Evolution of the long-range ferromagnetic order at a transition from a ferromagnet to a spin glass

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An anomalous feature has been observed in the nonlinear magnetic susceptibility of a disordered FeNiCr alloy below the Curie point. This feature is linked with a disruption of the long-range ferromagnetic order and the appearance of a spin-glass state.

The so-called ferromagnetic-(spin-glass) double transition has been predicted theoretically and observed experimentally in many crystalline and amorphous systems.[1] Opinion is divided, however, on the evolution of the long-range ferromagnetic order at a transition of this sort. For example, a study by Maletta *et al.*[2] of the temperature dependence of the peak intensity of magnetic neutron scattering in EuSrS magnetic semiconductors indicates that the long-range ferromagnetic order is disrupted. On the other hand, Murani[3] concluded that the long-range ferromagnetic order is preserved at the transition from the ferromagnet to a spin glass on the basis of a corresponding study, but involving measurements of the integrated intensity in the classical spin-glass system AuFe.

Neutron-diffraction methods are known to provide the most direct information on the magnetic state and magnetic structure of a material. Even when purely magnetic methods are used, however, it is frequently possible to draw definite conclusions about the events that occur in magnetic materials. In this letter we report measurements of the nonlinear magnetic susceptibility of disordered fcc FeNiCr alloys carried out in an attempt to determine the behavior of the long-range ferromagnetic order at a ferromagnet-(spin glass) transition.

We selected the alloys $Fe_{61}Ni_{21}Cr_{18}$ and $Fe_{56}Ni_{26}Cr_{18}$ for study. It had been shown previously[4] that the first of these alloys undergoes a paramagnet-(spin glass) transition during cooling, while the second undergoes a ferromagnet-(spin glass) transition. In general, the magnetization m of a ferromagnet in the limit of a weak magnetic field h can be written[5]

$$m = m_0 + \chi^{(1)}h + \chi^{(2)}h^2 + \chi^{(3)}h^3 + \dots, \quad (1)$$

where m_0 is the spontaneous magnetization, $\chi^{(1)}$ is the linear susceptibility, and $\chi^{(2)}$ and $\chi^{(3)}$ are the nonlinear susceptibilities. In the absence of a long-range magnetic order,

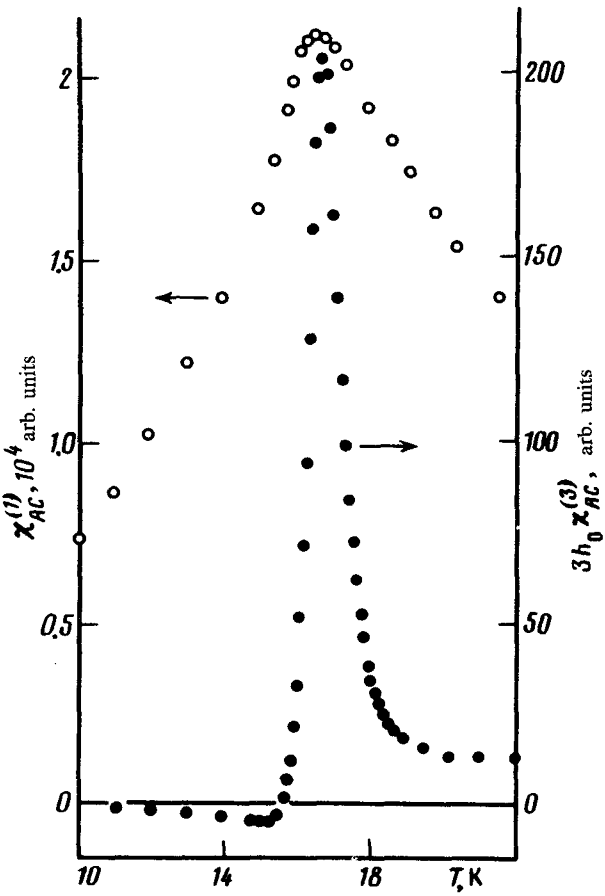

FIG. 1. Temperature dependence of the linear magnetic susceptibility $\chi^{(1)}$ and the nonlinear magnetic susceptibility $\chi^{(3)}$ of $Fe_{61}Ni_{21}Cr_{18}$.

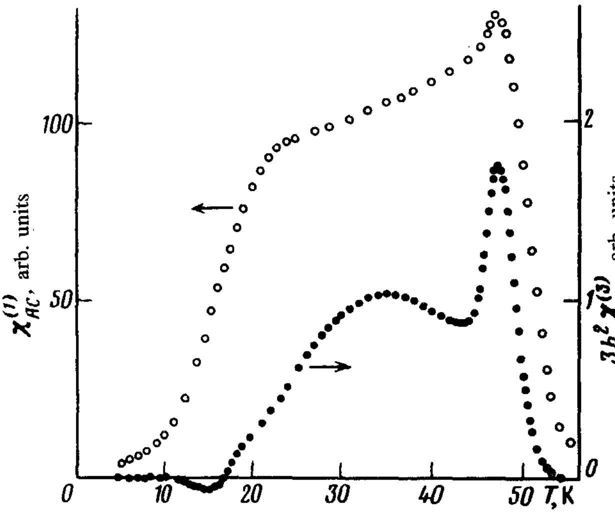

FIG. 2. Temperature dependence of $\chi^{(1)}$ and $\chi^{(3)}$ of the alloy $Fe_{56}Ni_{26}Cr_{18}$ as it undergoes a paramagnet-ferromagnet-(spin glass) transition.

expression (1) simplifies:

$$m = \chi^{(1)}h + \chi^{(3)}h^3 + \ldots . \quad (2)$$

In systems which do undergo a paramagnet-(spin glass) transition, one observes a slope change in the linear susceptibility $\chi^{(1)}$ at the temperature (T_f) corresponding to the freezing of the spin glass, while in $\chi^{(3)}$ a very sharp anomalous feature has been observed by several investigators.[6]

Figure 1 shows the temperature dependence of $\chi^{(1)}$ and $\chi^{(3)}$ for the alloy $Fe_{61}Ni_{21}Cr_{18}$. At the temperature $T_f = 17.7$ K we see, along with the $\chi^{(1)}$ peak, a very sharp anomalous feature in $\chi^{(3)}$. Below 16 K, $\chi^{(3)}$ becomes positive. A similar behavior of the nonlinear susceptibility has been noted in $Zn_xCd_{1-x}Cr_2Se_4$ dielectric spin glasses.[7]

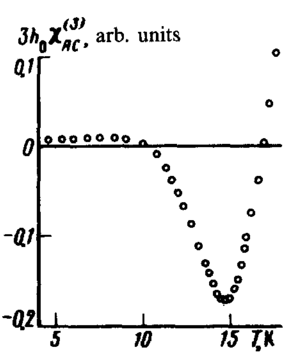

FIG. 3. Low-temperature anomalous behavior of the nonlinear susceptibility $\chi^{(3)}$ of the alloy $Fe_{56}Ni_{26}Cr_{18}$.

If we assume that the long-range ferromagnetic order is disrupted at the ferromagnet- (spin glass) transition, and the entire system goes into a spin-glass state, then we should observe an anomalous feature in the nonlinear susceptibility at T_b similar to that shown in Fig. 1. There is a single published paper[8] on the nonlinear susceptibility at a ferromagnet- (spin glass) transition. Below the Curie point T_c, $\chi^{(2)}$ has no anomalous features of any sort, while there has been absolutely no study of the behavior of $\chi^{(3)}$.

Figure 2 shows the temperature dependence of $\chi^{(1)}$ and $\chi^{(3)}$ of an alloy which has undergone a ferromagnet- (spin glass) transition. Near T_c the susceptibilities $\chi^{(1)}$ and $\chi^{(3)}$ exhibit the characteristic anomalous features which are seen, for example, in PdFeMn alloys.[8] At a temperature of about 15 K, on the other hand, $\chi^{(3)}$ has yet another anomalous feature (Fig. 3), similar to that found at the paramagnet- (spin glass) transition (Fig. 1). Interestingly, again in this case $\chi^{(3)}$ changes sign, becoming positive, as the temperature is lowered.

On the basis of this comparison of the temperature dependence of the nonlinear susceptibility $\chi^{(3)}$ for paramagnetic- (spin glass) and ferromagnet- (spin glass) transitions and on the basis of their qualitative similarity at $T \lesssim T_f$, T_b, it may be suggested that in the latter case, at least for the particular alloy studied, the long-range ferromagnetic order is disrupted and gives way to a spin-glass phase.

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