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Anomalous magnetic response of $CeRu_2$

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Abstract. Long ago S. B. Roy and co-workers had explored the appearance of anomalous paramagnetic response in the magnetization data near the H_{c2} phase boundary in samples of $CeRu_2$. Recently, an anomalous paramagnetic response has also been demonstrated in a Borocarbide superconductor $LuNi_2B_2C$, where the phenomenon has been related to the symmetry transition of the flux line lattice. We report here the magnetization data from vibrating sample magnetometer in a single crystal of $CeRu_2$. We demonstrate that the magnetization profile is dipolar like only at very low fields and as the applied field increases it gets drastically modified. The presence of quadrupole moment along with the dipole moment is needed to justify such a magnetization profile. We report that the quadrupole moment undergoes a large modulations near the H_{c2} phase boundary. Hence, there is a possibility of response from quadrupole moment getting mixed with that from dipolar response which might lead to paramagnetic anomaly prior to H_{c2}.

1. Introduction

In mixed state of cubic laves (C15) superconductor $CeRu_2$ ($T_c \sim 6.1\ K$) [1] has received a large attention during past two decades [2, 3, 4, 5, 6, 7, 8, 9, 10] due to effects which could be considered to relate to enhanced paramagnetism in its normal state and to the topology of its Fermi surface, like field-induced anisotropic enhancement in density of states around equatorial directions, anisotropy of energy gap, as in the case of borocarbide superconductors YNi_2B_2C etc. Long ago S. B. Roy had pointed [2] to the existence of an anomalous increase in magnetization in a $CeRu_2$ sample, which was later subsumed by observation of hysteretic responses *a la* ubiquitous peak effect phenomenon in the same (H,T) parameter space [7, 8, 9]. In recent years, Park et. al. [11] have reported observation of anomalous paramagnetic response at high fields and low temperatures along with a specific heat anomaly and argued in favour of flux line lattice (FLL) symmetry transition on approaching H_{c2} line. A FLL symmetry transition closer to the H_{c2} line and at low temperatures has been very recently elucidated in a Heavy Fermion Superconducting compound $CeCoIn_5$ [12]. While performing magnetization measurements using Vibrating Sample Magnetometer (VSM) in a single crystal of $CeRu_2$, we noticed a paramagnetic hump before the arrival of T_c(H), whose follow up revealed the possibility of such an anomaly arising from the admixture of quadrupolar response, from the mixed state, of the sample into the dipolar response from the sample. A perusal of similar measurements in a crystal of YNi_2B_2C accessible to us revealed anomalous behaviour in it. We report here the results obtained in $CeRu_2$.

2. Experimental

The single crystal of $CeRu_2$ chosen for the present work was grown along with the batch used for dHvA studies [5] and had been used for the exploration of peak effect phenomenon earlier [9]. The magnetization measurements have been made on Oxford Instruments 12 Tesla VSM, which employs astatic pair of coils for detection of induced signal. The coil geometry is such that if a small sized sample possess non-uniform magnetization, it can be preferentially located [13, 14] at different vertical positions to record responses emanating from uniform part of the magnetization (i.e., dipolar response) and the non-uniform part (i.e., the quadrupolar response). Fig. 1 shows the sample profile in VSM, i.e., measured signal vs. sample position (z_0) along the vertical axis. Typically the sample is located at the saddle-point M-position to record dipolar response and it can be moved to the Q-position, where M is expected to cross the zero value, for preferentially measuring the quadrupolar response.

3. Results and Discussion

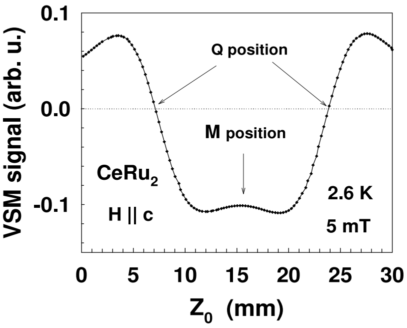

Figure 1. Plot of VSM signal vs. sample position, z_0, in ZFC state for applied field of 5 mT at 2.6 K.

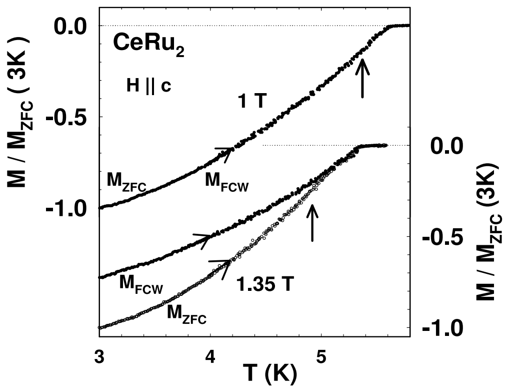

Figure 2. The isofield M-T data for 1 T and 1.35 T for both ZFC and FCW states for amplitude of sample vibration 0.3 mm.

Fig. 2 shows plots of normalized values of magnetization in zero field cooled (ZFC) and field cooled warm up (FCW) modes at 1 T and 1.35 T in the single crystal of $CeRu_2$. These data were obtained by carefully locating the sample at the M position and using vibration amplitude of 0.3 mm. The normalization has been done with respect to the respective M_{ZFC} values at 3 K. The arrows in fig. 2 mark the temperatures at which the peak of the PE would get fingerprinted in the in-phase ac susceptibility data in the same sample [9]. Note first that M_{ZFC} and M_{FCW} curves at H = 1 T overlap over the entire temperature range before and after the region of PE in the said field. However, in a field of 1.35 T, M_{ZFC} and M_{FCW} curves appear to merge, a little above the marked T_p(H) value, but, there is no anomalous change in the differences between M_{ZFC} and M_{FCW} values across T_p(H). This attests to the uniformity of the underlying dc field at the M-position over a distance of vibration amplitude of 0.3 mm.

Fig. 3 displays similar data for H = 1.35 T for sample nominally located in the center of the coil array and for vibration amplitude of 1.5 mm. The inset panel in fig. 3 displays similar data for H = 1 T. An anomalous paramagnetic hump in 1.35 T and a sharp peak implying paramagnetic enhancement over the equilibrium value in H = 1 T are clearly evident in fig. 3.

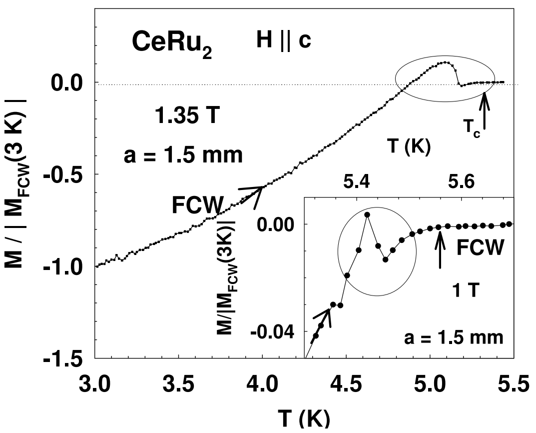

Figure 3. Plot of normalised magnetization vs. temperature for an applied field of 1.35 T and amplitude of vibration 1.5 mm

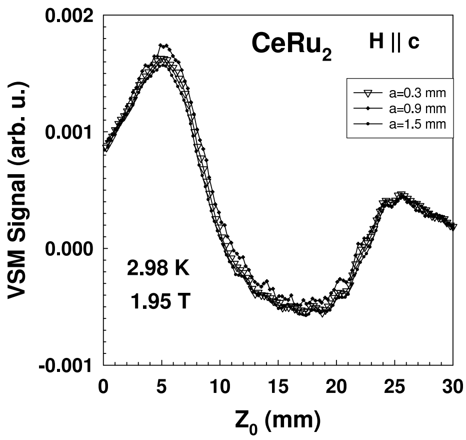

Figure 4. Plot of VSM signal vs. sample position, z_0, in ZFC state for applied field of 1.95 T at 2.58 K for mechanical amplitudes of vibrations 0.3 mm, 0.9 mm and 1.5 mm.

We reckoned that while recording the data displayed in fig. 2, we had located the sample at notional M position by centering the sample in a small field at the lowest temperature, whereas sometimes, we end up locating the sample in the M-position using higher fields. Fig. 4 shows the plot of VSM sample profiles recorded at T = 2.58 K for H = 1.95 T for different amplitudes of sample vibration, ranging from 0.3mm to 1.5mm. A comparison of these profiles with that displayed in fig. 1 establishes that they do not correspond to a pure dipolar response, their assymetric nature imply a contribution from the quadrupolar moment. Fig. 5(a) depicts the theoretical shapes of VSM profiles for dipolar (solid curve) and quadrupolar (dotted curve) responses in the given VSM system. Fig. 5(b) shows a superposition of responses from dipolar and quadrupolar moments in equal measure, the asymmetric nature of the resultant curve is well evident.

The shape of the profile in fig. 4 implies that the mixed state of $CeRu_2$has large quadrupolar response. The amount of its admixture into the dipolar response would depend on the nominal mean location of the sample and, also, to some extent on the amplitude of vibration chosen for recording the data. Fig 6(a) and (b) illustrates the VSM signals recorded at different nominal locations at H=1T for vibration amplitudes of 1.5 mm. It is apparent that phase of the signal changes as the sample get located from one end towards the other end. During the given set of measurements, the sample located at $z_0 \approx 20$ mm did not imbibe the paramagnetic anomaly. At $z_0 \approx 7.1$ mm, the dipolar response is minimum and the quadrupolar response displays a sharp peak (*a la* paramagnetic response in the superposed admixed state) across temperature region of PE, where peak position is marked by an arrow. The sharp change in quadrupolar response across PE can be reconciled by recalling that ordered vortex state undergoes amorphization across PE region, such a change could reflect in its quadrupole moment.

4. Summary

To summarize, we have explored the possibility of admixture of various multipole moments in the conventional magnetization (magnetic dipole moment) data. We have also illustrated that if the sample is not positioned accurately then admixtures can result in anomalies in magnetization

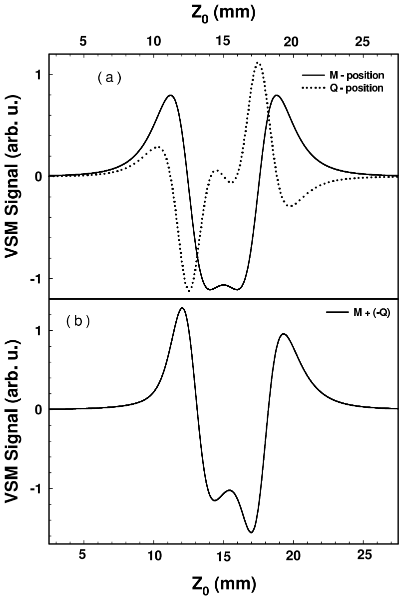

Figure 5. Panel (a) shows plots of theoretical VSM signal vs. sample position for a perfect dipole (continuous line) and quadrupole (dotted line). Panel (b) shows plot of VSM signal derived from the superposition of both the dotted and continuous curves of panel (a) vs. sample position

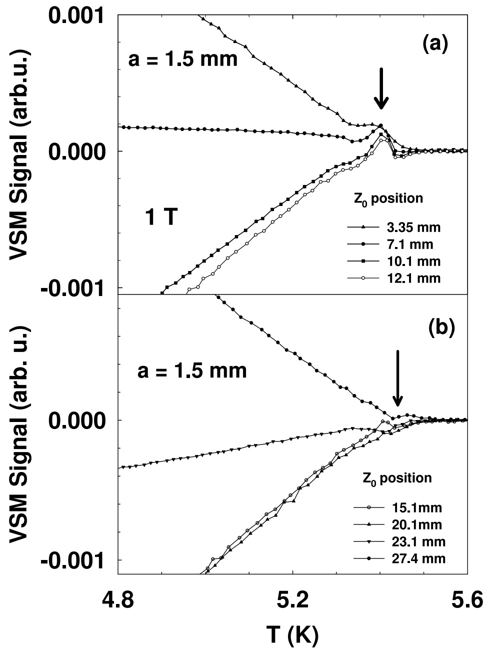

Figure 6. Plot of VSM signal vs. temperature at different postions, z_0, in ZFC state for an applied field of 1 T and for mechanical amplitude of vibration 1.5 mm. The regions of anomaly are marked by arrows.

across in a crystal of $CeRu_2$. It may have implications for similar anomalies reported in some of other systems.

5. References

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