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LETTER TO THE EDITOR

Anomalous magnetization of superconducting $CeRu_2$

S B Roy† and B R Coles‡

† Centre for Advanced Technology, Indore 452013, India

‡ Blackett Laboratory, Imperial College, London SW7 2BZ, UK

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Abstract. A number of recent measurements of this behaviour are discussed, and it is pointed out that there are two features of interest. One is a peak effect somewhat below H_{C2} of the type seen in some other type-II superconductors. The other is a so far unique excess magnetization (over that in the normal state) in a reversible region immediately below H_{C2}. It is speculated that the latter may be associated with the loss in the superconducting state of a Kondo compensation of Ce moments.

A number of recent papers [1–3] have drawn attention to the unusual behaviour of the C15 superconductor, $CeRu_2$, when its magnetization is measured as a function of field in the superconducting state. The purpose of the present letter is to make clear that *two anomalous features* have been observed, one of them being found in some other type-II superconductors and capable of reasonably satisfactory explanation. The other, quite different feature is clearly seen in earlier work [1,2] on polycrystalline specimens and in other specimens we have prepared; this is not yet adequately explained.

The first feature is what has been described as the 'peak effect' by Campbell and Evetts [4], and is explored in some detail by Isino *et al* [5] in V_3Si. It consists (see figure 2 of [2]) of a narrow range of irreversibility in $M(H)$ observed close to H_{C2}, even in samples that are fairly reversible at lower fields. This recovery of pinning close to H_{C2} has been widely discussed and ascribed to rigidity of the fluxoid line lattice [6]. It should be emphasized that figure 8 of [5] shows clearly that reversibility is recovered in the final field range above the peak and just below H_{C2}. That final reversible regime is found also in specimens of $CeRu_2$ showing the peak effect (see figures 2 and 3 of [1] and figure 3 of [2]), but the remarkable second feature is that in those polycrystalline specimens, although they differed in their reversibility at lower fields, the magnetization in the reversible range just below H_{C2} was significantly larger (more positive) than that just above H_{C2} in the normal state. The behaviour is shown schematically in figure 1. This feature, which we also observe in $CeRu_2$ with 5% of the Ce substituted by La, has not been reported for other type-II superconductors with significant normal state susceptibilities, often showing the peak effect: materials described by Hake [7] as extreme type-II superconductors. Neither was this feature reported for the single-crystal $CeRu_2$ specimen recently described [3], but it should be remembered that the magnetization data of that paper were taken in a SQUID magnetometer in such a way that the final magnetization curve (figure 1(*d*) of that paper) had to be reconstructed from raw data (figure 1(*a*) of that paper). As the authors pointed out, these raw data do not give the true, full hysteresis curve of the sample because they

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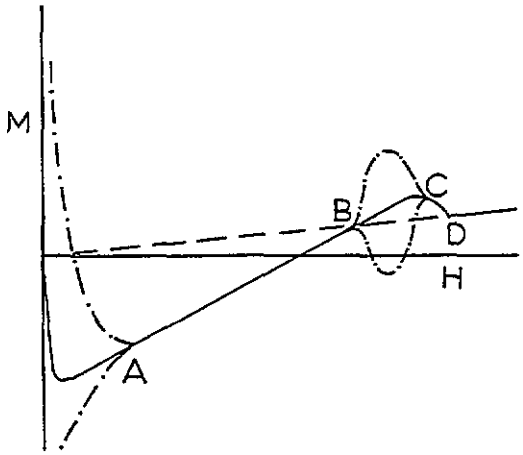

Figure 1. General features of the magnetization curves of $CeRu_2$ below T_C. The full curve represents what we believe a perfect, fully reversible specimen would show. The chain curves show two regimes of irreversibility, the upper one being the 1peak effect' separated in some specimens by a reversible regime AB. CD is the reversible regime of 'excess' magnetization found in all our specimens of $CeRu_2$ and those of [2].

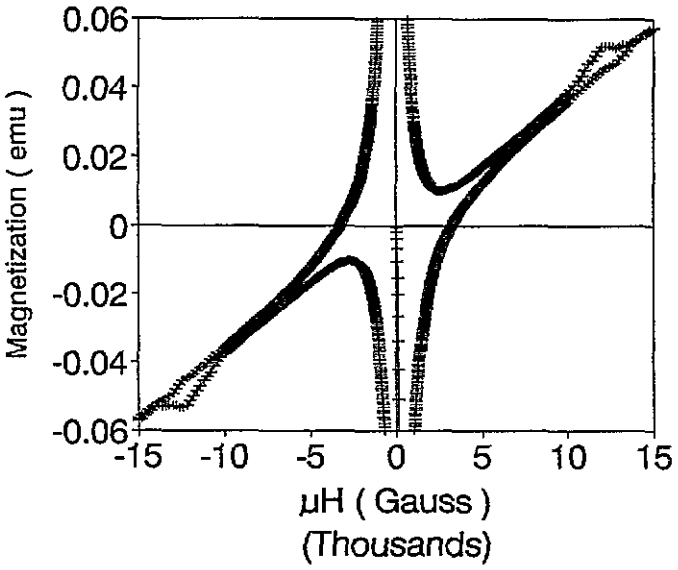

Figure 2. Magnetization (M) versus field (μH) plot of $(Ce_{0.95}Nd_{0.05})Ru_2$ at $T = 5.8$ K.

correspond to changes of flux as the sample is raised through the superconducting coils in a field that is not perfectly homogeneous.

In figure 2 we present the M versus H plot of a $(Ce_{0.95}Nd_{0.05})Ru_2$ sample. Note that with 5% Nd doping, the unusual phenomenon (namely a magnetization just below H_{C2}, larger and more positive than the normal state magnetization just above H_{C2}) observed in the parent compound $CeRu_2$ around H_{C2} has disappeared; however, a significant peak effect can be clearly observed. As in other materials showing the peak effect it appears

at higher fields at lower temperatures. It is interesting to note here that in contrast to the parent compound of the same batch [1], there is a distinct reversible regime at intermediate fields. The overall features of this sample appear to be quite similar to that reported for the single-crystal $CeRu_2$ [3]. This result along with the results of Yagasaki *et al* [2] show that to get a distinct peak effect one need not necessarily study a single-crystal sample. On a further increase of Nd concentration to 10% Nd, we could not even see the peak effect down to 4 K with fields up to 8 T. It should be recognized that the Nd moments give this alloy a much larger normal state susceptibility.

It is perhaps premature to speculate in detail on the origin of the remarkable excess magnetization just below H_{C2} in $CeRu_2$. One fascinating possibility that presents itself, however, is that the magnetic character of the Ce atoms (which are known from a variety of measurements to have 4f occupation) is modified from the Kondo-compensated non-magnetic state, which exists in the normal state, by the onset of superconductivity. Were the establishment of the superconducting gap at the Fermi level to remove the very single particle states whose hybridization with the 4f states demagnetizes the latter, Ce moments would appear to give a large paramagnetic response to any magnetic field they see. Thus on increasing the field towards H_{C2}, the Ce atoms in the superconducting phase would yield a paramagnetic response greater than that just above H_{C2}, where they will be in the normal phase. The spatial variation of the magnetic character of the Ce atoms in a flux lattice may prove a difficult problem for a proper calculation. The magnetic field seen by them will require the sort of considerations used by Baberschke *et al* [8] to discuss the behaviour of the ESR g value of Gd ions dissolved in $CeRu_2$ in the vortex state, and the anomalous increase in g shift they observe at the X band may be related to the effects we have discussed.

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