# Collapse of ferromagnetism in amorphous $(Fe_{0.65}Mn_{0.35})_{75}P_{16}B_6Al_3$

M. A. Manheimer
*Laboratory for Physical Sciences, College Park, Maryland 20740*

S. M. Bhagat
*Department of Physics, University of Maryland, College Park, Maryland 20742*

H. S. Chen
*Bell Laboratories, Murray Hill, New Jersey 07974*
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We present low-field dc-magnetization measurements on $(Fe_{0.65}Mn_{0.35})_{75}P_{16}B_6Al_3$ ribbons and show that in this system there exist two phase transitions, such that the spontaneous magnetization goes to zero at $T_c^-$ and $T_f^+$, while the low-field susceptibility diverges at $T_c^+$ and $T_f^-$.

## I. INTRODUCTION

In recent years, considerable attention has been given to both crystalline and amorphous alloys which show reentrant magnetic behavior. On cooling these alloys first become ferromagnetic [PM-FM (paramagnet-ferromagnet) transition], but at a lower temperature, the ferromagnetism seems to disappear giving rise to some kind of a spin-glass (SG) state.[1–5] In "specially prepared" crystalline Au-Fe alloys Crane and Claus[6] have shown that at the latter transition (FM-SG) the spontaneous magnetization goes to zero for $T \rightarrow T_f^+$ and the dc susceptibility ($\chi$) diverges for $T \rightarrow T_f^-$. However, no comparable measurements have been reported on amorphous alloys. Amorphous systems are useful to investigate because they can be expected to be structurally and chemically more homogeneous.

In this Communication we report low-field ($B_a \lesssim 1.2$ mT) dc magnetization ($M$) measurements on an amorphous alloy with the nominal composition $(Fe_{0.65}Mn_{0.35})_{75}P_{16}B_6Al_3$. We have chosen to work on this system because several independent studies have been reported on it with somewhat conflicting results. For instance, Yeshurun *et al.*[3] have measured dc magnetization for $B_a > 10$ mT and, although they could not identify the clear disappearance of ferromagnetism, they performed a scaling analysis of their $M(B_a,T)$ data to arrive at the parameters characteristic of such a transition. Geohegan and Bhagat[2] identified the transition by measuring the ac susceptibility in the presence of small dc fields and obtained a $T_f$ nearly 20 K higher than that of Ref. 3. SQUID (superconducting quantum interference device) measurements by Beckman *et al.*[7] give $T_f$ in agreement with Ref. 2.

In the present study we have (i) mapped out $M$ as a function of $T$ at a constant $B_a$ and (ii) obtained Arrott plots to identify $T_f$ and thereby show that the spontaneous $M$ goes to zero at $T_f^+$ while $\chi$ diverges for $T \rightarrow T_f^-$. Similar data for $T$ near $T_C$ (Curie temperature) are also presented.

## II. METHOD AND RESULTS

The magnetization was measured by the Faraday technique using a Cahn 2000 microbalance. Eight pieces of ribbon, each roughly ($15 \times 1 \times 0.03$ mm$^3$), were attached to a copper form using thin copper wire. The applied fields were varied between 0.1 and 1.2 mT with the field gradient over the sample length being about 3% of the center field. The temperature was monitored with a copper-Constantan thermocouple held in good contact with samples via helium exchange gas. The temperatures are good to about 1 K. In addition to measuring $M$ vs $B_a$ at a fixed temperature, data were taken both during cooling and heating at very slow rates. No thermal hysteresis was found. In order to obtain a quantity proportional to $M$ we divided the observed force by the field gradient. The effective demagnetization correction to $B_a$ was obtained from the low-field behavior of $M$ vs $B_a$ measured in the ferromagnetic regime ($\sim 77$ K).

Shown in Fig. 1 is the magnetization $M$ (in arbitrary units) of our sample in an applied field of $B_a = 0.1$ mT. There is a marked rise in $M$ below about 105 K as the sample becomes ferromagnetic, a relatively flat region between 85 and 70 K and a sharp decrease in $M$ below 70 K as the spin frozen state is approached. The zero magnetization state at low temperatures is significantly different from the paramagnetic state above $T_c$. To reveal this we have cooled our sample to 4.2 K in a constant applied field of 1.2 mT, and found that subsequently when we reverse the measuring field and gradient, the net force on the sample reverses, indicating that the sample is a permanent magnet—the spins are frozen.

True magnetic transition temperatures are defined

 

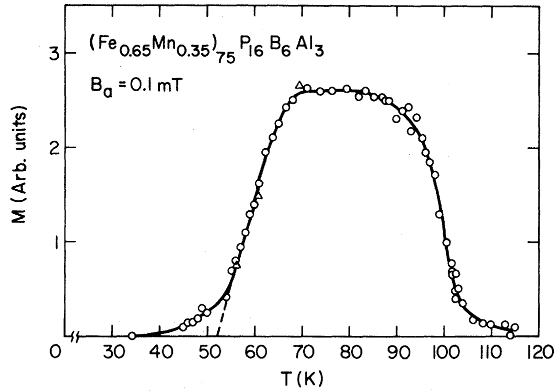


FIG. 1. Magnetization as a function of temperature in a constant applied field of 0.1 mT. As described in the text, the dotted line is used to obtain the effective transition temperature plotted in Fig. 2.

only at zero field. Since all experiments are performed in finite fields one must introduce an extrapolation procedure to fix the transition temperature. We have done this in two ways. First, we note from Fig. 1 that from about 55 to 65 K the magnetization is linear in $T$. Thus we use the $M=0$ intercept of a line fit through these data to define an effective transition temperature $T_f^*(B_a)$. For an applied field of 0.1 mT, $T_f^*=52$ K. We have made similar determinations of $M(T)$ for several values of $B_a$. For each run an extrapolation of the linear region was made to obtain a $T_f^*(B_a)$. Shown in Fig. 2 is a plot of these temperatures as a function of $B_a$. A straight line describes the data well and extrapolates to a zero-field transition at $T_f=58$ K which is to be compared with the value of $63 \pm 3$ K given in Ref. 2 and

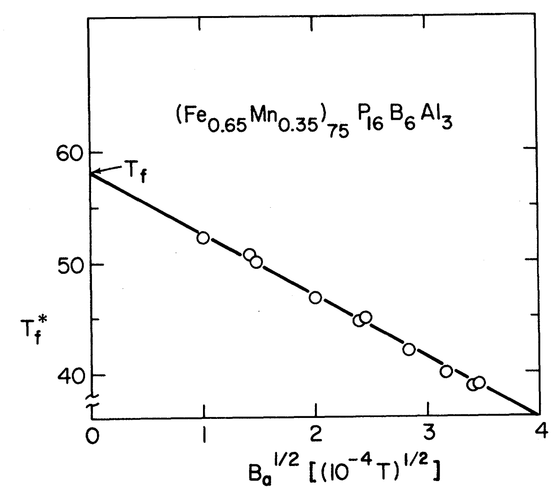


FIG. 2. Effective transition temperature $T_f^*$, defined from the $M=0$ intercept of the dotted line in Fig. 1, as a function of applied field. The intercept at $B_a=0$ gives the FM-SG transition temperature.

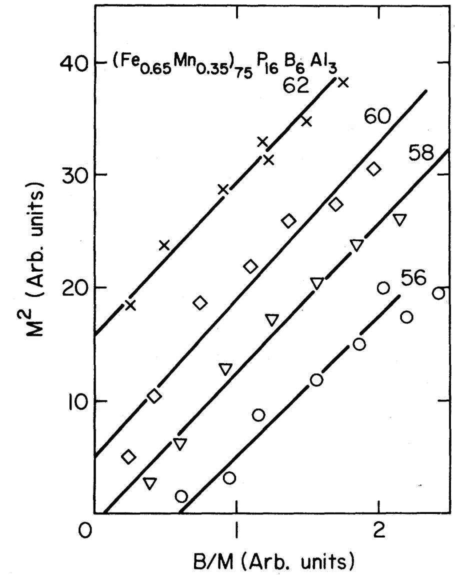


FIG. 3. Arrott plots (isotherms) in the vicinity of the FM-SG transition temperature. Note that spontaneous $M$ vanishes with reducing temperature while $B/M$ is going to zero on increasing $T$. The numbers designate the temperatures (in kelvin) of the isotherms.

57 K reported in Ref. 7.

Next, we constructed Arrott plots in the vicinity of $T_f$ and $T_c$. Figures 3 and 4 show $M^2$ vs $B/M$ for a series of temperatures in these regimes, respectively. As mentioned above the applied field has been corrected for demagnetization, hence $B$. It should be

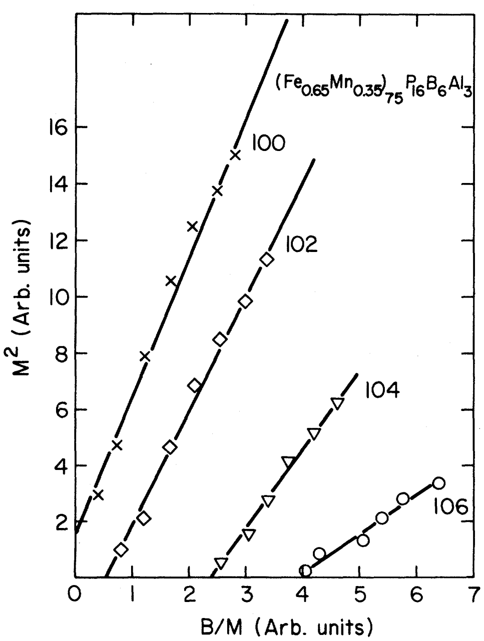


FIG. 4. Arrott plots (isotherms) in the neighborhood of the PM-FM transition temperature, $T_c$.

noted that the plots of Figs. 3 and 4 are not intended to imply mean-field behavior. We anticipate that data taken at higher fields will reveal the expected nonlinearities. For the present discussion, we note that the data in this restricted regime exhibit linear dependence so that one can extrapolate to obtain the spontaneous $M$ from the vertical intercept and $\chi^{-1}$ from the horizontal intercept. The three obvious results are (i) $T_c = 101$ K, $T_f = 58$ K, (ii) spontaneous $M$ goes to zero at $T \rightarrow T_f^+$, and $T_c^-$, and (iii) $\chi$ diverges at $T \rightarrow T_f^-$, and $T_c^+$. Again, we note that the present value of $T_f$ agrees with that of Refs. 2 and 7 but is much higher than that implied by the scaling analysis.

We are currently extending these measurements to other alloys of the Fe-Mn system as well as to other amorphous complexes. Also, noting the sharpness of the transition, we plan to measure detailed temperature dependences of the spontaneous $M$ and $\chi$ to arrive at values for the critical exponents.

In conclusion, low-field dc magnetization measurements have been used to demonstrate that in the amorphous alloy $(Fe_{0.65}Mn_{0.35})_{75}P_{16}B_6Al_3$ there exist two second-order phase transitions such that spontaneous $M \rightarrow 0$ for $T \rightarrow T_c^-$ and $T_f^+$ and $\chi \rightarrow \infty$ for $T \rightarrow T_c^+$ and $T_f^-$.

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