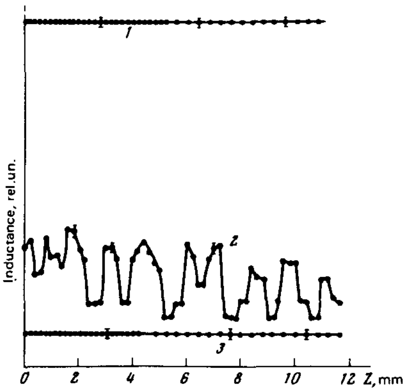

FIG. 2.

in an interval of 1 mK. The sample was mounted on the Dewar vertically. The experiments were performed near T_c ($\Delta T = 13$ mK) at approximate critical currents 2 A. Above T_c and below T_c, at zero current in the sample, the self-inductance of the coil was independent of its position on the sample (Fig. 2, curves 1 and 3). On the other hand, when a current somewhat larger than critical flowed through the sample, then in this case the axial distribution of the magnetic permeability of the sample revealed a rather distinct periodicity (Fig. 2, curve 2) with a period 1.3 ± 0.1 mm, although the structure was not so geometrically regular as in the model. The observed picture was surprisingly well duplicated during the day and even during different days. The character of the curve remained unchanged if the vertical component of the earth's field and the field of the measuring coil were cancelled out. The indicated curves were plotted over different time intervals, from 20 min to 1 h, and the temperature was maintained accurate to 0.5 mK during the experiment, while the current instability in the sample did not exceed 5 mA,

It seems that in the foregoing experiments we were able to observe directly an intermediate-state structure produced by the current in tin cylinders. It turned out to be static and similar to that proposed by London.

We are deeply grateful to B. G Lazarev for a number of valuable hints, for numerous fruitful discussions, and for constant interest in the work.

[1)]The procedure of the precision measurements of small inductances will be described later on.
[2)]We are grateful to B. N. Aleksandrov for supplying the single crystal.

[1]L. V. Shubnikov and N. E. Alekseevskiĭ, Zh. Eksp. Teor. Fiz. **6**, 1200 (1936).
[2]F. London, Superfluids, **1**, 120, New York-London, 1950.
[3]B. V. Makeĭ, Zh. Eksp. Teor. Fiz. **34**, 312 (1958) [Sov. Phys.-JETP **7**, 217 (1958)].
[4]A. G. Meshkovskiĭ and A. L. Shal'nikov, Zh. Eksp. Teor. Fiz. **17**, 851 (1947).
[5]L. Rinderer, Helv. Phys. Acta **29**, 339 (1956).
[6]L. Rinderer and F. Haenssler, Helv. Phys. Acta **32**, 320 (1959).
[7]C. J. Gorter, Physica **23**, 45 (1957).
[8]A. F. Andreev, Zh. Eksp. Teor. Fiz. **54**, 1510 (1968) [Sov. Phys.-JETP **27**, 809 (1968)].
[9]C. G. Kuper, Phil. Mag. **43**, 1264 (1952).
[10]D. C. Baird and B. K. Mukherjee, Phys. Rev. Lett. **21**, 996 (1968).

Magnetic properties of the superconducting compound $Mo_5SnGa_{0.5}S_6$

N. E. Alekseevskiĭ, Ch. Bazan,[1)] N. M. Dobrovol'skiĭ, and V. I. Tsebro

Institute of Physics Problems, USSR Academy of Sciences
(Submitted August 7, 1974)
ZhETF Pis. Red. **20**, No. 7, 465–468 (October 5, 1974)

It is shown that the investigated system has a phase diagram that differs from usual type-II superconductors in that strong paramagnetism (ferromagnetism) coexists with superconductivity in a definite range of fields and temperatures.

We have already reported that the dependence of the magnetic moment M on the magnetic field in Mo_5SnS_6 doped with Ga or Al, in the temperature region between the superconducting transition temperature T_c and $T \sim 30$ °K is nonlinear,[1] in contrast to pure Mo_5SnS_6. It was of interest to investigate the magnetic properties of such systems not only in the normal but also in the superconducting region.

We investigated $M(H)$ and $H_c(T)$ of $Mo_5SnGa_{0.5}S_6$ samples in a wide range of fields and temperatures.

The samples were cut from an $Mo_5SnGa_{0.5}S_6$ cylinder. This cylinder was obtained by sintering pressed powder of the compound obtained by direct synthesis of the components. The samples usually measured $1 \times 1 \times 5$ mm. To measure the magnetic moment, we used a vibration magnetometer.[2)] To obtain the $H_{c_2}(T)$ dependence we used the resistance plots $R(H)|_{T=\mathrm{const}}$ or $R(T)|_{H=\mathrm{const}}$. To measure the resistance, the ends of the samples were electrolytically coated with copper, after which current and potential leads were soldered to them.

Figure 1 shows plots of $M(H)$ obtained at various temperatures. It is seen from the figure that the magnetic moment is paramagnetic in the temperature region above T_c. The $M(H)$ dependence takes the form of a

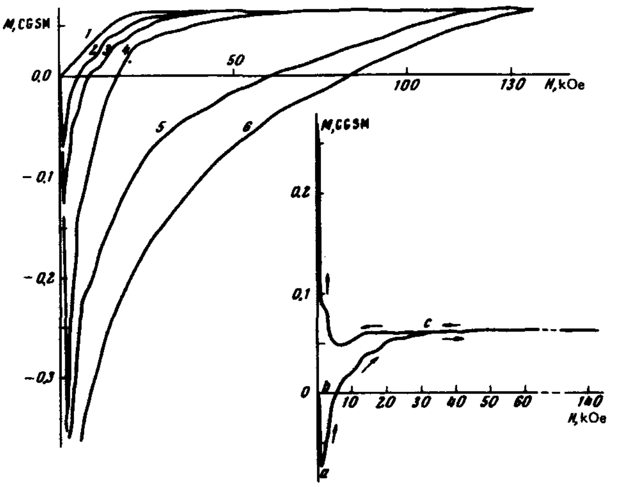

FIG. 1. Plot of magnetic moment $M(H)$ against the field, obtained at different temperatures. Curves 1, 2, 3, 4, and 6 correspond to T/T_c equal to 1.1, 0.96, 0.93, 0.89, 0.6, and 0.4, respectively. In the lower right-hand corner of the figure is shown a plot of $M(H)$ at $T/T_c = 0.96$, obtained by scanning the magnetic field in both directions.

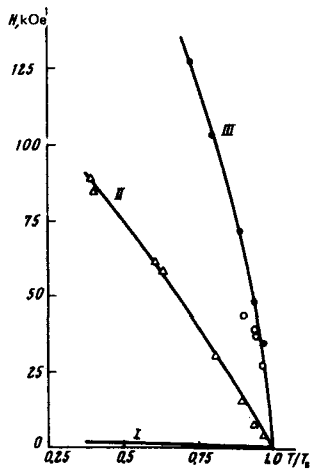

FIG. 2. Plots of $H_c(T)$: I) $H_{c_1}(T)$, II) $H_0^*(T)$, III) $H_{c_2}(T)$; H_0^*) magnetic field at which $M_{dia} = M_{para}$; ●) values of H_{c_2} obtained from measurement of the resistance; ○) values of H_{c_2} obtained from the value of the field at the points c, when the magnetic moment saturates.

curve with saturation, and at $H > 25$ kOe and up to 140 kOe the magnetic moment is independent of the magnetic field. At $T < T_c$ in a weak magnetic field, the magnetic moment is diamagnetic and the $M(H)$ plot assumes the customary shape for superconductivity. At $T/T_c = 0.96$, the maximum diamagnetic moment (the point a) is approximately equal to the paramagnetic moment M_{sat} in the saturation region. At the point b, the magnetic moment is equal to zero, i.e., $M_{dia} = M_{para}$. At the point c, the magnetic moment saturates, $M = M_{sat}$. It should be noted that M_{sat} does not depend on the temperature.

Figure 2 shows plots of $H_{c_1}(T)$ (curve I) and $H_{c_2}(T)$ (curve III), and also the temperature dependence (curve II) of the field H_0^* at which $M_{dia} = M_{para}$. The $H_{c_1}(T)$ plot was determined from the temperature dependence of the field at the point a,[3)] and $H_0^*(T)$ likewise at the point b. The values of $H_{c_2}(T)$ on curve III were obtained from the plots of the resistance, but some of the points on this same curve, in a region relatively close to T_c, were taken from the values of the field at the points c. We see that the values of H_{c_2} determined by different methods fit well the same curve.

It follows from Fig. 2 that the system investigated by us has a phase diagram different from ordinary type-II superconductors, namely, in weak fields $H < H_{c_1}$ the investigated samples are diamagnetic, at $H_{c_1} < H < H_0^*$ the samples are in a mixed state (i.e., in the Shubnikov phase), with a mean susceptibility $\bar{\chi} < 0$, and finally at $H_0^* < H < H_{c_2}$ the system is in a new mixed state with $\chi > 0$, i.e., in this region of fields the strong paramagnetism (or ferromagnetism) coexists with the superconductivity. It should be noted that if we plot the magnetic moment against the temperature for different values of the external field, then in weak fields, as the temperature decreases to $T < T_c|_H$, the sample goes over into a diamagnetic state, whereas in strong fields, upon cooling, the magnetic moment becomes unstable and a large paramagnetic moment, probably connected with frozen-in current, becomes frozen into the sample.

The system investigated in greatest detail was $Mo_5SnGa_{0.5}S_6$. It seems, however, that a few other multicomponent chalcogenides of molybdenum has similar properties. Thus, for example, similar properties are possessed by $Mo_5SnAl_{0.5}S_6$.

As already noted earlier,[1] the singularities of the magnetic properties of the investigated chalcogenides cannot be attributed to the presence of ferromagnetic impurities. It should be noted, however, that the composition of the samples can differ from that of the original batch, inasmuch as microscopic and electron-microscope investigations have revealed metallic inclusions enriched with Ga in these samples. The saturation moment M_{sat} seems to depend on the amount of the Ga in the compound.

The high critical temperature T_c, the rather high values of $\partial H_{c_2}/\partial T$, and the large electronic specific heat, all give grounds for assuming that both the superconducting and magnetic properties of these systems are determined by the large density of states on the Fermi surface $N(0)$. To ascertain the true cause of the singularities of these systems, further research must be performed.

1)International Laboratory for Strong Magnetic Fields and Low Temperatures, Wroclaw, Poland.

2)Such a magnetometer was constructed at the International Laboratory of Strong Magnetic Fields and Low Temperatures. In contrast to[1], the measurements of M were made in this case in a homogeneous magnetic field.

3)Such an approximation is admissible because the demagnetizing factor of the investigated samples is small.

1N. E. Alekseevskiĭ, N. M. Dobrovol'skiĭ, and V. I. Tsebro, ZhETF Pis. Red. 20, 59 (1974) [JETP Lett. 20, 25 (1974)].