bility at small β is particularly clearly seen from the χ' lines—at $\beta < 0.65$ these curves have no nodes at all (see Fig. 4a).

Calculation of the susceptibility lines shows that the resonant field H_r, corresponding to the maximum value of the imaginary part of the susceptibility

$$\chi_r''(H_r) = \max\{\chi''(H)\},$$

depends little on the parameter β. Much more sensitive to changes of this parameter are the quantity χ_r'' and the absorption line width ΔH at the height $\chi_r''/2$.

In the limit as $\beta \to \infty$ $(T/V \to 0)$ the line shape is determined by the Landau–Lifshitz equation, and therefore

$$\chi_r'' = \gamma M/2\xi\omega, \quad \Delta H/H_r = 2\xi.$$

With decreasing volume of the particle (with increasing ration T/V), the height of the absorption peak decreases monotonically, and the relative line width increases without limit.

It appears that the arguments advanced above can explain the results of Bagguley's experiment.[6] In an investigation of dilute colloidal suspensions of spherical ferromagnetic-metal particles (with linear dimensions on the order of 100 Å), he observed exceedingly broad (compared with those obtained with bulky samples) FMR lines: in a field $H \approx 3000$ Oe the width ΔH was 1400 Oe for iron and 1000 Oe for nickel, exceeding by one order of magnitude the anisotropic fields of the indicated metals. In both cases, the gyromagnetic ratio determined from the position of the resonance peak did not differ (with experimental accuracy) from that measured on a bulky sample.

[1)] *Editor's note*: This article is a consolidation, made at our request, of two almost simultaneously submitted papers.

[2)] Formulas perfectly similar to (3.8) are obtained also for the relaxation times of the magnetization of a suspension of rigid dipoles.[5] The "superparamagnetism" of such a suspension is ensured by the rotational diffusion of the particles in a liquid with viscosity η; therefore in place of τ from (3.2) the formulas of[5] contain the Brownian time $\tau_B = 3\eta N/kT$. As seen from a comparison of τ_B with τ, in the case considered in the present article the role of viscosity is played by the quantity $M/6\xi\gamma$ (magnetic voscosity).

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Temperature dependence of the density distribution of the superfluid component of helium II in pores

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An oscillating-disk method is proposed for the direct determination of the density of the superfluid component in pores. The validity of the $\langle\rho_s\rangle/\rho_{sb}$ distribution derived by Kiknadze and Mamaladze is demonstrated. It is established that near T_0 the density of the superfluid component of helium II in pores varies linearly with temperature ($\langle\rho_s\rangle \sim T_0 - T$), whereas far from T_λ it is described by the law $\langle\rho_s\rangle \sim (T_\lambda - T)^{2/3}$.

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The density distribution predicted by the Ginzburg-Pitaevskiĭ-Mamaladze (GPM) phenomenological theory[1,2] for the superfluid component of helium II in pores has been experimentally studied by quite a large number of foreign investigators,[3–8] who used, in the main, fourth-sound and gyroscopic techniques and studied the law of variation with temperature of the mean superfluid density $\langle\rho_s\rangle$ in pores. In[9,10], Kiknadze and Mamaladze derived an analytic expression for $\langle\rho_s\rangle/\rho_{sb}$ (ρ_{sb} is the bulk superfluid-component density) as a function of temperature and the geometry of the vessel. The present paper is devoted to the study of these problems in pores of cylindrical geometry by an oscillating-disk method. The proposed method enables us to obviate a number of difficulties encountered in fourth-sound experiments. We have in mind, for example, the correction for the scattering of sound by the grains of packed powder, the necessity for normalization of the temperature-dependence curves for the fourth-sound velocity, the application of a low-frequency signal for an independent determination of the transition temperature.

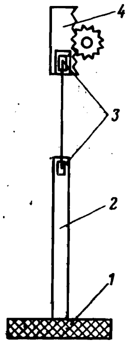

FIG. 1. Diagram of the instrument.

The instrument is a torsion pendulum, a diagram of which is shown in Fig. 1. A disk 1 of diameter 20 mm and thickness 4.5 mm, prepared from Vycor glass, was suspended with the aid of a straightened glass rod 2 of diameter 1 mm and length 400 mm on an elastic phosphor-bronze fiber 3 having a diameter of 20 μ. The disk was treated in the following manner: It was washed in distilled water, then placed in a bath with a concentrated solution of H_2O_2, and boiled for 5 hours. Further, the sample was dried in a desiccator by silica gel in the course of 3 days, after which it was maintained for 12 hours under a 10^{-6}-Torr vacuum at a temperature of 200 °C. The thus treated disk was placed in a special plastic ring with apertures. The period of oscillation of the suspended system was determined with the ChZ-30 electronic frequency meter to within 10^{-3} sec. The raising mechanism 4 enabled us to move the system in the liquid-helium bath.

The interpretation of the obtained experimental data depends on the structure of the Vycor glass used by us, a structure which, unfortunately, is not quite clear. If the pores in this glass interlace in such a way that the liquid can move relative to the sample in a direction perpendicular to its axis, then the superfluid liquid will not participate in the oscillation of the disk. Then our experiment is similar to the well-known Andronikashvili's experiment on the determination of the density of the normal component—the variation with temperature of the moment of inertia of the oscillating disk allows us to make a judgment about the density of the liquid that is not drawn into the oscillations, i.e., about the mean density, $\langle \rho_s \rangle$, of the superfluid component in the pores.

If, on the other hand, the pores of the Vycor glass are cylinders parallel to the sample axis, then the superfluid component will be forced to participate in the oscillations. In such a situation the experimentally observed decrease of the period with decreasing temperature (see below) can be explained only by the effluence of the liquid from the pores, Indeed, we can postulate that when the disk, filled with liquid helium, is removed from the bath at a temperature lower than the phase transition point, T_0, of helium in the pores, then the superfluid part of the liquid helium creeps out of the pores under the action of the temperature gradient (the vapor is somewhat warmer than the liquid in the pores). This also leads to an effective decrease, $\Delta\rho$, in the density of the liquid. The simultaneous presence of the above-described mechanisms of motion of the superfluid component is not excluded. In all the cases, we can use for the determination of the change, $\Delta\rho$, in the density the following formula:

$$\frac{\Delta\rho}{\rho_{eff}} = K\frac{\theta^2(T_\lambda)-\theta^2(T)}{\theta^2(T_\lambda)-\theta_0^2}. \tag{1}$$

Here $\theta_0 = (19.000 \pm 0.001)$ sec; $\theta(T)$ and $\theta(T_\lambda)$ are the periods of oscillation of the system in a vacuum and in helium-II vapor at temperatures T and T_λ; and K is a correction allowing for the contribution to the moment of inertia of the solid and highly compressed helium layers lining the walls of the pores[11]:

$$K=\{\rho_1[R^2-(r_0+d_2)^2]+\rho_2[(R-d_1)^2-r_0^2]\}/\rho_3 r_0^2=1.44.$$

Here d_1 and d_2 are the thicknesses of the solid and the highly compressed liquid-helium layers in the pores; $R = r_0 + d_1 + d_2$ is the pore radius, including the thicknesses d_1 and d_2; $r_0 = 32.2$ Å is the pore radius determined from the formula for the λ-point shift in cylindrical pores:

$$r_0=1.7\cdot 10^{-11}(T_\lambda-T_0)^{-2/3} \text{ cm},$$

using the experimental value $T_0 = (2.080 \pm 0.002)$ °K (see Fig. 2). The quantity ρ_{eff} was defined as the mean density of three phases: the solid phase with $\rho_1 = 0.24$ g/cm³, the highly compressed phase with $\rho_2 = 0.18$ g/cm³, and the liquid phase with $\rho_3 = 0.1466$ g/cm³:

$$\rho_{eff} = \frac{1}{V_i}\sum_{i=1}^{3}\rho_i V_i = 0.16 \text{ g/cm}^3,$$

where the V_i are the volumes of the corresponding phases.

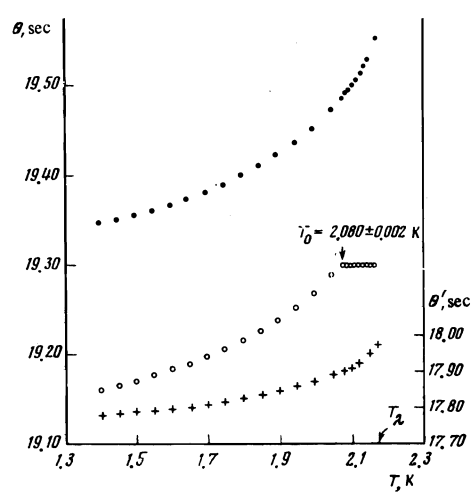

FIG. 2. Temperature dependences of the periods of oscillation of porous (θ) and continuous (θ') disks: ●) porous disk in the liquid; ○) porous disk in vapor; +) continuous disk in the liquid. $\theta_0 = (18.980 \pm 0.002)$ sec and $\theta_0' = (17.700 \pm 0.002)$ sec are the vacuum periods of oscillation of the porous and continuous disks respectively.

The results of the experiment are indicated in Fig. 3 (the open circles). The solid curve in the same figure corresponds to the assumption that $\Delta\rho = \langle\rho_s\rangle$. The curve was drawn, using Kiknadze and Mamaladze's data,[10] which are values of the ratio $\langle\rho_s\rangle/\rho_{sb}$ computed on the basis of the GPM theory. The complete qualitative and quite good quantitative agreement of our data with this curve confirms the validity of the theoretical calculation.

To ascertain the mechanism underlying the motion of the superfluid component in the pores during the oscillations of the disk in the vapor, a similar experiment was performed under conditions when the disk was immersed in the liquid. In such a situation the only cause of the temperature dependence of the moment of inertia of the liquid in the pores was the slipping of the superfluid liquid relative to the disk along closed contours oriented perpendicularly to the axis of oscillation. In Fig. 3 we present (the closed circles) the results of the experiment in the liquid. The results have been corrected for the temperature dependence of the moment of inertia of the viscous liquid-helium layer dragged along by the end and lateral faces of the oscillating porous disk, the correction being determined by the values of the periods of oscillation of a continuous disk (dimensionally identical to the porous disk) in the liquid (see Fig. 2). It can be seen that the effect of the slipping of the superfluid liquid in the pores is small ($\approx 10\%$).

Thus, we can acknowledge as justified the mechanism of effluence of the superfluid liquid from the pores during the oscillations of the disk in the vapor. However, the maximum possible effluence will be obtained in the case when the superfluid component continues to leave a pore until the remaining volume of the liquid (the film covering the cylindrical surface) assumes the critical dimension below which the superfluidity is completely suppressed. In this case

$$\Delta\rho/\rho_{eff} = 1 - r^2/R^2, \tag{2}$$

where r is the critical inside radius of the liquid film, to be calculated with the aid of the equation derived by Mamaladze in[2]. The graphical solution of the equation gives the dependence of r on temperature. The values of $\Delta\rho/\rho$ computed from the formula (2) are presented in Fig. 3 (the crosses). A comparison of these data with the experimental data and with the theoretical curve explains why $\Delta\rho < \langle\rho_s\rangle$ at $T \ll T_\lambda$. The fact that the $\Delta\rho$ measured by us exceeds the "maximum possible" value is apparently due to some nonequilibrium conditions created in the pores after the rapid effluence from them of the superfluid component as a result of the thermomechanical effect. Notice that if after such an effluence the temperature in the pores turns out to be lower than the outside temperature, then the superfluid component will not begin to flow into the pores, and other equilibrium-re-establishment mechanisms are virtually blocked by the narrowness of the pores. Let us also recall that, strictly speaking, the region $T \ll T_\lambda$ is outside the limits of applicability of the GPM theory, on which our calculations are based. Thus, we can consider that we have obtained satisfactory agreement of the experimental data with the assumption of total exclusion of the effect of the superfluid component from the oscillations of the disk after it has been moved from the liquid into the vapor. This allows us to regard our experiment as a procedure for the direct measurement of the density of the superfluid component in pores, a procedure which does not require the use of adjusting parameters.

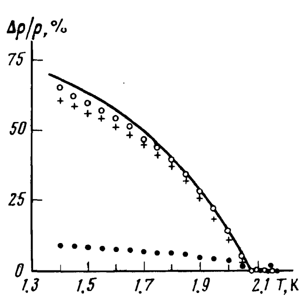

FIG. 3. Temperature dependences of $\Delta\rho/\rho$: ●) obtained in the experiment performed in the liquid; ○) results of experiment performed in the vapor; +) computed under the assumption of maximum effluence; the solid curve was computed on the basis of the GPM theory.

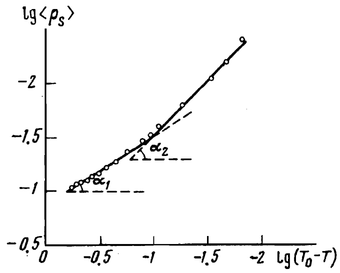

FIG. 4. Dependence of $\langle\rho_s\rangle$ on $T_0 - T$, plotted on the logarithmic scale; $\tan\alpha_1 = 2/3$, $\tan\alpha_2 = 1$.

The following temperature dependence of the bulk superfluid-component density is well known[3]:

$$\rho_{sb} \sim (T_\lambda - T)^{2/3}.$$

It makes sense to establish the dependence of $\langle\rho_s\rangle$ on the temperature difference $T_0 - T$ in the vicinity of the point T_0. The experimental data afford us such an opportunity. It can be seen from Fig. 4, which has been drawn on the logarithmic scale, that near T_0 in the temperature range $T > (T_0 - 0.15)$ °K the dependence is linear. In the range $T < (T_0 - 0.15)$ °K the $2/3$-power law, which is characteristic of bulk helium II, is observed.

Notice that the $2/3$-power law has been confirmed in a number of investigations.[3–8] However, in[4] Guyon and Rudnik obtained for narrow pores a result that is completely in agreement with our result. The linear dependence $\langle\rho_s\rangle \sim T_0 - T$ for $T \to T_0$ was used in Kiknadze and Mamaladze's theoretical paper.[9]

In conclusion, I want to express my gratitude to

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Translated by A. K. Agyei

Effect of light and an electric field on ferromagnetic resonance and photoconductivity in $CdCr_2Se_4$

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The effect of an electric field on the photo-induced changes of the ferromagnetic-resonance parameters and on the photoconductivity of $CdCr_2Se_4$ is investigated. It is shown that an increase of the photo-induced change of the ferromagnetic resonance field is observed in electric fields $E > E_{thr}$ (E_{thr} is the threshold field) and in this case the current-voltage characteristics become nonlinear. The behavior of the current-voltage characteristics of the photocurrent and the photo-induced shift of the ferromagnetic-resonance field are significantly different for samples exposed to "white" and monochromatic light. This is ascribed to the infrared photoconductivity quenching observed in $CdCr_2Se_4$. The experimental results are discussed on the basis of existing theories and concepts. It is shown that the most satisfactory interpretation of the experimental data can be obtained by assuming that the superexchange interaction integral is independent of the hole density produced by light or an electric field in the nonmagnetic sublattice.

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1. INTRODUCTION

The interaction of magnetic and electronic states in ferromagnetic semiconductors turns out to be in a number of cases quite strong and can lead to appreciable mutual changes of these states when the crystals are externally excited (by an electric field, by illumination, injection, ...).[1–3] The investigation of these changes of the magnetic and electronic states uncovers new possibilities for a more detailed study of carrier transport processes and the phenomenon of magnetic ordering.

The effects connected with the change of the magnetic state due to illumination of a sample were recently observed in the ferromagnetic semiconducting crystals $CdCr_2Se_4$.[4–6] In[4] it was shown, that the initial magnetic susceptibility of $CdCr_2Se_4$, doped with Ga decreases to approximately one-third when exposed to light. At helium temperatures, after the light is turned off, the initial susceptibility is not fully restored, and at nitrogen temperatures a slow return to the initial value is observed. In other studies[5,6] of the high-frequency magnetic permeability of $CdCr_2Se_4$ (Ga) exposed to light it was shown that the photo-induced changes of the magnetic permeability have low inertia and are observed at millisecond durations of the illumination.

In the cited studies[4–6] the photo-induced effects were investigated in the absence of an external magnetic field, when the sample was in a demagnetized state. In[7] some of us investigated the photo-induced changes in the parameters of the ferromagnetic resonance (FMR) of $CdCr_2Se_4$, crystals in the magnetic-saturation state. It was observed that illumination of the samples with "white" light leads to a change in the FMR field, and this effect, just as in the work of Veselago *et al.*,[5] has low inertia, the relative magnitude of the effect being $\delta H_r/H_r \sim 10^{-4}$ (H_r is the resonant field 2000 Oe, $\delta H_r = H_{111} - H_d$, where H_{111} is the resonant field in the presence of light and H_d is the resonant field in darkness).

We have investigated in this study the photo-induced change of the FMR field using additional excitation of electronic states of $CdCr_2Se_4$ with the aid of an electric field.

2. EFFECT OF ELECTRIC FIELD ON PHOTO-INDUCED CHANGES OF THE FERROMAGNETIC-RESONANCE PARAMETERS

The FMR was excited in the $CdCr_2Se_4$ crystals at a frequency 9000 MHz at $T = 77$ °K. The samples for the measurements were cut out of bulky single crystals in the form of disks ~ 100 μ thick with the basal plane