Weak-localization effects and electron-electron interactions in the resistivity of metallic glasses based on Zr at temperatures above the superconductivity transition

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We have studied the temperature dependence of the resistivity for the superconducting metallic glasses Zr_xBe_{1-x} ($x = 0.6, 0.7$) and for $Zr_{75}Rh_{25}$ in the temperature interval $T - T_k \gtrsim T_k$ (T_k is the superconducting transition temperature) for $H = 0$ and for a longitudinal magnetic field $H = 7.4$ T. The observed anomalous behavior of the resistivity of metallic glasses is adequately described by the theory of weak localization of electrons and electron-electron interaction (EEI) in three-dimensional disordered systems. At $H = 0$, EEI in the Cooper channel play a fundamental role in determining the temperature dependence of the resistivity; in the presence of a magnetic field, EEI in the diffusion channel play the same role.

INTRODUCTION

Experimental investigations of magnetoresistance based on contemporary theoretical ideas make it possible to find the parameters for inelastic, spin-orbit and other scattering processes involving conduction electrons; these parameters in turn determine the kinetic properties in ordered systems. In particular, such investigations can answer fundamental questions regarding the nature of inelastic electron scattering. At present there is a great deal of experimental material devoted to investigating the influence of quantum effects on the magnetokinetic properties of two-dimensional disordered systems. In recent years analogous investigations have been pursued in many places for three-dimensional systems, among them the metal-metal type of metallic glasses.[1–3]

It has been established both theoretically and experimentally that there are a number of contributions to the magnetoresistivity of these systems, connected with weak localization effects (WLE) of the electrons,[4] electron-electron interactions (EEI)[4,5] and spin splitting.[6]

It should be noted that, methodologically speaking, it is extremely difficult to separate these contributions in the course of determining the physical parameters for a specific electron scattering mechanism. However, this procedure is considerably simplified if certain interaction mechanisms can be suppressed, e.g., by choosing the appropriate objects of investigation and conditions for carrying out the measurements (e.g., choice of temperature and magnetic field interval). Such a choice ensures a correct comparison between theoretical predictions and experimental results.

It is particularly interesting to analyze the anomalous temperature dependence of the resistivity of metal-metal type metallic glasses[3] at low temperatures in the absence of a magnetic field and in the region of classically small magnetic fields ($\omega_{c\tau} \ll 1$, where ω_c is the cyclotron frequency and τ is the momentum relaxation time), basing the analysis on investigations of the anomalous magnetoresistivity and values obtained for τ_φ (the relaxation time for the phase of the electron wave function) and τ_{so} (the relaxation time for spin due to spin-orbit interactions in elastic electron scattering); these dependences have long resisted explanation either by the Kondo effect or by electron scattering from unstable ion configurations (tunnelling transitions).[7]

With this goal in mind, we have investigated the temperature dependence of the resistivity in the superconducting amorphous alloys Zr_xBe_{1-x} ($x = 0.6$, 0.7) and $Zr_{75}Rh_{25}$ in this paper, both in the absence of a magnetic field and in a magnetic field $H = 7.4$ T, over the temperature range from 4.2 K to 12 K.

FUNDAMENTAL RELATIONS OF WLE AND EEI THEORY

The conductivity of disordered metallic systems in the absence of a magnetic field and in a magnetic field is determined by WLE and EEI effects over a temperature region which significantly exceeds T_k ($T - T_k \gtrsim T_k$); in what follows we will investigate interelectron interactions in the Cooper channel and diffusive channel separately.[8]

The total correction to the static conductivity $\delta\sigma(0,T)$ of a three-dimensional disordered metallic system when the condition $T - T_k \gg \hbar/k_B\tau_\varphi(T)$ holds (k_B is Boltzmann's constant) for the case $H = 0$ can be represented in the form[9]

$$\delta\sigma(T) = \delta\sigma^L(T) + \delta\sigma^{EEI}(T), \qquad (1)$$

where

$$\delta\sigma^{EEI}(T) = \delta\sigma^C(T) + \delta\sigma^D(T) + \delta\sigma^{MT}(T).$$

Here $\delta\sigma^D$, $\delta\sigma^C$, $\delta\sigma^L$ are respectively the diffusive, Cooper, and localization corrections to the conductivity, while $\delta\sigma^{MT}$ is the Maki-Thompson correction. The first quantum correction is connected with interelectron interactions in the diffusion channel (interactions of electrons with small energy and momentum differences), the second with interactions in the Cooper channel (interactions of electrons with neighboring energies and small total momenta), and the third with localization of noninteracting electrons. The temperature dependences of these corrections in the absence of a magnetic field are determined by the following relations:

$$\delta\sigma^D(T) = 0.915 G_0 (T/\hbar D)^{1/2}\alpha,$$
$$\delta\sigma^C(T) = -0.915 G_0 (T/\hbar D)^{1/2}/\ln(T_k/T),$$
$$\delta\sigma^L(T) = \text{const} + G_0/[D\tau_\varphi(T)]^{1/2}, \qquad (2)$$

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where

$$\alpha = {}^2/_3 - 4[(1+0.5F)^{3/2} - 1 - 0.75F]/F, \quad G_0 = e^2/2\pi^2\hbar,$$

D is the diffusion coefficient of electrons,

$$F = (\varkappa^2/2k_F^2)\ln(1+4k_F^2/\varkappa^2)$$

is the interaction constant of electrons for small momentum differences, and $\varkappa^2 = 4\pi e^2\nu$ is the squared inverse screening length; ν is the electron density of states.

When investigating electron interactions in the Cooper channel, we must also separate out the Maki-Thompson correction. This contribution to the conductivity is due to quantum interference from scattering of two electrons by one and the same impurity, thereby forming a fluctuation pair. In the three-dimensional case the correction $\delta\sigma^{\mathrm{MT}}$ can be calculated only to the lowest order in $1/\ln(T_k/T)$; it is found to be of order $(T_\tau)^{1/2}/\ln^2(T_k/T)$ and is small compared to the Cooper contribution.[9]

Thus, the total correction to the static conductivity, including both localization and the effect of interactions (besides the contribution $\delta\sigma^{\mathrm{MT}}$), has the following form in the three-dimensional case:

$$\delta\sigma(0,\ T) = G_0\{(T/\hbar D)^{1/2}[\alpha - 1/\ln(T_k/T)]0.915 + [D\tau_\varphi(T)]^{-1/2}\}. \tag{3}$$

In the presence of a magnetic field, the corresponding quantum corrections to the conductivity have the following temperature dependences[9]:

$$\delta\sigma^D(H,\ T) = 0.915G_0\alpha(T/\hbar D)^{1/2} + B(H)T^{-3/2},$$

$$\delta\sigma^C(H, T) = -\frac{G_0}{2}\left(\frac{T}{\hbar D}\right)^{1/2}\left(\ln\frac{T_k}{T}\right)^{-1} \times\left[1.83 + 0.79\left(\frac{\Omega_H^2}{12\pi^2} + \frac{\omega_s^2}{\pi^2}\right)T^{-2}\right],$$

$$\delta\sigma^L(H,\ T) = G_0(eH/\hbar c)^{1/2}[{}^3/_2 f(\Omega_H\tau_\varphi^*(T)) - {}^1/_2 f(\Omega_H\tau_\varphi(T))], \tag{4}$$

where

$$B(H) = -\frac{0.0216e^2}{\hbar}\frac{(g\mu_B)^2\alpha_1}{(\hbar D)^{1/2}k_B^{3/2}}H^2,$$

$$\alpha_1 = F^{-1}[(1+F/2)^{-1/2} - 1 + F/4], \quad (\tau_\varphi^*)^{-1} = \tau_\varphi^{-1} + 2\tau_{so}^{-1}.$$

Here $\Omega_H = 4DeH/\hbar e$ is the cyclotron frequency, $\omega_s = g\mu_B H$ is the magnitude of the Zeeman splitting, g is the Landé factor for conduction electrons, and $\mu_B H$ is the Bohr magneton. The analytic form of the function is given in Ref. 4, and its asymptotic expansion, have the form

$$f(x) = \begin{cases} 0.605, & x \gg 1 \\ x^{3/2}/48, & x \ll 1 \end{cases}.$$

Thus, we can represent the temperature dependence of the conductivity for fixed values of magnetic, including the suppression of the Cooper contribution, in the form

$$\delta\sigma(H,\ T) = AT^{1/2} + B(H)T^{-3/2} + \delta\sigma^L(H,\ T), \tag{5}$$

where

$$A = \frac{e^2}{2\pi^2\hbar}\frac{0.915\alpha}{(\hbar D)^{1/2}}.$$

Equation (5) is written for the conditions realized in our experiments, i.e., $\tau_s^{-1} \to 0$ (Ref. 3), $\Omega_H/2\pi T \ll 1$, $\omega_s/\pi T \ll 1$, $t_s^{-1} \ll \omega_s$, T, where τ_s is the time for spin-flip inelastic scattering by paramagnetic ions, and $t_s^{-1} = \frac{4}{3}(\tau_s^{-1} + \tau_{so}^{-1})$ is the total spin relaxation time. It is especially noteworthy that for the three-dimensional case, in the presence of a magnetic field whose scale satisfies the conditions $k_B T > \hbar\Omega_H > \hbar\omega_s$, the temperature behavior of the conductivity within the framework of WLE and EEI theories is basically determined by interelectorn interactions in the diffusive channel, which are reflected in Eq. (5).

For the systems under investigation here, the quantities D, $k_F l$ (l is the mean free path of electrons) and τ_{so}, along with the temperature-dependence of $\tau_\varphi(T)$, were given in Ref. 3. In Eqs. (3) and (5), the contribution associated with Aslamazov-Larkin processes is not included because, as was shown in Ref. 8, for $T - T_k \gg \hbar/k_B\tau_\varphi(T)$ this contribution is found to be small compared to the Cooper correction. We note that this inequality is satisfied for the systems under study here.

EXPERIMENT

The alloys Zr_xBe_{1-x} ($x = 0.6, 0.7$) and $Zr_{75}Rh_{25}$ were prepared from electrolytically pure zirconium (99.99%) and pure beryllium (99.88%) and rhodium (99.95%). The samples were melted in an induction furnace in the suspended state with a small overpressure of helium and through a dispensing setup were quenched from the liquid state on the external surface of a copper disk turning at a quenching speed of 10^6 degrees/sec.

The amorphous samples consisted of strips of width 1–2 mm and thickness 0.03 mm. We studied the sample structure using x-ray and electron diffraction techniques.[10–12] The diffraction pictures of samples quenched out of the liquid state are typical of amorphous systems, and show that long-range order is absent. More detailed information on these samples is provided in Ref. 3.

The resistance was measured at constant current I by the four-contact method on samples of length 40 mm without a field and in a longitudinal ($I \| H$) magnetic field to an accuracy now worse than 10^{-5}. The superconducting transition temperatures T_k measured resistively, and the specific sample resistivities $\rho(4.2\ \mathrm{K})$ of the $Zr_{75}Rh_{25}$, $Zr_{60}Be_{40}$, and $Zr_{70}Be_{30}$ samples, were 2.7, 3.5, 4.23 K and 307, 300, and 230 $\mu\Omega$-cm, respectively.

EXPERIMENTAL RESULTS AND DISCUSSION

In Fig. 1 we show the temperature dependences of the normalized electrical resistivity without a field and in a magnetic field $H = 7.4$ T in the interval, 4.2 to 12 K for samples of Zr_xBe_{1-x} ($x = 0.6, 0.7$) and $Zr_{75}Rh_{25}$. As is clear from Fig. 1, in the absence of a magnetic field the resistivity of the systems under investigation falls as the temperature decreases, while it increases in a field; as T_k increases and the quantity $\rho(4.2\ \mathrm{K})$ decreases, the temperature dependences of the samples under study become stronger at $H = 0$, while those measured in a magnetic field weaken.

For the superconducting metallic glasses with high val-

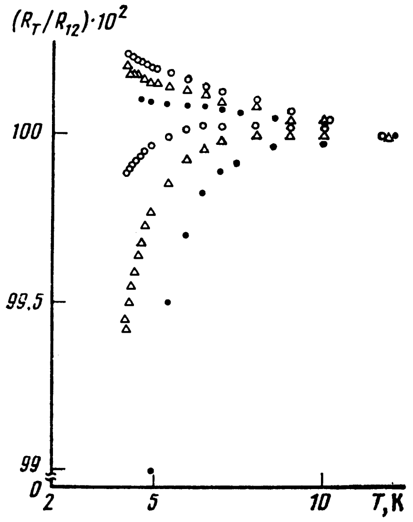

FIG. 1. Temperature dependence of the resistivity of the metallic glasses $Zr_{60}Be_{40}$ (O), $Zr_{70}Be_{30}$ (Δ) and $Zr_{75}Bh_{25}$ (●) without a field (the three lower curves) and in a longitudinal field $H = 7.4$ T (three upper curves), $R_{12} = R(12\text{ K})$.

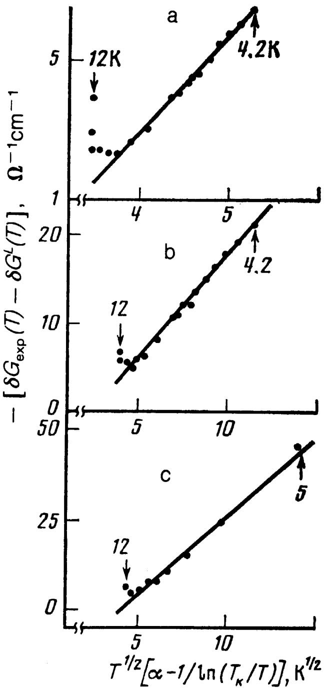

FIG. 2. Temperature dependence of the conductivity of the metallic glasses in coordinates based on expression (3): a—$Zr_{60}Be_{40}$, b—$Zr_{70}Be_{30}$, c—$Zr_{75}Rh_{25}$.

ues of specific electrical resistivity ($\rho \approx 200$–$300\,\mu\Omega$-cm) the main feature in the temperature behavior of $\rho(T)$ in the absence of a magnetic field is a noticeable decrease in the value of ρ with decreasing temperature for temperatures much larger than T_k ($\ln(T/T_k) < 1$). This circumstance can in no way be explained by the Aslamazov-Larkin fluctuation mechanism, which is present when $(T - T_k)/T_k \ll 1$.

Still more surprising is the behavior of $\rho(T)$ which occurs when a magnetic field is applied, in the presence of which a nonlinear growth in the electrical resistivity is observed with decreasing temperature. Neither of these effects has been explained satisfactorily in the past.

Within the framework of WLE and EEI theories it is possible to give as satisfactory explanation of the observed temperature behavior of the electrical resistivity in a field and in the absence of one. With this goal in mind, in Fig. 2 we show the temperature dependence of the conductivity $-[\delta\sigma_{exp}(T) - \delta\sigma^L(T)]$ of the systems under study in coordinates appropriate to relation (3). Here $\delta\sigma_{exp}(T) \approx [\rho(T) - \rho(12K)]/\rho^2(12K)$. The value of the parameters F and α for the systems under study are presented in the Table. From Fig. 2 it is clear that in the temperature range in question the experimental data are linear functions in the coordinates shown; for the samples with smaller T_k the deviation from linearity begins at lower temperatures. Analysis of the experimental data shows that for all the systems under study the temperature range over which the linear law holds satisfies the general condition $4.2\text{ K} \lesssim T \lesssim 2.5\ T_k$, and the experimental value of the slope coefficient K_{exp} ($H = 0$) is comparable in order of magnitude to the theoretical value K_{theor} ($H = 0$) (see the Table). In order to calculate the quantity K_{theor} ($H = 0$), we used the experiment values of k_F and ν. The observed disagreement between the theoretical and experimental values of the slope coefficient in the absence of a magnetic field is most likely related to the fact that it is not possible to take into account properly the temperature dependence of the Maki-Thompson correction in the temperature range of interest. This assertion is confirmed by the improvement in quantitative agreement between the theoretical and experimental values of K ($H = 0$) in the case of $Zr_{75}Rh_{25}$, for which it has been established[13] that the Maki-Thompson contribution is suppressed by the effect of disruption of the superconducting pairs.

In investigating the temperature dependence of the total conductivity in a magnetic field, we should note that in the magnetic field being used the contribution to the conductivity corresponding to Cooper channel interactions is sup-

TABLE I. Experimental and calculated parameters of amorphous systems based on Zr.

System	A, $\Omega^{-1}\cdot$cm$^{-1}\cdot$K$^{-1/2}$	B, $\Omega^{-1}\cdot$cm$^{-1}\cdot$K$^{3/2}$	F	α	$H=0$: $K_{exp}\pm 0.1$	$H=0$: K_{theor}	$H=7.4$ T: $K_{exp}\pm 0.02$	$H=7.4$ T: K_{theor}
$Zr_{75}Rh_{25}$	2.11	18.60	0.95	0.33	4.4	6.3	1.3	1.0
$Zr_{70}Be_{30}$	1.99	17.82	0.96	0.33	2.5	6.0	1.0	1.0
$Zr_{60}Be_{40}$	1.82	16.32	0.96	0.33	2.9	5.5	1.4	1.0

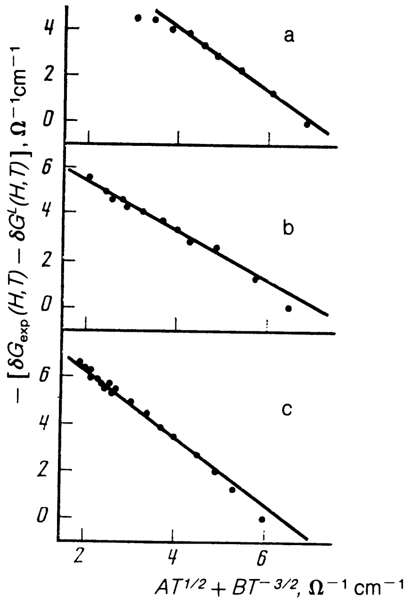

FIG. 3. Temperature dependence of the conductivity in a magnetic field of 7.4 T for the metallic glasses in coordinates based on expression (5): a—$Zr_{60}Be_{40}$, b—$Zr_{70}Be_{30}$, c—$Zr_{75}Rh_{25}$.

pressed, and the function $\delta\sigma_{\text{exp}}(H,T)$ we observe must be determined by the interelectron interaction in the diffusion channel. In this case, according to the relation (5), the experimental temperature dependences of the conductivity in a magnetic field which are correlated with the effects of weak electron localization must be linear in the coordinates $\delta\sigma_{\text{exp}}(H,T) - \delta\sigma^L(H,T)$ versus $AT^{1/2} + BT^{-3/2}$. The parameters A and B for the systems we studied are presented in the Table.

The experimental dependences of $\delta\sigma_{\text{exp}}(H,T)$ for the systems under discussion in the coordinates described above are shown in Fig. 3, from which it is clear that in the temperature interval under study a linear dependence actually is observed with satisfactory agreement between the theoretical values $K_{\text{theor}}(H)$ and the experimental values $K_{\text{exp}}(H)$ of the slope coefficient (see Table). The observed deviation from linearity in the region of small values of the argument for the $Zr_{75}Rh_{25}$ system (Fig. 3) can be related to the violation of the condition $T - T_k \gg \hbar/k_B\tau_\phi(T)$, which leads to a relative growth of the contribution due to Aslamazov-Larkin processes. The scale of the latter was investigated experimentally in Ref. 14.

Therefore, analysis of the experiment data shows that the observed temperature dependence of the resistivity of superconducting metallic glasses is due to the joint appearance of localization and interelectron effects, and is satisfactorily described by the present theories. As for the processes which give rise to this temperature dependence, a fundamental role is played by EEI in the Cooper channel for $H = 0$; in the presence of a magnetic field ($H = 7.4$ T), these processes are dominated by EEI in the diffusive channel.

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