Anomalous temperature dependence of the upper critical field of the magnetic superconductor $NdMo_6S_8$

N. E. Alekseevskiĭ and V. N. Narozhnyĭ
Institute of Physical Problems, Academy of Sciences of the USSR

(Submitted 28 March 1984)
Pis'ma Zh. Eksp. Teor. Fiz. **39**, No. 10, 456–458 (25 May 1984)

The $H_{c2}(T)$ curve of $NdMo_6S_8$ has a maximum at $T \sim 1.3$ K.

Stoichiometric ternary compounds containing magnetic rare-earth ions have recently attracted considerable research interest. Among these compounds are the ternary chalcogenides of molybdenum,[1,2] $REMo_6X_8$ (X is S or Se, and RE is a rare earth), and compounds of the composition[3] $RERh_4B_4$. Although about 10% of the ions in the lattice are magnetic, many compounds of these groups are superconductors (see Ref. 4, for example), apparently because the exchange interaction is quite weak in these compounds.

Research on the electrical, magnetic, and thermal properties of these superconductors has revealed several anomalous features in some of them. It has been suggested that a magnetic ordering occurs at temperatures below T_c (Refs. 3, 5, and 6). Neutron-scattering measurements have revealed that the compounds $ErRh_4B_4$ (Ref. 7) and $HoMo_6S_8$ (Ref. 8) do in fact exhibit a ferromagnetic ordering of the rare-earth ions, which disrupts the superconductivity at $T_m < T_c$. In the compounds $DyMo_6S_8$, $TbMo_6S_8$, and $ErMo_6S_8$ (Ref. 9), on the other hand, an antiferromagnetic ordering which occurs at $T_m < T_c$ does not disrupt the superconductivity, simply giving rise to an anomalous feature on the temperature dependence of the upper critical field $H_{c2}(T)$.

In this letter we report observing ananomalous temperature dependence $H_{c2}(T)$ for the compound $NdMo_6S_8$. Several measurements were carried out with samples of the compound $DyMo_6S_8$, which has been studied previously.[6] The samples were prepared by direct synthesis of the necessary amounts of Mo, S, and NdS (the composition of the original material was $Nd_{1.2}Mo_6S_8$) at $T = 900$ °C. The samples were rendered homogeneous by pulverizing them in an agate mortar, compression, and annealing at $T = 1100$ °C for about 20 h.

The measurements in the temperature interval 0.5–1.5 K were taken in an apparatus with He-3 vapor pumping at the International Laboratory of Strong Magnetic Fields and Low Temperatures, Wrocław, Poland. Temperatures down to 0.05 K were produced by adiabatic demagnetization of yttrium aluminum garnet with a partial substitution of erbium[10] in an apparatus with a cold plate similar to that described in Ref. 11.

Figure 1 shows the resistance $r(T, H)$ of an $NdMo_6S_8$ sample versus the temperature for various magnetic fields. At $H = 0$ the sample goes superconducting at $T_c = 3.4$ K. In magnetic fields up to 1 kOe, the sample remains completely superconducting at temperatures below 2 K. At higher magnetic fields, an incomplete superconducting transition is observed, and the resistance increases as the temperature is lowered below 1 K. At $T \sim 0.3$ K, the $r(T)$ curve has a slight maximum, at a position

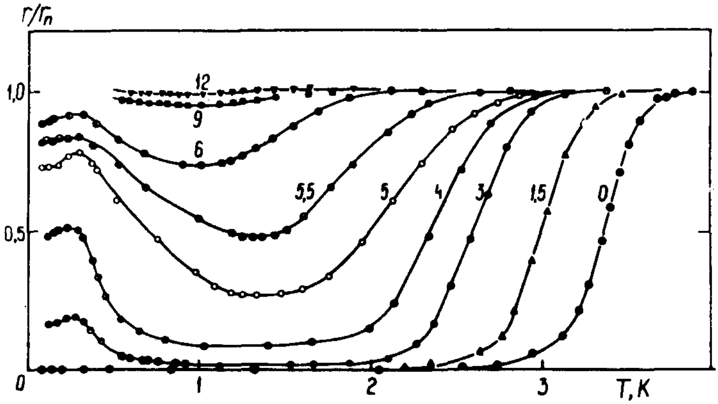

FIG. 1. Superconducting transitions of $NdMo_6S_8$. The curves are labeled with the magnetic field H in kilo-oersteds.

which does not depend on the magnetic field. In contrast, the temperature at which the resistance begins to rise before the maximum on the $r(T)$ curve depends strongly on the magnetic field. It should be noted that the measurements were taken at a constant value of H; the increases in H were carried out systematically after heating above T_c.

The results of the measurements of $r(T, H)$ for the compounds $DyMo_6S_8$ agree well with the data of Ref. 6. At fields above 1 kOe, lowering the temperature below T_c produces a sharp maximum on the $r(T)$ curve, at a position which does not depend on the magnetic field. In contrast with the results for $NdMo_6S_8$, in the compound $DyMo_6S_8$ the temperature at which the resistance increases in front of the maximum is essentially independent of the magnetic field.

If we plot $H_{c2}(T)$ from the centers of the transitions, we find curves with a maximum. For $DyMo_6S_8$, the $H_{c2}(T)$ curve has a characteristic minimum at $T{\sim}0.2$ K. In contrast with the results of Ref. 6, at $T<0.2$ K we observe a further increase in $H_{c2}(T)$ with decreasing temperature. For $NdMo_6S_8$, we observe a far fainter structural feature on the $H_{c2}(T)$ curve at $T{\sim}0.2$ K.

Our results on $r(T, H)$ and $H_{c2}(T)$ for $NdMo_6S_8$ are basically similar to those obtained in Ref. 6 on $ErMo_6S_8$. For $ErMo_6S_8$, an antiferromagnetic ordering has been

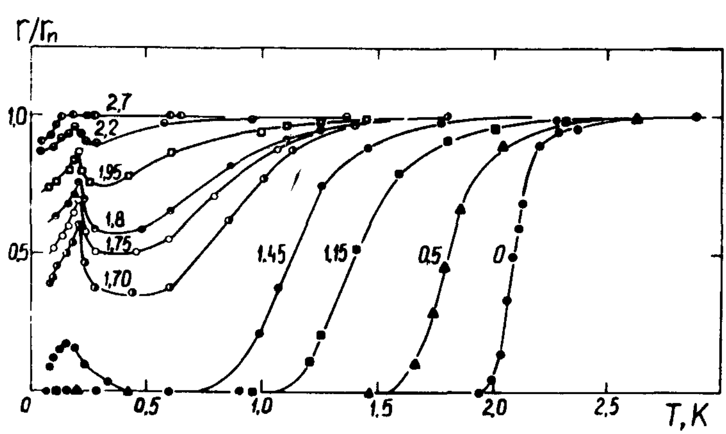

FIG. 2. Superconducting transitions of $DyMo_6S_8$. The curves are labeled with the magnetic field H in kilo-oersteds.

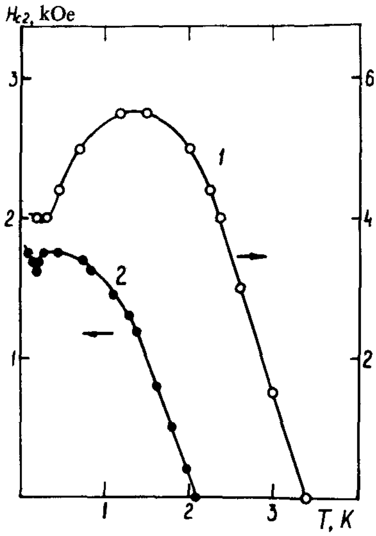

FIG. 3. Temperature dependence of the upper critical magnetic field H_{c2}. 1—$NdMo_6S_8$; 2—$DyMo_6S_8$.

observed in neutron-scattering measurements in a field of 250 Oe at $T\sim 0.2$ K (Ref. 9). In Ref. 6, an $H_{c2}(T)$ curve with a maximum, similar to that which we found in the present measurements for $NdMo_6S_8$, was attributed to an increase in the effective internal "depairing" field with decreasing temperature. This field is associated with the increase in the magnetic susceptibility of the sublattice of Er^{3+} ions, which precedes the magnetic ordering. The $H_{c2}(T)$ dependence observed for $NdMo_6S_8$ in the present experiments can apparently be explained in a similar way.

The neutron-scattering measurements of Ref. 9 showed that the compound $DyMo_6S_8$ goes into an antiferromagnetically ordered state at $T\sim 0.4$ K.

In summary, we have observed an anomalous $H_{c2}(T)$ dependence (with a maximum) for the compound $NdMo_6S_8$. This dependence is similar to that observed previously[6] for the compound $ErMo_6S_8$. The apparent reason for this anomalous structural feature is an antiferromagnetic ordering at $T\sim 0.3$ K in the system of Nd^{3+} ions, with the compound remaining in the superconducting state.

We wish to thank Yu. A. Deniskin, E. P. Khlybov, A. S. Rudenko, and Kh. Medge for assistance in the experiments.

[1]Ø. Fischer, A. Treyvaud, R. Chevrel, and M. Sergent, Solid State Commun. **17**, 721 (1975).
[2]R. N. Shelton, K. W. McCallum, and A. Adrian, Phys. Lett. **56A**, 213 (1976).
[3]W. A. Fertig, D. C. Johnston, L. E. DeLong, K. W. McCallum, M. B. Maple, and B. T. Matthias, Phys. Rev. Lett. **38**, 987 (1977).
[4]H. Matsumoto and H. Umezawa, Cryogenics 37 (January 1983).
[5]M. Ishikawa and Ø. Fischer, Solid State Commun. **23**, 37 (1977).
[6]M. Ishikawa and Ø. Fischer, Solid State Commun. **24**, 747 (1977).
[7]D. E. Moncton, D. B. McWhan, J. Eckert, G. Shirane, and W. Thomlinson, Phys. Rev. Lett. **39**, 1164 (1977).
[8]J. W. Lynn, D. E. Moncton, W. Thomlinson, G. Shirane, and R. N. Shelton, Solid State Commun. **26**, 493 (1978).
[9]W. Thomlinson, G. Shirane, D. E. Moncton, M. Ishikawa, and Ø. Fischer, Phys. Rev. **B23**, 4455 (1981).

[10]N. E. Alekseevskiĭ, A. P. Dodokin, C. Bazan, Kh. S. Bagdasarov, E. A. Fedorov, and L. M. Belyaev, Cryogenics 598 (October 1981).
[11]N. E. Alekseevskiĭ and Yu. P. Gaĭdukov, Pis'ma Zh. Eksp. Teor. Fiz. **25**, 383 (1953).

Translated by Dave Parsons
Edited by S. J. Amoretty