Scaling analysis of amorphous $Fe_{90-x}Mn_xZr_{10}$ alloys near the paramagnetic-to-ferromagnetic transition

G. K. Nicolaides
National Center for Scientific Research "Demokritos" Institute of Material Science, Aghia Paraskevi, 153 10, Greece

G. C. Hadjipanayis
Department of Physics and Astronomy, University of Delaware, Newark, Delaware 19716

K. V. Rao
Department of Condensed Matter Physics, Royal Institute of Technology, S-10044 Stockholm, Sweden

(Received 2 September 1992; revised manuscript received 17 May 1993)

A scaling analysis near the paramagentic-to-ferromagnetic transition temperature has been performed on amorphous $Fe_{90-x}Mn_xZr_{10}$ ($x=1.2$ and 5.0) alloys. The extracted values for the critical exponents β, γ, and δ are found to be higher than those predicted by the three-dimensional Heisenberg model. This result supports the idea that below T_c the magnetic state is not a collinear ferromagnetic state.

I. INTRODUCTION

The low-temperature magnetic behavior of amorphous Fe-rich Fe-Zr alloys is rather interesting. Namely, when the Zr content is lower than 12 at. %, a "reentrant" behavior appears in the χ_{ac} susceptibility measurements. For example, it has been found that the $Fe_{90}Zr_{10}$ ac-susceptibility data indicate a double transition behavior.[1,2] As the temperature is lowered below room temperature, the first transition encountered in the χ_{ac} data resembles a paramagnetic (PM) to a ferromagnetic-like state (FM), while at a lower temperature the χ_{ac} data indicates the possibility of a ferromagnetic to a spin-glass-like state transition. In our recent work[3] we probe the lower temperature transition mechanism at T_f of Fe-Zr amorphous alloys with small Mn substitutions for Fe. It was found that no continuous phase transition actually occurred at the lower freezing temperature T_f, but, rather, a progressive magnetic hardening of a noncollinear (asperomagnetic) phase. This noncollinear ferromagnetic phase forms below T_c and we suggest that it persists down to 4.2 K (Ref. 3). This picture explains the experimental results such as the high-field susceptibility observed even in the ferromagnetic plateau, the unidirectional anisotropy observed at all the temperatures below T_c (Ref. 3), and also is consistent with the results of small-angle neutron scattering (SANS) experiments performed on Fe-Zr amorphous alloys.[4,5] Here, to investigate the nature of the PM to FM-like transition, we attempt a scaling analysis on two of the previously[3] studied $Fe_{88.8}Mn_{1.2}Zr_{10}$ and $Fe_{85}Mn_5Zr_{10}$ amorphous alloys. We make use of high-field dc magnetic measurements in order to extract the critical exponent values β, γ, and δ and we compare these values with those predicted for the three-dimensional (3D) Heisenberg model which applies to a collinear ferromagnet. The detailed magnetic characterization of these alloys are presented elsewhere.[3]

II. EXPERIMENT

$Fe_{90-x}Mn_xZr_{10}$ (with $x=1.2$ and 5 at. %) amorphous alloys were prepared with the melt-spinning technique under argon atmosphere. The obtained ribbons were shiny, with a width 1–2 mm, 30 μm thickness, and a length of 2 cm to several meters.

The composition was determined by using the energy dispersive x-ray analysis (EDAX) method and it was found to be very close to the nominal composition of the alloy ingots used for melt spinning. The amorphicity was checked with conventional x-ray diffraction and also with selected area diffraction (SAD) using a Jeol 100C TEM. The samples used for the magnetic measurements were prepared by stacking together three to four pieces of ribbon with a length of 1 cm, and in all cases, the measurements were performed along the long axis to minimize demagnetizing effects. The magnetization measurements were obtained with a Quantum Design superconducting quantum interference device (SQUID) magnetometer.

III. RESULTS AND DISCUSSION

To perform a scaling analysis near to a PM-FM transition, one has to know very precisely the value of the critical (Curie) temperature T_c, since this value is the crucial parameter of the entire analysis. On the other hand, the value of T_c obtained using techniques such as the dc and ac susceptibility, can vary not only from one apparatus to the other (due to different thermometry systems), or from one technique to the other (due to the different magnitude of the applied magnetic field), but also depends on the method of extraction of this value, i.e., first derivative, graphical method, etc.

To find the right temperature in which the magnetic isotherms should be measured we use initially the T_c extracted from dc-susceptibility measurements, while the critical temperature (Curie) T_c used for the scaling

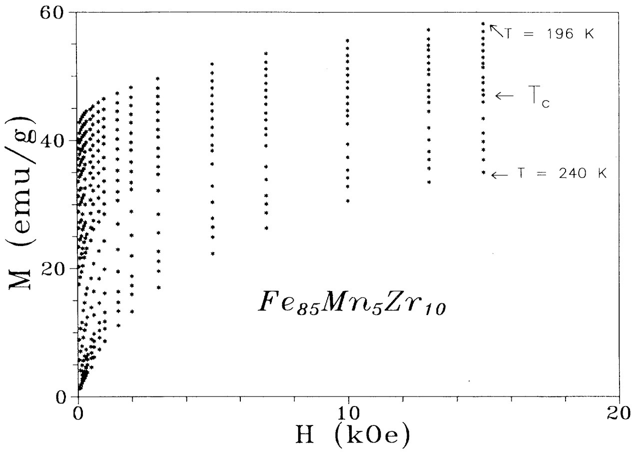

FIG. 1. Magnetic isotherms for $Fe_{85}Mn_5Zr_{10}$.

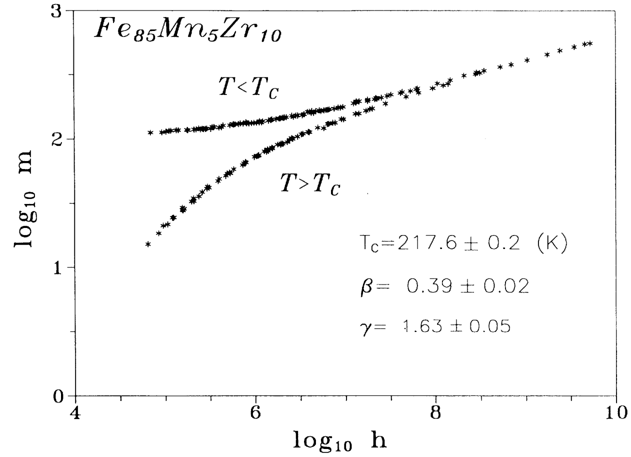

FIG. 4. Scaled magnetization m vs scaled field h in a log-log plot for the $Fe_{85}Mn_5Zr_{10}$ sample.

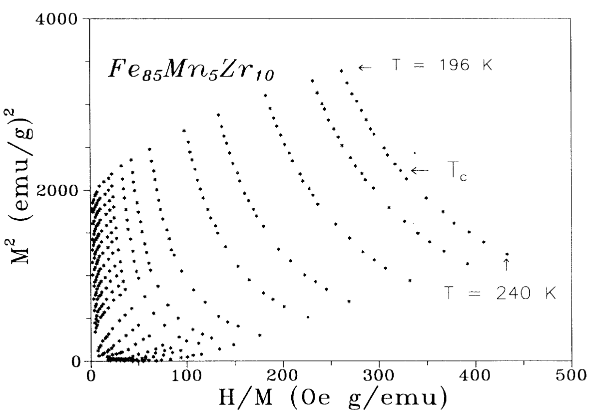

FIG. 2. Arrott plots for $Fe_{85}Mn_5Zr_{10}$.

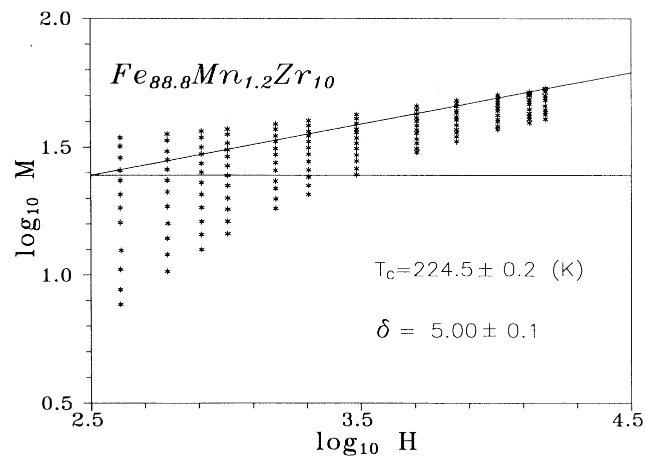

FIG. 5. Log-log plot of the magnetic isotherms for $Fe_{88.8}Mn_{1.2}Zr_{10}$.

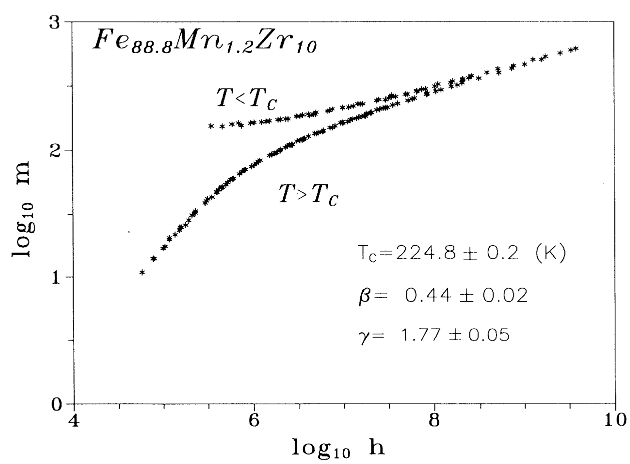

FIG. 3. Scaled magnetization m vs scaled field h in a log-log plot for the $Fe_{88.8}Mn_{1.2}Zr_{10}$ sample.

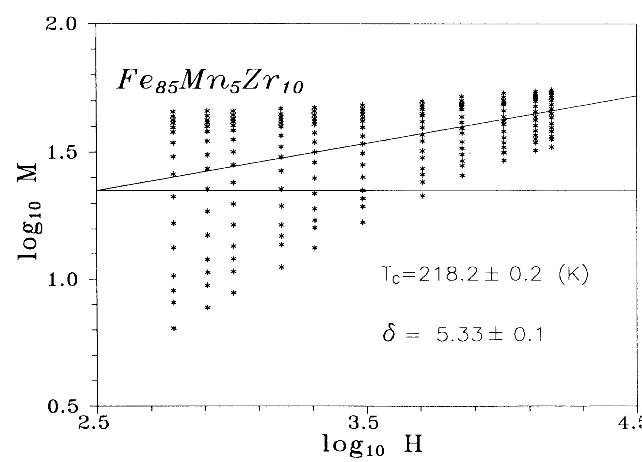

FIG. 6. Log-log plot of the magnetic isotherms for $Fe_{88.8}Mn_{1.2}Zr_{10}$.

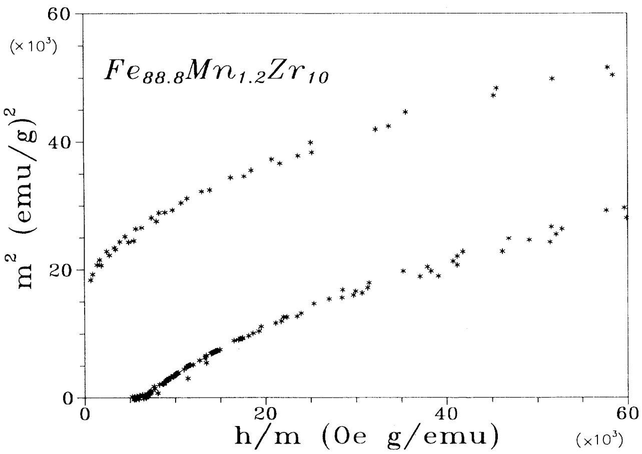

FIG. 7. m^2 vs h/m for $Fe_{88.8}Mn_{1.2}Zr_{10}$.

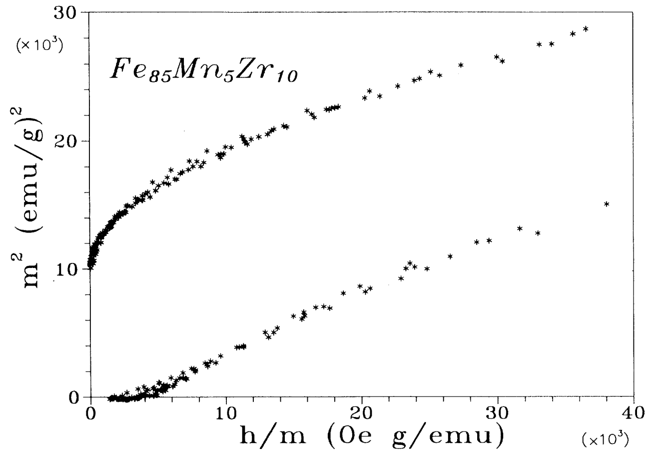

FIG. 8. m^2 vs h/m for $Fe_{85}Mn_5Zr_{10}$.

analysis is determined using the following two different methods. First we use the Arrott plots, M^2 vs H/M, where M and H stand for the magnetization and the applied magnetic field, respectively. Plotting the magnetic isotherms in this form, a set of curves is obtained which, according to the mean-field theory for a pure ferromagnet, should be very well approximated by a set of straight lines. Then T_c is the temperature of the isotherm whose extrapolation towards the low-field regime passes through the origin. For the samples studied here, the Arrott-plots are not straight lines, and indeed, there is a strong curvature which is an indication that the mean-field model does not apply here. Figure 1 shows the magnetic isotherms and Fig. 2 shows the Arrott plots for the sample with $x=5$ at. % of Mn content. To find the critical exponents β and γ, the isotherms are plotted according to the scaling relation $\log(m)$ vs $\log_{10}(h)$. Here m and h are the reduced magnetization and the reduced field, respectively, where

$$m = M(\varepsilon,H)/|\varepsilon|^{\beta}, \quad h = H(\varepsilon,M)/|\varepsilon|^{\beta+\gamma},$$

$$\varepsilon = (T - T_c)/T_c \; .$$

We have varied the T_c by 0.5 K, the β from 0.3 to 0.6, the γ from 1.2 to 2.5, and $|\varepsilon| = 0.01-0.1$, while in the work of Yamauchi, Onodera, and Yamamoto,[6] and Winschuh and Rosenberg.[7] $|\varepsilon| = 0.02-0.2$. Nevertheless, the results we obtain are consistent with their work,[6,7] as it is shown in Table I. The correct values of T_c, β, and γ are the values which, in the high-field regime, cause the collapse of the two branches of the isotherms in a $\log_{10}(m)$ vs $\log_{10}(h)$ diagram almost onto the same line (in reality the two branches for the high-field regime converge toward the same limit). The obtained values of the exponents β, γ, and the value of T_c are presented in the Table I while the scaling is presented in Figs. 3 and 4. The second method for obtaining the T_c is based on the fact that since the magnetization at the Curie temperature can be expressed as follows: $M(H,T_c) = AH^{1/\delta}$, in a $\log_{10}(M)$ vs $\log_{10}(H)$ plot, the isotherm corresponding to the T_c is a straight line. From the slope of this line we calculate the exponent δ, as shown in Figs. 5 and 6.

Table I shows the values of the critical exponents β and γ which are rather higher than the values predicted for a 3D Heisenberg ferromagnet. In addition to this, if we assume that the static scaling hypothesis is valid, then we can calculate the value of δ from the relation $\beta+\gamma=\beta\delta$. The values of δ, obtained from the static scaling law, are almost identical with the ones obtained by the $\log_{10}(M)$ vs $\log_{10}(H)$ plot method. Figures 7 and 8 show the diagrams of m^2 vs h/m for the samples with $x=1.2$ and 5, respectively, and the critical amplitude values M_0 and h_0

TABLE I. Critical exponents for $Fe_{90-x}Mn_xZr_{10}$ ($x=1.2$ and 5) amorphous alloys compared with the ones obtained for the $Fe_{90}Zr_{10}$ and those predicted for the 3D Heisenberg model.

x	β	γ	δ	$1+\gamma/\beta$
0[a]	0.56±0.03	1.87±0.02	4.84±0.06	4.34
0[b]	0.44±0.01	1.79±0.07	· · ·	5.10±0.08
1.2	0.44±0.02	1.77±0.05	5.00±0.1	5.02±0.3
5.0	0.39±0.02	1.63±0.05	5.33±0.1	5.18±0.3
3D Heisenberg[c]	0.365(3)[d]	1.405(2)[d]	4.85(4)[d]	· · ·

[a]Reference 6.
[b]Reference 7.
[c]Reference 11.
[d]Numbers in parentheses denote the uncertainty in the least significant figure.

are found to be[8] as follows: $m_0 = 126.5$ emu/g and $h_0/m_0 = 6\times10^3$ Oe g/emu for $x = 1.2$, while $m_0 = 100$ emu/g and $h_0/m_0 = 3.5\times10^3$ Oeg/emu for $x = 5$. These values are used to calculate the $m_0/M_s(0)$ ratios and compare them with theory. It is found that for the sample with 1.2 at. % Mn content, $m_0/M_s(0) = 1.1$ and for the sample with 5 at. % Mn content, $m_0/M_s(0) = 1.0$. These values are smaller than those predicted for the 3D Heisenberg model, where $M_0/M_s(0) = 1.22$.[9,10] The ratio $\mu_0 h_0/k_B T_c$, where $\mu_0 = \mu_B$/at. % of the corresponding alloy, is found to be 0.3 and 0.13 for the $x = 1.2$ and 5, samples, respectively.

IV. CONCLUSION

Scaling analysis has been performed near the T_c temperature on the amorphous $Fe_{88.8}Mn_{1.2}Zr_{10}$ and $Fe_{85}Mn_5Zr_{10}$ alloys. The critical exponents β, γ, and δ are extracted, and they are found to be higher than those predicted by the 3D Heisenberg model, indicating that the mean-field model cannot apply in these amorphous Fe-Zr alloys. This result connected with the results of detailed magnetic studies of these alloys[3] (presence of nonsaturation of hysteresis loops at high magnetic fields and of unidirectional anisotropy at all temperatures below T_c) and the outcome of the experimental work of Rhyne and Fish[4,5] support the idea that the magnetic state in which these amorphous alloys enter at temperatures below T_c is not a collinear ferromagnetic (ideal), but, indeed, is a noncollinear (asperomagnetic)[12] state. The critical amplitude values m_0 and h_0 are extracted, and from these the ratios $m_0/M_s(0)$ are calculated. These values are found to be somewhat smaller than those predicted for the 3D Heisenberg model.

[1] H. Hiroyoshi and K. Fukamichi, J. Appl. Phys. **53**, 2226 (1982).

[2] Y. Obi, L. C. Wang, R. Motsay, D. G. Onn, and M. Nose, J. Appl. Phys. **53**, 2304 (1982).

[3] G. K. Nicolaides, G. C. Hadjipanayis, and K. V. Rao (unpublished).

[4] J. J. Rhyne and G. E. Fish, J. Appl. Phys. **57**, 3407 (1985).

[5] J. J. Rhyne, J. A. Fernadez-Baca, and G. E. Fish, J. Appl. Phys. **63**, 4080 (1988).

[6] H. Yamauchi, H. Onodera, and H. Yamamoto, J. Phys. Soc. Jpn. **53**, 747 (1984).

[7] K. Winschuh and M. Rosenberg, J. Appl. Phys. **61**, 4401 (1987).

[8] S. N. Kaul, J. Magn. Magn. Mater. **53**, 5 (1985).

[9] S. Milosevic and H. E. Stanley, Phys. Rev. B **6**, 986 (1972).

[10] R. Krasnow and H. E. Stanley, Phys. Rev. B **8**, 332 (1973).

[11] M. Ferer, M. A. Moore, and M. Wortis, Phys. Rev. B **4**, 3954 (1971).

[12] K. Moorjani and J. M. D. Coey, *Magnetic Glasses* (Elsevier, New York, 1984).