhvalov, E. L. Nagaev, and others). Soviet physicists have made an important contribution to the problem of the phonon–magnon interaction (A. I. Akhiezer, E. A. Turov, V. G. Shavrov, V. G. Bar'-yakhtar, A. S. Borovik-Romanov, K. B. Vlasov, V. I. Ozhogin, S. V. Peletminskiĭ, and E. G. Rudashevskiĭ). L. D. Landau and simultaneously the French physicist L. Néel predicted the existence of antiferromagnetism. V. L. Ginzburg and S. V. Vonsovskiĭ applied Landau's theory of second-order phase transitions to the ferromagnetic paramagnetic transition. E. K. Zavoĭskiĭ discovered electron paramagnetic resonance, and the Kazan' school of physicists which he founded has gone on under the guidance of B. M. Kozyrev and S. A. Al'tshuler to make an extensive contribution to the research on this important phenomenon. The phenomenon of weak ferromagnetism (slightly noncollinear antiferromagnetism) was discovered and explained in an experimental study of Borovik-Romanov and colleagues and a theoretical study of Dzyaloshinskiĭ. Studies by Turov also made an important contribution to science. Very important research by Soviet physicists dealt with nuclear methods for studying magnetism: magnetic neutron diffraction (see the monograph by Yu. A. Izyumov and R. P. Ozerov[1]), nuclear magnetic resonance in magnetically ordered materials (see the monograph by Turov and M. P, Petrov[2]), the Mössbauer effect, etc. We should also mention the study by I. E. Tamm and S. A. Al'tshuler which predicted a magnetic moment for the neutron and the discovery by L. N. Dobretsov and A. N. Terenin of the hyperfine structure of spectral lines. The work on the problem of intense magnetic fields was begun in the well-known studies by P. L. Kapitsa, and work on the problem continues today in many laboratories in the Soviet Union (V. G. Veselago, V. I. Ozhogin, *et al.*).

We should mention that in addition to some of the studies listed above, which clearly demonstrate the great role played by Soviet physicists in the field of magnetism, research on the physics of magnetic phenomena has increased even further in scope and depth in recent years, and there is no hope of covering all this work in a brief report. In the days of our all-nationalities celebration—days marking the 60th anniversary of the formation of the Union of Soviet Socialist Republics, the first multinational socialist state, which has demonstrated for more than half a century and to the entire world the vitality of the Leninist nationality policy, we can point out again that this policy had led to some extremely beneficial results in the field of science also. We now know that teams of physicists specializing in magnetism are working actively everywhere over the immense expanse of the Russian Federation from Leningrad and Moscow to Sverdlovsk, Krasnoyarsk, Irkutsk, and Vladivostok. There are other active groups of this sort, whose work is known not only in the Soviet Union but elsewhere, in the Ukraine, Belorussia, and Moldavia; in the Baltic and Caucasian republics, and in the Central Asian republics.

Soviet physicists specializing in magnetism gather every other year at All-Union Conferences on the Physics of Magnetic Phenomena, where they discuss the results of the most important research which has been carried out on magnetism throughout our immense country. These conferences are held in very different places and are associated with various scientific centers of the Union republics where active research is being carried out on magnetism. In addition to the All-Union Conferences, there are many other conferences every year of narrower scope, symposia, and schools on questions in the physics of magnetic phenomena.

The magnetic research is coordinated, and the large magnetic forums are organized, by the Scientific Council on the problem of the Physics of Magnetic Phenomena of the USSR Academy of Sciences.

[1]Yu. A. Izyumov and R. P. Ozerov, Magnitnaya neĭtronografiya, Nauka, Moscow, 1966 (Magnetic Neutron Diffraction, Plenum Press, New York, 1970).

[2]E. A. Turov and M. P. Petrov, Yadernyĭ magnitnyĭ rezonans v ferro- i antiferromagnetikakh, Nauka, Moscow, 1969 (Nuclear Magnetic Resonance in Ferro- and Antiferromagnets, Israel Program for Scientific Translations, Jerusalem; Wiley, New York, 1972).

Research on amorphous magnetic materials has become one of the most pressing questions in the physics of magnetic phenomena. Amorphous magnetic materials already acquired much practical importance as extremely promising soft magnetic materials. A purely physical study of these materials also yields much of interest. Such research was the subject of the report by V. A. Ignatchenko, who outlined the results of theoretical and experimental work of the Institute of Physics, Siberian Branch, USSR Academy of Sciences, Krasnoyarsk, on an important aspect of the physics of amorphous magnetic materials.

An amorphous magnetic material is a typical stochastic system. Because of the structural and chemical disorder, all the properties of the spin system (exchange, magnetization, and anisotropy) are random functions of the spatial coordinates. The mathematical expectation values of these properties, which are studied experimentally, are only the simplest characteristic of these functions. The most important characteristics of these functions are the autocorrelation functions and the mutual-correlation functions of the properties. In many cases, knowledge of these functions is all we need, since they contain the basic information about the magnitude of the fluctuations and their extent (the correlation radius). Until recently no methods at all were available for measuring spatial correlation functions. An effort was accordingly undertaken at the Kirenskiĭ Institute of Physics, Siberian Branch of the USSR Academy of Sciences, to develop a phenomenological theory of amorphous magnetic materials in which the correlation functions of each property of the spin system which fluctuates over space would appear in a general form, as certain unknown functions. The problem was solved in the approximation of a continuous medium for both amorphous ferromagnetic and amorphous ferrimagnetic materials. This theory has led to the discovery of several effects, whose study can furnish measurements of the correlation functions of the basic magnetic properties. The spin-wave dispersion law is the most informative characteristic, incorporating information on the correlation functions of all fluctuating properties. The fluctuations of each property cause a distinctive modification of the dispersion law. This result is the theoretical basis for a new method for studying amorphous magnetic materials: spin-wave spectroscopy. Experiments in cobalt–phosphorous amorphous thin films by the spin-wave-resonance method have revealed the theoretically predicted modifications of the dispersion law of the corresponding volume fluctuations, and in Co–Ni–P alloys they have also revealed magnetization fluctuations. The correlation radii of the volume and magnetization fluctuations have turned out to be ~20–30 Å, much larger than the structural correlation radius, ~5–8 Å. The stochastic characteristics of amorphous magnetic materials are not confined to the dispersion law. For example, fluctuations of the anisotropy axis have made it possible to determine the magnitude and correlation radius of the local magnetic anisotropy of an amorphous magnetic material; it has turned out to be ~100–150 Å. During the crystallization of an amorphous alloy, the anisotropy correlation radius does not change, remaining equal to the average crystallite radius. The fact that this radius does not change means that during crystallization the crystallites which form have a size equal to some characteristic dimension which already exists in the amorphous phase. The results imply large regions in which the magnetic properties do not change significantly and are smoothed out by interactions of some sort. For this reason, the ordinary theory of amorphous magnets with a zero correlation radius is a very poor approximation. We are led to ask whether long-range correlations are an internal property of the spin system, seen against the background of a structural chaos in which the correlations die out in two or three interatomic distances, or whether we are seeing manifestations of some sort of long-wavelength correlations which exist in the very atomic structure of the amorphous substances. On the whole, the experimental results which have been established support the latter possibility. We thus have the problem of developing direct structural methods which would make it possible to detect the same types of long-range correlations in the arrangement of atoms of amorphous alloys as are presently being observed in the properties of the spin system.

The problem of ferromagnetic and ferrimagnetic semiconductors has recently attracted particular interest, since these materials simultaneously exhibit two striking physical properties of solids; an atomic magnetic order in the system of electrons in the incomplete electron shells of transition-element atoms and a special (gap) energy spectrum of the system of collectivized conduction electrons. This wealth of different physical properties also makes these materials extremely promising for practical use in modern quantum electronics. Active research is presently being carried out on the various physical properties of these materials in the Institute of the Physics of Metals, Ural Scientific Center, of the USSR Academy of Sciences. Some results of these studies were also predicted by A. A. Samokhvalov and V. V. Osipov. The interaction of current carriers drifting in the intense electric field and magnetic elementary excitations—magnons (spin waves)—in magnetic semiconductors may also give rise to some completely new effects. In particular, the theory predicts an amplification of spin waves, a Cherenkov generation of magnons, and a heating of magnons by current carriers.[1,2] These effects may change the physical properties of magnetic semiconductors: their electrical conductivity, magnetization, permeability, etc. In EuO and $CdCr_2Se_4$, for example, a Cherenkov generation of magnons has been detected experimentally; beyond a certain threshold, this generation of magnons reduces the electrical conductivity, while causing the carrier drift velocity to become higher than the lowest phase velocity of the spin waves. It also causes a heating of carriers, accompanied by nonlinearities on the voltage-current characteristics,[3] and a heating of magnons, which reduces the magnetization.[4,5] It is fair to say that these results of the excitation of magnons by current carriers are the first step toward the development of a new branch of quantum electronics: semiconductor magnetoelectronics.

[1]A. I. Akhiezer, V. G. Bar'yakhtar, and S. V. Peletminskiĭ, Zh. Eksp. Teor. Fiz. 45, 337 (1963) [Sov. Phys. JETP 18, 235 (1964)].
[2]I. Ya. Korenblit and B. G. Tankhilevich, Fiz. Tverd. Tela (Leningrad) 18, 62 (1976) [Sov. Phys. Solid State 18, 34 (1976)].

[3]A. A. Samokhvalov, V. V. Osipov, V. T. Kalinnikov, and T. G. Aminov, Fiz. Tverd. Tela (Leningrad) 20, 595 (1978) [Sov. Phys. Solid State 20, 344 (1978)].
[4]A. A. Samokhvalov, V. V. Osipov, V. T. Kalinnikov, and T. G. Aminov, Pis'ma Zh. Eksp. Teor. Fiz. 28, 413 (1978) [JETP Lett. 28, 382 (1978)].
[5]A. A. Samokhvalov, V. V. Osipov, V. T. Ivaev, V. T. Kalinnikov, and T. G. Aminov, Pis'ma Zh. Eksp. Teor. Fiz. 30, 658 (1979) [JETP Lett. 30, 623 (1979)].

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There is no decrease in the level of research on the magnetic properties of compounds of actinide-group elements. The primary motivation for this research is that the electrons of atoms of the actinide group have an extremely complicated structure, containing, along with a valence shell, a set of electrons from various incomplete inner shells. R. Z. Levitin revealed recent research results on these materials. Back in 1952, the well known Polish physicist W. Trzebiatowski and colleagues discovered the first ferromagnetic actinide compound, β-UH_3. At present, more than 130 magnetically ordered binary actinide compounds have been identified, not counting solid solutions. The properties of these compounds are affected by the particular structure of the actinide 5f shell, which is being completed; this shell occupies an intermediate position between the 4f shell of the rare earth elements and the d shells of ordinary transition metals. With increasing atomic number of the actinide (the pure elements) we observe an increase in the degree of localization of the 5f electrons, which causes a transition from the Dorfman-Pauli paramagnetism of uranium (nearly completely collectivized 5f electrons) to a Curie antiferromagnetism (localized 5f electrons). An extremely complicated problem is that of the mixed valence of actinide compounds. Uranium, for example, exhibits valences ranging from + 2 to + 6 in certain cases. In the actinide compounds, because of their magnetic properties, we have the interesting concept of a critical distance between actinide-actinide nearest neighbors; at this critical distance, there is a transition from a collectivized state to a localized state for 5f electrons, with the consequence that a magnetic ordering arises. The concept of an indirect exchange interactions through conduction electrons (Ruderman-Kittel-Kasuya-Yosida exchange) apparently also applies to actinides. Recently, however, the localized-spin model has come under serious criticism, and an important role is being played here by the results of recent experiments on the optical properties of actinide compounds. The possibility of quite pronounced hydridization of 5f and 6d states is also being discussed. New data have recently been obtained on the atomic magnetic structures of actinide compounds. The structures exhibit pronounced variety and complexity. In addition, giant magnetocrystalline anisotropy and giant magnetostriction have been observed in actinide compounds. The first attempts are being made to explain these phenomena using the model of single-ion anisotropy, with allowance for the interaction of the orbital angular momentum of the 5f shell with the crystal field of the lattice. An effort has begun to study the magnetic excitations (spin waves, etc.) in actinide compounds.

Many questions were raised in the course of the reports, and there was a lively discussion.

Translated by Dave Parsons