Magnetic-field-induced superconductivity

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(Received 22 June 1981; Revised manuscript received 11 September 1981)

The electrical resistance, R, of the pressure-induced superconductors $Sn_xEu_{1.2-x}Mo_6S_8$ with $x=0.0$ and 0.12 has been investigated as a function of magnetic field up to 17 T and at pressures up to 18 kbar. At the pressure where T_c is a maximum, 14 kbar, a minimum is observed in the resistance versus field at temperatures below 4.2 K and for fields between 10 and 15 T. In particular, for the sample with $x=0$, R approaches 0 in this high-field region. At other pressures and for the other sample the anomaly is not as pronounced.

The interplay between magnetism and superconductivity has been a subject of interest for many years. The magnetic ions through their exchange interactions I with the conduction electrons, break Cooper pairs and thus depress the superconducting transition temperature T_c. In their theoretical study, Maekawa and co-workers[1,2] have shown that in the mean-field approximation the superconducting pair potential in the presence of magnetic ions is modified to $g=g_0-c\chi$, where g_0 is the pair potential in the absence of the magnetic ions, c a constant proportional to I^2, and χ the magnetic susceptibility. They pointed out that in some cases a *normal* magnetic metal (χ large) can be transformed into a *superconductor* ($g>0$) by the application of an external magnetic field H which suppresses spin fluctuations such that $\chi\rightarrow 0$ provided $g_0(H)>0$. It is clear that this kind of field-induced superconductor is a type-II superconductor: it exists only between H_{c1} and H_{c2} where the flux penetrates and only when $\mu H/kT >> 1$ so that the spins are saturated. The Jaccarino-Peter-type compensation field acting on conduction-electron spins is another possible way in which magnetic field can induce superconductivity. If the negative exchange field induced by the Eu^{2+} spins polarizes the conduction electrons and destroys superconductivity, the positive applied field can compensate the exchange field and superconductivity would reappear at high magnetic field.

Recently, Isino *et al.*[3] measured the resistance of a superconductor, $Eu_{0.80}Sn_{0.20}Mo_6S_7$, in an applied magnetic field. At 1.49 K, as they increased the field, the sample first became resistive and then at a higher field the resistance decreased approaching 0. This reduction in the resistance could be the result of magnetic-field-induced superconductivity. In view of this interesting result, and the ability to "vary" superconductivity continuously by hydrostatic pressure, we have studied the resistance of $Sn_xEu_{1.2-x}Mo_6S_8$ ($x=0$ and 0.12) as a function of pressure and field.

The samples are the same as those used in Ref. 4, and a pressure cell similar to that in Ref. 4 was used. These samples are metallic at pressures above 12 kbar at all temperatures and show a very anomalous temperature dependence of the critical field above this pressure. At lower pressures the samples undergo a lattice transformation and become semiconducting below the transformation.[5]

Figure 1 shows our R-vs-H data for the $x=0$ sample at $P\approx 14$ kbar where T_c is a maximum. At high temperature (8.9 K), the R-H curve is ordinary. At 4.2 K, the curve is anomalous, indicating the interactions of the conduction electrons and the Eu^{2+} spins aligned by the applied field. At 2.5 K,

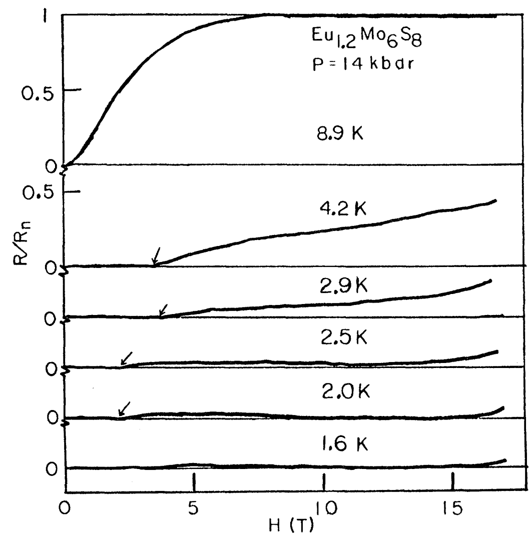

FIG. 1. Normalized resistance R/R_n plotted versus magnetic field H for $Eu_{1.2}Mo_6S_8$ for various temperatures at $P=14$ kbar. The scale for each curve is the same. The arrows point to the onset of resistance.

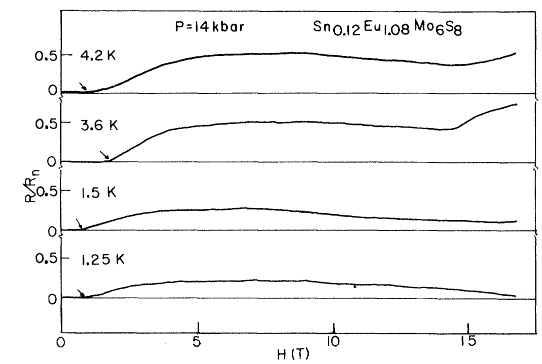

FIG. 2. Normalized resistance R/R_n plotted versus magnetic field H for $Sn_{0.12}Eu_{1.08}Mo_6S_8$ for various temperatures at $P=14$ kbar. The arrows point to the onset of resistance.

R increases first and then decreases at higher fields. At 2 K, R is nearly zero between ~ 10 and ~ 15 T. Similar results are observed at 1.6 K. These data clearly show that the field-induced reduction of R occurs only at low T and high field where $\mu H/kT >> 1$. Using the formalism of the Jaccarino-Peter effect, the magnetic field acting on the Mo can be expressed as[6] $B_{in}=B_{ext}-cI\langle S_z\rangle$, where B_{ext} is the external field, c the magnetic ion concentration, I the exchange interaction, and $\langle S_z\rangle$ the thermal average of the z component of the magnetic ion spin. It has been shown that the compensation exchange field $cI\langle S_z\rangle$ increases very strongly with increasing pressure.[6] As a result, at a very high pressure the spin effect dominates and the resulting exchange field requires too large an external field to induce superconductivity. Conversely, at low pressures the orbital effect overshadows the spin effect. Therefore, the observation of a field-induced effect is very sensitive to the applied pressure and thus should appear in a very narrow pressure window which in fact is exactly what is observed. At pressures both above and below 14 kbar this effect rapidly vanishes. Another interesting feature illustrated by the figure is that below 3 K, the field at which R starts to appear decreases with decreasing temperature. This might be related to magnetic ordering effects.[7]

Figure 2 displays our result for the sample with $x=0.12$ at 14 kbar. Again a segment with $dR/dH<0$ has been observed for each temperature curve, but R does not approach "zero" as in the previous figure. However, from the curve for $T=1.25$ K, it seems that R/R_N might approach 0 at higher field and a lower T. The reason for the absence of a nearly zero resistance in this sample is that the compensation field is proportional to the magnetic ion concentration and hence the spin effect never completely dominates the orbital effect above 1.21 K, as is the case for $x=0.0$.

Above all, we have observed the field-induced reduction of R in the field range between H_{c1} and H_{c2}. Even though it is likely that this reduction could be caused by field-induced superconductivity, it is also possible that this reduction is the result of an ordinary negative magnetoresistance. However, measurements on these samples in the metallic state above 12 kbar (Ref. 5) show a very small positive magnetoresistance consistent with the magnetoresistance data on $Sn_{0.48}Eu_{0.72}Mo_6S_8$, which also shows a positive magnetoresistance.[8] In addition, the assumption that the 0 resistance at 2 K between ~ 9 and 15 T results from negative magnetoresistance requires the further assumption that the resistance between ~ 2 and 8 T originates solely from Eu^{2+} spin fluctuations. This latter assumption is unlikely because the resistance should at least partly arise from normal electrons depaired by the applied field. The field, in fact, should depress the depairing due to Eu^{2+} spin fluctuations because χ decreases with increasing H. Hence the disappearance of resistance between ~ 9 and 15 T should result from field-induced superconductivity.

We would like to thank C. W. Chu, P. D. Hambourger, and J. D. Thompson for discussions and assistance. Two of us (Huang and Harrison) were supported by the U.S. Department of Energy and another of us (Luo) by the National Science Foundation under Grant No. DMR-78 24281.

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