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MUON SPIN RELAXATION IN FERROMAGNETIC PdMn

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ABSTRACT

Positive-muon (μ^+) spin relaxation experiments have been carried out in the dilute ferromagnetic alloy Pd + 2 at.% Mn ($T_c = 5.8$ K). In the paramagnetic state the inhomogeneous μ^+ linewidth is proportional to the bulk magnetization. Below T_c the μ^+ linewidth and the width of the μ^+ local field distribution in zero applied field are both in qualitative accord with the Sherrington-Kirkpatrick theory of disordered magnets.

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I. INTRODUCTION

Many properties of magnetic materials have been found to depend sensitively on the presence and statistical properties of random exchange interactions. If the width of the distribution of exchange constants is much larger than the mean exchange constant one speaks of a spin glass system, whereas in the opposite limit the system is ferromagnetic, even though the exchange constant is not unique. The binary alloy PdMn appears to exhibit both spin-glass and ferromagnetic phases [1], depending on the Mn concentration. The ferromagnetic phase (Mn concentrations below ~3 at. %) allows the study of ferromagnetism in the presence of considerable disorder in the exchange interactions.

We have carried out muon spin relaxation (μ SR) experiments in a ferromagnetic PdMn alloy, to obtain microscopic information on the nature of ferromagnetism in a disordered alloy and to compare this information with similar experiments on true spin-glass systems [2,3]. Comparison of μ SR data with magnetization measurements and with mean-field theories of uniform [4] and disordered [5] ferromagnets can be used to infer microscopic properties of such systems. In particular, the observed "shortfall" of the saturation magnetization in ferromagnetic PdMn alloys [6] is mirrored in the μ SR transverse relaxation rate λ_1 . This suggests that disorder in the ferromagnetic spin configuration is indeed microscopic in scale. Inhomogeneous broadening of the μ SR in the paramagnetic state of PdMn is very different from that in the "classic" spin glasses, such as AgMn [2] and CuMn [3]; this appears to be due to the effect of disorder in the exchange constants.

II. EXPERIMENT

μ SR experiments were carried out on a $\text{Pd}_{1-x}\text{Mn}_x$ alloy, $x = 2$ at. %, at the Stopped Muon Channel of the Clinton P. Anderson Meson Facility (LAMPF), Los Alamos National Laboratory. Both transverse and longitudinal geometries (with respect to the initial muon polarization) were employed; the longitudinal geometry permits experiments in zero and finite applied longitudinal fields. Since longitudinal spin-lattice relaxation was found to be much weaker than transverse relaxation over most of the range of temperature and field, the transverse relaxation rate $\lambda_{\perp}$ reflects only the width of the distribution of quasistatic internal dipolar [2,3] fields. Data were taken for temperatures between 3 and 300 K and for applied magnetic fields between 0 and 0.5 T. Time-differential histograms were analyzed by least-squares fits to standard expressions for differential count rates [7]. The distribution width $a(T)$ in zero applied field was obtained from fits of zero-field μ SR data to the well-known "spin glass" relaxation function [2,3], which is also appropriate to a dilute random ferromagnet with dipolar coupling between μ^+ and impurity spins and randomly-oriented domains.

III. STATIC LOCAL FIELD DISTRIBUTIONS

Figure 1 gives the temperature dependence of $\lambda_{\perp}$ for three values of the applied field. At high temperatures ($T \gtrsim 1.5T_c$) the data are well fit by a Curie-Weiss law (solid lines in Fig. 1)

$$\lambda_{\perp} = 4.91 \text{ H}/(T - \theta_p) = M_z, \quad (1)$$

where M_z is the bulk magnetization, with $\theta_p = 7.1$ K. The ratio $\lambda_{\perp}/M_z$ is in

good agreement with the calculation of Walstedt and Walker [8] (WW) of the NMR or μ SR linewidth due to randomly-positioned paramagnetic impurities, each with the same polarization $\langle S_z \rangle$, which interact with nuclei or μ^+ moments via dipolar fields. This suggests that any inhomogeneity in the Mn impurity-spin polarization, if present above T_c , is not evident in the μ SR data. This behavior is to be contrasted with μ SR measurements in spin-glass AgMn [9], where the observed linewidth becomes more rapid than predicted from the magnetization as the "glass" temperature is approached from above.

The μ^+ linewidth $(\lambda_L)_{sat}$ corresponding to a saturated Mn spin system ($\langle S_z \rangle = S$) can also be calculated following WW, and is indicated on Fig. 1. It is of the same order of magnitude as the measured λ_L at $T = 3 \text{ K} \approx 0.52 T_c$, but there is a considerable "shortfall". A simple mean-field (MF) model for a homogeneous spin system polarization ($\langle S_z \rangle$ independent of position) leads to the dashed curves of Fig. 1 for the μ^+ linewidth, which overestimate the data below T_c . Moreover, the width $a(T)$ of the quasistatic dipolar field distribution in zero applied field, shown in Fig. 2, also exhibits a shortfall with respect to the homogeneous MF model (dash-dot line in Fig. 2). An even greater shortfall has been observed in the spontaneous bulk magnetization [6], and attributed to the formation of antiferromagnetic pairs.

A qualitative description of these results is given by the Sherrington-Kirkpatrick (SK) model of a random magnet [5]. This model assumes Ising spins and a Gaussian distribution of infinite-ranged exchange interactions. The replica-symmetric [5] mean-field solution of the model yields coupled equations for the quantities $m \equiv \langle S_z \rangle$ and $q \equiv \langle S_z^2 \rangle$, where $\langle \rangle$ indicates a thermal average and $[]$ indicates an average over the exchange dis-

tribution. Then in the fast-fluctuation limit [8] appropriate to the ferromagnetic state [10] both λ_L and $a(T)$ are proportional to the quantity $r \equiv [|\langle S_z \rangle|]$. (The absolute value reflects the invariance of the dipolar field distribution under inversion of the impurity spins.) The temperature dependence of r can then be obtained using its definition and the values of $\underline{m}$ and $\underline{q}$ obtained from the SK equations.

This has been done for various values of J_0 and J , where J_0/N is the mean and J^2/N is the variance of the exchange-constant distribution [5]. Here N is the number of spins. The results are shown in Fig. 2. (If $J_0 > J$ in the SK model, the system is ferromagnetic with a Curie temperature $T_c = J_0/k_B$.) For $J_0/J = 1.1$ (solid curve in Fig. 2) the result is in good qualitative agreement with the experimental data. Similar agreement is found in non-zero applied field, and for the spontaneous magnetization data [6] from a Pd + 2.7 at. % Mn specimen [10]. The fact that a microscopic model for these phenomena agrees well with both macroscopic (spontaneous magnetization) and microscopic (μ SR linewidth) data suggests that the Mn-spin system disorder is indeed microscopic in scale, rather than being due to large ferromagnetic clusters or domains. The μ SR data are insensitive to the ferromagnetic correlation length, but in principle this information is available from neutron diffraction studies [11].

A fuller account of our results, including a description of μ^+ spin-lattice relaxation measurements, will be published elsewhere [10]. This work was performed under the auspices of the U.S. Department of Energy, and was supported by the U.S. National Science foundation, grant nos. DMR-7909223 and DMR-8115543, and by the Netherlands "Stichting voor Fundamenteel Onderzoek der Materie" (FOM).

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FIGURE CAPTIONS

FIG. 1. Temperature and field dependence of the transverse μ^+ relaxation rate $\lambda_{\perp}(H,T)$ in ferromagnetic Pd + 2 at. % Mn. Circles: $H = 200$ Oe. Triangles: $H = 1$ kOe. Squares: $H = 5$ kOe. The solid curves were obtained from magnetization data (see text). The dashed curves were obtained from the homogeneous mean-field model (see text).

FIG. 2. Temperature dependence of the zero-field μ^+ quasistatic field distribution width $a(T)$ (in frequency units) in Pd + 2 at. % Mn. Solid curve: SK model (see text), $J_0 = 5.8$ K, $J_0/J = 1.1$. Dashed curve: SK model, $J_0 = 5.8$ K, $J_0/J = 1.5$. Dash-dot curve: homogeneous mean-field model, $T_c = 5.8$ K, $S = 5/2$.