Noncollinear magnetic state in a frustrated Heisenberg antiferromagnet

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(Submitted 20 February 1991)
Pis'ma Zh. Eksp. Teor. Fiz. **53**, No. 7, 343–346 (10 April 1991)

A noncollinear antiferromagnetic state (or antiasperomagnetic state) has been detected in a Heisenberg antiferromagnet, FeNiCr, by the method of μ^+ spin relaxation for the first time. As the temperature is lowered, the following sequence of magnetic transitions occurs in the alloy: paramagnet → collinear antiferromagnet → antiasperomagnet → spin glass.

It has been shown in several places that as frustrated ferromagnets are cooled, the appearance of a reentrant spin-glass phase is preceded by the formation of a noncollinear ferromagnetic (or asperomagnetic state), which may be thought of as a superposition of a ferromagnetic ordering of spins along a certain direction and a spin-glass ordering of the transverse components.[1-4]

Can a noncollinear antiferromagnetic (antiasperomagnetic) state form in a frustrated Heisenberg antiferromagnet? In an effort to resolve this question, we selected the alloy $Fe_{64}Ni_{16}Cr_{20}$, which is an antiferromagnetic Heisenberg alloy of fcc iron[5,6] and which is close in composition to the critical concentration for the appearance of a long-range antiferromagnetic order.[7]

Figure 1 shows the temperature dependence of the magnetic susceptibilities χ^{ZFC} and χ^{FC} of this alloy. The susceptibility χ^{ZFC} was found after the sample was cooled from $T = 30$ K to $T = 4.2$ K in a zero magnetic field; χ^{FC} was found after cooling to the same temperature in the measurement magnetic field of 100 Oe. It can be seen from Fig. 1 that below the Néel temperature $T_N = 24$ K this alloy goes into an antiferromagnetic state, in agreement with neutron-diffraction data.[6] At lower temperatures we find a difference between $\chi^{ZFC}(T)$ and $\chi^{FC}(T)$; i.e., we find the irreversible effects which are characteristic of spin glasses (the effects of a thermal magnetic history). The temperature $T_f = 11$ K, at which χ^{FC} becomes equal to χ^{ZFC}, is usually identified as the temperature of the transition to the phase of a degenerate spin glass.[8]

The results in Fig. 1 thus show that when the alloy $Fe_{64}Ni_{16}Cr_{20}$ is cooled, there is a reentrant thermal transition: paramagnet to antiferromagnet to spin glass. Unfortunately, these results are not a sufficient basis for drawing any conclusions about the magnetic structure of the phases and states that arise. Such information is provided by a study of the spin depolarization of a μ^+ meson in a zero magnetic field.[9] Results of this sort can be used to study the distribution of local magnetic fields in a sample.

In this method, one measures the time evolution $N(t)$ of the positrons from the decay $\mu^+ \to e^+ + \nu + \bar{\nu}$:

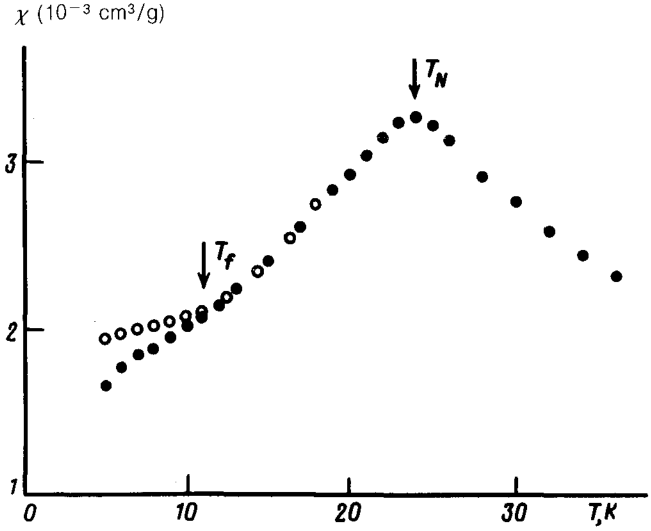

FIG. 1. Temperature dependence of the static magnetic susceptibility of the alloy $Fe_{64}Ni_{16}Cr_{20}$ in a magnetic field of 100 Oe. Filled circles—χ^{ZFC}; open circles—χ^{FC}. T_N) Néel point; T_f) freezing point of the spin glass.

$$N(t) = \frac{N_0}{N_\mu}\{[1 + a_0 G(t)]\exp(-t/\tau_\mu) + N_\phi/N_0\}, \tag{1}$$

where N_μ is the number of muons which have been stopped in the target, $\tau_\mu = 2.2\ \mu$s is the muon lifetime, and the quantities $N_0/N_\mu = 0.075$, $a_0 = 0.3$, and $N_\phi/N_0 = 0.001$ are constants of the experimental apparatus and the muon beam. The function $G(t)$ is chosen in the form

$$G(t) = G_d(t)G_s(t), \tag{2}$$

where $G_d(t)$ and $G_s(t)$ characterize the dynamics and statics, respectively, of the local magnetic fields in the test sample.

The experimental data on $N(t)$ for the test sample at the various temperatures are described best when the functions $G_d(t)$ and $G_s(t)$ are chosen in the form[10]

$$G_d(t) = \exp(-\lambda t) \tag{3}$$

and

$$G_s(t) = \sum_i \frac{a_i}{a_0}\left\{\frac{1}{3} + \frac{2}{3}\left[\cos\gamma_\mu B_i t - \frac{(\gamma_\mu \Delta_i t)^\alpha}{\gamma_\mu B_i t}\sin(\gamma_\mu B_i t)\right]\exp\left[-\frac{(\gamma_\mu \Delta_i t)^\alpha}{\alpha}\right]\right\} \tag{4}$$

In expressions (3) and (4), λ is the rate of muon spin depolarization, γ_μ is the gyromagnetic ratio of the μ^+ meson, B_i and Δ_i are the mean value and dispersion of the local magnetic field, and a_i is the volume fraction of magnetic phase i which arises in the sample as it is cooled.

Expression (4) holds for a Heisenberg magnetic material without a magnetic texture.[10] The parameter value $\alpha = 1$ corresponds to a Lorentz distribution, and $\alpha = 2$ to a Gaussian distribution, of the local magnetic fields. The second term in the first set of square brackets in (4) is zero for a noncollinear magnetic material ($B_i \gg \Delta_i \simeq 0$); for a collinear magnetic material (an antiasperomagnet) we would have $B_i \simeq \Delta_i$, and for a spin glass $\Delta_i \gg B_i \simeq 0$.

A least-squares fit of Eqs. (1)–(4) to the experimental data confirms that there is a reentrant antiferromagnet-(spin glass) transition in the alloy $Fe_{64}Ni_{16}Cr_{20}$. It also reveals features of the magnetic states which occur in this alloy at the various temperatures.

Figure 2 shows the temperature dependence $\lambda(T)$. Near T_N and T_f, the phase-transition temperatures determined above by magnetic methods, there are clearly defined peaks in the muon relaxation rate. According to Ref. 9, these peaks signify the development of critical fluctuations near the corresponding temperatures.

Analysis of the measured distribution of the static magnetic fields shows that different types of magnetic states occur in different temperature regions for the alloy $Fe_{64}Ni_{16}Cr_{20}$ (Fig. 3). In particular, at temperatures $T_A = 17$ K $< T < T_N = 24$ K this alloy is a collinear antiferromagnet with a Lorentzian distribution of local magnetic fields. In the temperature interval $T_f = 11$ K $< T < T_A = 17$ K the magnetic structure of this alloy can be thought of as a superposition of a collinear antiferromagnet and a noncollinear magnetic material (antiasperomagnet), with the same sort of distribution of local magnetic fields. Finally, at $T < T_f = 11$ K, the alloy goes into a phase of a reentrant spin glass, in which a spin glass coexists with an antiasperomagnetism, with a Gaussian distribution of local magnetic fields.

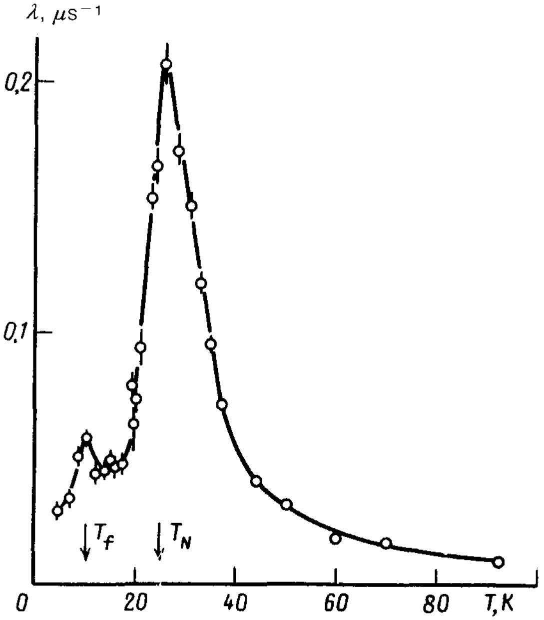

FIG. 2. Temperature dependence of the depolarization rate λ of the μ^+ spin for the alloy $Fe_{64}Ni_{16}Cr_{20}$.

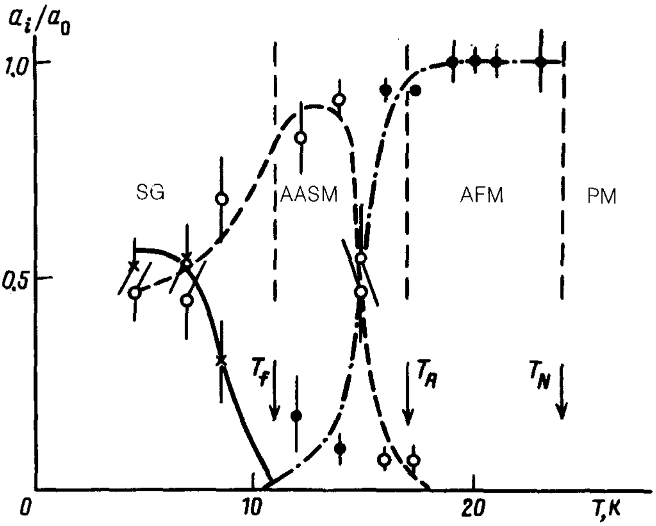

FIG. 3. The volume fraction a_i/a_0 of the magnetic phases which arise in the alloy $Fe_{64}Ni_{16}Cr_{20}$ at various temperatures. PM—Paramagnet; AFM—collinear antiferromagnet; AASM—noncollinear antiferromagnet (antiasperomagnet); SG—spin glass. T_N, T_A, T_f)—Respectively, the Néel temperature, the temperature at which the antiasperomagnetic phase arises, and the temperature at which the reentrant spin glass appears.

In summary, a noncollinear (antiasperomagnetic) state has been detected experimentally in a frustrated Heisenberg antiferromagnet for the first time. This state is an intermediate state in a transition from a collinear antiferromagnet to a reentrant spin glass.

It was shown in Refs. 7 and 11 that a reentrant spin glass does not form in the antiferromagnetic alloys $Fe_xNi_{80-x}Cr_{20}$ with $x \geqslant 68$ at.% in a zero magnetic field. The results of the present study suggest that the magnetic ground state (at $T = 0$ K) of these alloys should be regarded as an antiasperomagnetic state. However, this point requires further research.

We wish to thank V. G. Bar'yakhtar for interest in this study.

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Translated by D. Parsons