Evidence for a magnetic contribution to the electrical resistivity in amorphous $Fe_{80}B_{20-x}C_x$ alloys

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The electrical resistivity ρ as a function of temperature has been measured for amorphous $Fe_{80}B_{20-x}C_x$ $(0 \leq x \leq 10)$ alloys in the temperature range 4.2–300 K. A detailed quantitative analysis of the resistivity data for the first time establishes that besides a dominant structural contribution ρ_{str}, there exists a significant magnetic contribution ρ_{mag} to ρ in such glasses. The values of ρ_{mag} for the investigated glassy alloys reveal that the quenched disorder does not exert any noticeable influence on the *coherent* scattering of electrons from long-wavelength magnons and that the net contribution to ρ due to the *elastic* and *incoherent* components of electron-magnon scattering is negligibly small. Furthermore, the present data analysis permits a straightforward calculation of the Debye temperature Θ_D, the structure factor $S_0(2k_F)$, and $2k_F$ from ρ_{str}; and the values of these quantities so determined, in turn, bring to the limelight various limitations of the extended Ziman theory so far as its application to glasses containing a strong scattering transition metal (e.g., Fe in the present case) is concerned.

I. INTRODUCTION

Immense scientific activity[1–4] in the field of electron transport in amorphous metallic alloys witnessed during the past decade has been basically triggered by fundamental questions such as (i) how does quenched disorder influence the electronic structure and (ii) are the band structure and the glass-forming ability of amorphous alloys related in some simple way? Of all transport coefficients, the electrical resistivity ρ has received the most attention. Despite such intense efforts, the origin of the resistivity minimum phenomenon[2] and the T^2 dependence of ρ at low temperatures, especially for ferromagnetic glasses, remain disputed. Since the latter controversial aspect of $\rho(T)$ is the main concern of this paper, it deserves a more elaborate description.

The temperature dependence of resistivity, $\rho(T)$, characteristic of a wide variety of glassy metallic alloys (including both nonmagnetic and magnetic glasses) can be summarized as follows. $\rho(T)$ goes through a Kondo-like minimum (not observed in some nonmagnetic glasses) at low temperatures (generally below ~ 20 K), varies as T^2 in the intermediate-temperature region (normally $40 \lesssim T \lesssim 100$ K) and exhibits a linear temperature dependence at high temperatures (above ~ 150 K). It has been a common practice[5–7] to completely disregard the magnetic state of the glassy alloy under consideration and to explain the intermediate- and high-temperature resistivity data in terms of the diffraction model,[8] which takes into account not only the scattering of the conduction electrons by the ion cores that carry a muffin-tin potential but also the change in the shape of the structure factor, $S(k)$, as T is varied. The reasons for this appear to be twofold. First, in the intermediate- and high-temperature regions ρ exhibits the same temperature dependence in both magnetic and nonmagnetic glasses. Second, the diffraction model yields both the quadratic and the linear temperature dependence of ρ at low ($T \ll \Theta_D$, Debye temperature) and high ($T \gtrsim \Theta_D$) temperatures, respectively. However, overwhelming experimental evidence exists to demonstrate that the diffraction model does not form an adequate description of the T^2 term in $\rho(T)$ for the amorphous ferromagnetic alloys, in particular. For instance, the existence of well-defined long-wavelength spin-wave excitations which follow a normal ferromagnetic dispersion relation, $\hbar\omega_k = Dk^2$, has now been well established in ferromagnetic glasses by inelastic neutron scattering, magnetization, and Mössbauer measurements,[9] and a sharp anomaly in the temperature derivative of resistivity at the Curie temperature reminiscent of the critical resistivity behavior normally found in crystalline ferromagnets has been observed[10] in such glasses. These observations assert that in addition to a contribution due to the scattering of conduction electrons from the structural disorder, electron-magnon scattering (which at low temperatures gives rise to a quadratic temperature dependence for crystalline ferromagnetic $3d$ transition metals) gives a significant contribution to ρ in magnetic glasses and hence the customary approach of completely neglecting the magnetic contribution, $\rho_{mag}(T)$, while analyzing the resistivity data on ferromagnetic glasses is not correct. Theoretical investigations[11,12] that pursue this line of thinking and use spin-wave approximation to calculate $\rho_{mag}(T)$ for amorphous ferromagnets reveal that (i) $\rho_{mag}(T)$ comprises two *positive* contributions; one varying as T^2, as in crystalline ferromagnets, and the other as $T^{3/2}$, and (ii) the contribution to $\rho_{mag}(T)$ from the $T^{3/2}$ term (which appears only in the amorphous case) is at least 2 orders of magnitude greater than the one arising from the T^2 term. These theories, therefore, predict a $T^{3/2}$ power law for $\rho(T)$ at low temperatures in amorphous ferromagnets as contrasted with the T^2 dependence found in these materials. This

discrepancy between theory and experiment has been taken as evidence for[11] or against[12] a magnetic origin of the observed T^2 term. Despite the fact that a clear distinction between the T^2 and $T^{3/2}$ power laws in a narrow temperature range (typically from 40 to 100 K) poses an extremely difficult problem in practice, experimental evidence for the fractional exponent (1.5), and hence for a contribution of electron-magnon scattering to ρ, has recently been claimed for some amorphous Fe- and Fe-Ni-based ferromagnetic ribbons[13–16] and sputtered films.[17] But, as pointed out by Mogro-Campero *et al.*,[16] a power-law fit with exponent 1.5 found in some temperature region ($T_{\min} \leq T \leq T_{\max}$) cannot be considered as sufficient evidence for a magnetic contribution to ρ because the temperature interval $T_{\min} \leq T \leq T_{\max}$ may well be the transition region separating the temperature regimes, where the asymptotic T^2 ($T \lesssim T_{\min}$) and T ($T \gtrsim T_{\max}$) behaviors are observed, and this transition region could be well described by a $T^{3/2}$ power law. So the possibility of explaining the experimental findings in terms of electron-ion potential scattering alone cannot be completely ruled out.

With a view to resolve the above-mentioned controversy surrounding the origin of the T^2 power law of $\rho(T)$ in the intermediate-temperature range for ferromagnetic glasses, we undertook detailed electrical resistivity studies on amorphous $Fe_{80}B_{20-x}C_x$ alloy series. The choice of this alloy system was motivated by the simple logic that one expects to detect the magnetic contribution to ρ with greater ease in alloys with a high transition-metal content than in those with a low transition-metal content. Exhaustive data analysis of the experimental results not only enables us to establish for the first time beyond doubt the existence of a magnetic contribution, ρ_{mag}, to ρ but also to make a reliable estimate of ρ_{mag} in these alloys.

II. THEORETICAL BACKGROUND

Experimental findings that the electron transport properties of amorphous metals are usually similar[18] to those of the corresponding liquid metals have led various workers to use a theoretical formalism, originally proposed for simple liquid metals by Ziman[19] and subsequently extended by Evans *et al.*[20] to include liquid transition metals, to explain a number of pecularities observed in the transport properties of metallic glasses. This theory takes into account the scattering of conduction electrons from the potential of the disordered lattice of a transition-metal system and gives the following expression[20] for resistivity:

$$\rho \approx \frac{30\pi^3\hbar^3}{me^2k_F^2E_F\Omega}\sin^2[\eta_2(E_F)]S_T(2k_F) , \tag{1}$$

where k_F and E_F are the Fermi wave vector and energy, respectively, Ω is the atomic volume, $\eta_2(E_F)$ is the d-partial-wave phase shift describing the scattering of the conduction electrons by the ion cores which carry a muffin-tin potential centered on each ion position, $S_T(2k_F)$ is the temperature-dependent structure factor, and $\hbar$, m, and e have their usual meaning. In this expression, $S_T(2k_F)$ determines the temperature dependence of ρ. Several calculations[8,21,22] of $S_T(k)$ within the framework of a model, now known as the diffraction model, are available but the one[8] used in this work yields

$$S_T(k) \cong 1+[S_E(k)-1]e^{-2W_k(T)} , \tag{2}$$

where $S_E(k)$ is the equilibrium structure factor and $e^{-2W_k(T)}$ is the Debye-Waller factor with $W_k(T)$, in the Debye approximation, given by[23]

$$W_k(T) = W_k(0)+4W_k(0)\left[\frac{T}{\Theta_D}\right]^2\int_0^{\Theta_D/T}\frac{zdz}{e^z-1} , \tag{3a}$$

where

$$W_k(0) = 3\hbar^2k^2/8Mk_B\Theta_D , \tag{3b}$$

M is the atomic mass, k is the wave vector, and k_B is the Boltzmann constant. With the aid of Eqs. (1) and (2), the resistivity as a function of temperature can be expressed as[8]

$$\rho_{\text{str}}(T) = \frac{30\pi^3\hbar^3}{me^2k_F^2E_F\Omega}\sin^2[\eta_2(E_F)] \times\{1+[S_0(2k_F)-1]e^{-2[W_{2k_F}(T)-W_{2k_F}(0)]}\} . \tag{4}$$

Note that ρ_{str} is the structural contribution to the total resistivity ρ and the parameters $W_{2k_F}(T)$ and $W_{2k_F}(0)$ appearing in Eq. (4) denote the values of $W_k(T)$ and $W_k(0)$ at $k=2k_F$, i.e.,

$$W(0) = W_{2k_F}(0) = \frac{3\hbar^2k_F^2}{2Mk_B\Theta_D} , \tag{5}$$

replaces $W_k(0)$ in Eqs. (3a) and (3b). Dropping henceforth the subscript $2k_F$ in $W_{2k_F}(T)$ and $W_{2k_F}(0)$ and str in ρ_{str} for the sake of simplicity, the temperature coefficient of the resistivity (TCR) can be calculated from Eq. (4) with the result

$$\alpha = \frac{1}{\rho}\frac{\partial\rho}{\partial T} = 2\left[\frac{1-S_T(2k_F)}{S_T(2k_F)}\right]\frac{\partial W(T)}{\partial T} = 8\left[\frac{1-S_T(2k_F)}{S_T(2k_F)}\right]\frac{W(0)}{T} \times\left[2\left[\frac{T}{\Theta_D}\right]^2\int_0^{\Theta_D/T}\frac{z}{e^z-1}dz-\frac{1}{e^{\Theta_D/T}-1}\right] , \tag{6}$$

where use has been made of Eq. (3a) to calculate $\partial W(T)/\partial T$. Equation (6) demonstrates that $\partial W(T)/\partial T > 0$ at all temperatures and as such α is *negative* if $S_T(2k_F) > 1$ and *positive* if $S_T(2k_F) < 1$. Alternatively, a *negative* α is expected only when $2k_F$ lies in the vicinity of k_p, the k value corresponding to the first peak of $S(k)$; otherwise a *positive* α is expected.

In the low- and high-temperature limits, Eq. (3a)

reduces to[8]

$$W(T)\simeq\begin{cases} W(0)+4W(0)\dfrac{\pi^2}{6}\left[\dfrac{T}{\Theta_D}\right]^2, & T\ll\Theta_D \quad (7a)\\ 4W(0)\left[\dfrac{T}{\Theta_D}\right], & T\gtrsim\Theta_D. \quad (7b)\end{cases}$$

An estimate of $W(0)$, using the values $\Theta_D\cong 300$ K, $M\cong 8\times 10^{-23}$ g and $E_F\cong 10$ eV, typical of metallic glasses, in the relation $W(0)=3\hbar^2k_F^2/2Mk_B\Theta_D=(3E_F/k_B\Theta_D)(m/M)$, shows that $W(0)\simeq 0.013$. Bearing in mind that $W(0)\ll 1$, Eqs. (4) and (7) can be combined and the exponential function in the modified version of Eq. (4) expanded in power series to yield the asymptotic temperature dependence of ρ as

$$\rho(T)\simeq\begin{cases} C\left\{S_0(2k_F)+\left[\dfrac{2\pi}{\Theta_D}\right]^2\dfrac{W(0)}{3}[1-S_0(2k_F)]T^2\right\}, & T\ll\Theta_D \quad (8a)\\ C\left\{S_0(2k_F)-2W(0)[1-S_0(2k_F)]+\dfrac{8W(0)}{\Theta_D}[1-S_0(2k_F)]T\right\}, & T\gtrsim\Theta_D \quad (8b)\end{cases}$$

with

$$C=\frac{30\pi^3\hbar^3}{me^2k_F^2E_F\Omega}\sin^2[\eta_2(E_F)]\,.$$

In order to facilitate a direct comparison between theory and experiment, a different form of Eq. (4) has been used in the present work, i.e.,

$$r(T)=\frac{\rho(T)}{\rho(T_0)}=a_1+a_2e^{-2[W(T)-W(0)]}$$
$$=a_1+a_2\exp\left[-8W(0)\left[\frac{T}{\Theta_D}\right]^2\int_0^{\Theta_D/T}\frac{z}{e^z-1}dz\right]$$
$$\equiv f_1(T)\,, \quad (9)$$

where

$$a_1=\{1+[S_0(2k_F)-1]e^{-2[W(T_0)-W(0)]}\}^{-1}\,, \quad (10a)$$
$$a_2=a_1[S_0(2k_F)-1]\,, \quad (10b)$$

or

$$S_0(2k_F)=1+(a_2/a_1)\,,$$

and $T_0=273.15$ K is the ice temperature.

In view of the experimental evidence already presented in the Introduction, electron-magnon scattering is expected to significantly contribute to ρ in ferromagnetic metallic glasses at low temperatures. Within the framework of the spin-disorder model, Richter *et al.*[12] have calculated $\rho_{\rm mag}(T)$ at low temperatures for an amorphous Heisenberg ferromagnet in the spin-wave approximation with the result

$$\frac{\rho_{\rm mag}(T)}{\rho_{\rm mag}(0)}=1+\frac{\Omega_c}{(2\pi)^2S}\Gamma(\tfrac{3}{2})\xi(\tfrac{3}{2})\left[\frac{k_BT}{D}\right]^{3/2}+\frac{1}{J_s(2k_F)}\left[\frac{\pi^2}{3S}\left[\frac{k_BT}{D}\right]^2-\int_0^{2k_F}dk\frac{k^3S(k)(\hbar\omega_k/k_BT)}{(e^{\hbar\omega_k/k_BT}-1)(1-e^{-\hbar\omega_k/k_BT})}\right] \quad (11a)$$

and

$$\rho_{\rm mag}(0)=\frac{2\Omega_c}{3h^3}\left[\left[\frac{\Omega}{N_ee}\right]mSJ_{sd}\right]^2J_s(2k_F)\,, \quad (11b)$$

where Ω_c and Ω are the atomic and sample volumes, respectively, S is the spin of the local magnetic moment, N_e denotes the number of electrons, D is the spin-wave stiffness constant given by the magnon dispersion relation $\hbar\omega_k=Dk^2$, Γ and ξ are the gamma and Riemann zeta functions, respectively, J_{sd} is the s-d exchange coupling constant and $J_s(2k_F)=\int_0^{2k_F}k^3S(k)dk$. In Eq. (11a), the second term is an outcome of a partial cancellation of two competing $T^{3/2}$ terms; one arises from *incoherent* (momentum nonconserving) electron-magnon scattering and *increases* with increasing temperature, and the other originates from the *elastic scattering* of conduction electrons from the randomly oriented temperature-dependent local moments and *decreases* as the temperature is increased, whereas the third term is a *coherent* spin-wave term. The fourth (integral) term, which arises because of disorder, forms only a minute correction to the T^2 term

indicating thereby that the coherent scattering of electrons by long-wavelength magnons is not significantly altered by the quenched disorder. Another important feature pertaining to Eq. (11) is that $\rho_{\rm mag}(0)$ and the $T^{3/2}$ term both vanish in the case of crystalline ferromagnets whereas they possess finite values for amorphous ferromagnets. With a view to find out the relative importance of the $T^{3/2}$ and T^2 terms, Richter *et al.*[12] have estimated the order of magnitude of these terms assuming $a=3$ Å, $\Omega_c=a^3$, $S=1$, $D=185$ meV Å^2 and $k_F=1.36$ Å^{-1} as

$$\frac{\rho_{\rm mag}(T)}{\rho_{\rm mag}(0)}=1+1.6\times10^{-5}T^{3/2}+2.4\times10^{-7}T^2\ , \qquad (12)$$

where the temperature is measured in K. Equation (12) indicates that $\rho_{\rm mag}(T)$ in amorphous ferromagnets should vary as $T^{3/2}$ at low temperatures as contrasted with the T^2 variation of $\rho_{\rm mag}(T)$ in the crystalline case.

III. EXPERIMENTAL DETAILS

Amorphous $Fe_{80}B_{20-x}C_x$ alloy ribbons ($\sim$1 mm wide and 30 μm thick) were prepared by rapid quenching from the melt onto a rotating copper drum and procured from the General Electric Company, New York. While copper wires of 0.13 mm diameter attached to the ends of a 20-mm-long ribbon by means of silver paste formed the current contacts, the voltage contacts ($\sim$5 mm apart) were made by bonding very thin aluminum wires of 25 μm diameter onto the sample using the ultrasonic method. The sample was then pasted to 1 mm thick glass or sapphire wafer with Apiezon-N grease, which serves two purposes. First, it ensures a good thermal contact of the sample with the resistance thermometers, which find themselves placed underneath the wafer. Second, it allows for the changes in the sample dimensions during thermal cycling and thereby avoids stress-induced effects, which could otherwise significantly affect the results in stress-sensitive materials like metallic glasses.

Electrical resistivity was measured at $\sim$0.5 K intervals ($\lesssim$0.1 K intervals for $T\lesssim50$ K) in the temperature range 4.2 to 300 K employing a four-probe dc method. The experimental setup used for these measurements could resolve a few ppm change in resistivity with ease. The sample temperature below and above 50 K was monitored by calibrated germanium and platinum-resistance thermometers, respectively.

Large error in the measurement of the ribbon thickness and width, arising mainly due to an erratic variation of these quantities over the entire length of the ribbon, results in a large inaccuracy ($\sim$10%) in the absolute values of ρ. In order to get rid of such uncertainties, the values of ρ at different temperatures have been normalized to the resistivity value at $T_0=273.15$ K, which is the ice point.

IV. RESULTS AND ANALYSIS

The temperature dependence of the normalized resistivity ratio $r(T)=\rho(T)/\rho(T_0)$ in the temperature range 4.2 to 300 K for amorphous $Fe_{80}B_{20-x}C_x$ alloys with $x=0$, 2, 4, and 10 is shown in Fig. 1. It is noticed from this figure that the total variation of $r(T)$ within the in-

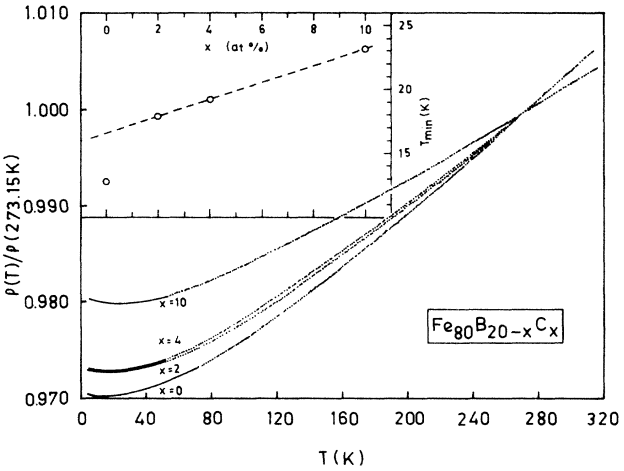

FIG. 1. Temperature dependence of the normalized resistivity ratio for amorphous $Fe_{80}B_{20-x}C_x$ alloys. The inset displays the concentration dependence of $T_{\rm min}$.

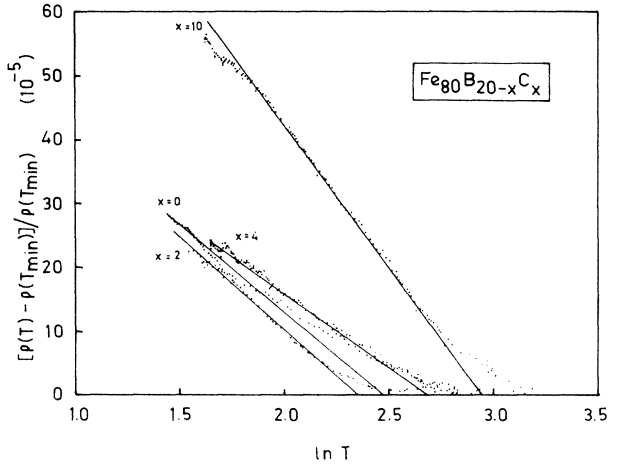

FIG. 2. $[\rho(T)-\rho(T_{\rm min})]/\rho(T_{\rm min})$ vs $\ln T$ for a-$Fe_{80}B_{20-x}C_x$ alloys. The continuous straight lines through the data points serve as a guide to the eye.

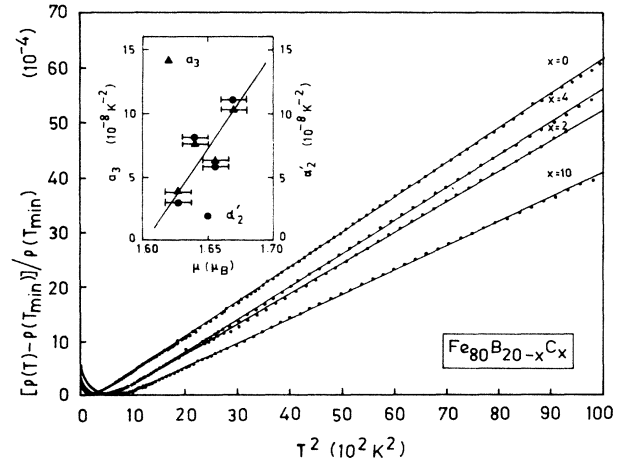

FIG. 3. $[\rho(T)-\rho(T_{\rm min})]/\rho(T_{\rm min})$ vs T^2 for a-$Fe_{80}B_{20-x}C_x$ alloys. Straight lines through the data points are intended to serve as a guide to the eye. In the inset, the coefficients a_3 and α_2' are shown plotted against magnetic moment μ. The least-squares-fit straight line through the data points is also shown.

TABLE I. Details of the low-temperature least-squares fits, based on Eqs. (13) and (14) of the text, for amorphous $Fe_{80}B_{20-x}C_x$ alloys. Numbers in the parentheses denote the estimated uncertainty in the significant figure.

x (at. %)	α_0	α_2 (10^{-7} K^{-2})	Fit range ΔT (K)	χ^2 (10^{-10})	β_0	β (10^{-4} ln K)	Fit range ΔT (K)	χ^2 (10^{-11})
0	0.970	6.13(1)	50–100	3.70	0.971	−3.28(2)	4.0–8.0	1.13
2	0.972	5.52(1)	50–100	2.67	0.973	−1.81(2)	5.0–12.0	1.15
4	0.973	5.85(2)	50–100	7.11	0.973	−2.21(2)	4.5–12.0	2.83
10	0.979	4.41(2)	50–100	5.23	0.981	−4.31(2)	6.0–15.5	2.23

vestigated temperature range *decreases* with *increasing* x and does not, in any case, exceed 4% of the value of r at 300 K. At low temperatures (10–25 K), ρ as a function of temperature goes through a well-defined *minimum* at a temperature $T_{\min}$, which increases roughly linearly with x (inset in Fig. 1).

Figures 2 and 3 serve to demonstrate that resistivity exhibits a variation with temperature which can be well described by the relations

$$r(T)=\beta_0+\beta \ln T, \quad T<T_{\min} \tag{13}$$

and

$$r(T)=\alpha_0+\alpha_2 T^2, \quad T>T_{\min} \tag{14}$$

in the temperature ranges $4 \lesssim T \lesssim 12$ K and $50 \leq T \leq 100$ K, respectively. Least-squares fits to the resistivity data based on Eqs. (13) and (14) in the specified temperature ranges give the values for the coefficients β_0, β, α_0, and α_2 listed in Table I.

In order to bring out the functional dependence of ρ on T for $T>100$ K, the temperature derivative of $r(T)$ has been plotted as a function of temperature in Fig. 4. A cursory glance at this figure indicates that in the temperature interval $120 \lesssim T \lesssim 300$ K $r(T)$ obeys the simple relation:

$$r(T)=\alpha_0'+\alpha_1' T+\alpha_2' T^2 . \tag{15}$$

However, a close scrutiny of the $dr(T)/dT[=r'(T)]$ curves reveals that they present a slight but finite curvature up to a temperature as high as $\simeq$200 K and beyond this temperature $r'(T) \propto T$. This inference is corroborated by the finding that the parameters α_0', α_1', and α_2' in the least-squares-fit computer program are found to vary when the resistivity data are fitted to Eq. (15) over a temperature range, defined by $T^* \leq T \leq 300$ K, which is progressively narrowed down by increasing T^* from an initial value of 120 K to a final value of 200 K; the values of the coefficients remain essentially unaltered when the temperature range of the fit is further narrowed down by increasing T^* beyond 200 K. The values of the coefficients α_0', α_1', and α_2' for the two extreme fitting ranges, i.e., $120 \leq T \leq 300$ K and $200 \leq T \leq 300$ K, are given in Table II.

V. DISCUSSION

To begin with, we completely ignore the magnetic contribution to ρ and attempt a *quantitative* explanation of the results in terms of the diffraction model. According to this model, the fractional change of resistivity between 0 and 300 K, $\Delta\rho/\rho$, the normalized resistivity at 300 K, r(300 K), and the temperature coefficient of resistivity, α_1', are given by the expressions

$$\frac{\Delta\rho}{\rho}=\frac{\rho(300\text{ K})-\rho(0\text{ K})}{\rho(0\text{ K})}=\frac{2[1-S_0(2k_F)]}{S_0(2k_F)}W(0)\left[\frac{4\times 300}{\Theta_D}-1\right], \tag{16}$$

$$r(300\text{ K})=\frac{S_0(2k_F)+2W(0)[1-S_0(2k_F)][(4\times 300/\Theta_D)-1]}{S_0(2k_F)+2W(0)[1-S_0(2k_F)][(4T_0/\Theta_D)-1]}, \tag{17}$$

TABLE II. Details of the high-temperature least-squares fits, based on Eq. (15) of the text, for amorphous $Fe_{80}B_{20-x}C_x$ alloys. Numbers in the parentheses denote the estimated uncertainty in the least significant figure.

x (at. %)	α_0'	α_1' (10^{-4} K^{-1})	α_2' (10^{-8} K^{-2})	Fit range ΔT (K)	χ^2 (10^{-10})	Θ_D (K)
0	0.965	1.029(3)	9.71(7)	120–300	5.04	328(4)
	0.964	1.106(12)	8.15(25)	200–300	3.59	342(4)
2	0.968	0.909(4)	10.02(9)	120–300	11.50	331(5)
	0.968	0.854(11)	11.15(21)	200–300	4.35	319(5)
4	0.968	0.897(5)	9.57(11)	120–300	14.93	301(7)
	0.971	1.083(17)	5.83(33)	200–300	9.71	338(7)
10	0.976	0.725(3)	5.55(8)	120–300	8.42	310(5)
	0.974	0.858(11)	3.00(21)	200–300	4.54	349(5)

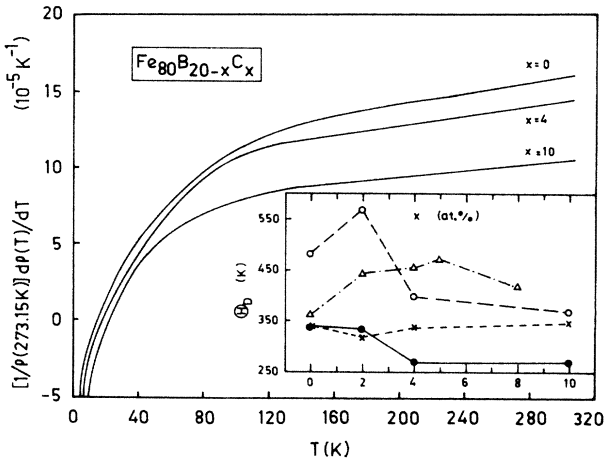

FIG. 4. The temperature derivative of the normalized resistivity ratio as a function of temperature for a-$Fe_{80}B_{20-x}C_x$ alloys. The inset depicts the concentration dependence of the Debye temperature; Θ_D values obtained from $f_1(T)$ fits, open circles; Θ_D values extracted from $f_2(T)$ fits, closed circles; values deduced from the asymptotic fits [Eq. (20) of the text], crosses; values determined from the specific-heat measurements and taken from Ref. 36, open triangles.

and

$$\alpha_1' = \frac{8W(0)[1-S_0(2k_F)]/\Theta_D}{S_0(2k_F)+2W(0)[1-S_0(2k_F)][(4T_0/\Theta_D)-1]} , \tag{18}$$

which derive their origin from Eq. (8). These relations demonstrate that a direct comparison between theory and experiment cannot be made without prior knowledge of $W(0)$,Θ_D, and $S_0(2k_F)$. In order to arrive at the numerical estimates of these quantities, $r(T)$ data have been fitted to Eq. (9), which gives the complete functional form of $\rho(T)$, over the temperature range $50 \leq T \leq 300$ K by using a nonlinear least-squares-fit computer program, which treats a_1, a_2, $W(0)$, and Θ_D as free parameters and is based on the Marquardt's maximum-likelihood algorithm.[24] The parameter values so obtained and the corresponding values of k_F and $S_0(2k_F)$ deduced from them using Eqs. (5) and (10b), respectively, are presented in Table III. Theoretical values of $\Delta\rho/\rho$, r(300 K), and α_1' are then deduced by using the values of $W(0)$, Θ_D, and $S_0(2k_F)$ from Table III in Eqs. (16)–(18) and compared with the observed values in Table IV. From Tables III and IV one notices that (i) a close agreement between the calculated and observed values of $\Delta\rho/\rho$ and r(300 K) can be achieved but not without paying the heavy penalty in terms of *the unphysically large* k_F values, and (ii) even after paying such a high price, a large discrepancy between the experimental and theoretical values of α_1' remains. While the former observation provides an experimental confirmation for the previous theoretical result[25] that for metallic glasses containing a strong-scattering transition metal (Fe or Co), the extended Ziman-Faber theory (on which the diffraction model is based) repro-

TABLE III. Parameter values for amorphous $Fe_{80}B_{20-x}C_x$ alloys obtained by fitting $r(T)$ data to the expressions $r(T)=f_1(T)$ [Eq. (9)] and $r(T)=f_1(T)+a_3T^2\equiv f_2(T)$ [Eq. (22)] in the temperature interval $50 \leq T \leq 300$ K. While the values within the square brackets pertain to the least-squares fits based on the relation $r(T)=f_2(T)$, the numbers in the parentheses denote estimated uncertainty in the least significant figure.

x (at. %)	a_1	a_2	$W(0)$	Θ_D (K)	$S_0(2k_F)$	k_F (Å^{-1})	χ^2 (10^{-9})	a_3 (10^{-8} K^{-2})	d (g/cm^3)	μ/alloy atom at 77 K (μ_B)
0	1.270(4)	−0.300(4)	0.0363(7)	486(3)	0.764(14)	3.37(4)	9.311		7.39[a]	1.640(10)[b]
	[1.269(9)]	[−0.299(9)]	[0.0183(6)]	[341(2)]	[0.764(32)]	[2.00(3)]	[0.452]	[7.62(11)]		
2	1.116(2)	−0.144(2)	0.093(3)	571(7)	0.871(17)	5.85(10)	21.979		7.41[a]	1.670(10)[a]
	[1.080(3)]	[−0.108(3)]	[0.044(2)]	[334(8)]	[0.900(28)]	[3.08(8)]	[3.365]	[10.36(24)]		
4	1.534(5)	−0.562(5)	0.0133(2)	400(4)	0.634(9)	1.85(16)	8.926		7.44[a]	1.656(10)[a]
	[1.533(22)]	[−0.561(22)]	[0.0068(3)]	[271(5)]	[0.634(41)]	[1.09(3)]	[1.734]	[6.36(20)]		
10	1.699(10)	−0.720(10)	0.0069(1)	370(3)	0.576(15)	1.28(1)	3.705		7.51[a]	1.627(10)[a]
	[1.699(16)]	[−0.720(16)]	[0.0040(2)]	[270(5)]	[0.576(24)]	[0.84(2)]	[1.172]	[3.82(17)]		

[a]Data taken from Ref. 34.
[b]Reference 35; value at 4.2 K.

TABLE IV. Comparison between the experimentally observed and theoretically calculated values of $\Delta\rho/\rho$, $r(300\text{ K})$, and α_1' for amorphous $Fe_{80}B_{20-x}C_x$ alloys. The theoretical values are deduced using the parameter values, obtained by fitting the $r(T)$ data to the expressions represented by the functions $f_1(T)$ and $f_2(T)$, in the Eqs. (16)–(21) of the text. Numbers in the parentheses denote estimated uncertainty in the least significant figure.

x (at. %)	$\Delta\rho/\rho$ (%)			$r(300\text{ K})$			α_1' (10^{-4}K^{-1})		
		Calculated			Calculated			Calculated	
	Observed	f_1	f_2	Observed	f_1	f_2	Observed	f_1	f_2
0	3.47	3.29(37)	3.74(71)	1.0042	1.0048(5)	1.0049(9)	1.106(12)	1.796(185)	1.285(287)
2	3.16	3.03(67)	3.57(112)	1.0040	1.0050(11)	1.0048(12)	0.854(11)	1.882(376)	1.136(456)
4	3.19	3.07(22)	3.59(81)	1.0039	1.0040(3)	1.0045(9)	1.083(17)	1.496(95)	1.124(288)
10	2.28	2.28(21)	2.62(41)	1.0027	1.0029(2)	1.0033(4)	0.858(11)	1.077(92)	0.853(150)

duces the experimental resistivity value only when too high a value of E_F or k_F is chosen, the latter one points to the fact that the diffraction model is unable to account for the additional T^2 term that we observe in $\rho(T)$ at high temperatures [Eq. (15)]. In this context, it should be noted that with one exception,[26] all previous studies on ferromagnetic metallic glasses do not report the existence of this additional term in $\rho(T)$ at high temperatures. This disagreement between our observations and previous observations on similar glassy alloys basically stems from the fact that in the temperature range $120 \leq T \leq 300$ K, the term *linear in* T gives a contribution to ρ which is at least one order of magnitude *greater* than that arising from the T^2 term (see Table II) so that the "raw" $\rho(T)$ data with relatively small number of data points, as happens to be the case in most of the previous works, could be approximated by a straight line in this temperature range. Although the existence of a T^2 term at low temperatures and a T term at high temperatures, and the positive TCR for $S_0(2k_F) < 1$ (Table III) conform well with the predictions of the diffraction model, the linear temperature dependence of ρ (in case we ignore for the moment the relatively small contribution due to the T^2 term) persists to temperatures well below Θ_D as contrasted with the prediction of this model that $\rho \propto T$ for $T \gtrsim \Theta_D$. To elucidate this point further, a dominant linear term ($\alpha_1' T$) in $\rho(T)$ has been observed down to temperatures as low as 120 K whereas the diffraction model for the glassy alloys under consideration yields values of Θ_D ranging from 370 to 570 K (see Table III); the values of Θ_D are so large as to exceed even the value $\Theta_D = 464$ K observed[27] for crystalline Fe. Similar observations have been recently made on amorphous Fe-B alloys.[7] The above-mentioned inconsistencies between the predictions of the diffraction model and the experimental results strongly suggest that a total neglect of the magnetic contribution to ρ is not justified.

In view of the theoretical result[12] that up to the second order in the scattering potential the Matthiessen's rule, i.e.,

$$\rho(T) = \rho_{\text{str}}(T) + \rho_{\text{mag}}(T) , \tag{19}$$

where $\rho_{\text{str}}(T)$ and $\rho_{\text{mag}}(T)$ are, respectively, the structural and magnetic contributions to the total resistivity, is obeyed, we argue that the magnetic contribution to ρ goes unnoticed at low temperatures primarily because $\rho_{\text{str}}(T)$ and $\rho_{\text{mag}}(T)$ both follow a T^2 power law but shows up very clearly at high temperatures where $\rho_{\text{str}}(T)$ exhibits a transition from a quadratic to a linear temperature dependence while $\rho_{\text{mag}}(T)$ continues to vary as T^2. This implies that we attribute the extra T^2 term (i.e., $\alpha_2' T^2$) in the high-temperature fits [Eq. (15)] to the contribution to $\rho(T)$ arising from the electron-magnon scattering, $\rho_{\text{mag}}(T)$. However, considering the finding that the transition region between the asymptotic temperature regimes where $\rho_{\text{str}}(T)$ follows a T^2 ($50 \lesssim T \lesssim 100$ K)—and a T ($200 \lesssim T \lesssim 300$ K)—variation is as wide as 100 K [which is reflected in the finite curvature of $r'(T)$ curves in Fig. 4 up to about 200 K] in the present glassy alloys, an unambiguous determination of $\rho_{\text{mag}}(T)$ is possible only when such a transition is complete, i.e., for $T \gtrsim 200$ K. Numerical assessment of the terms $\alpha_2' T^2$, $\alpha_2 T^2$, and $\alpha_1' T$ at dif-

ferent temperatures, employing the values of α_1', α_2' and α_2 given in Tables I and II, reveals that ρ_{str} dominates (greater by at least an order of magnitude) over ρ_{mag} in the entire temperature range from 50 to 300 K and hence the magnetic contribution to ρ can be easily missed unless great care is exercised while analyzing the results. With the terms $\alpha_2 T^2$, $\alpha_1' T$, and $\alpha_2' T^2$ of the low- and high-temperature fits, Eqs. (14) and (15), identified as $[\rho_{str}(T)+\rho_{mag}(T)]$, $\rho_{str}(T)$ and $\rho_{mag}(T)$, respectively, Eqs. (6)—(8), (14) and (15) can be combined to give Θ_D as

$$\Theta_D \simeq \frac{\pi^2}{6}\frac{\alpha_1'}{\alpha_2-\alpha_2'} . \tag{20}$$

Values of Θ_D deduced from this relation using the values of α_2, α_1', and α_2' obtained from the low- and high-temperature fits (Tables I and II) are listed in Table II.

Apart from the fits in the asymptotic temperature regions [Eqs. (14) and (15)], two types of fits to the experimental data in the temperature range 50 to 300 K, both based on Eq. (19) with $\rho_{str}(T)$ and $\rho_{mag}(T)$ given by Eqs. (4) and (11), respectively, have been attempted by using a nonlinear least-squares-fit computer program of the kind mentioned earlier. Before going into the details of these fits, we make a rough estimate of $\rho_{mag}(0)$ with the intention of finding out how small or big this quantity is for amorphous ferromagnets. With the aid of the well-known free-electron expressions, namely, $E_F=\hbar^2 k_F^2/2m$ and $k_F^3=3\pi^2 N_e/\Omega$, Eq. (11b) can be rewritten in the form

$$\rho_{mag}(0)=\frac{3\pi\hbar\Omega_c S^2}{16e^2 k_F^2}\left[\frac{J_{sd}}{E_F}\right]^2 J_s(2k_F) . \tag{21}$$

Substitution in this equation of the typical values $\Omega_c=a^3=(3)^3$ Å^3, $S=1$, $k_F=1.36$ Å^{-1}, $J_s(2k_F)=3.0$ Å^{-4}, $J_{sd}\simeq 0.1$ eV, and $E_F\simeq 10$ eV yields $\rho_{mag}(0)\simeq 0.1$ $\mu\Omega$ cm. This value should be compared with that of $\rho_{str}(0)$ which for amorphous ferromagnets could be as large as 100 $\mu\Omega$ cm. This comparison and the remark made in Sec. II about the magnitude of the fourth term in Eq. (11a) permit us to neglect the first and fourth terms in this equation [Eq. (11a)] while attempting the above-mentioned fits. In the first type of fit, we drop the second term in Eq. (11a) also and fit the $r(T)$ data to the following relation:

$$r(T)=f_1(T)+a_3 T^2 \equiv f_2(T) , \tag{22}$$

where $f_1(T)$ is given by Eq. (9). The values of the fit parameters a_1, a_2, a_3, $W(0)$, and Θ_D so determined are used in Eqs. (10b) and (5) to calculate $S_0(2k_F)$ and k_F, respectively, and in the following expressions

$$\frac{\Delta\rho}{\rho}=\frac{2[1-S_0(2k_F)]}{S_0(2k_F)}W(0)\left[\frac{4\times 300}{\Theta_D}-1\right]+\frac{a_3\times(300)^2}{S_0(2k_F)} , \tag{23}$$

$$r(300\text{ K})=\frac{S_0(2k_F)+2W(0)[1-S_0(2k_F)][(4\times 300/\Theta_D)-1]+a_3\times(300)^2}{S_0(2k_F)+2W(0)[1-S_0(2k_F)][(4T_0/\Theta_D)-1]+a_3 T_0^2} , \tag{24}$$

$$\alpha_1'=\frac{8W(0)[1-S_0(2k_F)]/\Theta_D}{S_0(2k_F)+2W(0)[1-S_0(2k_F)][(4T_0/\Theta_D)-1]+a_3 T_0^2} , \tag{25}$$

to compute $\Delta\rho/\rho$, $r(300\text{ K})$, and α_1'. Values of all the above-mentioned quantities are then compared in Tables III and IV with those deduced previously by fitting the $r(T)$ data with the function $f_1(T)$. Such a comparison demonstrates that the inclusion of the magnetic contribution [the term $a_3 T^2$ in Eq. (22)] in the expression for total resistivity does not significantly change the values of a_1, a_2 [and hence of $S_0(2k_F)$, except for the alloy with $x=2$ for which a_1 and a_2 do change but $S_0(2k_F)$ remains unaltered within the error limits], $\Delta\rho/\rho$ and $r(300\text{ K})$ but considerably improves the quality of the fits as inferred from the reduced (by an order of magnitude) value of the sum of squares (χ^2), removes the discrepancy between observed and calculated values of α_1' and lowers the values of Θ_D and k_F so as to make them fall within the physically acceptable range. Other important findings include the following: (i) in accordance with the predictions of the diffraction model, positive TCR is accompanied by $2k_F$ values that are either well below or well above k_p [in the absence of the structural data on amorphous $Fe_{80}B_{20-x}C_x$ alloys, we compare the determined $2k_F$ values with $k_p\simeq 3.1$ Å^{-1}, where the first peak in the $S(k)$ vs k curves for amorphous $Fe_{80}B_{20}$ occurs,[28] since no appreciable shift in k_p is expected when B in $Fe_{80}B_{20}$ is partially replaced by C] and Θ_D values are now reasonably close to $T^*\simeq 200$ K, the temperature above which ρ_{str} exhibits a linear temperature dependence, and (ii) the high-temperature and $f_2(T)$ fits give roughly the same value for the coefficient of the magnetic term [the T^2 term in Eqs. (15) and (22)]. Moreover, the values of this coefficient in the expression for total resistivity, i.e., $\beta'=\rho(T_0)a_3$ or $\beta''=\rho(T_0)\alpha_2'$, for the present glassy alloys fall within the range of values obtained for the same coefficient in crystalline ferromagnetic metals and alloys.[29–32] For instance, the values $\beta'=(0.91\pm 0.03)\times 10^{-11}$ Ω cm K^{-2} and $\beta''=(0.98\pm 0.05)\times 10^{-11}$ Ω cm K^{-2} [$\rho(T_0)=120\pm 2$ $\mu\Omega$ cm] determined in this work for $Fe_{80}B_{20}$ are in excellent agreement with the value 0.96×10^{-11} Ω cm K^{-2} previously reported[29] for crystalline Fe. This observation resurrects our earlier (Sec. II) remark that the quenched disorder does

not significantly influence the *coherent* electron-magnon scattering contribution to ρ.

In order to verify the theoretical prediction,[12] Eq. (12), concerning the relative importance of the $T^{3/2}$, and T^2 terms in Eq. (11a), the second type of fit, wherein the $r(T)$ data are fitted to the expression

$$r(T)=f_1(T)+a_3T^2+a_4T^{3/2}$$
$$=f_2(T)+a_4T^{3/2}\,, \tag{26}$$

has been attempted. A nonlinear least-squares-fit computer program in which all six parameters a_1, a_2, a_3, a_4, Θ_D, and $W(0)$ are varied to achieve the best fit has been employed for this purpose. Such a fitting procedure is found to converge for some of the investigated glassy alloys only and in such cases (i) the values of all the parameters (except for a_4) are widely different from those obtained from the previous fits, (ii) Θ_D once again assumes unphysically large values, (iii) the coefficient a_4 is *negative,* and (iv) the quality of the fits deteriorates, as inferred from the increased value of χ^2 compared with the corresponding values determined in previous fits. Efforts to fit the $r(T)$ data in the temperature range 50 to 100 K to the relation $r(T)=\alpha_0+\alpha_2T^2+\alpha_3T^{3/2}$ also met the same fate. Recent electrical resistivity studies[33] on amorphous $Fe_{80}B_{20}$ also yield an unphysical negative value for the coefficient α_3 in the temperature range $20\leq T\leq 100$ K. The above findings strongly suggest that the $T^{3/2}$ term in Eq. (11a), if present, is negligibly small [implying thereby that the competing contributions to $\rho_{\rm mag}(T)$ due to the *incoherent* and *elastic* components of electron-magnon scattering almost balance each other] compared to the T^2 term. This inference is at variance with the theoretical prediction[12] that for amorphous ferromagnets the $T^{3/2}$ term should dominate (greater by 2 orders of magnitude) over the T^2 term in the intermediate-temperature range.

We now focus our attention on the concentration dependence of the parameters α_1', α_2', α_2, β, a_3, and Θ_D (Fig. 5 and the inset of Fig. 4). The results of recent magnetization[34,35] and specific-heat[36] measurements have also been included in these figures for comparison. It is evident from Fig. 5 that a_3, α_2', β, and μ (magnetic moment per alloy atom at 4.2 and 77 K) present a strikingly similar concentration dependence which completely differs from that of α_1' and α_2, which among themselves, exhibit roughly the same functional dependence on x. This implies that basically two different physical mechanisms are responsible for the existence of the terms in $\rho(T)$ with coefficients (a_3, α_2', β) and (α_1' and α_2). The marked similarity in the concentration dependence of a_3, α_2', and μ is further highlighted in the inset of Fig. 3 where a_3 and α_2' are shown to scale with μ. This observation lends a firm support to our contention that the T^2 terms in the $f_2(T)$ and high-temperature asymptotic fits are *purely of magnetic origin.* Figure 5 would normally tempt one to make a similar statement about the logarithmic term in $\rho(T)$ at low temperatures but a check on this temptation is provided by the observations: (a) the value of β depends on the temperature interval chosen for the fit and (b) our measurements do not extend to sufficiently low temperatures (mK range) where one expects to observe a *saturation* in resistivity which is a *prerequisite* for attempting a physically meaningful distinction[2] between various models proposed in the literature for explaining the resistivity-minimum phenomenon in metallic glasses. A more cautious statement would be that the logarithmic up turn of resistivity at low temperatures in the glassy alloys in question *does not solely arise from the structural disorder,* as some of the existing theories claim, but the magnetic state of these alloys also plays a vital role. In view of the structural origin of the linear temperature dependence of ρ at high temperatures [the term $\alpha_1'T$ in Eq. (15)], the close resemblance between $\alpha_1'(x)$ and $\alpha_2(x)$ suggests that the quadratic temperature dependence of $\rho(T)$ in the intermediate-temperature range results mainly from the scattering of conduction electron from the structural disorder. However, a small contribution to this T^2 term [i.e., the α_2T^2 term in Eq. (14)] from the *coherent* electron-magnon scattering cannot be completely ruled out. Finally, a few remarks can be made concerning the concentration dependence of Θ_D in the present glassy alloys. One notices from the inset of Fig. 4 that the values of Θ_D deduced from the f_2 fits and Eq. (20) are in reasonable agreement with one another but they are smaller in magnitude by about 40% than those obtained from the recent specific-heat data[36] with the exception of $Fe_{80}B_{20}$ for which the resistivity and specific-heat measurements both

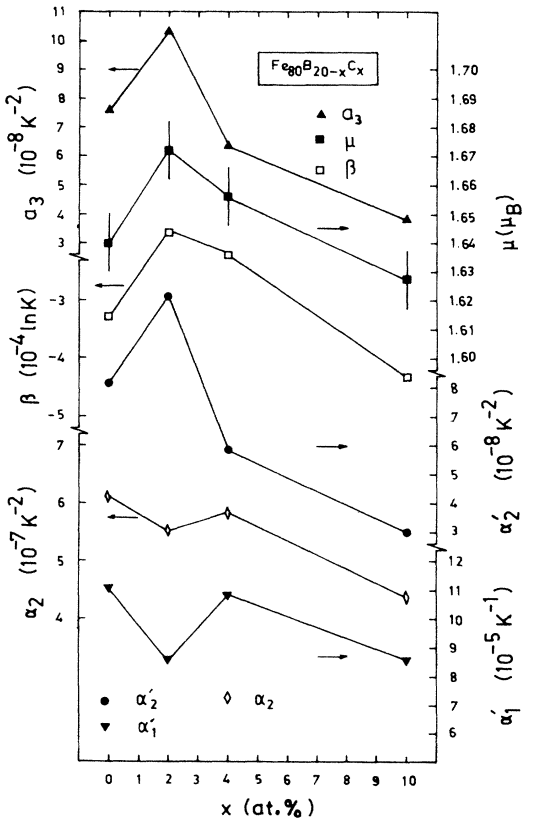

FIG. 5. Concentration dependence of the coefficients α_1', α_2', α_2, β, and a_3, and the magnetic moment μ. Note that the values of μ for the alloys with $x=2$, 4, and 10, taken from Ref. 34, have been measured at $T=77$ K whereas the value of μ for $Fe_{80}B_{20}$, taken from Ref. 35, is the moment value at $T=4.2$ K.

yield values which are fairly close to each other. Such a discrepancy between different sets of Θ_D values, in our opinion, arises from the fact that the values of Θ_D determined in Ref. 36 do not represent the values of Θ_D at 0 K, which are more relevant when a comparison with the Θ_D values deduced from the resistivity data is sought, but the *average* values over the temperature interval $1.5 \leq T \leq 10$ K. It is evident from Fig. 1 of Ref. 36 that $\Theta_D(T)$ approaches a limiting value $\Theta_D(0)$ only for $T \lesssim 7$ K ($T \lesssim 10$ K for $Fe_{80}B_{20}$) and beyond $T \simeq 7$ K $\Theta_D(T)$ increases with increasing temperature. The average value of Θ_D over an extended temperature range is, therefore, inevitably higher than $\Theta_D(0)$.

VI. CONCLUSIONS

A quantitative comparison between the theoretical predictions and the present experimental results permits us to draw the following conclusions.

(i) Both the electron-ion potential scattering and electron-magnon scattering contribute to resistivity.

(ii) The structural contribution dominates over the magnetic contribution in the entire temperature range of the present investigation.

(iii) Quenched disorder does not have any appreciable effect on the *coherent* electron-magnon scattering contribution to ρ.

(iv) The competing contributions to $\rho_{mag}(T)$ arising from the *incoherent* and *elastic* parts of the electron-magnon scattering are of the same magnitude roughly and hence the $T^{3/2}$ term in the expression for $\rho_{mag}(T)$ is negligibly small compared to the T^2 term.

(v) The magnetic state of the metallic glasses under consideration cannot be ignored while seeking an interpretation of the logarithmic increase of ρ for $T < T_{min}$ in the light of the existing theories.

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wrong high-temperature expression of $W(T)$ given in Ref. 8 while deriving the expression of $\rho(T)$ for $T \gtrsim \Theta_D$ and leads to wrong theoretical values of ρ at room temperature in this reference.

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