Divergence of the phase relaxation time τ_φ near T_c in 3D metallic glasses

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The magnetoresistance of 3D glasses $Zr_{100-x}Ni_x$ has been studied. The temperature dependence of the relaxation time τ_φ and that of the parameter β have been determined. Both are anomalous near T_c. The relaxation time τ_φ diverges in proportion to $(T-T_c)^{-3/2}$, while β diverges in proportion to $(T-T_c)^{-1/2}$, not $(\ln T/T_c)^{-1}$, as predicted theoretically by Al'tshuler *et al.* {Zh. Eksp. Teor. Fiz. **81**, 768 (1981) [Sov. Phys. JETP **54**, 411 (1981)]}.

The important role played by "quantum corrections" to the low-temperature kinetic coefficients in highly disordered conductors has recently been established. A dependence of the quantum corrections on a magnetic field leads to, for example, an anomalous magnetoresistance at classically weak magnetic fields.[1] A study of this magnetoresistance makes it possible to find the magnitude and temperature dependence of the phase relaxation time of the electron wave function and of the parameter β, which arises when the Maki-Thompson fluctuational correction is taken into account.[2]

Studies of 2D objects reveal a good agreement with the theory of Ref. 1, and τ_φ is usually observed to obey $\tau_\varphi \sim T^{-p}$, where p depends on the particular relaxation mechanism (see, for example, the review by Bergmann[3]).

The research on 3D objects of the metallic-glass type has received far less attention, but the results available[4,5] show that the theory of Ref. 1 is applicable to them, and the behavior $\tau_\varphi \sim T^{-2}$ is found far from T_c. The studies of the magnetoresistance which have been carried out, especially in 3D systems, have been carried out far from T_c, so that the behavior of τ and β near T_c has not been studied.

In the present letter we report a study of the magnetoresistance of 3D amorphous superconducting alloys $Zr_{100-x}Ni_x$ ($x = 17$, 18.5, 20, and 25 at.%) prepared by quenching from the liquid state on a rotating disk in an argon atmosphere. The samples have a resistivity $\rho_{4.2\,K}$ ranging from 300 to 190 $\mu\Omega$·cm, and they have T_c values ranging from 3.54 K to 2.65 K, depending on the composition. Figure 1 shows the magnetoconductance $\Delta R^{-1} = R^{-1}(H) - R^{-1}(0)$ versus the magnetic field for various temperatures for the alloy $Zr_{75}Ni_{25}$. All the results found for the alloys of other compositions are qualitatively the same, and we will not reproduce them in this brief paper.

According to Ref. 1, in the 3D case, for a system with a strong spin-orbit interaction, the magnetoconductance can be written

$$\Delta R^{-1} = -\frac{e^2}{2\pi^2\hbar}\left(\frac{eH}{\hbar c}\right)^{1/2}\left\{\left(\beta+\frac{1}{2}\right) f_3\left(\frac{H}{H_\varphi}\right) - \frac{3}{2} f_3\left(\frac{H}{H_{s0}}\right)\right.$$

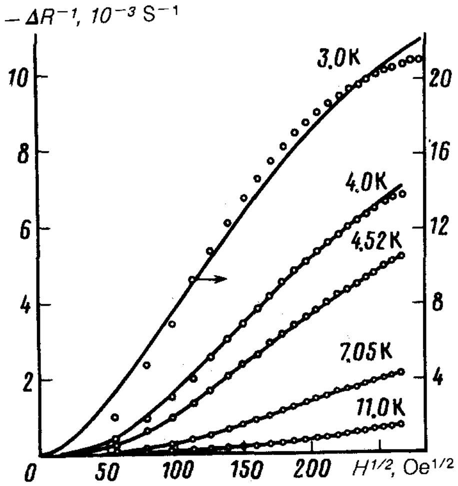

FIG. 1. Magnetoconductance of an amorphous $Zr_{75}Ni_{25}$ alloy at various temperatures. The solid lines are calculations from (1) with the maximum values of β and H_φ.

$$+\frac{1}{2\pi}g(T)\varphi_3\left(\frac{H}{H_T}\right)\Bigg\}\frac{s}{l}. \qquad (1)$$

where

$$H_\varphi=\hbar c/4De\tau_\varphi,\; H_{s0}=\hbar c/4De\tau_\varphi^*,\; H_T=k\pi cT/2De,\; \tau_\varphi^{-1}=\tau_\epsilon^{-1}+2\tau_s^{-1},$$

$$\tau_\varphi^{*-1}=\tau_\epsilon^{-1}+\frac{2}{3}\tau_s^{-1}+\frac{4}{3}\tau_{s0}^{-1};$$

s and l are the cross-sectional area and length of the sample, respectively; f_3 and φ_3 are functions given in Ref. 1; β is a function which is tabulated in Ref. 2; and $g(T)=-(\ln T/T_c)^{-1}$.

We determined the values of D and τ_{so} from an analysis of the temperature dependence of the upper critical field; for all the alloys studied we found $\tau_{so}\lesssim 10^{-13}$ s and $D\approx 0.3$ cm^2/s. In the field range $H<80$ kOe which we studied, the term $(3/2)f_3(H/H_{so})$ can thus be ignored. We also ignore the dependence of β and g on H, since we have $H<ckT/eD$ over the interval studied. Furthermore, we are ignoring the component of the magnetoconductance which arises from the field suppression of the Aslamazov-Larkin correction; this component is small under the condition $k(T-T_c)\gg\hbar\tau_\varphi^{-1}$.

The experimental dependence $\Delta R^{-1}(H)$ is thus approximated by expression (1), which contains only terms $\varphi_3(H/H_T)$ and $f_3(H/H_\varphi)$. In numerical calculations, H_φ is varied to find the best least-squares fit of the experimental data; the value of β is found automatically as a result. The calculated results on $\Delta R^{-1}(H)$ are shown by the solid lines in Fig. 1.

Figure 2 shows the temperature dependence of τ_φ^{-1}. At high temperatures we find $\tau_\varphi^{-1}\sim T^2$, and the numerical value of this time is of the same order of magnitude as that which is usually found in metallic glasses.[4,5] As T is lowered, τ_φ^{-1} begins to

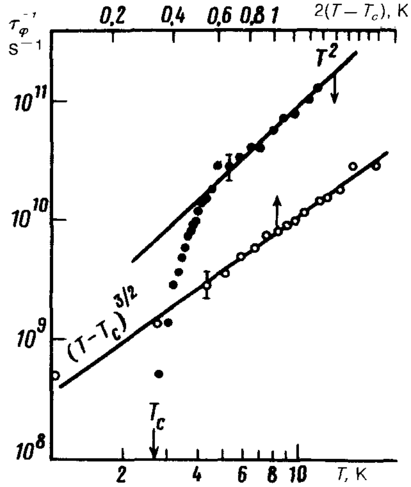

FIG. 2. Temperature dependence of τ_φ^{-1}.

decrease rapidly, and a detailed analysis shows that we have $\tau_\varphi^{-1} \sim (T - T_c)^{3/2}$. In other words, the energy relaxation slows as we approach T_c. An increase in τ_φ in the normal state near T_c is conceivable in view of the corresponding increase in the quasi-particle lifetime, $\tau_r \sim (T_c - T)^{-1}$, in the superconducting state as T_c is approached from below (Ref. 6, for example). There are some indications of a possible increase in τ_ϵ in the normal state in the presence of superconducting fluctuations in Ref. 7, where a study was made of the influence of fluctuations on the electron thermal conductivity.

The result found by us is directly opposite the result of Ref. 8, where a divergence of τ_φ^{-1}, not of τ_φ, was observed near T_c in $2D$ objects. The reasons for this divergence apparently lie in the different effects of fluctuations on τ_φ in $2D$ and $3D$ systems.

Figure 3 shows the temperature dependence of β. At high temperatures, there is a good agreement with Larkin's theory,[2] but as $T \to T_c$ the value of β is found to be considerably lower than the theoretical values, and it is furthermore proportional to $(T - T_c)^{-1/2}$, rather than $(\ln T/T_c)^{-1}$, as in the theory of Ref. 2.

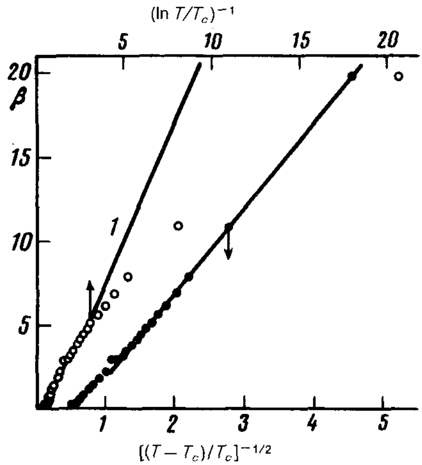

FIG. 3. Temperature dependence of β. Curve 1 is the theoretical prediction of $\beta(T)$ from Ref. 2.

We would like to point out that an expression more general than (1) will be required for analyzing the magnetoconductance near T_c. There are some generalizations of the theory of Ref. 2, incorporating a dependence of β on τ_φ for the $2D$ systems in Ref. 9, but not for $3D$ systems.

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