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Spin wave collapse and incommensurate fluctuations in URu_2Si_2

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Abstract

To test if the $T_N = 17.7$ K transition in URu_2Si_2 is driven by a divergence of a magnetic order parameter we performed high-resolution neutron scattering . At the ordering wave vector the spin-wave energy collapsed and the susceptibility diverged as T_N was approached. This confirms that the order parameter is the magnetic dipole, as shown by recent symmetry arguments and polarized neutron experiments [1]. We also observe incommensurate fluctuations, suggesting that competing temperature-dependent interactions may influence this weak-moment transition.

Speculation exists that the ordered phase that precedes superconductivity in the heavy-fermion systems URu_2Si_2 ($T_N = 17.7$ K) [2] and UPt_3 ($T_N = 5$ K) [3] might not be magnetic. The low apparent moments, $0.04\mu_B$ and $0.01\mu_B$, respectively, have led to suggestions that the broken-symmetry Bragg peaks are quadrupolar [4] or a more exotic non-trivial phase [5]. To test these ideas we have made not only an elastic neutron scattering study [6] but also present here a detailed study of the critical dynamics which provide a separate indicator of the nature of the transition. For non-magnetic order, there is no requirement for the magnetic susceptibility to diverge at T_N, nor is there need of a soft spin-wave mode. We therefore studied the spin response at the ordering wave vector, $Q_0 = (1\,0\,0)$, to observe the temperature dependence of the gap energy, $\Delta(T)$, its damping, Γ, and the susceptibility, $\chi(Q_0, T)$.

Neutron scattering was performed at the TAS7 cold-neutron spectrometer at Risø National Laboratory with a scattered energy of 5 meV. When folded with the spectrometer resolution, the spin spectrum was well described by that of a damped simple harmonic oscillator. The gap energy (Fig. 1) collapses to a low value and the susceptibility passes through a peak at T_N. The large resolution corrections near T_N, where the dispersion becomes a deep minimum, lead to larger errors in the fitted parameters. Considering also the large damping, $\Gamma/\Delta \sim 2$, our results are consistent with a complete softening of the gap to zero energy. The strong peak in $\chi(Q_0)$ shows that the magnetic susceptibility arising from the spin excitations has diverged.

The damping grows rapidly (similarly to the electronic specific heat) as $T \rightarrow T_N$. It reaches a value much less, $\Gamma = 1.4$ meV, than the 6 meV observed [2] at the non-critical wave vector (1,0.4,0). There the spin wave is more energetic (4 meV at 4 K) and so can decay into more

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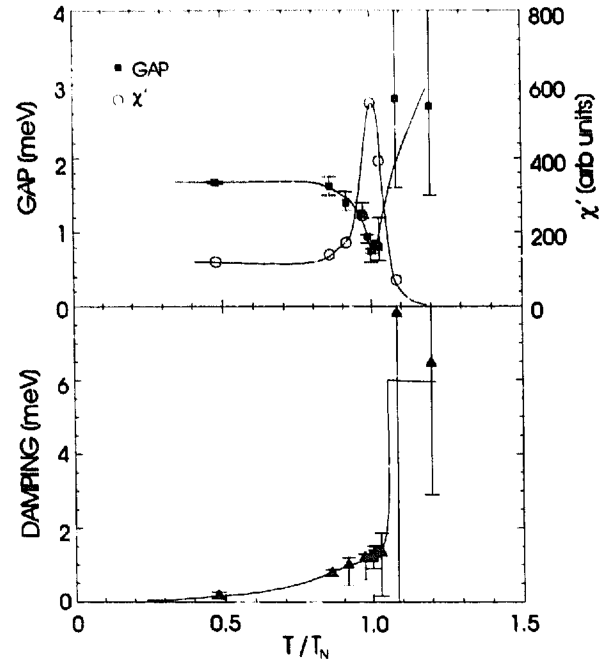

Fig. 1. For $Q = (100)$ in URu_2Si_2 the spin gap (squares), the susceptibility (circles) and the damping (triangles).

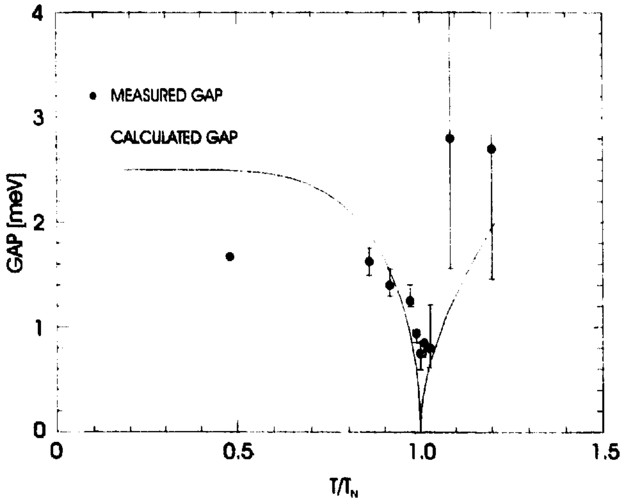

Fig. 2. The measured gap and the prediction of the induced moment model.

channels of the electron gas or spin spectrum as the minimum gap at Q_0 closes. Above the transition the gap energy rises in a fashion qualitatively similar (Fig. 2) to the predictions of the two-singlet model proposed in Ref. [2].

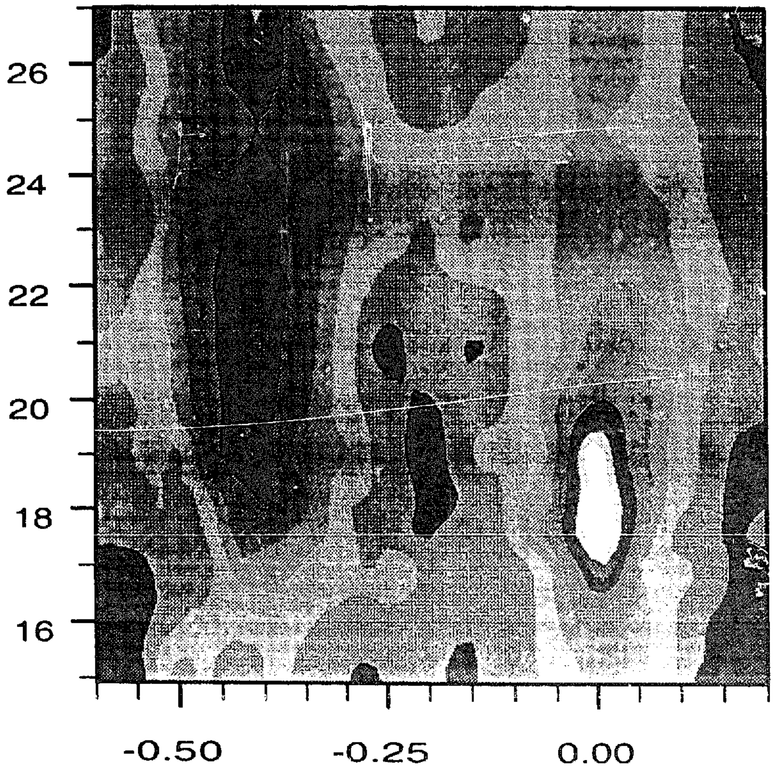

Fig. 3. Contours of intensity at 0.3 meV in the temperature (vertical axis) – wave vector (horizontal axis) plane. Incommensurate fluctuations are observed near $(1,\eta,0)$ for an $\eta = -0.4$ offset from the ordering wave vector.

There is a very narrow temperature (and Q) range in which the gap is really small so it is not surprising that our fits cannot extract an identically zero gap energy.

Above the transition we find that the amplitude, A, of the inelastic response in $\chi = 2A/\Delta$, becomes very weak. This missing susceptibility has been found in a narrow central peak, resolution limited in Q and in energy. The amplitude transfers from the inelastic response to the central peak almost completely by $T/T_N = 1.1$. On raising the temperature there is no sign of a shortening correlation range or correlation time in the central peak as is normal for critical scattering. The central peak accounts for the tailing of the elastic scattering [2] and is present in all crystals.

Most surprising is the discovery that incommensurate fluctuations centred on (1,0.4,0) coexist with the (1,0,0) central peak as shown in Fig. 3. For $T > 20$ K the critical scattering transfers predominantly to the incommensurate position where a finite correlation range is observed. A ring of incommensurate fluctuations was known earlier [2] to exist in the a^*–b^* plane at a radius of $\sim 0.4a^*$ from the (1 0 0) wave vector at which order finally occurs. These competing fluctuations may help understand why the moment that condenses is so weak.

We have therefore shown that the dynamic spin response has the soft-mode behaviour and susceptibility divergence characteristic of a magnetic transition. The critical dynamics above the transition is highly unusual and consists of extremely slow, long-range commensurate correlations that give over to shorter-range incommensurate fluctuations not far above the transition.

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