Chapter 5

Summary

In this work we have assembled the results of our investigations maid during the years of Phd studying in the University of Bochum in the cowork with the advisers K. B. Efetov and A. F. Volkov. We have considered three problems which are the main topics of this work and are included as the chapter. At the end of these thesis we want to summarize and make an outlook.

In these thesis we have discussed new unusual properties of structures consisting of conventional superconductors in a contact with ferromagnets. It has been known that such systems might exhibit very interesting properties like a non-monotonous reduction of the superconducting temperature as a function of the thickness of the superconductor, possibility of a π-contact in Josephson junctions with ferromagnetic layers, etc.

However, as we have seen, everything is even more interesting and some spectacular phenomena are possible that, at first glance, even might look as a paradox. The common feature of the effects discussed in this work is that all of them originate in situations when the exchange field is not homogeneous. As a consequence of the inhomogeneity, the spin structure of the superconducting condensate function becomes very complicated and, in particular, the triple component are generated. In the presence of the inhomogeneous exchange field, the total spin of a Cooper pair is not necessarily equal to zero and the spin unity with all projections onto the direction of the exchange field is possible.

We have discussed the main properties of the odd triplet superconductivity in the S/F structures. This superconductivity differs from the well known types of superconductivity: a) singlet superconductivity with the s-wave (conventional T_c superconductors) and d-wave (high T_c superconductors) types of pairing; b) odd in momentum p and even in frequency ω triplet superconductivity observed, e.g., in

$SrRuO$.

The odd triplet superconductivity that we discussed in these thesis has a condensate (Gor'kov) function that is an odd function of the Matsubara frequency ω and an even function (in the main approximation) of the momentum p in impure samples. It is insensitive to the scattering on nonmagnetic impurities and therefore may be realized in thin film S/F structures where the mean free path is very short.

For the first time, the condensate function of this type has been suggested by Berezinskii many years ago as a possible candidate to describe superfluidity in He^3. Later, it was established that the superfluid condensate in He^3 had a different structure - it was odd in p and even in ω. In principle, there is an important difference between the triplet superconductivity discussed here and that predicted by Berezinskii who assumed that the order parameter Δ was also an odd function of ω. In our case the order parameter Δ is determined by the singlet, s-wave condensate function and has the ordinary BCS structure (i.e., it does not depend on the momentum p and frequency ω). The structure of the triplet condensate function $\check{f}$ in the diffusive case considered here coincides with that suggested by Berezinskii: it is an odd function of the Matsubara frequency ω and, in the main approximation, is constant in the momentum space. The antisymmetric part of $\check{f}$ is small compared with the symmetric part, being odd in p and even in ω.

The triplet component with the projection of the total spin $S = \pm 1$ penetrates the ferromagnet over a long distance of the order of $\xi_N \approx \sqrt{D_F/2\pi T}$, which shows that the exchange field does not affect the triplet part of the condensate. At the same time, the exchange field suppresses the amplitude of the singlet component at the S/F interface that determines the amplitude of the triplet component. The long-range triplet component arises only in the case of a nonhomogeneous magnetization. The triplet component appears also in a system with a homogeneous magnetization but in this case it corresponds to the projection $S = 0$ and penetrates the ferromagnet over a short length $\xi_h = \sqrt{D_F/h} << \xi_N$.

The triplet component exists also in magnetic superconductors with a spiral magnetic structure. However, it always coexists with the singlet component and cannot be separated from it. In contrast, in the multilayered S/F structures with a nonhomogeneous magnetization and with the thickness of the F layers d_F exceeding ξ_h, the Josephson coupling between S layers is realized only through the long-range triplet component and this separates the singlet and triplet components from each other. As a result, the "real" odd triplet superconductivity may be realized in the transverse direction in such structures.

An interesting peculiarity of the S/F structures is the inverse proximity effect, namely, the penetration of the magnetic order parameter (spontaneous magnetic moment M) into the superconductor and a spatial variation of the magnetization direction in the ferromagnet under the influence of the superconductivity. It turns out that both the effects are possible. A homogeneous distribution of the magnetization M_F in the S/F bilayer structures may be energetically unfavorable in F even in a one-domain case resulting in a nonhomogeneous distribution of $\mathbf{M}_F$ in the ferromagnet.

As concerns the experimental situation, certainly there are indications in favor of the long-range triplet component, although an unambiguous evidence does not exist so far. For example, the resistance of ferromagnetic films or wires in the S/F structures changes on distances much exceeding the length of the decay of the singlet component ξ_h (Petrashev 1995,Pannetier 1996,Chandrasekhar 1999, Klapwijk 2006). A possible reason for this long-range proximity effect in the S/F systems is, or course, the long-range penetration of the triplet component. However a simpler effect might also be the reason for this long-range proximity effect. It is related to a rearrangement of a domain structure in the ferromagnet when the temperature lowers below T_c. The Meissner currents induced in the superconductor by a stray magnetic field affect the domain structure, and the resistance of the ferromagnet may change (Geim). At the same time, the Meissner currents should be considerably reduced in an one dimensional geometry for the ferromagnet like that used in (Pannetier 1996) and the explanation in terms of the long range penetration of the triplet component are more probable here.

Pena and coauthors also obtained some indications on the existence of a triplet component in a multilayered $S/F/S/F$ structure. The samples used by Pena contained the high T_c material $YBa_2Cu_3O_7$(as a superconductor) and the half-metallic ferromagnet $La_{0.7}Ca_{0.3}MnO_3$ (as a ferromagnet). They found that superconductivity persisted even in the case when the thickness of the Flayers d_F essentially exceeded ξ_F ($d_F \gtrsim 10nm$ and $\xi_F \approx 5nm$). In a half-metal ferromagnet with spins of free electrons aligned in one direction the singlet Cooper pairs cannot exist. Therefore it is reasonable to assume that the superconducting coupling between neighboring S layers is realized via the triplet component (Eschrig).

In spite of these experimental results that may be considered as, at least preliminary, confirmation of the existence of the triplet component in the S/F structures, there is a need in additional experimental studies of the unconventional superconductivity discussed in this review. One of the important issues would be to understand whether a long range proximity effects already observed experimentally are due to the triplet pairing or to a simple redistribution of the domain walls by the Miessner currents. We believe that measurements on thin ferromagnetic wires where the Meissner currents are reduced may clarify the situation.

It is very interesting to distinguish between the two possible inverse proximity effects experimentally. Although both the formation of the cryptoferromagnetic state and the induction of the magnetic moments in the superconductors are very interesting effects, it is still not completely clear which of them has been observed in Refs.

The enhancement of the Josephson current by the presence of the ferromagnet near the junction is one more theoretical prediction that has not been observed yet but, certainly, this effect deserves an attention.

The last but not the least: study of the proximity effects in the S/F structures may be extended to include ferromagnets in contact with high temperature superconductors. Although it is very difficult to make good contacts between the ferromagnets and the high T_c cuprates now, it may become possible in a future. This can bring not only useful applications but also a new physics. The high T_c materials the symmetry of superconducting condensate is d -wave. At the same time, without ferromagnetic interaction the condensate contains the singlet component only. This means that many effects considered in this review can also occur in the high T_c materials but, there will certainly be differences with respect to the conventional superconductors with the s-pairing. Although some theoretical work has been already made (Maki), the proximity effect in high T_c materials deserves an attention, too.

As a very interesting new kind of superconducting materials were discussed - the two-band superconductors.

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