Observation of the dynamics of local magnetic fields in frustrated ferromagnets by the μSR method

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Slowly relaxing processes are shown to occur in the spin system of frustrated ferromagnets in the group of structurally ordered $(Mn_{1-x}Fe_x)Pt_3$ alloys. These processes result from a dynamic crossover from a state of ferromagnetism to asperomagnetism.

Disordered magnetic systems with a competing exchange interaction between atoms contain frustrated spins. These spins are responsible for the tendency toward a transition, at low temperatures, to a state of a reentrant spin glass or a mixed phase which is described by ferromagnetic and antiferromagnetic order parameters simultaneously. The magnetic state of such systems below the Curie temperature T_C and above the Néel temperature T_N remains uncertain. It can be viewed as either (a) an asperomagnetic state (a "planar spin glass") with an infinite interaction radius in terms of the ferromagnetic Z projections and the spin-glass X and Y projections of the total magnetic moment[1] or (b) a system of weakly exchange-coupled ("melted") and slowly relaxing spins against the background of a ferromagnetic matrix in which there is a strong damping of spin waves.[2] Efforts to solve this problem run into the difficulty of trying to observe the dynamics of a spin system which is not of the spin-wave type. In particular, inelastic neutron scattering is ineffective because of the short duration of the interaction of a neutron with an atomic spin ($\sim 10^{-12}$–10^{-10} s). In an effort to overcome these difficulties, we have used the method of muon spin relaxation (μSR) in the present study. This method allows one to study the dynamics of the local internal magnetic fields in a zero external magnetic field over times $\sim 10^{-8}$–10^{-5} s.[3,4]

For this study we selected structurally ordered $(Mn_{1-x}Fe_x)Pt_3$ alloys. These alloys are ideal systems of randomly distributed Fe and Mn atoms with a competing exchange interaction of the type $J_{MnMn} > 0$, $J_{MnFe} > 0$, and $J_{FeFe} < 0$ within a simple cubic lattice. The reason, as was established in Ref. 5, is that the magnetic atoms of iron ($\mu_{Fe} = 3.3\mu_B$) and manganese ($\mu_{Mn} = 4.2\mu_B$) are distributed in a statistical way among the corners of the cubes, while the nonmagnetic platinum atoms are at the centers of the faces of the cubes. Previous studies of these alloys by magnetic and neutron diffraction methods[5–7] have made it possible to construct a magnetic phase diagram (Fig. 1). It turns out to be characteristic of systems with two strongly interacting vector order parameters and a single scalar order parameter.[5,8]

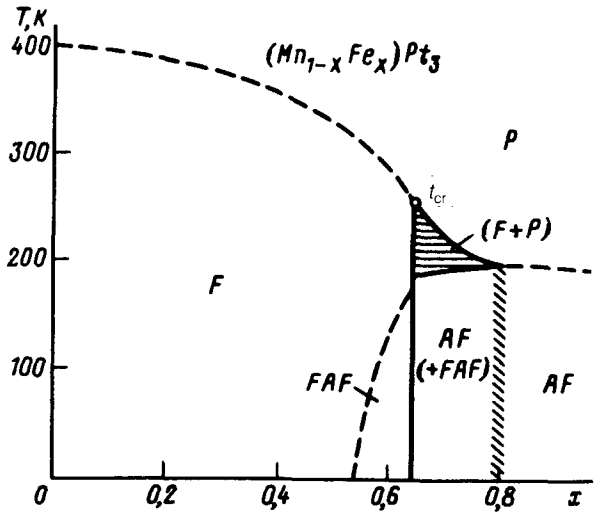

FIG. 1. Magnetic phase diagram of the alloys $(Mn_{1-x}Fe_x)Pt_3$ (Ref. 5) in a structurally ordered state in which the magnetic iron and manganese atoms have a simple cubic lattice. Dashed lines—Lines of a second-order phase transition; solid lines—of a first-order phase transition; t_{cr}—tricritical point; FAF—mixed phase which is described by ferromagnetic and antiferromagnetic order parameters.

The dynamics of local internal magnetic fields in a zero external magnetic field was studied by the μSR method in the muon channel at the St. Petersburg Institute of Nuclear Physics, Russian Academy of Sciences, in the temperature range 10–340 K. The time evolution of the spectrum of decay positrons was measured:

$$n(t)=N_\mu^{-1}\{N_0\exp(-t/\tau_\mu)[1+\alpha_0\exp(-\lambda t)G_{st}(t)]+N_B\}, \quad (1)$$

where N_μ is the number of muons which were stopped in the target, $\tau_\mu = 2.2$ μs is the muon lifetime, the function $G_{st}(t)$ describes the muon spin depolarization in the static local fields, and the parameters N_0/N_μ, a_0, and N_B/N_μ depend on only the characteristics of the experimental apparatus and of the muon beam. For these test samples, the distribution of static fields in the magnetically ordered phase was such that at $t>0.05$ μs the value $G_{st}(t)\simeq 1/3$ prevailed.[4] Here λ is the rate at which the muon spin undergoes depolarization, reflecting the dynamics of the magnetic fields at $t>0.05$ μs.

In these experiments we used alloys with $x=0.45$, 0.55, 0.6, and 0.65, which belong to the ferromagnetic region of the phase diagram and which are close to the critical concentration $X_c = 2/3$, which separates the ferromagnetic region (F) from the antiferromagnetic region (AF). As had been shown previously[5] by neutron diffraction, these alloys (except those with $x=0.45$ and 0.8) go into a state of a mixed phase at low temperatures. This state is described by two wave vectors simultaneously: $K_F = 2\pi/a(0,0,0)$ and $K_{AF} = 2\pi/a(1/2,1/2,0)$. The μSR study of these samples revealed (Fig. 2) clearly defined peaks on the plot of $\lambda(T)$ at the temperatures of the magnetic

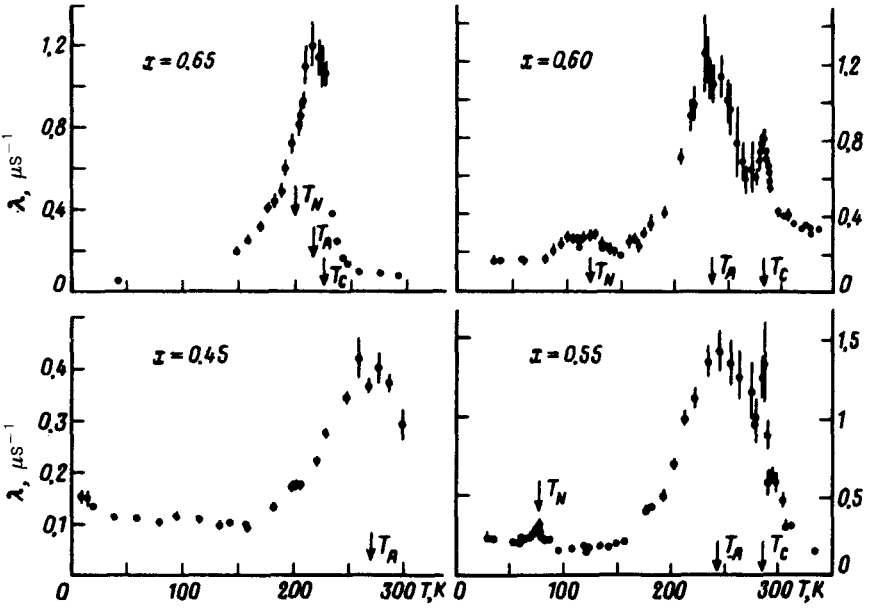

FIG. 2. Temperature dependence of the rate of muon depolarization in $(Mn_{1-x}Fe_x)Pt_3$ alloys measured in a zero external magnetic field. The arrows mark the temperatures T_C and T_N, taken from the phase diagram (Fig. 1). The temperature T_A is the position of the intermediate peak.

phase transitions to the AF and F phases (i.e., at T_N and T_C). Within the errors, the values of these temperatures are the same as the transition temperatures which have been found by other methods.

For the samples with $x < 0.65$, however, we find a third, comparatively broad peak with a maximum at an intermediate temperature, $T_N < T_A < T_C$, where $T_A = 235(10)$ K for $x=0.60$, 243(2) K for $x=0.55$, and 270(5) K for $x=0.45$. This third peak evidently indicates that yet another phase transition, which is not detected by the other methods, is occurring.

We measured the temperature dependence of the susceptibility as we heated the samples after they had been cooled to 4.2 K in the absence of an external field (χ_{ZFC}) and also in an external field (χ_{FC}). The results (Fig. 3) indicate that a significant irreversibility arises at temperatures below T_A.

It is thus logical to suggest that the magnetic restructuring observed near T_A is due to a transition of the system from a ferromagnetic state to an asperomagnetic state. The latter is nonuniform from site to site because of the statistical distribution of iron and manganese atoms over the sublattice, and also because of the pronounced spatial dispersion of the exchange energy over the crystal. This transition, which stretches out over a significant temperature interval, probably corresponds to a dynamic crossover from a state with a single (ferromagnetic) order parameter, which forms at the Curie temperature as the result of a "freezing of the Z projections of the magnetic moment,

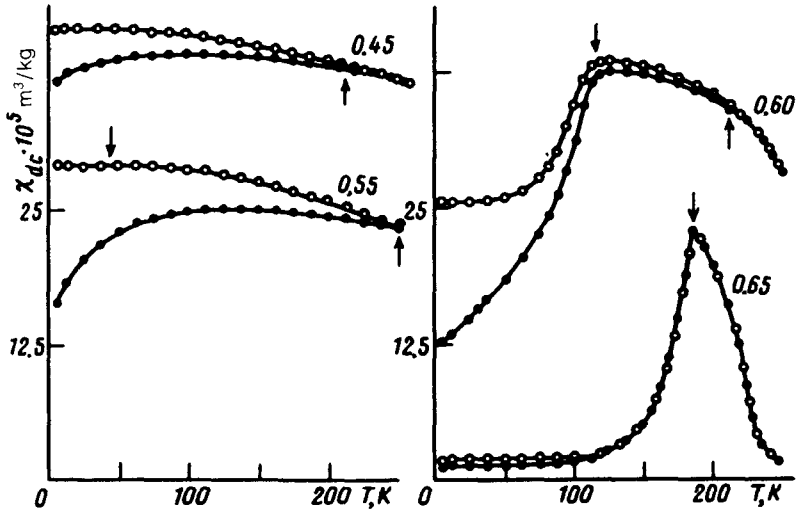

FIG. 3. Temperature dependence of the static susceptibility for $(Mn_{1-x}Fe_x)Pt_3$ alloys of various compositions measured during the heating of a sample after it had been cooled to 4.2 K. Filled points—Cooled in the absence of a magnetic field; open points—cooled in a magnetic field $H=0.04\times10^6$ A/m. The temperature T_A is the point at which a slight irreversibility begins; T_N corresponds to the transition to the mixed phase. The numbers on the curves are the iron concentrations x.

to a state related to a critical slowing of the X and Y projections of the total moment at a certain temperature which is characteristic of each local configuration of iron and manganese atoms. Over the entire crystal, the slowly relaxing processes thus occur in a broad temperature range.

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