Phase transitions in a two-dimensional ferromagnet with "easy-plane" anisotropy

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Two phase transitions were observed in a layered compound of $NiCl_2$ with graphite; in a definite temperature region, the compound is in a disordered state and has an inifinite initial susceptibility.

Layered interstitial compounds are very convenient objects for the study of two-dimensional magnets. In compounds of graphite with chlorides of transition metals, the interaction between the magnetic ions inside the layer remains exactly the same as in the pure chlorides, whereas the interaction between neighboring layers can be made so weak that it has no effect on the observed magnetic properties.[1,2] It was previously observed that $NiCl_2$ compounded with graphite goes over into a ferromagnetic state at 18.1 °K.[3] This transition is very unusual and cannot be described by similarity theory.[4] The results of the present paper show that the $NiCl_2$ with graphite undergoes two phase transitions at different in temperatures. At the higher temperature T_{c1} there is a transition from the paramagnetic state to a state with infinite initial susceptibility, and only at the lower temperature T_{c2} does a transition to an ordered state takes place.

For the magnetic measurements we used spherical samples of oriented pyrolytic graphite, into which a relatively small amount of $NiCl_2$ was introduced (1–2% by weight). In all the measurements, the magnetic field was applied parallel to the layers, so that we could neglect the demagnetization fields, for in this case the demagnetizing factor of each individual layer is equal to zero, and the surface effects are small because of the small ferromagnetic moment of the sample. As follows from Fig. 1, the $M(H)$ dependence can be represented at all $T \geqslant T_{c2}$ in the form $M \sim H^{1/\delta}$, where the exponent $1/\delta$ depends on the temperature. In the paramagnetic state ($T > T_{c1}$) we have $\delta \equiv 1$, and the moment is proportional to the field, the proportionality coefficient being the magnetic susceptibility. With decreasing temperature, the susceptibility increases (Fig. 2), but at a certain temperature the value of δ begins to increase smoothly. If $1/\delta < 1$, then the initial susceptibility $\chi = \lim_{H \to 0}(\partial M/\partial H)$ is equal to infinity. At the point T_{c1} the susceptibility has a discontinuity, being finite everywhere at $T > T_{c1}$ and becoming jumpwise infinite at $T = T_{c1}$.

The state of a two-dimensional ferromagnet in the temperature region $T_{c2} < T < T_{c1}$ can be characterized by the value of the exponent $1/\delta$ shown in Fig. 2. Linear extrapolation of the plot of $1/\delta$ to unity value yields $T_{c1} = 2.05 \pm 0.3$ °K. The difference between $1/\delta$ and unity can be attributed to the fact that in a two-dimensional

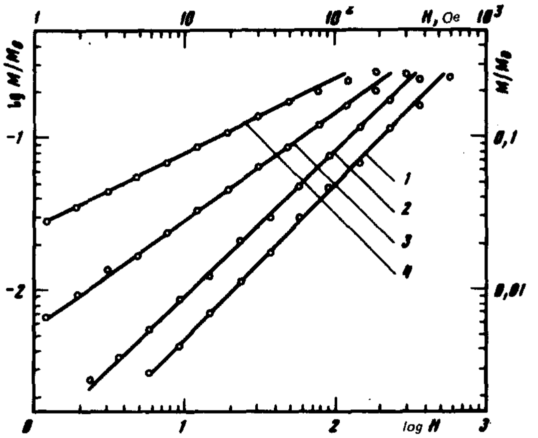

FIG. 1. Field dependence of the magnetic moment of the sample at various temperatures: 1) $T=21.66$ °K, 2) $T=20.22$ °K, 3) $T=18.82$ °K, 4) $T=17.43$ °K.

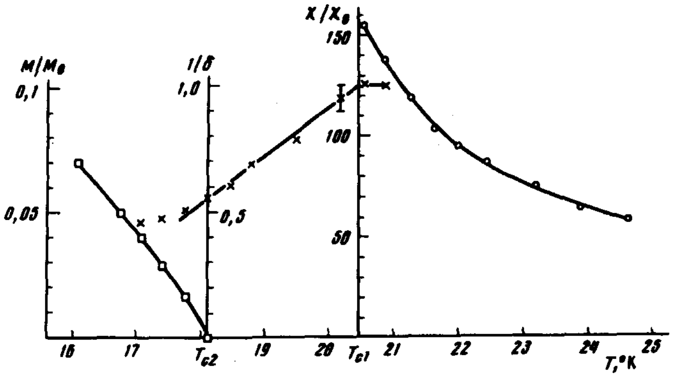

FIG. 2. Temperature dependences of the reduced susceptibility (circles), of the exponent $1/\delta$ (crosses), and of the residual ferromagnetic moment (squares); χ_0 is the magnetic susceptibility in the limit when there is no interaction (according to Curie).

spin system, below a definite temperature T_{c1}, there sets in a spin rigidity[5,6] which is the analog of the density of the superfluid component for a Bose liquid. With decreasing temperature, the rigidity increases, while the magnetic order arises at the temperature T_{c2} because of the hexagonal anisotropy in the plane of the layer (the Ni^{+2} ions form a regular triangular lattice).

The presence of a phase transition at a higher temperature ($T_c = 20.2$ °K) is confirmed by data on the specific heat (Fig. 3). In this temperature region there is a noticeable maximum of the specific heat. The other transition in the region of 18 °K could not be observed, it is apparently weaker, and the increase in the specific heat does not exceed the experimental accuracy (±1%).

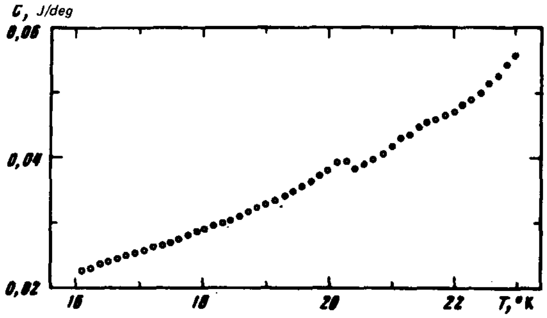

FIG. 3. Dependence of the specific heat on the temperature of a compound of $NiCl_2$ with graphite, containing 47.7% $NiCl_2$ by weight.

Establishment of short-range magnetic order in two-dimensional magnets causes the specific heat to go through a broad maximum, without an accompanying phase transition. For the compound of $NiCl_2$ with graphite, the maximum of the magnetic specific heat should occur in the region of 70 °K.[2] The phase transitions observed at lower temperatures change the energy of the spin system relatively little, and this leads to small anomalies in the specific heat.

The existence of an intermediate phase of a two-dimensional magnet, when the initial susceptibility is equal to infinity and there is no spontaneous magnetization, is connected with the presence of magnetic anisotropy of the "easy-plane" type. Indeed, in the Heisenberg unbounded two-dimensional model there are apparently no phase transitions at finite temperatures.[7] On the other hand, in the planar model of a two-dimensional magnet, as shown by the analysis of Pokrovskii and Uimin,[6] such a phase can exist. In the compound of $NiCl_2$ with graphite, the plane of the layer is an easy-magnetization plane,[2,3] and at sufficiently low temperatures the influence of even a weak anisotropy is exceedingly large, so that the properties of this compound will be similar to some degree to the properties of a planar magnet, as is indeed observed.

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