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MUON SPIN RELAXATION IN SPIN GLASS PdMn

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ABSTRACT

Muon spin relaxation (μ SR) rates have been measured in transverse, longitudinal, and zero applied field for the spin glass PdMn (7 at. %), and are compared with a previous study of the disordered ferromagnet PdMn (2 at. %). The calculated paramagnetic state transverse field relaxation rate for non-interacting spins is much larger than the observed rate in spin glass PdMn, but is in good agreement with ferromagnetic PdMn. The zero field relaxation rate shows a sharp cusp at $T_g=5K$. An applied longitudinal field of 5 kG is insufficient to suppress this cusp in spin glass PdMn, but will suppress a similar cusp in ferromagnetic PdMn. Below T_g , a distribution of quasistatic local fields is observed in zero field, which has the same temperature dependence for both samples. Comparisons with model calculations are discussed.

I. Introduction

Spin glass PdMn has been widely studied as an example of a non-RKKY spin glass.^{1,2} A competition between direct anti-ferromagnetic couplings and long range ferromagnetic couplings leads to a complicated phase diagram with a ferromagnetic phase for $c \lesssim 3$ at. %, and a spin glass phase for $c \gtrsim 5$ at. %.³ In this work, muon spin relaxation (μ SR) is used as a microscopic probe of the ordering in spin glass PdMn (7 at. %). The main goal of this work is to measure the temperature and field dependence of both the quasistatic local field distribution at the muon site and the muon's dynamic spin lattice relaxation. Theories of linewidths and relaxation mechanisms in dilute alloys are used to infer features of the impurity spin configuration. Comparisons with a previous study of ferromagnetic PdMn (2 at. %)⁴ are used to show how the difference in magnetic ordering brought about by a change in concentration influences microscopic properties.

The experiments were carried out at the Stopped Muon Channel of the Clinton P. Anderson Meson Physics Facility (LAMPF) at the Los Alamos National Laboratory, using a standard μ SR spectrometer.⁵ The sample was in the form of a polycrystalline disk 3 mm thick and 30 mm in diameter; preparation techniques have been described in an earlier paper.⁴ Ac susceptibility measurements showed a cusp at $T_g = 5K$, consistent with the system phase diagram.⁶

II. Quasistatic Field Distributions

Figure 1 shows measured transverse field exponential relaxation rates for applied fields of 200 G, 1 kG, and 5 kG. Measured spin lattice relaxation rates (discussed below) indicate that

the non-secular contribution to λ_1 is small. In addition, measurements of muon diffusion in Pd with Gd impurities indicate a negligible diffusion rate below about 100K.⁷ Thus the rates shown in figure 1 represent only the quasistatic field distribution in PdMn.

Walstedt and Walker⁸ (WW) have shown that if the local environment around the muon consists of non-interacting and equivalent, rapidly fluctuating spins distributed at random at concentration c , then in the dilute limit the relaxation is exponential with rate

$$\lambda_1 = \lambda_{10} \langle S_z \rangle \quad (1)$$

where $\langle S_z \rangle$ is the thermal average of the z component of the impurity spin. If the impurity spins are quasistatic (slow fluctuations) then this expression becomes

$$\lambda_1 = \lambda_{10} \langle |S_z| \rangle \quad (2)$$

For pure dipolar coupling,

$$\lambda_{10} = \frac{8\pi^2}{9\sqrt{3}} N_0 c \gamma_\mu^2 g^2 \quad (3)$$

where N_0 is the density of impurity sites, γ_μ is the muon gyromagnetic ratio, and g is the impurity spin g factor. These expressions are for the case of a large applied field, so that only components of impurity spins parallel to the applied field contribute to the z component of the local field distribution at the muon.

The observed paramagnetic susceptibility in a PdMn (5 at. %) sample is well described by a $g = 2$, $S = 5/2$ Curie law for $T \gtrsim 3T_g$

and low field,¹ so that using this Curie law for $\langle S_z \rangle$ in equation (1) gives the lines shown in Figure 1. At low temperatures, we simulate the spin glass state by assuming spins to be quasistatic and equally distributed among the $2S + 1 M_S$ states in calculating the order parameter $\langle |S_z| \rangle$. Equation (2) then gives the high field frozen spin linewidth

$$(\lambda_1)_{\text{frozen}} = 57.1 \mu\text{s}^{-1} \text{ (high field)}. \quad (4)$$

A concentration of 7 at. % is not ordinarily considered to be in the dilute limit, so we have calculated a polycrystalline averaged lineshape numerically; the result differs in width from the WW result by no more than 7%.

The discrepancy in figure 1 between the λ_1 data and the WW prediction using a Curie law well above T_g is not understood. Similar data on the disordered ferromagnet PdMn (2 at. %) ⁴ show very good agreement with the WW result. We conclude that the observed discrepancy is due to the spin glass ordering, and is present for T well above T_g . Transverse field μ SR results in spin glass AgMn show an increase above the WW result to at least $10 T_g$.⁹

In zero applied field, the WW result is no longer valid, since all three components of the local field distribution contribute to the muon relaxation. Mikaelyan and Smilga¹⁰ have generalized the WW expression to the case of zero field relaxation in a spin glass. The low temperature spin glass state is simulated by assuming quasistatic classical impurity spins, each of length S

and oriented along a randomly chosen local field direction. The resulting muon local field distribution is Lorentzian, with width

$$a = 0.827 \lambda_{LO} S \quad (5)$$

which is in good agreement with the Monte Carlo simulation of Fiory.¹¹ For PdMn(7 at. %), equation (5) gives a zero field frozen spin linewidth

$$a_0 = 78.8 \mu s^{-1} \text{ (zero field)}. \quad (6)$$

The zero field muon relaxation function allows a separation between a quasistatic field distribution of width a , and relaxation due to dynamic spin lattice relaxation processes. If we assume the fluctuation rate to be fast compared with a , then the long time decay will be a 'root exponential'.¹² Thus for fast dynamic fluctuations, the zero field relaxation function is

$$G_z(t) = \frac{1}{3} \exp(-(\lambda_{||} t)^{1/2}) + \frac{2}{3} (1 - at) \exp(-at). \quad (7)$$

The measured zero field relaxation data were fit to equation (7) for the width of the quasistatic local field distribution (a) below T_q . The temperature dependence of a is shown in figure 2, normalized to a_0 . The scaled quasistatic width in ferromagnetic PdMn(2 at. %)⁴ is also shown in figure 2. The similar temperature dependence in the two cases indicates that the development of a static field distribution is independent of the character of the magnetic ordering.

III. Spin Lattice Relaxation

Figure 3 presents measured muon spin lattice relaxation rates in zero and applied longitudinal field above and below T_g . Above T_g , the relaxation was fit to the 'root exponential' form appropriate for rapidly fluctuating (paramagnetic) spins in a dilute alloy,¹²

$$G_z(t) = \exp(-(\lambda_{||} t)^{1/2}) \quad (8)$$

with rates plotted in figure 3. Fits of the data to a simple exponential form for $G_z(t)$ yield a similar chi-squared value, so that we have not explicitly demonstrated the root exponential form. Below T_g , we expect that fluctuations will remain rapid, since this has been observed by μ SR in spin glass AgMn.¹³ Thus a root exponential decay of the 1/3 component (equation (7)) was used to fit the zero field data for $\lambda_{||}$.

The peak in the zero field spin lattice relaxation rate at T_g is interpreted as being due to a change in the power spectrum of Mn spin fluctuations near the glass transition. Other μ SR measurements in spin glass systems (AgMn, CuMn)^{13,14} show a similar dramatic change in the Mn spin fluctuations around T_g . Note that a relaxation mechanism is still effective near T_g in an applied field of 5 kG, whereas in ferromagnetic PdMn (2 at. %) an applied field of 5 kG completely suppresses the fluctuation induced relaxation.⁴

At temperatures well below T_g , spin lattice relaxation is presumably due to low energy excitations of the ground state.¹⁵

¹⁶
 A calculation of the spectrum of excitation frequencies for spin glass PdMn (10 at. %) has shown a complicated three peak structure, with the mean spectral weight at a frequency $\sim 5 \times 10^{12} \text{ s}^{-1}$. Since these fluctuations are much too fast to cause depolarization via the dipolar interaction in the lifetime of the muon, the observed relaxation must be due to some other, lower frequency component of the excitation spectrum. Recent analytic theories of spin wave excitations in spin glasses predict that small k magnons can propagate through the system with a dispersion relation linear in k .¹⁷ These excitations are at frequencies lower than the localized modes, and may be responsible for the relaxation observed at low temperatures. Future zero field μ SR studies in spin glasses at lower temperatures may provide useful data on relaxation for comparison with these theories.

IV. Conclusions

The transverse field relaxation rate $\lambda_{\perp}$ is not proportional to the observed Curie law magnetization in PdMn (7 at. %) for temperatures as high as 100K ($20 T_g$), where the onset of muon diffusion makes interpretation of $\lambda_{\perp}$ difficult. This result is especially surprising since $\lambda_{\perp}$ in ferromagnetic PdMn (2 at. %) is proportional to a Curie-Weiss magnetization over a wide temperature range, indicating that the observed reduction in $\lambda_{\perp}$ below

the Curie law prediction may be a high temperature precursor of the spin glass phase. We know of no satisfactory explanation for this effect nor for the increase in $\lambda_{\perp}$ above the measured magnetization in spin glass AgMn (1.6 at. %).

In zero field, we observe the onset of a quasistatic field distribution below T_g with a similar temperature dependence to that observed in PdMn (2 at. %). Spin lattice relaxation near T_g shows a strong cusp, indicating a change in the spectrum of Mn spin fluctuations. These fluctuations continue to induce relaxation in a large applied field, in contrast to PdMn (2 at. %).

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FIGURE CAPTIONS

- Figure 1. Temperature and field dependence of the transverse muon relaxation rate $\lambda_{\perp}$ in PdMn(7 at. %). Circles: 200 G. Triangles: 1 kG. Squares: 5 kG. The solid lines are from equation (1) using a Curie law for $\langle S_z \rangle$. $(\lambda_{\perp})_f$ is the frozen spin rate (equation (4)).
- Figure 2. Reduced temperature dependence of the zero field quasistatic field distribution width $a(T)$, normalized to the theoretical zero field frozen rate a_0 . Open circles: PdMn (2 at. %), $a_0 = 28. \mu s^{-1}$, $T_c = 5.8$ K. Filled circles: PdMn (7 at. %), $a_0 = 78.8 \mu s^{-1}$, $T_g = 5$ K.
- Figure 3. Temperature and field dependence of the muon spin lattice relaxation rate. Circles: zero field. Triangles: 200 G. Squares: 5 kG. Fitting functions used are described in the text.

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Fig. 2

Fig. 3