Magnetic excitations in the ferromagnetic superconductor UGe$_2$ under pressure.

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Abstract. Ferromagnetism and superconductivity coexist in UGe$_2$ under pressures in the range of 10-16 kbar. Here, equal spin electrons are paired to give a spin triplet state but the pairing mechanism is still not verified experimentally. The work presented here attempts to verify whether the longitudinal magnetic fluctuations associated with a magnetic transition within the ferromagnetic state might be responsible for the electron pairing. We show that the energy scale of these fluctuations must be smaller than those associated with the second order phase transition at the Curie temperature. Furthermore, there is no significant change of the energy scale of the fluctuations at the Curie temperature as a function of pressure.

1. Introduction

UGe$_2$ is one of the most extensively studied ferromagnetic superconductors [1-7]. The magnetic properties of UGe$_2$ are due to the uranium 5f electrons. The crystal structure of the material is orthorhombic with the space group $Cmmm$ [2]. The $a$-axis is the easy axis with an ordered magnetic moment $M_0 \approx 1.4 \mu_B$ at zero temperature. The Curie temperature ($T_c = 53$ K at ambient pressure) decreases with increasing pressure and is completely suppressed at the critical pressure of $p_c = 16$ kbar as shown on Fig. 1 [7]. This paramagnetic to ferromagnetic (PM-FM) transition is 2nd order in nature at lower pressures but at the tricritical point (TCP) at $p_{TCP} = 14.1$ kbar, it changes to 1st order [6]. Within the ferromagnetic region, there are two distinct ferromagnetic phases, the high temperature high pressure FM1 phase and the low temperature low pressure FM2 phase. At low pressures, there is a cross-over region between the two phases but at the critical end point (CEP), very close to 12 kbar, a 1st order FM1-FM2 transition emerges where the ordered magnetic moment jumps from $M_0 \approx 0.9 \mu_B$ (FM1 phase) to $M_0 \approx 1.4 \mu_B$ (FM2 phase) [6]. Superconductivity appears only within the ferromagnetic state and the superconducting critical temperature is maximised at pressure of $p_x = 12$ kbar with $T_{SC} \approx 0.8$ K [2].

The superconducting pairing mechanism in UGe$_2$ is not yet fully understood. Theory suggested that magnetic fluctuations in the vicinity of a ferromagnetic phase transitions could induce the Cooper pairing with odd-parity resulting in spin triplet superconductivity [8]. It was also shown experimentally with the NMR spectroscopy in another uranium based ferromagnetic superconductor, UCoGe, that longitudinal spin fluctuations might be responsible for spin triplet superconductivity [9]. The work we present here attempts to verify using inelastic neutron.
scattering (as a direct probe) whether the longitudinal magnetic fluctuations in UGe$_2$ are responsible for unconventional superconductivity.

**Fig. 1:** The schematic space phase diagram of UGe$_2$ [7]. The paramagnetic to ferromagnetic phase line is second order at low pressures (thin line) and first order at higher pressures (thick line). The dashed line indicates the crossover region between FM1 and FM2 phases. Solid thick line between FM1 and FM2 is first order. The shaded region is the region of superconductivity with the maximal critical temperature of $T_{SC} \approx 0.8$ K. Dots indicate the critical points.

2. Experiment
The sample used in the experiment was a single crystal grown by the Czochralski technique. The sample was spark cut to the dimensions of 6.1×3.4×4.0 mm. The electrical resistivity was measured at ambient pressure using the four-point method with a lock-in amplifier and is presented on Fig. 2(a). The clear drop of resistivity indicates the PM-FM transition at $T_c = 53$ K. The value of the residual resistivity ratio (RRR) was 62.

The pressure cell used in the experiment was the large volume two-layered piston-cylinder pressure cell described in [10]. The cell combines a large sample volume with a safe operating pressure limit of 18 kbar and was optimised for inelastic neutron scattering experiments [10]. Pressure inside the cell at low temperature was determined to be 11.8 kbar using the established phase diagram of UGe$_2$, Fig. 1. The measured crystal parameters at that pressure were: $b = 14.968$ Å and $c = 4.100$ Å. The rocking curve, Fig. 2(b), taken through $Q = 2\pi(0,0,1)/c$ at the same pressure gave the mosaic of 1.3°. This value of $Q$ was chosen since this Bragg peak is almost entirely magnetic due to very small nuclear contribution.

To obtain elastic and inelastic neutron scattering data we used the triple axis spectrometer IN14 at the Institut Laue-Langevin (ILL). For measurements at low temperatures, the cell was loaded in the ILL orange cryostat with a base temperature of 1.5 K. The inelastic data points were taken on $Q = 2\pi(0,0,1.04)/c$ at different temperatures at two energy transfers of 0.15 meV and 0.25 meV. A cool beryllium filter was placed on the incident momentum side. We used a neutron beam with fixed final momentum $k_f = 1.3$ Å$^{-1}$. The energy resolution was determined from the incoherent scattering with $Q = 2\pi(0,0.4,1.04)/c$ and had a full width at half maximum (FWHM) of 0.10 meV. We used $W$-configuration as a setup geometry and a PG (002) analyser with horizontal and vertical focusing. The temperature was measured using a Cernox thermometer which was mounted at the end of the probe very close to the
pressure cell. The neutron scattering intensity of the elastic scan taken on \( Q = 2\pi(0,0,1)/c \) is proportional to the square of magnetisation and clearly showed the two transitions: first, PM-FM with \( T_C = 33.5 \pm 0.5 \) K; and second, FM1-FM2 with \( T_x = 8.5 \pm 0.5 \) K, Fig. 3. An increase of inelastic scattering intensity is observed at \( T_C = 33.5 \pm 0.5 \) K at energy transfer of 0.15 meV. This increase is due fluctuations associated with the second order PM-FM transition.

The intensity of inelastic scattering (relative to background) decreases at higher energy transfer, Fig. 3. The data do not show any significant increase of scattering intensity at \( T_x = 8.5 \pm 0.5 \) K.

**Fig. 2:** (a) Resistivity of UGe\(_2\) at ambient pressure with current along c-axis within bc-plane. The PM-FM transition is observed at \( T_c = 53 \) K. (b) The rocking curve taken at \( p = 11.8 \) kbar on \( Q = 2\pi(0,0,1)/c \) at \( T = 1.6 \) K (background subtracted). Solid line is the Gaussian fit to the data. The measured mosaic was 1.3° at FWHM.

**Fig. 3:** Right axis shows elastic scattering points (▲) taken at \( Q = 2\pi(0,0,1)/c \) and at \( p = 11.8 \) kbar. Two phase are clearly seen: PM-FM with \( T_C = 33.5 \pm 0.5 \) K; and FM1-FM2 with \( T_x = 8.5 \pm 0.5 \) K. Left axis shows inelastic scattering points at \( Q = 2\pi(0,0,1.04)/c \) and at \( p = 11.8 \) kbar with two different energy transfers of 0.15 meV (●) and 0.25 meV (■).
3. Conclusion and future outlooks
The work presented here does not reveal ferromagnetic spin fluctuations at \( T_x \) associated with the FM1-FM2 transition. Instead, we observed fluctuations at \( T_C \) associated with the PM-FM transition. Furthermore, the energy scale of the fluctuations at \( T_C \) at high pressure is similar to the energy scale at ambient pressure where there is no superconductivity [7]. This might suggest that the fluctuations at \( T_C \) are unlikely to play a significant role in inducing superconductivity. On the other hand, the previous results [7, 11-12] show that the 5f electron still contribute to most of the differential susceptibility and are responsible for most of bulk magnetic properties at the temperature and pressure conditions similar to those presented in our work. However, it was also suggested by the muon spin spectroscopy measurements [12] that the FM1-FM2 transition might be due to conduction electrons which would not be detected in our experiment. The inelastic scattering from the conduction electrons is strongly suppressed by the magnetic form factor and cannot be measured in the standard three-axis geometry. More work is required to fully study the magnetisation fluctuations from components due to other orbitals and to understand their role in forming superconductivity.

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