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Magnetization distribution in an amorphous ferromagnet

C. C. Tsuei and H. Lilienthal
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598

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Experimental results of magnetization and Mössbauer measurements on an amorphous alloy $Fe_{75}P_{15}C_{10}$ are presented to show that there is a sizable fluctuation in exchange interaction in amorphous ferromagnets. Like several other amorphous ferromagnetic alloys, the spontaneous magnetization as a function of the reduced temperature for the amorphous alloy falls characteristically below those of crystalline ferromagnets such as Fe_3P and Fe. A comparison of the magnetization data with Handrich's theory for amorphous ferromagnets suggests that in the amorphous alloy the average variation in the exchange constant (J) can be as large as J itself. The Mössbauer spectrum is analyzed in terms of a distribution of hyperfine fields which suggests a spatial distribution of magnetization that is compatible with the exchange fluctuation as deduced from the temperature dependence of magnetization. The origin of magnetization fluctuation in amorphous alloys is discussed. It is pointed out that a broad distribution of magnetic ordering is consistent with the experimental observation of the coexistence of Kondo-type resistance minimum and ferromagnetism in amorphous alloys.

I. INTRODUCTION

Amorphous ferromagnetism has been a subject of considerable interest in recent years.[1] Both experimental and theoretical progress have been made towards a better understanding of the ferromagnetic ordering in solids which do not possess long-range periodicity in the atomic arrangement. In most of the theoretical work, amorphous ferromagnetism is discussed in terms of a distribution of the Heisenberg exchange interaction.[2-7] There is, however, a school of thought[8-12] which advocates that, at least in amorphous rare-earth transition-metal alloys (such as $HoFe_2$ and $TbFe_2$), the exchange interaction strength should be constant throughout the amorphous material because the basic interaction is believed to be of the Ruderman-Kittel-Kasuya-Yosida type. Therefore, it is important to investigate experimentally whether there is any significant fluctuation in exchange interaction in amorphous ferromagnetic alloys and what is the origin of the distribution of magnetization in these materials.

In this investigation, we present experimental results of magnetization and Mössbauer measurements on an amorphous ferromagnetic alloy $Fe_{75}P_{15}C_{10}$ to show that there is a sizable fluctuation in exchange interaction in this type of alloy. The manifestation of this unusually broad distribution of magnetic ordering in other properties such as low-temperature electrical resistivity will be discussed.

II. EXPERIMENTAL

The amorphous state of the alloy $Fe_{75}P_{15}C_{10}$ (atomic percents) is obtained by rapid quenching from the liquid state at a cooling rate of $\sim 10^6$ °C/sec. The details of alloy preparation were published elsewhere.[13] This alloy is chosen for this study for the following reasons: (i) It is a relatively well-studied amorphous ferromagnetic alloy system. For instance, the structure has been studied by x-ray diffraction.[14,15] Results of specific-heat,[16] neutron scattering[17] and transport-properties measurements[18,19] have been published. Some magnetization and Mössbauer studies have been performed on an alloy with a slightly different composition ($Fe_{80}P_{12.5}C_{7.5}$).[20] (ii) This alloy contains only one magnetic constituent and there is no complication of local magnetic anisotropy. (iii) The major component of the alloy, Fe, facilitates the Mössbauer measurement which provides important information about the distribution of the hyperfine field at the Fe nuclei. (iv) It is found that this alloy can be more readily quenched into the amorphous state than any other compositions of this alloy system. (v) Any macroscopic compositional gradient that might exist in a sample is highly undesirable for a magnetization distribution study because it can result in misleading conclusions. Fortunately, the extremely fast cooling of the liquid quenching[21] virtually insures the homogeneity of the amorphous alloys prepared with this technique.

In this investigation, two kinds of measurements were made on the amorphous ferromagnetic alloy: (i) spontaneous magnetization as a function of temperature up to the Curie temperature T_C and (ii) Mössbauer spectrum at room temperature.

At each temperature, the magnetization was measured as a function of magnetic field up to 20 kG with a standard-force magnetometer. The spontaneous magnetization was obtained either by extrapolation to zero field or, near the Curie point T_C by the method of thermodynamic parameter[22] as will be discussed in some detail in Sec. III. After being heated up to about 620 °K, the sample was remeasured at room temperature. The fact that there was no detectable change of magnetization value indicates that there was probably no irreversible change in the sample during the magnetization measurement. This is consistent with the fact the crystallization of this amorphous alloy starts around 400 °C when subjected to a heating at a rate of 1 °C/min.[23]

In order to gain information about the microscopic magnetic properties of this alloy, a Mössbauer spectrum at room temperature was obtained. This was done with a standard constant-acceleration Mössbauer spectrometer. The source was ^{57}Co in Cu which gave a linewidth of 0.28 mm/sec when used with a thin Fe absorber. The liquid-quenched samples are foils about 1 in. in diameter and ~40 μm thick. These foils were used directly as absorbers in the Mössbauer experiment. Both source and absorber were kept at room temperature.

III. EXPERIMENTAL RESULTS AND DATA ANALYSES

A. Spontaneous magnetization at absolute zero and determination of Curie temperature

Extrapolated to absolute zero, the spontaneous magnetization $M_s(0)$ is found to be 151 emu/g which corresponds to $1.8\mu_B$ per Fe atom (density of this alloy is 6.95 g/cm^3). The value of $M_s(0)$ for crystalline Fe$_3$P (the closest crystalline counterpart of amorphous Fe$_{75}$P$_{15}$C$_{10}$) is found to be ~$1.8\mu_B$/Fe atom. This result indicates that the amorphous nature of this alloy probably does not play an important role in effecting the value of the average magnetic moment of the Fe atom.

In order to present a meaningful reduced magnetization $\sigma = M_s(T)/M_s(0)$ versus reduced temperature T/T_C curve, the Curie temperature has to be determined unambiguously. The method of thermodynamic parameter[22] was used for this purpose. Near the Curie temperature, the following expression has been found to be useful in describing the magnetization σ:

$$\alpha(T) + \beta(T)\sigma^2 = H/\sigma \ , \qquad (1)$$

where $\alpha(T)$ and $\beta(T)$ are parameters to be determined experimentally and H is the applied magnetic field. A plot of σ^2 vs H/σ at various temperatures near the T_C for amorphous Fe$_{75}$P$_{15}$C$_{10}$ is shown in Fig. 1. The Curie temperature can be determined by the condition: $\alpha(T_C) = 0$. For the amorphous Fe$_{75}$P$_{15}$C$_{10}$ alloy, T_C is found to be 596.5 °K. This agrees very well with those obtained by measuring specific heat,[16] electrical resistivity,[23] and the method of inductance change.

B. Temperature dependence of spontaneous magnetization

With $M_s(0)$ and T_C determined, it is then straightforward to present the reduced spontaneous magnetization σ as a function of reduced temperature T/T_C except for temperatures near the Curie point. In this temperature range (say $0.85 < T/T_C \leq 1.0$), with the aid of Eq. (1), σ_s can be expressed as

$$\sigma_s^2 = -\alpha(T)/\beta(T) \ , \qquad (2)$$

where $\alpha(T)$ and $\beta(T)$ can be determined from Fig. 1. This method of determining σ_s near the T_C has been used in the magnetic study of crystalline Ni, disordered alloys Ni-Si, Ni-Cu,[22] and amorphous Co-P alloys.[24]

The temperature dependence of σ_s for amorphous Fe$_{75}$P$_{15}$C$_{10}$ is shown in Fig. 2. For comparison the σ_s-vs-T/T_C curves for crystalline Fe$_3$P and pure Fe are also presented in the same figure. The Curie temperature of Fe$_3$P was found to be 710 °K in good agreement with the published result.[25]

The results shown in Fig. 2 suggest that the corresponding states curve for the amorphous ferromagnetic material falls definitely below that for crystalling Fe$_3$P, and the σ-vs-T/T_C curve for Fe$_3$P is in turn lower than that for crystalline Fe. These experimental findings will be discussed in Sec. IV.

C. Mössbauer spectrum and hyperfine field distribution

The Mössbauer spectrum at room temperature is shown in Fig. 3(a). In contrast to the case of amorphous rare-earth–transition-metal alloys,

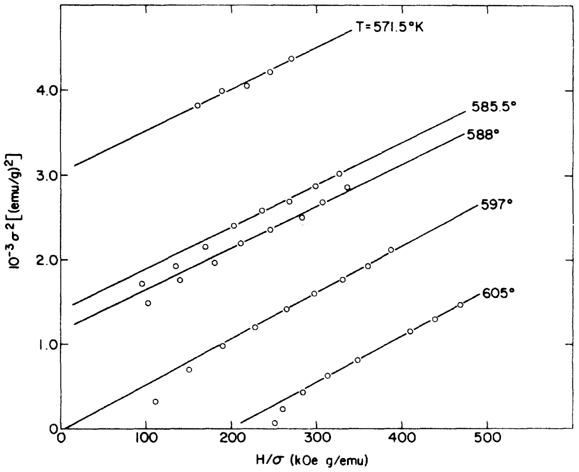

FIG. 1. Isotherms of the σ^2-vs-H/σ plot for the amorphous Fe$_{75}$P$_{15}$C$_{10}$ alloy. The Curie temperature T_C is 596.5 °K.

the Mössbauer spectrum (at $T/T_C \sim 0.5$) already shows a well-resolved and symmetrically located six-peak pattern with a considerable broadening of the outer peaks. It is noted that the inner peaks are relatively sharp. These features clearly suggest that, in this amorphous alloy, there is a distribution of hyperfine fields which reflects all possible varieties of local environments. As found in amorphous Fe-Pd-P alloys, the apparent absence of quadruple interaction below T_C can be attributed to a directional range of electric field gradients, with respect to the hyperfine field, which gives rise to a broadening rather than a line shift.[26] The Mössbauer spectrum can therefore be fitted in terms of a distribution of hyperfine fields $P(h)$, an average isomer shift and a linewidth which is allowed to vary in order to take into account of the effect of a random distribution of crystal fields. The best fit to the experimental data has been achieved by using the following model[26] of $P(h)$:

$$P(h)=\begin{cases} A[(h-h_0)^2+(\Delta_0/2)^2]^{-1} & \text{for } 0\le h\le h_0\,, \\ (4A/\Delta_0^2)\exp[-(h-h_0)^2/2\Delta_1^2] & \text{for } h>h_0\,, \end{cases} \tag{3}$$

where A is a normalization constant determined by the condition

$$\int_0^{\infty} P(h)\,dh=1\,. \tag{4}$$

The fitting of the experimental data based on this model is shown in Fig 3(a) by the solid curve (calculated spectrum). The fitting parameters used were

$$h_0=264.8,\quad \Delta_0=195.6,$$

$$\Delta_1=27.6 \text{ (all in units of kOe)}\,.$$

It should be mentioned that during the fitting, the linewidth of the component spectrum was allowed to vary to include the effects of random crystal-field distribution. The component linewidth of the calculated spectrum was found to be identical to that for the quadruple spectrum at $T>T_C$. This lends additional credence to the data fitting process itself. It should be mentioned also that the agreement between the experimental and the calculated spectra is much improved over that in a previous work.[20]

The $P(h)$ curve that corresponds to the fitting of Fig. 3(a) is plotted in Fig. 3(b). From this $P(h)$ curve, one can see that the hyperfine field as experienced by various iron sites range from 0 to a value close to that for pure iron (330 kOe). Of particular significance, there is a significant

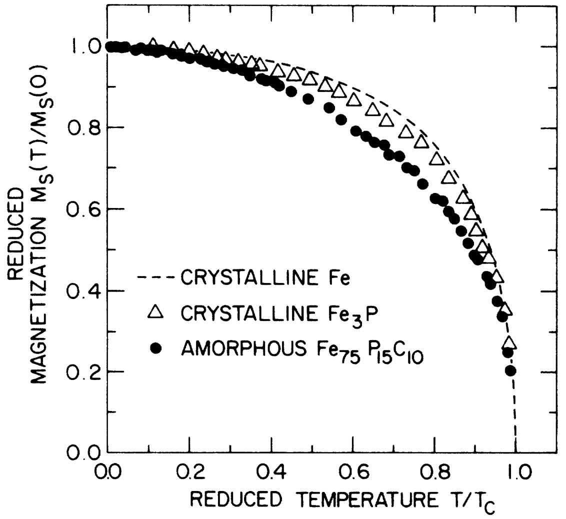

FIG. 2. Temperature dependence of the spontaneous magnetization of the amorphous $Fe_{75}P_{15}C_{10}$ alloy, crystalline Fe, and Fe_3P.

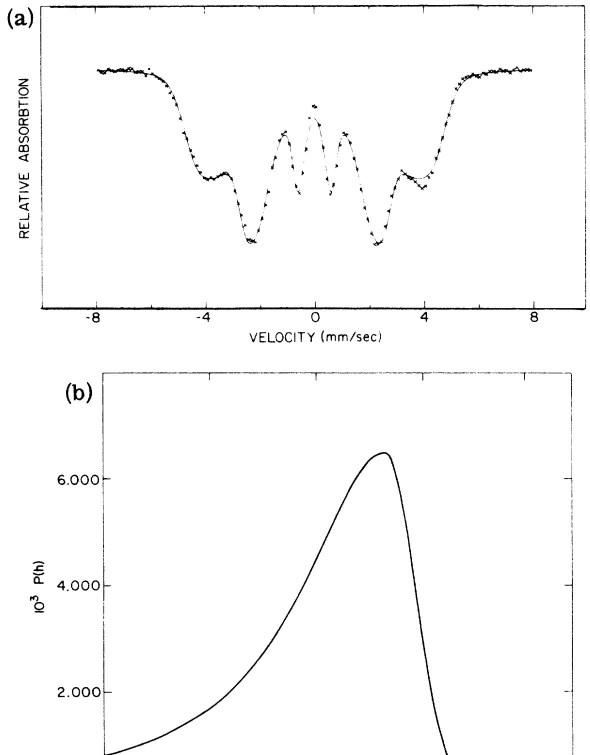

FIG. 3. (a) Mössbauer spectrum of the amorphous $Fe_{75}P_{15}C_{10}$ at room temperature. (b) The hyperfine field distribution function $P(h)$ for the amorphous $Fe_{75}P_{15}C_{10}$ alloy as obtained from the fitting of the Mössbauer spectrum shown in Fig. 3(a).

fraction of Fe atoms residing in a low effective field. The effect of this wide distribution of hyperfine field on other physical properties will be discussed in Sec. IV.

IV. DISCUSSION

A. Brief review of structural properties

As the magnetic properties of the amorphous $Fe_{75}P_{15}C_{10}$ is expected to be significantly influenced by its atomic arrangement, a brief summary of the results of structural study on this alloy is in order.

The structure of amorphous metallic alloys has been studied extensively by x-ray and electron diffraction. A comprehensive review of the experimental results in this field is provided by Cargill.[27] The basic findings can be summarized as the following: (i) The radial distribution functions (RDF) of the amorphous metallic alloys are basically quite similar if the differences in the atomic sizes are taken into account. This observation suggests that the structures (especially the short-range order) of these alloys are probably quite close to each other. Most of the amorphous alloys exhibit a split second peak in their RDFs which does not exist in the RDFs of liquid metals and alloys. (ii) It has been demonstrated that the structure of the amorphous alloys can be adequately described in terms of a model such as dense random packing of hard spheres (metal atoms) with glass former (Si, P, or B) occupying the larger holes inherent in a Bernel structure. This model provides an explanation for the splitting of the second RDF peak. It also indicates that in the amorphous alloys short-range order of intermetallic compounds such as Fe_3P and Fe_3C are essentially preserved. (iii) From the RDF results, it is found that there are about 12–13 nearest neighbors for a given metal atom. These neighboring atoms are located at an average distance of ~2.6 Å (for Fe-P-C alloys) and with a spread of ~0.5 Å.

B. Effect of structural disorder on M_s (0) and T_C

In view of the structural features just mentioned in Sec. IV A, it is of interest to find out, to what extent, basic magnetic properties such as $M_s(0)$ and T_C are effected by structural disorder. The answer can be obtained, in principle, by comparing the magnetic properties of an amorphous ferromagnet and those of its crystalline counterpart. This is, however, not feasible for the case of amorphous $Fe_{75}P_{15}C_{10}$ which crystalizes at ~400 °C into a predominant "Fe_3P" phase and other minor phases such as "Fe_3C" and "α-Fe."[23] Therefore, in the following discussion, the $M_s(0)$ and T_C of the amorphous $Fe_{75}P_{15}C_{10}$ are compared to those of the crystalline compounds Fe_3P [with $M_s(0) = 1.8\mu_B$/Fe atom and $T_C = 710$ °K] and Fe_3C [$M_s(0) = 1.9\mu_B$/Fe atom[28] and $T_C = 507$ °K].[29] The value of $M_s(0)$ for amorphous $Fe_{75}P_{15}C_{10}$ is $1.8\mu_B$/Fe atom which is essentially the same as that of the compounds Fe_3P and Fe_3C. The Curie temperature of the amorphous alloy is found to be 596.5 °K. A hypothetical compound ($Fe_3P_{0.6}C_{0.4}$) with a composition the same as that of the amorphous alloy would have a T_C of ~629 °K, if the T_C of this compound can be described as a linearly weighted average of the T_C's of Fe_3P and Fe_3C. At this point, it is of interest to point out again that the short-range order of crystalline Fe_3P and Fe_3C is essentially retained in the amorphous alloy. Therefore, it appears that magnetic properties such as $M_s(0)$ and T_C of the amorphous alloy are determined by short-range order and are not significantly effected as a result of the loss of long-range structural order.

C. Temperature dependence of magnetization

As shown in Fig. 2, the $M_s(T)/M_s(0)$-vs-T plot for the amorphous alloy is considerably lower than that of Fe_3P (the closest crystalline counterpart of the amorphous alloy) or crystalline Fe. This seems to be a general feature common to many amorphous ferromagnets.[20,24,26,30] The basic mechanism which is responsible for the phenomena is somewhat controversial. Various theoretical models have been proposed to explain the lowering of the corresponding state curve of the magnetization in amorphous ferromagnets. These theoretical investigations can be classified basically into two categories. (i) A unique constant exchange interaction between the magnetic constituents is assumed and the amorphous nature of the alloy is manifested in a random distribution of local anisotropy field.[9,10] (ii) In contrast to the approach just mentioned, a distribution of exchange integrals is assumed to reflect the structural fluctuations in the amorphous alloys.[3–8] It should be mentioned that this model does not exclude the possibility of a random distribution of electric field gradients. Both of the above-mentioned approaches predict that the $\sigma(T)$-vs-T/T_C curve for an amorphous ferromagnetic material will characteristically fall below that for the crystalline counterpart. Based on model (i) it was suggested[9,31] that amorphous ferromagnets should exhibit a flat (structureless) Mössbauer spectrum below T_C. This is not consistent with the experimental findings of this investigation and previous Mössbauer studies[20,26] on amorphous metallic alloys. Therefore, the magnetization results as a function of temperature for the amorphous alloy $Fe_{75}P_{15}C_{10}$ will be compared with the theoretical predictions based on model (ii). Of the various theories, the molecular-field approach by Handrich[3] is the most representative. Handrich's theory starts from the Heisenberg-Dirac Hamiltonian

$$H = -\sum_{i,j} J_{ij} \vec{S}_i \cdot \vec{S}_j \; . \qquad (5)$$

The basic assumption is that the structural fluctuations in amorphous ferromagnets will lead to fluctuations in the exchange interaction strength (J_{ij}). It is found that the effect of these fluctuations is to produce the following equation of state for the reduced magnetization:

$$\sigma(T) = \tfrac{1}{2}\{B_s[(1+\delta)\chi] + B_S[(1-\delta)\chi]\} \; , \qquad (6)$$

where $\chi = [3S\sigma/(S+1)]\,(T_C/T)$, and δ is a measure of the degree of disorder and is defined as the root mean square of deviation from an average exchange integral between two nearest-neighbor spins:

$$\delta^2 = \langle \Delta J^2 \rangle / \langle J \rangle^2 \; .$$

The magnetization as a function of T/T_C as calculated from Eq. (6) for the case of $S=1$ and various values of δ is shown in Fig. 4. It can be seen from these curves that the effect of increasing structural disorder is an increase in the depression of magnetization over the entire temperature range for $T \leq T_C$. It is of interest to point out in terms of this theory, the magnetization data for crystalline Fe and Fe_3P and amorphous $Fe_{75}P_{15}C_{10}$ as shown in Fig. 3 qualitatively suggest that the fluctuation in J in amorphous $Fe_{75}P_{15}C_{10}$ is the largest among the three. And that the magnetization curve for crystalline Fe_3P is lower than that of pure Fe is in accord with the fact that Fe_3P crystallizes in a tetragonal lattice[32,33] (space group $I\bar{4}$) with three equivalent crystallographic sites for Fe atoms.

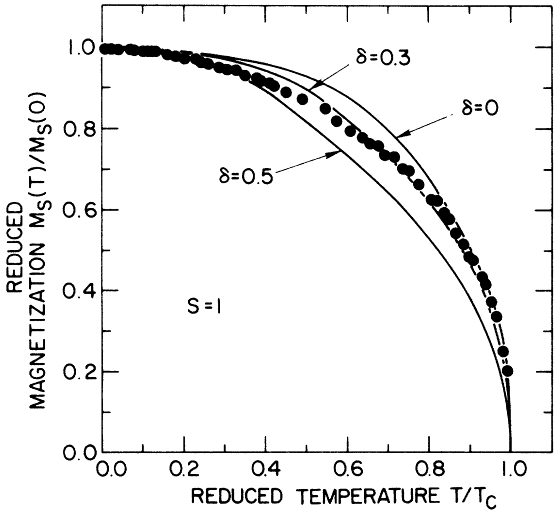

FIG. 4. Temperature dependence of the spontaneous magnetization for the amorphous $Fe_{75}P_{15}C_{10}$ alloy as compared with the prediction of Handrich's theory for $S=1, \delta=0, 0.3,$ and 0.5.

The experimental data for the amorphous alloy $Fe_{75}P_{15}C_{10}$ were shown again in Fig. 4 for a quantitative comparison with the prediction of Handrich theory. It was found that the curve with $\delta = 0.3$ gives the best over-all fit to the experimental points. From Fig. 4, it is quite obvious that the theory does not quantitatively describe the temperature dependence of the magnetization, especially at low temperatures. It does, however, provide an order-of-magnitude estimate of the fluctuation in exchange interaction. In the case of amorphous $Fe_{75}P_{15}C_{10}$, the experimental data ($\delta \cong 0.3$) suggest that the average variation in J can be the same order of magnitude as J itself. In this regard, the magnetic hyperfine field data also suggest a spatial distribution of magnetization that is comparable with the exchange fluctuation as deduced from the temperature dependence of magnetization. This can be best seen by calculating the following quantities:

$$\bar{h} = \int_0^\infty P(h)h\,dh = 203 \text{ kOe} \; ,$$

$$\Delta^2 = \int_0^\infty (h - \bar{h})^2 P(h)\,dh = 5522 \text{ kOe}^2 ,$$

$$\Delta = 74.3 \text{ kOe}, \quad \Delta/\bar{h} = 0.36 \; .$$

Since in nondilute Fe alloys, it has been established experimentally that the magnetic hyperfine field seen by a given ^{57}Fe atom is proportional to its local magnetization,[34] the quantity $\Delta/\bar{h}$ is then a measure of the ratio of root mean square to the average magnetization. Therefore, the quantity $\Delta/\bar{h} = 0.36$ is consistent with the estimate of $\delta \sim 0.3$ from the temperature dependence of magnetization.

As it is well-known that the molecular-field theory of magnetization is inadequate in describing the demagnetization behavior at low temperatures, the data are plotted as a function of $T^{3/2}$ for temperature below 125 °K (i.e., $\sim 0.2T_C$). As shown in Fig. 5, the low-temperature results follow closely the Bloch spin-wave theory and can be described by

$$\sigma(T) = 1 - BT^{3/2} \; ,$$

where B is found to be $\sim 2.2 \times 10^{-5}$ $(°K)^{-3/2}$ which is comparable with those found previously in several other amorphous ferromagnetic alloys.[35,36]

D. Origin of magnetization fluctuation

Both magnetization and Mössbauer data show that there is a spatial distribution of magnetization in the amorphous alloy under investigation. In an amorphous solid, there are two kinds of disorder which can be the source of the observed fluctuation in magnetization: (i) compositional disorder and (ii) structural disorder. The former is common in both the crystalline and amorphous alloys while the latter prevails only in amorphous materials. It is rather difficult to decide to what extent each kind of disorder contributes to the magnetization distribution. From the fact that the Mössbauer spectra in amorphous ferromagnets could not be fitted with a model in which the hyperfine field at a given Fe site is a function of the number of P or C nearest neighbors as determined by a binomial distribution, one can conclude that the contribution by the structural disorder must be quite significant. Furthermore, the magnetization curve for amorphous $Fe_{75}P_{15}C_{10}$ alloy is lower than that of crystalline Fe_3P in spite of the fact that they have similar short-range order suggests that the lack of long-range structural periodicity and the spread in the interatomic distances are instrumental in lowering the magnetization curve.

Given a distribution of exchange interaction among the Fe atoms, the over-all temperature dependence of the magnetization of the amorphous alloy can also be qualitatively understood in terms of the spin-wave "impurity" states in ferromagnets.[37-40] The magnetization of an impurity atom in a ferromagnetic host (for instance an Fe alloy containing 1.5-at.% Mn) has been experimentally found to decrease much faster than that of the host.[41] This temperature dependence of the impurity magnetization can be described well by a simple molecular-field model based on the concept of virtual spin-wave state. The theoretical justification of this approach was pointed out by Callen *et al.*[40] in a thermal Green's-function calculation of the magnetization of spin impurities in ferromagnets. Similar calculations[38,39] also show that localized spin-wave states above the spin-wave band as well as virtual states within the band could be formed for a ferromagnet containing weakly coupled magnetic impurities. Of these states, the low-lying virtual s-like states which result in a large density of states at low energies, were shown to give rise to an accumulation of spin disorder in the vicinity of the impurity resulting in a local decrease in magnetization.[39]

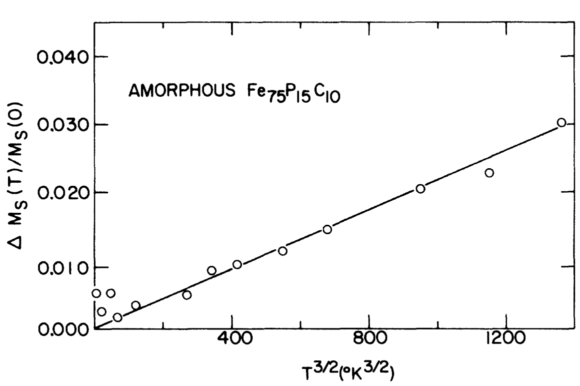

FIG. 5. Demagnetization behavior of the amorphous $Fe_{75}P_{15}C_{10}$ alloy at low temperatures [$\Delta M_s(T) \equiv M_s(o) - M_s(T)$].

A similar situation probably exists in the amorphous ferromagnet where a distribution of the exchange interaction could lead to spatial fluctuations in magnetization as inferred from the Mössbauer data. The characteristic relatively fast decrease in magnetization with increasing temperature for amorphous ferromagnets is then just a manifestation of the temperature dependence of those magnetic spins with exchange interaction strength that deviates sufficiently from the average. The concept of a distribution of exchange integral is also in accord with the experimental observation of the coexistence of the Kondo-type resistance minimum and ferromagnetism: The existence of Kondo-type effect in a ferromagnet was first observed in the Co-Pd-Si alloy system.[42] Similar results were reported in several amorphous ferromagnetic alloys including Fe-P-C alloys.[43,44] As Kondo-type s-d scattering is based on the condition that d spins have the spin-flip capability,[45] this experimental finding requires some reconciliation with the original Kondo theories which are all based on the assumption that the magnetic spins are all isolated from each other. In this regard, there were several theoretical attempts[46-49] to explain the phenomenon. The possibility of the existence of weakly coupled d spins in a strongly ferromagnetically ordered material suggests, however, that the observed effect can be due to the fact that these weakly coupled Fe atoms can still contribute in the spin-flip-scattering process which leads to a Kondo-type resistance minimum as pointed out previously.[26] It should be recognized that the original Kondo theory which is based on a single-impurity assumption is probably not adequate to describe the spin-flip scattering in amorphous ferromagnets as the many-impurity effect has to be taken into account.

V. CONCLUDING REMARKS

We have analyzed the results of magnetization and Mössbauer measurements on an amorphous alloy $Fe_{75}P_{15}C_{10}$ to show that there is a significant magnetization distribution in an amorphous ferromagnet. It was concluded that the magnetic properties such as $M_s(0)$ and T_C of an amorphous ferromagnet are determined mainly by short-range order and are not significantly effected as a result of losing the long-range structural order. The lack of periodicity and the spread in the interatomic distance are instrumental in that the spontaneous magnetization as a function of the reduced temperature for amorphous alloys falls characteristically below those of crystalline ferromagnets. The over-all temperature dependence of the magnetization of an amorphous alloy can be qualitatively understood in terms of the spin-wave "impurity" states in ferromagnets, if a distribution of exchange interaction among the magnetic constituents is assumed. A magnetization fluctuation in amorphous alloys is also consistent with the experimental observation of the coexistence of Kondo-type resistance minimum and ferromagnetism.

In view of the results discussed in this work, it is clear that a realistic distribution of exchange interaction is essential in any theoretical description of the temperature dependence of magnetization in an amorphous ferromagnet. The effect of a magnetization distribution is expected to give rise to a large increase in low temperature specific heat.[39] Therefore, it is worthwhile to measure the specific heat of amorphous ferromagnets over a wide temperature range and to compare with that of nonmagnetic amorphous alloys such as Pd-Si or Ni-P alloys.

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