14. N. Mott and H Massey, The Theory of Atomic Collisions [Russian translation], Mir, Moscow (1969).
15. J. Perel and H. Dalley, "Charge-transfer collisions involving electron transfer to excited states," Phys. Rev. A, 4, 162 (1971).
16. M.-T. I. Soskida and V. S. Shevera, "A study of the charge transfer by He^+, Ne^+, and Ar^+ at the Beutler states of cadmium and zinc atoms at low energies," Pis'ma Zh. Eksp. Teor. Fiz., 22, No. 11 (1975).
17. I. P. Bogdanova, V. D. Marusin, and V. E. Yakhontova, "A study of charge transfer of helium ions at mercury atoms," Opt. Spektrosk., 37, 643 (1974).
18. E. E. Nikitin and S. Ya. Umanskii, Nonadiabatic Transitions in Slow Atomic Collisions [in Russian], Atomizdat, Moscow (1979).

POSSIBLE EFFECTS IN SOLIDS IN ULTRASTRONG MAGNETIC FIELDS

V. V. Druzhinin, A. I. Pavlovskii, and O. M. Tatsenko

UDC 538:114.665.61

The history of solid-state theory and the detection of major interactions in solids are closely related to research on the effects of external magnetic fields on characteristics such as the magnetization, volume, specific heat, conductivity, thermal conductivity, spectral parameters, and so on, since almost all of these are affected by magnetic fields. Advances in producing fields of 100-300 kOe have been accompanied by improvements in research methods since the pioneering studies by Kapitsa [1], in which the law of linear increase in magnetoresistance was discovered for various metals, and there have since been numerous physics researches in this range of magnetic fields. Anomalies in magnetization have been observed [2] along with the magnetocaloric effect [3], magnetooptic effects [4], and other features. A very important discovery was that of the gap-free state in a solid [5], which represents an essentially new type of ordering in condensed media at low temperatures in strong magnetic fields. Naturally, the region of even stronger fields, up to 10^7 G, should reveal new effects or special features in known ones. Here we examine some possible phenomena related to the action of fields up to 10^7 G on the condensed state.

The magnetocaloric effect is a major one to be considered in experiments with pulsed magnetic fields. In fact, the field increases under adiabatic conditions, and the changes in internal magnetic energy are considerable, and they may attain the energies of the spin-orbit and exchange interactions or the energies of the crystalline field at about 10^4 cm^{-1} per ion. As the total entropy is conserved (magnetic plus phonon), while the magnetic entropy tends to zero in the external field under ordinary conditions, the phonon component increases considerably, which increases the temperature. To calculate the rise, it is necessary to solve a system of equations consisting of Shroedinger's equations and the equations of statistical thermodynamics:

$$\hat{H}\Psi_n = E_n\Psi_n,\ S_m(T_0, 0) + S_{ph}(T_0) = S_m(T_k, H) + S_{ph}(T_k),$$

$$S_m = -n_m S_p\left[\left(e^{-\hat{H}/T}/z\right)\ln\left(e^{-\hat{H}/T}/z\right)\right],\quad S_{ph} = 3n\left\{-\ln\left(1-e^{-\Theta/T}\right) + 12\,(T/\Theta)^3\int_0^{\Theta/T}\frac{z^3dz}{e^z-1}\right\}$$

being the magnetic and phonon entropies of the specimen per formula unit, while n_m and n are the numbers of magnetic ions and of all ions in the formula unit, and Θ is the Debye temperature. These formulas give a large temperature rise $\Delta T = T_k - T_0$. Figure 1 shows the calculated value of ΔT in metallic Tb in a field of 1.5 MG. The Néel temperature is 230°K, while the Debye temperature is 177°K. It is evident that the largest value $\Delta T = 120$°K occurs in the region of a magnetic phase transition. One can estimate the limiting value of ΔT as follows. For $T >> \Theta/4$ with $H = 0$, $S_m = n_m \ln(2J + 1)$, where J is the momentum quantum number and $S_{ph} = 3n \ln T + c$. In a limiting strong field, where $s_m = 0$, the adiabatic equation takes the form

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 16-19, November-December, 1984. Original article submitted September 7, 1983.

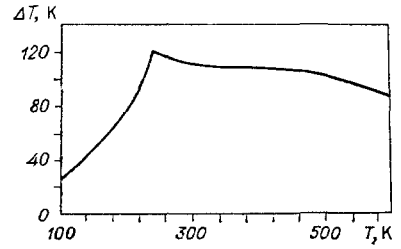

Fig. 1

$$n_m \ln(2J+1) + 3n \ln T_0 = 3n \ln T_k,$$

which gives the maximum value $T_k = T_0(2J+1)^{n_m/3n}$. We estimate the maximum possible temperature rise in a field of 10 MG for a film of metallic holmium. This metal was chosen because $n_m = n = 1$ for it and the maximum possible value is $J = 8$. If the initial temperature is $T_0 = 300°K$, the splitting in a field of 10 MG between the nearest Zeeman sublevels is $\Delta E = g\mu_B H \simeq 1000°K$. Then $T_k = 770°K$. With these relations, the condition $S_m(T_k) = 0$ is obeyed quite closely. Here it is necessary to take a holmium film of thickness less than that of the skin layer for the penetration of the pulsed field into the metal in order that magnetic-field pressure effects should not occur. This conversion of magnetic energy to thermal form can be identified from the change in the equilibrium thermal radiation. In fact, according to Stefan's law, the energy luminosity $R_E = \sigma \cdot T^4$ increases by a factor 43, while the wavelength of the maximum in the emissivity is $\lambda_m = 2.9 \cdot 10^3/T$ (μm), which is 3.76 μm at $T = 770°K$, i.e., the main radiation occurs in the near infrared. This can be recorded by optical methods.

In some cases, there is a negative magnetocaloric effect, i.e., the temperature falls as the field increases adiabatically. Kittel [6] first pointed out this possibility, and the theory was devised in [7, 8], while the effect was recorded in [9]. The basic reason for this phenomenon is that the ground-state splitting due to the crystalline field is such that the lower level is a singlet and the first excited level is a doublet, which is split in the magnetic field. At the instant when its component intersects the ground state, the magnetic entropy per ion increases from zero to $S_m = \ln 2 = 0.69$ (at a sufficiently low initial temperature). The corresponding decrease in the phonon entropy reduces the temperature at the time of level intersection. In principle, the temperature may oscillate as the field increases if the crystalline field is described by an operator of the type $V_{cr} = A\hat{J}_z^2$, $A > 0$. The SLJ level then splits as indicated above, and as the field increases, the sublevels having $J_z = -1, -2, \ldots, -J$ successively intersect the ground state. Then the values of the field at which the temperature falls are $H_m = A(2m-1)/g\mu_B$, $m = 1, 2, \ldots, J$. The phase of this process is displaced for half-integer J. A typical value is $A \simeq 10^2$–10^3 cm^{-1}. With $J = 5$ and $A = 2 \cdot 10^2$ cm^{-1}, there should be three falls in temperature in fields up to 10 MG, which occur at 2.1, 6.3, and 10.5 MG. The temperature fall is determined by the initial value $T_k = T_0/2^{3n/nm}$. In the case $T_0 \simeq 300°K$ and $n_m = n$, $T_k = 40°K$. Here it is assumed that the spin–spin and spin–lattice relaxation times are much shorter than the pulse length. At low temperatures (about 4.2°K), the level intersection may produce considerable temperature reduction, which opens up unique scope for examining solids in ultrastrong magnetic fields at ultralow temperatures.

When an ultrastrong magnetic field acts on a magnetic material, there can be some particular features in known effects. The modern theory of magnetism introduces a molecular field, which influences the spin degrees of freedom in the same way as an external magnetic field. This field is about 10 MG. An external field acts on the spin and orbital degrees of freedom, and in that respect it differs from a molecular field. One of the possible effects in an ultrastrong magnetic field is that the exchange interaction via the conduction electrons is switched off. The theory of this type of exchange has been given in [10, 11], which implies that one should allow for the f-s exchange interaction of the localized f electrons and the collectivized s ones for a rare-earth metal in the second approximation of perturbation theory, which leads to the Heisenberg operator $\hat{H}_{ex} = -(g-1)^2 I(\hat{J}_1 \cdot \hat{J}_2)$. Here the value of the exchange integral I is dependent on the shape of the Fermi surface, the conduction-band width, and the specific resistance. Theoretical analysis indicates that the splitting of the conduction band into Landau subbands reduces the conduction-electron mobility and increases the localization of these electrons in the perpendicular direction. This leads to an exponential decrease in the exchange integral, and the most rapid fall for a rare-earth metal is to be expected in the region of 7–8 MG. This value can be estimated as follows. The conduction-electron delocalization radius is determined by the so-called magnetic length $L = (c\hbar/eH)^{1/2} = 2.5 \cdot 10^{-7} h^{-1/2}$ cm, where h is in MG. This formula imples that $L = 9 \cdot 10^{-7}$ mm in a field of 7 MG,

which is comparable with the lattice constant $a = 5 \cdot 10^{-7}$ mm in an REM. Here the resistance of the metal also increases sharply. Therefore, the following effect may occur: The magnetization may decrease in response to the magnetic field, since the molecular field is switched out, and this is comparable in magnitude with the external field. Estimates of the effect for rare-earth metals show that the possible stepout in the paraprocess curve towards reduced magnetization is not more than 10% in the paramagnetic region, which is very difficult to observe. A possible way of observing this effect may be to magnetize a thin film of the ferromagnetic $NdCo_5$. At T = 250°K, the easy magnetization axis lies in the basal plane. If the external field is directed along that axis and increases, the loss of the exchange interaction between the Nd and Co sublattices causes the hexagonal axis to become the easy direction, and the crystal will tend to rotate and will be disrupted because of the large rotational moments.

An external magnetic field in the megagauss range may convert any magnetic material to a ferromagnetic. Calculations show that the sublattice collapse field in yttrium ferrite-garnet at 300°K is about 9 MG, and this is a ferromagnetic with one of the highest Curie temperatures. The change in free energy per ion in the external field is about 10^4 cm^{-1}, which is comparable with the crystalline-field energy and the energies of the exchange and spin-orbit interactions, as well as the local-distortion energy in the Jahn–Teller effect. Some crystals show symmetry reductions as the temperature falls in the regions of the paramagnetic–antiferromagnetic–weak ferromagnetic phase transitions. This is determined by the overall reduction in the free energy, which includes the phonon and magnetic subsystems. As the role of the increasing external field in a certain sense is equivalent to reducing the temperature at constant field, one expects symmetry changes in an external field. An examination of the probability of this effect indicates that possible crystals are the orthoferrite $RFeO_3$, antiferromagnetics of the type of Fe_2O_3 and $KMnF_3$, and similar materials.

A pulsed field in the megagauss range can be used to excite laser radiation if the relaxation time is much greater than the field rise time. This idea was suggested in early papers on the theory of laser radiation. We consider ultrastrong fields in that respect. The splitting in the ground-state SLJ multiplet in a magnetic field is such that the magnetic-dipole transition between nearest sublevels has energy $\Delta E = g\mu_B H$. For the rare-earth ion Gd^{3+}, this is 92.8h cm^{-1}. This means that a field of about 11 MG will produce a wavelength of 10.2 μm for the strongest transition $m + 1 \to m$, where $m = -J, -J + 1, \ldots, J - 1$, i.e., the wavelength of a CO_2 laser. A promising medium for this experiment is a glass containing Gd^{3+}. Recent ESR measurements on such media indicate that the relaxation times at 4.2°K are about 10^{-3} sec [12], which are much greater than the field rise times of $\Delta t \approx 10^{-6}$ sec. Evidently, one could amplify a transmitted beam with a wavelength of $\lambda \approx 10.2$ μm in such a field. Also, conditions of shorter wavelength are possible because the crystalline field mixes states differing in J_m.

A solid is a very complicated physical object, and the modern theory does not give an exhaustive quantitative treatment of the properties, so the number of possible effects in ultrastrong fields might be extended. Here we have indicated some obvious consequences of ultrastrong magnetic fields acting on solids. In real experiments, these effects and others not stated here may be mingled, and a comprehensive analysis may be required to interpret the results.

LITERATURE CITED

1. P. L. Kapitza, "Magnetoresistance of metals," Proc. Cambr. Phil. Soc., 21, 511 (1923); Proc. Roy. Soc., A105, 191 (1924).
2. V. L. Yakovenko, V. E. Bril', et al., "Magnetization of an erbium single crystal in the basal plane in a strong magnetic field," Zh. Eksp. Teor. Fiz., 78, 157 (1980).
3. V. V. Druzhinin, B. K. Ponomarev, and S. P. Zapasskii, "A theoretical and experimental study of the characteristics of terbium and dysprosium in strong magnetic fields," Fiz. Tverd. Tela, 19, 47 (1977).
4. N. F. Kharchenko, V. V. Eremenko, and L. I. Belyi, "Magnetooptic studies on the noncollinear state induced by a magnetic field in antiferromagnetic cobalt fluoride," Zh. Eksp. Teor. Fiz., 82, 827 (1982).
5. N. B. Brandt, E. A. Svistova, and G. Kh. Tabieva, "Magnetoresistance of Bi in fields up to 450 kOe at helium temperatures," Pis'ma Zh. Eksp. Teor. Fiz., 4, No. 1 (1966); A. A. Abrikosov, "The phase diagram of an exciton insulator in a strong magnetic field," Zh. Eksp. Teor. Fiz., 65, 1508 (1973).
6. C. Kittel, "Decrease of temperature by adiabatic magnetization," Physica, 24, 388 (1958).

7. W. P. Wolf, "Cooling by adiabatic magnetization," Phys. Rev., 115, 1196 (1959).
8. V. V. Druzhinin, V. M. Mel'nikov, and V. V. Shkarubskii, "The magnetocaloric effect in strong magnetic fields," Fiz. Tverd. Tela, 21, 1750 (1979).
9. V. V. Znamenskii and N. G. Fakidov, "The magnetocaloric effect in pulsed magnetic fields," Fiz. Met. Metalloved., 13, 312 (1962); A. S. Nikitin, A. S. Andrienko, et al., "Magnetic phase transitions and the magnetocaloric effect in Tb–Y alloys," Zh. Eksp. Teor. Fiz., 73, 228 (1977).
10. C. Kittel, The Quantum Theory of Solids [Russian translation], Nauka, Moscow (1967).
11. V. V. Druzhinin and Yu. P. Irkhin, "The spin Hamiltonian for exchange interactions in rare-earth metals," Zh. Eksp. Teor. Fiz., 51, 1856 (1966).
12. A. A. Antipin, S. P. Zapasskii, and S. G. Lukter, "Electron spin resonance on impurity ions in glasses," in: Abstracts for the Seventh All-Union Symposium on Crystal Spectra [in Russian], Leningrad (1982).

SIMULATING THE RETARDATION OF AN UNCOMPENSATED ELECTRON BEAM IN A THIN ABSORBER

V. I. Boiko, E. A. Gorbachev, and V. V. Evstigneev

UDC 537.533.7:539.124.17

1. Introduction. Advances in accelerator engineering have extended the range of applications for high-current electron beams HCEB [1]. A feature of the interaction between HCEB and matter is that allowance must be made for the inherent magnetic fields in the beam and the change in the properties of the medium through which it passes. There are many experimental difficulties, while the algorithms are complicated and many different conditions are used with HCEB (vacuum gas, plasma, solids, and geometry associated with boundary conditions), while there are various interaction mechanisms with the matter and fields, so the problem has not been completely solved. Theoretical models are approximate and usually involve the assumption of one or two interaction mechanisms with matter and fields (problems in electron optics [2-5], Coulomb scattering, and the effects of electric fields [6] or magnetic ones [7, 8] for the beam, as well as magnetohydrodynamic description [9]), together with simplifying assumptions. We have previously considered the quasistationary treatment of relativistic HCEB absorption at currents, where we made allowance for Coulomb scattering and the effects of the electric and magnetic fields of the beam in two-dimensional geometry, particularly the relative contribution from these to HCEB retardation [10, 11].

Here we consider the passage of an uncompensated HCEB through a thin target, which is of practical interest in relation to extracting the beam through an anode foil or a foil in a drift chamber, as well as to the use of foils as constructional components in diagnostic equipment.

2. Model and Calculation Program. An iteration method was used in this quasistationary method, which enables one to split up the self-consistent treatment into a series of non-self-consistent ones [4, 5], together with the Monte Carlo method for calculating the beam particle paths with allowance for Coulomb scattering. We used two-dimensional geometry with azimuthal symmetry, which included the exit foil in the accelerator, the cylindrical drift tube, the absorber (in general, of arbitrary thickness and having a coaxial hole), and the collector (Fig. 1). This general geometry enables one to consider a large range of transport problems (absorption in thin targets and total-absorption absorbers, and also transport and collimation with allowance for the component of the electron flux scattered in matter).

The following conditions are required if a quasistationary treatment is to apply. Firstly, it is assumed that the magnetic-field diffusion depth into matter is comparable with the electron range or with the absorber thickness. This condition is obeyed for most high-current accelerators with characteristic pulse lengths of about 10^{-7} sec for foil thicknesses $\leqslant 10^{-4}$ m. Secondly, the fast-electron energy relaxation time in a condensed medium is $\sim 10^{-11}$-10^{-12} sec, and the retardation times in megavolt electric fields of $\leqslant 10^{-10}$ sec

Tomsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 20-25, November-December, 1984. Original article submitted August 30, 1983.

 0021-8944/84/2506-0828$08.50