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Point contact spectroscopy on the ferromagnetic superconductor $HoMo_6S_8$

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Abstract

Point contact spectroscopy performed in single crystals of the ferromagnetic superconductor $HoMo_6S_8$, has been used to study the evolution in temperature and competition of the two order parameters. At temperatures of the order of the superconducting transition, we observe the onset of a structure in the dV/dI versus V characteristics that may be related to the development of the superconducting energy gap. At temperatures close to the ferromagnetic transitions, we also observe the growth of another structure in the dV/dI versus V characteristics that may be correlated with the development of the magnetic order parameter. This feature in the dV/dI versus V characteristic develops in a direction opposite to the structure associated with the superconducting energy gap.

Superconductivity and magnetism are two phenomena that compete each other. One example of this behavior is found when a superconductor is doped with paramagnetic impurities: the interplay between Cooper pairs and magnetic impurities results in pair breaking, and therefore in the destruction of superconductivity. This process has been very well explained in the theoretical model of Abrikosov and Gor'kov [1]. Another beautiful example of this interplay between magnetism and superconductivity, can be found in the case of reentrant superconductivity. Here a compound transits to the superconducting state, with a transition temperature T_{C1}, similar as in a normal superconductor. If the temperature decreases there is another transition temperature, T_{C2}, where the compound reenters the normal state. This kind of physical process was found in compounds such as $ErRh_4B_4$ [2], $HoMo_6S_8$ [3], and in the recently discovered $HoNi_2B_2C$ [4]. This reentrance behavior is due to the fact that the compound presents a magnetic ordering below the superconducting transition temperature: ferromagnetism occurs in the case of the two first compounds, and antiferromagnetic in the case of $HoNi_2B_2C$. The competition between the two processes is the reason for the reentrance behavior.

In this paper, we present our initial studies of the ternary compound $HoMo_6S_8$ using point contact spectroscopy (PC). This compound is known as a Chevrel phase, it presents a superconducting transition temperature of around $T_{C1} = 1.8$ K. At temperatures of 0.75 and 0.70 K two magnetic transitions occur, these are of ferromagnetic character. At $T_{C2} = 0.65$ K the reentrance starts and the material returns to the normal state. The recovery to the normal state originates by the magnetic ordering that occurs in the sites of the Ho ions in the crystal structure of the compound. The ferromagnetic ordering generates an internal magnetic field that couples with the superconducting order parameter, leading to a competition between these two long range ordered states. The competition results in a sinusoidal magnetic order with a wavelength of the order of 200 Å [5]. These two magnetic transitions are named; $T_{M2} = 0.70$ K and $T_{M1} = 0.75$ K. At much lower temperatures of the order of $T = 0.10$ K, the ferromagnetic state has a magnetic moment of about $(9.5 \pm 0.3)\ \mu_B/Ho^{3+}$,

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where the magnetic domains are oriented along the *c*-axis of the hexagonal crystallographic structure, indicating that the magnetic order is a bulk effect and also strongly anisotropic [6].

Point contact spectroscopy is a technique that has been used both in the past and recently to study the spectrum of the electronic excitations at energies close to the Fermi level in a wide variety of compounds, metals and alloys [7]. The non-linearities observed in the PC characteristics; i.e. current versus voltage, or differential resistance ($\mathrm{d}V/\mathrm{d}I$) versus voltage (V) characteristics, are related with the electronic dispersions caused by the elementary excitations in the compound under study. The information that one can obtain with PCs will depend on the ratio of certain characteristic lengths in the region of the contact: one is the radius of the constriction or contact, a, the other is the mean free path of the electrons, l. In this way, if the ratio $l/a \gg 1$, the so called ballistic limit, then it should be possible to observe with PC experiments the phononic spectrum of the excitation of the material by obtaining the derivative of the $\mathrm{d}V/\mathrm{d}I$ versus V. In another approach Blonder, Thinkham and Klapwijk (BTK) [8] demonstrated, that if this technique is applied to the study of constrictions of the type normal–superconductor (NS) or superconductor–superconductor (SS), then it should be possible to observe the signature of the superconducting energy gap through the Andreev reflections. Furthermore, another important result of the theory is the prediction of the amount of excess of current, I_{exc}, which is one of the most direct evidence of the Andreev reflection. In this way, the proportion of Andreev to normal reflections will depend on this excess. It is worth noting, that this result was also demonstrated by Artemenko et al. [9], and Zaitsev [10]. Many experiments have been performed in other compounds and they have probed the power of this technique [11].

Our point contact experiments were made using single crystals of $\mathrm{HoMo_6S_8}$ with typical dimensions of $1\times1\times2$ mm^3. They were grown as described by Peña et al. [12]. To form the junction we used as the second electrode a thin gold wire of diameter 5 μm. A single crystal of irregular form was glued onto a glass substrate, the junction is formed when the gold wire is crossed perpendicularly to the piece of the compound and touches it on one of the surfaces on the top of the crystal. We can adjust the strength of the wire and in this form we can control the resistance of the contact.

Due to the irregular form of the crystal it was difficult to determine with precision the position with respect to the easy axis c where the gold wire makes contact on the single crystal. Nevertheless, the point contact features were reproducible when we used the same facet on the crystal. When the PC was made on a different facet, the background observed in the $\mathrm{d}V/\mathrm{d}I$ versus V characteristics was different, but, in general, they showed the same trend of behavior. This was also valid, when we used different single crystals.

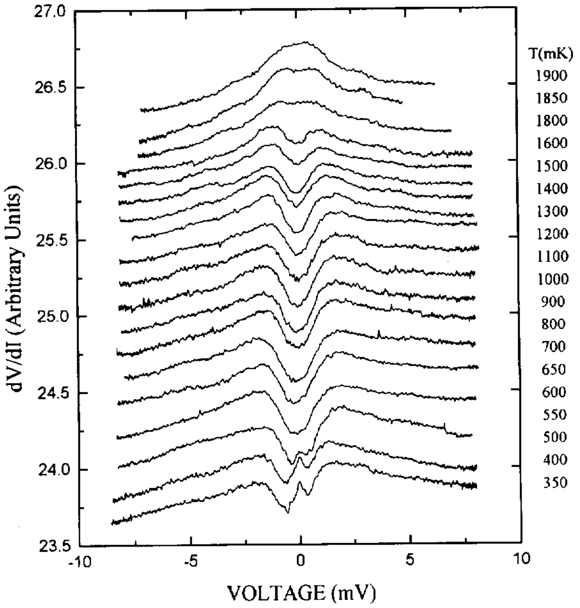

Fig. 1. Differential resistance versus voltage data of $\mathrm{HoMo_6S_8}$–Au point contact at different temperatures. The curves have been displaced vertically for clarity.

In those experiments the general trend of behavior was observed, with small variations on the background.

The $\mathrm{d}V/\mathrm{d}I$ versus V characteristics were obtained using a standard modulation and lock-in technique at 1 KHz. The temperature at which the data were taken was varied from 0.3 to 4 K using a ^{3}He refrigerator. In this manner, we can produce point contacts with zero bias resistance $(\mathrm{d}V/\mathrm{d}I)_{V=0}$ that are between 5 and 50 Ω. The radii of the point contacts were estimated to be between 254 and 43 Å. These values were obtained by using the interpolation formula of Wexler [13], with an electronic mean free path of $l=50$ Å [14], resistivity measured at 2 K with a value of $\rho=25$ μΩ cm [12], and with values of the function between $0.7 \leqslant \Gamma(K) \leqslant 0.85$.

The critical temperature of the single crystal was determined by resistance measurements using the conventional four probe AC technique (inset of Fig. 3). The current through the crystal was kept small, of the order of 100 μA in order to keep heating effects as low as possible. The values obtained varied between 1.2 and 1.6 K depending on the crystal. In the crystal used to report the PC data for this paper, the transition temperature was $T_{\mathrm{C1}}=1.59$ K, the reentrance transition was $T_{\mathrm{C2}}=0.65$ K, the onset temperatures were 1.78 and 0.57 K, respectively.

In Fig. 1, we show data of evolution with temperature of a point contact at temperatures between 0.35 and 1.9 K in a range of ±8 mV. There are two interesting features: a minimum at zero bias starts to develop close to the onset of the transition temperature of 1.8 K. This anomaly evolves

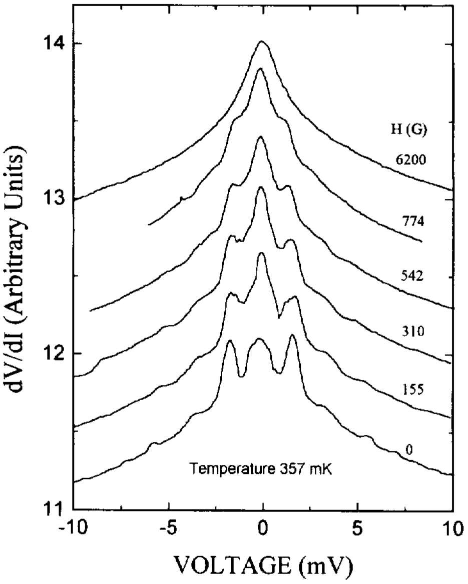

Fig. 2. Effect of the magnetic field on the dV/dI versus V characteristics of $HoMo_6S_8$–Au point contact. Note that the features of the energy gap disappear when the field was increased. The curves were vertically displaced.

with decreasing temperature. It appears when the material is transiting to the superconducting state and below, we assume therefore, that this may be associated with the developing of the superconducting energy gap. The anomaly becomes more complex with additional structure close to the ferromagnetic transitions and a maximum emerges in the differential resistance. This maximum increases with decreasing temperature, and at the same time the feature that we associated with the superconducting state starts to diminish.

Fig. 2 shows the PC characteristics, in a different point contact measured at 357 mK as a function of the applied magnetic field. The curve obtained without magnetic field shows three maxima; two at a voltage of about ± 1.7 mV and the other at zero bias. By increasing the magnetic field, we can observe that the external maxima smear out, and the structure is cancelled at magnetic fields of about 0.62 T. This behavior, and the fact that the normal resistance of the crystal is lower than the value that must exist at low temperatures, may be an indication that the superconducting state still persists under the presence of ferromagnetic order.

To analyze the data of Fig. 1 we used a procedure similar to one described by Goll et al. [15]. We calculated the area enclosed between dV/dI versus V curve and the corresponding normal state background. The reason for using this procedure is that the structure in the dV/dI versus V curves below T_{C1} is so complicated, that it is not possible to relate it with only the Andreev reflections as in the BTK model. We must keep in mind that the two ferromagnetic transitions will introduce additional structure in the dV/dI versus V characteristics, and therefore, the data will be more complicated to analyse. However, as a first approach in this paper, the procedure is discussed in detail below. Firstly, we have normalized the dV/dI versus V data with the value of dV/dI at $V=-7$ mV, this step is equivalent to calculating $(1/R_N)(\mathrm{d}V/\mathrm{d}I)$. Secondly, we obtain the area, A, enclosed by the curve of dV/dI versus V at temperature above T_{C1}, and the curves of dV/dI versus V below T_{C1}. The last step consists in normalizing the calculated area over the maximum value A_m. This value is found when the anomaly is bigger, and this occurs close to $T=0.65$ K. The ratio of areas A/A_m versus T is plotted in Fig. 3 as black dots, and the variation of the energy gap with temperature predicted by the BCS model is also shown in this figure by a continuous line.

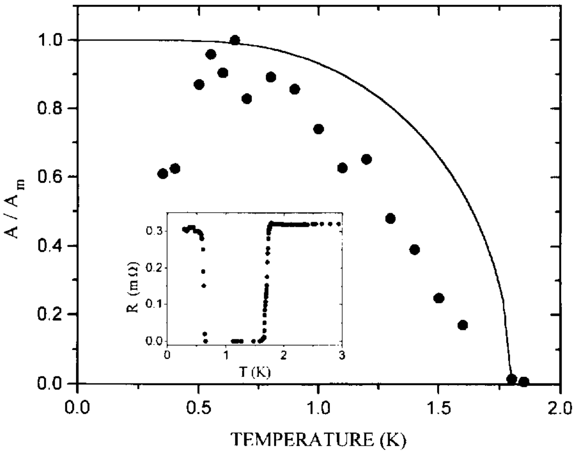

Fig. 3. Temperature dependence of the normalized area of the gap feature (circles). The continuous curve is the temperature dependence of the order parameter predicted by the BCS model. The inset shows the resistance versus temperature of the single crystal used in our PC.

Our results suggest that below the ferromagnetic transitions the superconducting state still persists. It appears that the temperature dependence of the ratio A/A_m that we related with the superconducting order parameter does not follow the behavior predicted by the BCS model.

To conclude, we have studied the reentrance behavior of the superconductor $HoMo_6S_8$. Our initial results show that point contact spectroscopy may reveal the interplay between two order parameters with long range order such as superconductivity and magnetism, further work needs to be done using point contact spectroscopy to understand better the anisotropic behavior of the magnetic and superconducting order parameters of this compound.

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References

[1] A.A. Abrikosov and L.P. Gor'kov, Zh. Eksp. Teor. Fiz. 39 (1960) 1781.

[2] W.A. Fertig et al., Phys. Rev. Lett. 38 (1977) 987.

[3] M. Ishikawa and Ø. Fisher, Solid State Commun. 23 (1977) 37.

[4] H. Eisaki et al., Phys. Rev. B 50 (1994) 647.

[5] J.W. Lynn, G. Shirane, W. Thomlinson and R.N. Shelton, Phys. Rev. B 46 (1981) 386.

[6] P. Burlet et al., J. Magn. Magn. Mater. 54–57 (1986) 1534.

[7] I.K. Yanson, Zh. Eksp. Teor. Fiz. 66 (1974) 1035. [Sov. Phys. JETP 39 (1974) 506]; A.G.M. Jansen, A.P. van Gelder and P. Wyder, J. Phys. C 13 (1980) 6073.

[8] G.E. Blonder, M. Tinkham and T.M. Klapwijk, Phys. Rev. B 25 (1982) 4515.

[9] S.N. Artemenko, A.F. Volkov and A.V. Zaitsev, Pis'ma Zh. Eksp. Teor. Fiz. 28 (1978) 637 [JETP Lett. 28 (1978) 589].

[10] A.V. Zaitsev, Zh. Eksp. Teor. Fiz. 78 (1980) 221 [Sov. Phys. JETP 51 (1980) 111].

[11] R. Escudero, F. Morales and P. Lejay, Phys. Rev. B 49 (1984) 15 271; K. Hasselbach, J.R. Kirtley and P. Lejay, Phys. Rev. B 46 (1993) 5826; Physica B 186–188 (1993) 201.

[12] O. Peña and M. Sergent, Progr. Solid State Chem. 19 (1989) 165.

[13] G. Wexler, Proc. Phys. Soc. 89 (1966) 927.

[14] L.N. Bulaevskii, A.I. Buzdin and M. Kulić, Phys. Rev. B 34 (1986) 4928.

[15] G. Goll, H.v. Löhneysen, K. Yanson and L. Taillefer, Phys. Rev. Lett. 70 (1993) 2008.