Investigation of the superconducting state of V_3Ga by the μ^+ method

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It is shown, with V_3Ga as an example, that it is possible to measure by the μ^+-meson method the relative volume of the superconducting and nonsuperconducting phases of a type-II superconductor as a function of the external magnetic field. The magnetic field B_{c_1} is estimated for the alloy V_3Ga.

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The μ^+-meson method was used by Murnick[1] to investigate niobium and an alloy of lead with indium in the superconducting state. In the present study, the μ^+-method is used to investigate the superconducting state of the alloy V_3Ga. A polycrystalline V_3Ga sample was used, with less than 0.01 at.% impurities, in the form of a disk 80 mm in diameter and 10 mm thick. The external magnetic field B was directed along the radius of the disk. The measurements were made at a temperature $T = 9 \pm 1$ K. The work was performed with the JINR synchrocylotron in Dubna.

It is known that in the magnetic field interval $B_{c_2} > B > B_{c_1}$ the superconducting V_3Ga is in the Shubnikov phase, which is characterized by partial penetration of the external magnetic field B into the superconductor.[2,3] The penetration of the magnetic field B into the superconductor is well recorded by the μ^+-method, since the spin of the μ^+ mesons that land in these regions of the metal precess with a Larmor frequency $\omega = eB/m_\mu c$ corresponding to the magnetic field B. In the superconducting regions of V_3Ga, the external magnetic field does not penetrate into the metal and the μ^+ mesons that land in these regions are acted on only by dipole magnetic fields due to the nuclear magnetic moments of the vanadium and gallium. The average value of the dipole magnetic moments is equal to zero, and they therefore lead only to relaxation of the μ^+-meson spin. Thus, the experimentally observed time dependence of the count $N(t)$ of the positrons of the $\mu^+ \to e^+$ decay in a transverse magnetic field B takes the form of a sum of two terms corresponding to precession and relaxation of the μ^+-meson spin:

$$N(t) = N_0 e^{-t/\tau_0} [1 - a_1 e^{-\Lambda_1^2 t^2} - a_2 e^{-\Lambda_2^2 t^2} \cos \omega t]. \qquad (1)$$

Here $\tau_0 = 2.2$ μsec is the lifetime of the μ^+ meson, a_1 and a_2 are the experimental coefficients of the asymmetry of the angular distribution of the positrons of the $\mu^+ \to e^+$ decay, corresponding to relaxation of the μ^+-meson spin in the superconducting phase and to precession of the μ^+-meson spin in the nonsuperconducting phase of the metal,

Λ_1 and Λ_2 are the relaxation rates of the μ^+-meson spin in these two phases. It is assumed in (1) that in both the superconducting and the nonsuperconducting phases of V_3Ga the time dependence of the μ^+-meson spin relaxation is Gaussian, $P_1(t) = e^{-\Lambda_1^2 t^2}$ and $P_2(t) = e^{-\Lambda_2^2 t^2}$, this being typical of nondiffusing particles.[4] It follows from (1) that the ratios a_1/a_Σ and a_2/a_Σ, where $a_\Sigma = a_1 + a_2$, determine the respective fractions of the superconducting and nonsuperconducting phases of the metal.

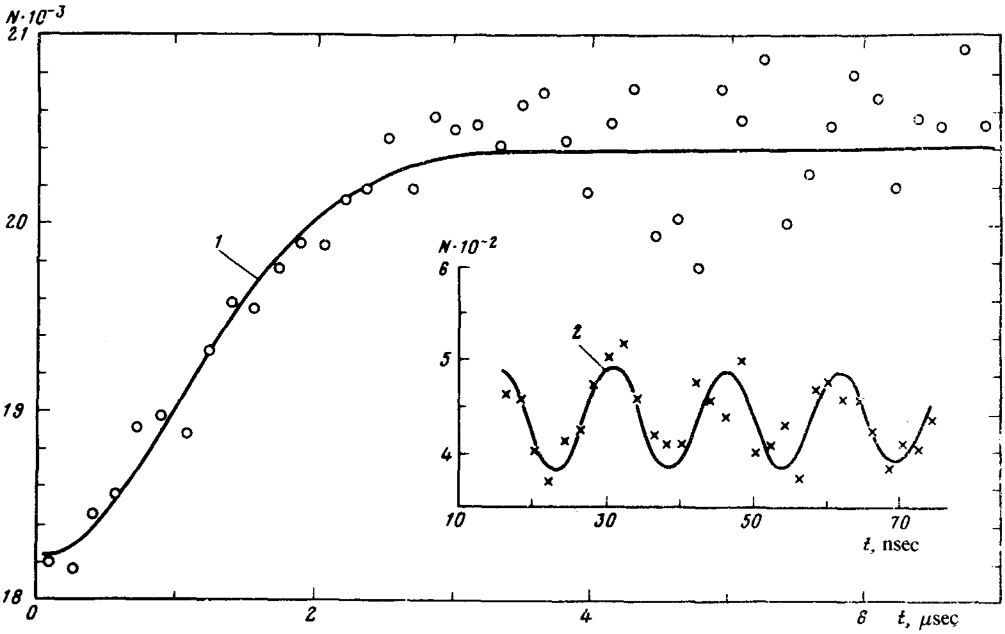

FIG. 1. Relaxation of μ^+-meson spin in the superconducting phase (curve 1) and precession of the μ^+-meson spin in the nonsuperconducting phase (curve 2) of the alloy V_3Ga in a field $B = 5200$ Oe at 9 K. The smooth curves are the calculated plots of (1) with time resolution $\delta t = 160$ nsec and $\delta t = 2$ nsec for curves 1 and 2, respectively. The $N(t)$ curves calculated from experiment were "corrected" for the exponent of the μ^+-meson decay.

Figure 1 shows the experimental $N(t)$ dependence for V_3Ga in a transverse field $B = 5200$ Oe. The $N(t)$ dependence is shown in the form of two curves corresponding to two different time resolutions. The experimental values of $N(t)$ for curve 1, plotted in the interval $t = 0$–7 μsec, corresponds to a temporal analyzer channel with $\delta t = 160$ nsec. This resolution is insufficient for the observation of fast oscillations of $N(t)$, corresponding to the precession of the μ^+-meson spin in a field $B = 5200$ Oe in the nonsuperconducting phase. Therefore the plot "1" of $N(t)$ in Fig. 1 demonstrates only the relaxation of the μ^+-meson spin in the superconducting phase of V_3Ga. The $N(t)$ oscillations due to the precession of the μ^+-meson spin in the field $B = 5200$ Oe are shown in Fig. 1 at a much higher time resolution $\delta t = 2$ nsec in the interval $t = 0$–80 nsec (curve 2).

It is seen from Fig. 1 that the μ^+-meson method makes it possible to observe simultaneously both phases of the type-II superconductor, nonsuperconducting and superconducting, and determine the metal volume occupied by them. Plots of the coefficients $a_1(B)$ and $a_2(B)$, as well as the plot of $a_\Sigma(B)$ of their sum, is shown in Fig. 2.

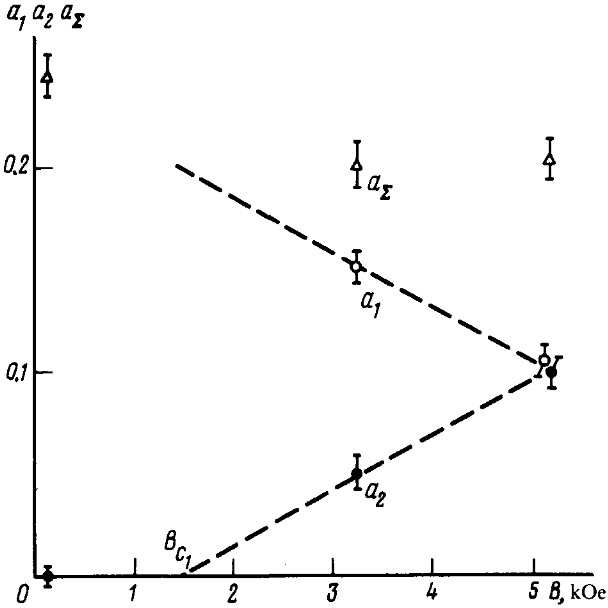

FIG. 2. Experimental plots of the coefficients a_1, a_2, and a_Σ against the external field B in V_3Ga at $T = 9$ K. The dashed lines are linear extrapolations of the experimental $a_1(B)$ and $a_2(B)$ plots.

It is seen from Fig. 2 that with increasing field B the nonsuperconducting phase proportional to the coefficient a_2 increases in volume, and the volume of the superconducting phase, which is proportional to the coefficient a_1, decreases. The combined coefficient $a_\Sigma = a_1 + a_2$ remains constant, as it should. Some decrease of a_Σ, observed at $B \gtrsim 2$ kOe, compared with the value a_Σ $(B \to 0)$, is apparently due to the onset, in the type-II superconductor, of regions with large inhomogeneity of the magnetic field, where the μ^+-meson spin relaxes rapidly. In weak fields B, there is practically no nonsuperconducting phase. The $a_2(B)$ dependence makes it possible to determine experimentally the field B_{c_1} at which the superconductor V_3Ga is laminated into two phases. The linear extrapolation of the experimental $a_2(B)$ curve shown in Fig. 2 (see the dashed straight line on Fig. 2) leads to the estimate

$$B_{c_1}\ (T = 9\ \mathrm{K}) \approx 1{,}5\ \mathrm{kOe}.$$

The theoretical dependence

$$B_{c_1}(T) = B_{c_1}(0)\left[1-\left(\frac{T}{T_c}\right)^2\right],$$

where $T_c = 14.5$ K is the critical temperature for the V_3Ga alloys, makes it possible to calculate the value of the field B_{c_1} at $T = 0$, namely $B_c(T = 0) \approx 2.5$ kOe, and consequently to calculate the parameters κ and B_c that characterize the Shubnikov phase of the superconductor[5]:

$$B_{c_2}(0) = \sqrt{2}\,\kappa B_c ,$$

$$B_{c_1}(0) = \frac{\ln \kappa + 0.08}{2\kappa} B_c \,.. \tag{2}$$

It follows from (2) that $\kappa = 8$ and $B_c = 20$ kOe. In these calculations we used the value $B_{c_2} = 208$ kOe obtained in Ref. 6.

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