Anisotropy of the magnetic properties of a URu_2Si_2 single crystal in weak magnetic fields

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The temperature dependence of the magnetic susceptibility of a URu_2Si_2 single crystal has been studied in weak magneti c fields ($H<5$ kOe) for the first time. The results indicate that weak ferromagnetic correlations of an anisotropic nature arise at temperatures below 35 K. © *1995 American Institute of Physics.*

The superconductor URu_2Si_2 is the first heavy-fermion system in which an unusual coexistence of superconductivity and magnetism has been discovered, with a superconducting transition temperature ($T_c \sim 1.2$ K) well below the temperature of the antiferromagnetic ordering[1,2] ($T_N \approx 17.5$ K). On the one hand, the nature of the magnetic order remains an open question, since no model can explain the extremely small magnetic moment of the order along with a significant jump in specific heat. On the other hand, even the type of nontrivial pairing (d- or p-wave) with a nonzero orbital angular momentum in the superconducting phase is still uncertain. Since the antiferromagnetic moment is oriented along the c tetragonal axis, it is incapable of lifting the degeneracy of the vector order parameter. In this situation, a possible lowering of the symmetry of the normal phase as a result of other magnetic or structural phase transitions plays an important role for a symmetry analysis based on the Ginzburg–Landau model.

In this letter we are reporting the first experimental study of the magnetic susceptibility χ of a URu_2Si_2 single crystal over the temperature range $1.7<T<300$ K in magnetic fields from 100 to 5×10^4 Oe. The error in the orientation of the sample did not exceed 3–4°. The measurements were carried out with the help of a commercial (Quantum Design) SQUID. To the best of our knowledge, all the studies which have been published to date have been carried out in magnetic fields above 5 kOe (Ref. 2). At temperatures $T>50$ K and in strong magnetic fields, our results agree with data in the literature. To save space, we will not reproduce these results here.

Figure 1 shows the temperature dependence of the magnetic susceptibility of URu_2Si_2 in magnetic fields of 100, 500, and 5000 Oe, directed along the basal plane. In weak magnetic fields we observe a substantial deviation in the direction corresponding to an increase in the magnetic susceptibility (Fig. 1). A magnetic field $H>10^3$ Oe suppresses this effect. The field dependence of the magnetic moment M, shown up to 4×10^3 Oe in the inset in Fig. 1, is linear up to 5×10^4 Oe, without any visible signs of

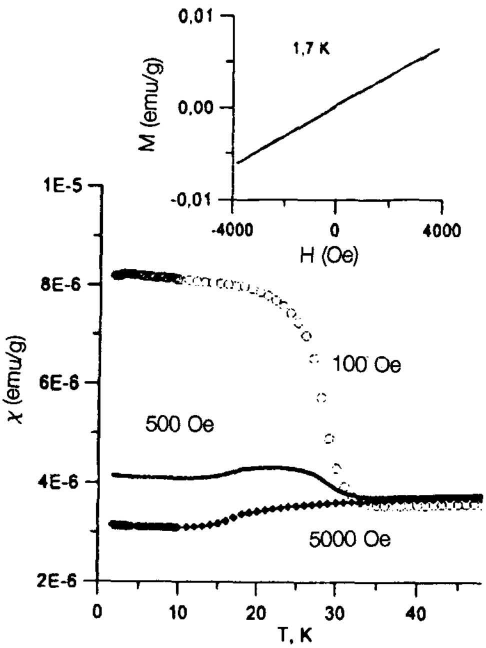

FIG. 1. Temperature dependence of the magnetic susceptibility and field dependence of the magnetic moment (inset) of a URu_2Si_2 single crystal in a magnetic field along the *ab* direction.

hysteresis. In fields of 500 and 5000 Oe at $T \approx 18$ K, there is an obvious change in slope on the $\chi(T)$ curve, which corresponds to an antiferromagnetic transition. Curiously, this anomaly is difficult to distinguish in a field of 100 Oe.

Figure 2 shows the measurements of the magnetic susceptibility of a URu_2Si_2 single crystal in magnetic fields of 100, 500, and 5×10^3 Oe, directed along the c tetragonal axis. In weak magnetic fields, as in the case of fields H along the basal plane, correlations of the ferromagnetic type, suppressed by a magnetic field, arise. The most convincing argument in favor of a ferromagnetic nature of the interactions which arise at $T<35$ K is the presence of a slight hysteresis on the field dependence of the magnetic moment (see the inset in Fig. 2). The transition to an antiferromagnetic state, which has been reported in the literature, is observed as a change in slope of $\chi(T)$ near 18 K. Its amplitude, in contrast with the $H\|ab$ case, depends only slightly on the direction of the magnetic field. Note also that near $T\sim3$ K, for both field directions, we see a slight anomaly (smaller than 1% in the case $H\|ab$) in the magnetic susceptibility. The absolute magnitude of this anomaly depends weakly on the direction of the magnetic field.

In this letter we restrict the discussion to the ferromagnetic instability near $T\sim35$ K. The anisotropic nature of the effect suggests that the transition is not due to the presence of ferromagnetic impurities. Ramirez *et al.*[3] have suggested a ferromagnetic instability below 35–40 K (this suggestion has not been supported by experimental data). Their suggestion was an effort to explain a splitting of the superconducting transition, observed in several samples, on the basis that the samples consist of two phases. The second phase, which would be responsible for the ferromagnetic instability, would presumably be formed by regions in which the crystalline symmetry is disrupted by a shift of the basal

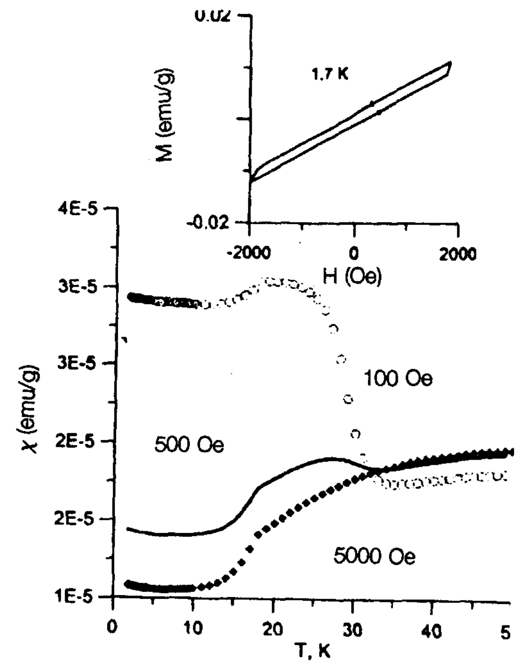

FIG. 2. Temperature dependence of the magnetic susceptibility and field dependence of the magnetic moment (inset) of a URu_2Si_2 single crystal in a magnetic field along the c tetragonal axis.

planes perpendicular to the c axis. However, in a recent study of magnetostriction in a URu_2Si_2 single crystal with a narrow, unsplit superconducting transition (i.e., in a specially selected "single-phase" sample), an unusual change in the sign of the spontaneous magnetostriction was observed in a magnetic field along the tetragonal axis. This change was attributed to the presence of both a superconducting hysteresis and a paramagnetic one.[4] The direct observation of a hysteresis in the magnetic properties of a URu_2Si_2 single crystal in a magnetic field along the c axis, reported in the present letter, combined with the data of van Dijk *et al.*,[4,5] may thus constitute evidence that the observed ferromagnetic instability is of a bulk nature with an effective magnetic moment less than $10^{-3}\mu_B$ per uranium atom.

Ferromagnetic correlations are exceedingly unusual for heavy-fermion systems. In this case one usually considers only the possibility of antiferromagnetic interactions in the normal state. Interestingly, the temperature below which ferromagnetic correlations are observed corresponds, as in UBe_{13} (Ref. 6), to the energy of the splitting of the nonmagnetic ground state by the crystal field,[7] $\Delta_{CF} \approx 40$ K. Accordingly, only a change in the nature of the magnetism of uranium atoms occurring at $T < \Delta_{CF}$ can induce a slight ferromagnetism at these temperatures.

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[1] W. Schlabitz, J. Bauman, B. Politt *et al.*, Z. Phys. B **52**, 171 (1986).

[2] T. T. M. Palstra, A. A. Manovsky *et al.*, Phys. Rev. Lett. **55**, 2727 (1986).
[3] A. P. Ramirez *et al.*, Phys. Rev. B **44**, 5392 (1991); E. A. Knetsch, Ph.D. Thesis, U. Leiden, 1993 (unpublished).
[4] N. H. van Dijk, A. de Visser, J. J. M. Franse, A. A. Menovsky *et al.*, to be published in *Proceedings of SCES '94*, Amsterdam, 1994.
[5] N. H. van Dijk, Ph.D. Thesis, UvA, 1994 (unpublished).
[6] F. G. Aliev, S. Vieira, R. Villar, and J. L. Martinez, JETP Lett. **60**, 582 (1994).
[7] G. J. Nieuwenhuys, Phys. Rev. B **35**, 5260 (1987).

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