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SPIN-GLASSES IN AMORPHOUS \((\text{Ni}_{100-x}\text{Fe}_x)^{79}\text{P}_{13}\text{B}_8\) ALLOYS

J. DURAND* and S.J. POON**

W.M. Keck Laboratory of Engineering Materials, California Institute of Technology, Pasadena, California 91125, U.S.A.

INTRODUCTION.- From magnetization, remanence and magnetoresistivity data for dilute and concentrated spin-glasses in the amorphous La-Gd-Au system /1/, it has been shown that spin-glass phenomena in an amorphous medium can be analyzed in terms of RKKY (and dipolar) interactions the same way as usually done for canonical crystalline spin-glasses. In particular, magnetization and susceptibility data for \(x_{\text{Fe}}>1\) at. \% were found to follow the Blandin-Souletie-Tournier /2/ (BST) scaling laws of the form \(x = f(T/x)\) and \(M/x = f(H/x,T/x)\). For \(x_{\text{Fe}}>1\), no such regularities were observed. However, the freezing temperature \(T_{\text{M}}\) (defined by a sharp cusp in the zero-field susceptibility) still scales with \(x\) up to \(x=12\) at. \%. Such singularities were tentatively explained within a ferromagnetic cluster mean-field description of concentrated spin-glasses /4/. The departures from the BST scaling laws observed for magnetization of concentrated spin-glasses were attributed to the building up of clusters, whose average size \(S^*\) and concentration \(x^*\) are correlated to the individual spin parameters \(x\) and \(S\), by \(x^* S^* = xS\). These clusters are coupled by an effective RKKY interaction, the strength of which \(V^*\) is concentration dependent and verifies roughly the relation \(V^* = V_0 S^*/x S(S+1)\), being defined in the dilute limit. Thus, \(T_{\text{M}}\) which is proportional to \(x^* S^* (S^*+1)V^*/V_0 = x S(S+1)V_0\) remains proportional to \(x\) even in the concentrated spin-glasses as long as the clusters do not overlap. In contrast, the BST scaling laws for magnetization have to be modified for clusters into the form \(M/x = f(H/x,T/x)\). It is interesting to check whether such a model holds for concentrated 3d amorphous spin-glasses.

For this purpose we studied the magnetization of amorphous \((\text{Ni}_{100-x}\text{Fe}_x)^{79}\text{P}_{13}\text{B}_8\) alloys of nominal concentration \(x=0.2, 1, 2, 3\) and \(4\) at. \%. A brief description of the magnetic phase diagram of the amorphous \(\text{Ni-Fe-P-B}\) system has been already presented /5/. Up to \(x=4\) at. \% \(\text{Fe}\), the zero-field susceptibility cusp \(T_{\text{M}}\) is proportional to \(x(T_{\text{M}}^*/x = 1.8 \text{K/at.}%)\). At higher concentrations, \(T_{\text{M}}^*/x\) increases more rapidly with \(x\). The critical concentration for ferromagnetism is estimated to be \(x_\text{c} \approx 7\) at. \%. The magnetic properties of the \(\text{Ni}_{73}\text{P}_{13}\text{B}_8\) matrix have been discussed previously /6/.

RESULTS AND DISCUSSION.- We report on results of magnetization (\(600\text{ kG}\)) measurements with a Faraday balance for temperatures ranging from 1.8 to 300 K. The samples were prepared by splat-cooling from the melt. Each foil was checked by a Norelco X-ray diffractometer.

The saturation moment at 1.8 K (as determined by an extrapolation to \(1/\text{Bo}\)) varies linearly with \(x\) and its intersection at \(x=0\) gives exactly the value measured for the matrix. Thus, the nominal concentration will be taken as exact. The saturation moment per \(\text{Fe}\) atom (after correction for
the matrix) is $4.5 \pm 0.2$ which yields $S=2.25 \pm 0.10$ by assuming $g=2$. The linear dependence on $x$ of the Curie-Weiss constant at high temperature $\frac{1}{5}$ gives for $S$ a value of $2.35 \pm 0.30$. Therefore, the Fe moment is localized in the sense of the Rhodes-Wohlfarth criterion $\frac{1}{7}$. An interesting feature observed in these spin-glass alloys is that the magnetization does not follow the BST scaling laws which characterize a canonical spin-glass over the concentration range where $T_M$ varies linearly with Fe content. This can be explained in the same way as for amorphous La(Gd)Au alloys $\frac{1}{4}$ within a description of ferromagnetic clusters for concentrated spin-glasses.

For the $x=0.2$ at.% sample, no clustering effect is visible from the Curie-Weiss constant at low temperature ($T>1.8$ K). The strength of the RKKY interaction $V_o$ as determined from Larkin’s method $B_l$ is $V_o = 2.45 \times 10^{-37}$ erg cm$^3$. This value is higher by an order of magnitude than that obtained for dilute Gd in amorphous La$_{90}$Au$_{20}$. It is much lower than $V_o$ in crystalline Mn$_{1.2}$Fe$_{8.8}$/9, but quite close to $V_o$ in crystalline MnFe $\frac{1}{10}$, in agreement with the values of $T_M/x$ in these different systems.

For the $x>1$ samples, ferromagnetic clusters are evidenced at low temperatures ($T<T<0$). For example, in the $x=1$ alloy $\frac{1}{5}$ $T_M=1.8$ K, $\delta=30$ K ($\delta$ being the extrapolation of the Curie-Weiss law at high temperature), from initial susceptibility and saturation moment the size $S^{*}$ and concentration $x^{*}$ of clusters are roughly constant between 4.2 and 14 K and equal to 6.2 and 0.37 at.% respectively. Concentration of clusters can be evaluated at progressing concentration by scaling two isotherms for different Fe content over the whole field range (figure 1), yielding $x^{*}=0.45$ and 0.50 for $x=2$ and $x=3$ samples, respectively. The BST scaling laws modified for clusters do not hold for $x=4$, anymore, indicating a trend toward percolation. Assuming non-overlapping ferromagnetic clusters the relation $x^{*}S^{*}$ for $x=2$ and 3, $8^{*}=10$ and 13, respectively. The strength $V_0^{*}$ of the effective intercluster interaction as determined from Larkin’s method is $0.09$, $0.37$, and $0.15$ (in $10^{-37}$ erg cm$^3$), for $x=1$, 2 and 3, respectively. For $x=1$, one obtains $V_0^{*}$=5.7$\times$10$^{-37}$ erg cm$^3$, which is very close to $V_0 S = 5.5 \times 10^{-37}$ erg cm$^3$ deduced in the dilute limit ($x=0.2$). For higher concentrations, $V_0^{*}$ departs gradually from $V_0 S$ ($V_0^{*} S^{*}=3.7$ for $x=2$) suggesting that the assumption of non-overlapping clusters is not perfectly satisfied.

![Fig. 1: Reduced magnetization $\Delta M/x$ as a function of reduced magnetic field for clusters $H/x$ at two different reduced temperatures for alloys with $x=1$, 2 and 3. (Matrix contribution is subtracted in $\Delta M$).](image)

To conclude, our model for concentrated spin-glasses can explain qualitatively the concentration dependence of $T_M$ and $H(x,T)$ ($T_M < 0$) in amorphous Ni(Fe)PB alloys. Due probably to the spatial extent of 3d wave functions as compared with 4f ones (and, possibly, due to polarization of surrounding Ni atoms), the quantitative agreement is poorer than in amorphous La(Gd)Au alloys.

References