Energy dependence of the Andreev reflection of $YBa_2Cu_3O_{7-\delta}$

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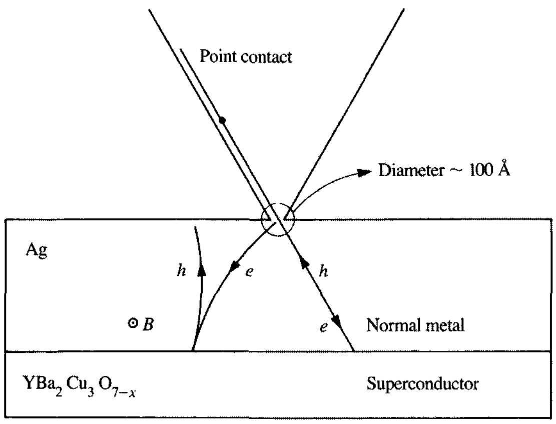
Measurements of the energy dependence of the Andreev reflection have been performed on a Ag–$YBa_2Cu_3O_{7-\delta}$ interface. The observation of the Andreev reflection indicates a ground state of zero-momentum pairs. It is shown that, in principle, the bulk Δ (electron pair potential) can be determined from the energy dependence of the Andreev reflection. In the present experiment, however, due to the limited mean free path of the electrons in the silver, only a lower limit of Δ was found.

1. Introduction

Two years after the discovery of the high-T_c superconductors [1], the worldwide research effort still has not brought any consensus on its origin nor on the nature of the ground state of the superconductors. To gain more insight into the nature of the ground state, we studied the reflectivity properties of a normal-metal–superconductor interface for electrons coming from the normal-metal side. When an electron with an energy smaller than the gap energy hits the interface between a normal metal and a "classical" superconductor, the electron cannot enter the superconductor because there are no states available. The electron will be reflected, or it can condense with another electron from the normal metal into the superconducting ground state. In the latter case, it will leave behind a hole in the normal metal which will travel back in a direction determined by the laws of conservation of momentum and energy. For superconductors with a zero momentum paired ground state, as is the case for the classical superconductors, the holes move back precisely in the direction of the incoming electrons when these electrons have zero energy relative to the Fermi energy. This type of reflection is called Andreev reflection [2]. In a quantitative study, Blonder, Tinkham, and Klapwijk have studied the Andreev reflection probability as a function of energy, also taking into account the presence of a scattering potential at the interface [3]. Their results have been used to explain the current–voltage relations in normal-metal–superconductor point contacts [4].

In the experiments described in this paper, we study the energy dependence of the Andreev reflection of a silver–$YBa_2Cu_3O_{7-\delta}$ interface using the arrangement shown in **Figure 1**. The electrons are injected into the metal by a point contact which has a contact diameter that is small compared to the electron mean free path (Sharvin contact [5]). For such a contact, the injected electrons have an energy above the Fermi energy up to eV, where V is the applied voltage. (Applying suitable modulation and detection techniques allows the electrons with energy eV to be studied selectively.) As can be seen in Figure 1, in the case of an



Experimental arrangement. The electrons are injected into the normal metal (silver) with known energy by a Sharvin point contact.

ideal Andreev reflection, for every electron injected a hole comes back through the point contact, doubling the current (so-called excess current), or, in other words, halving the resistance. By measuring the point-contact resistance as a function of energy, the energy dependence of the Andreev reflection can in principle be determined. Several effects such as mean free path effects and nonideal interfaces generally reduce the excess current.

The configuration we use, with a separation in space between the injector and the reflector, allows a clear discrimination of different effects. For example, electrons which are scattered or specularly reflected at the interface do not enter the point contact and do not contribute to the resistance. In addition, as indicated in Figure 1, the returning holes can be turned away from the contact by an applied magnetic field, so an independent determination of the magnitude of the excess current can be made.

The described method has been applied to silver–lead and to bismuth–tin interfaces both in single- and double-point-contact geometries, and good agreement between theory and experiment has been found [6–9].

For the high-T_c superconductors, an interesting question is which value of the order parameter will be measured. From measurements of critical fields, it is concluded that the coherence length is extremely short. As a consequence it is expected that the order parameter at the surface is considerably reduced [10]. This effect could strongly influence the results of tunneling experiments where one probes the outer layer of the superconductor, and might make the interpretation of those measurements difficult. For the Andreev reflection experiment, however, the situation is completely different. Roughly speaking, an incoming electron travels until it reaches the plane where $\Delta(x)$ equals its energy. More precisely, one has to take into account the spatial dependence of the order parameter in the whole region in which the electron travels. A quantitative analysis of van Son et al. [11] shows that also in the case of a varying order parameter the Andreev reflection probability still allows the determination of the bulk Δ. This is illustrated in **Figure 2**, taken from [11], where the energy dependence of the Andreev reflection is given for a sharp transition of Δ, being zero in the normal metal and Δ-bulk in the superconductor, as treated in [3] (dashed line) and for a Δ which is, due to the proximity effect, position-dependent, as indicated in inset (a) (solid line). The figure shows that the probability is different for the case of an order parameter which changes gradually, but still the bulk value dominates the shape of the curve and can be determined. Experiments to verify this have been described in [7]. Moreover, in that paper it has been shown that by careful analyses of the Andreev reflection the proximity effect can also be observed.

2. Sample preparation, measurements, and results

The $YBa_2Cu_3O_{7-\delta}$ samples used for the Andreev experiments were nonoriented films (1-μm thickness) prepared by a co-evaporation technique. A full description of the preparation can be found in [12]. A silver film 0.25 μm thick was deposited on these films. Precautions had to be taken to ensure that the superconducting film kept its superconducting properties [13].

The point contacts were made by carefully placing electrochemically etched Ag wires on the silver film at liquid helium temperature. The point-contact diameter can be deduced from the resistance by using the Sharvin relation [5].

Some results of resistance versus applied voltage are shown in **Figure 3**. For comparison a typical Ag–Pb result is also shown in the same figure. The point-contact resistance shows a minimum at zero voltage and a strong decrease at around 12.5 meV.

Generally it has been found that the Ag–Pb results can be understood quantitatively if several effects such as energy-dependent mean free path, temperature broadening, nonideal retroreflection at nonzero energy, and proximity effect are taken into account [6, 7]. For the Ag–$YBa_2Cu_3O_{7-\delta}$, however, there is the possibility that a considerable reduction in the number of retroreflected holes occurs because of the energy dependence of the electron–phonon interaction. Experiments have shown that just around 12 meV the Eliashberg function α^2F reaches a maximum, which results in a strong reduction of the mean free path in that energy region [14]. Unfortunately the direction dependence of α^2F is not known well enough to allow a precise correction of our data. Therefore, it cannot be precluded that the strong

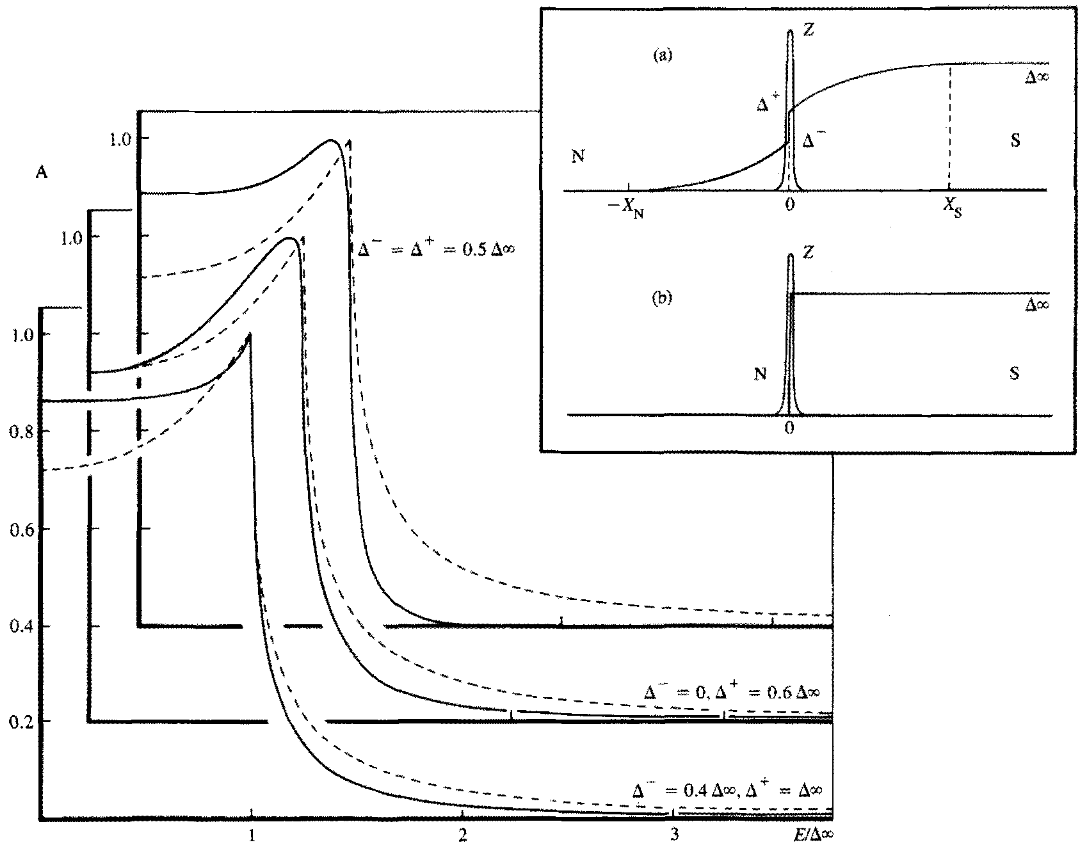


Figure 2

Energy dependence of the Andreev reflection probability for three sets of the pair potential Δ as indicated in inset (a) (solid lines). The dashed lines give the results of Blonder et al. for a Δ varying as indicated in inset (b). N = normal metal, S = superconductor. (From [11]).

change of the point-contact resistance around 12 meV may be due to this effect, so the experiment gives only a lower limit for the gap value. A way to overcome this difficulty is by using a normal metal with a higher Debye temperature.

To test whether the Andreev reflection is indeed the cause of the effects observed, we apply a magnetic field parallel to the surface. Because of the Lorentz force, the orbits of electrons and holes are bent, and the retroreflected holes no longer arrive at the point contact (see Figure 1). As a consequence, the point-contact resistance increases gradually with increasing field, which can be understood quantitatively by considering the overlap of the returning holes and the point contact (inset of **Figure 4**). Since the contact diameter is known from the Sharvin resistance and the film thickness from the evaporation conditions, there are no free parameters. In Figure 4 we have plotted the magnetic field dependence of the difference between the resistance at 20 meV (above the gap-energy) and at 7.5 meV (below the gap) together with the calculated dependence. We did indeed observe a gradual decrease of the difference in resistance, in good agreement with the calculations based on the model of the inset of Figure 4.

3. Conclusions

Andreev reflection can be used to determine the bulk order parameter of superconductors which have a zero-momentum paired ground state. The experiments performed on $YBa_2Cu_3O_{7-\delta}$ indicate that this material does indeed show Andreev reflection and so has a zero-momentum ground state. However, the gap value determination can be

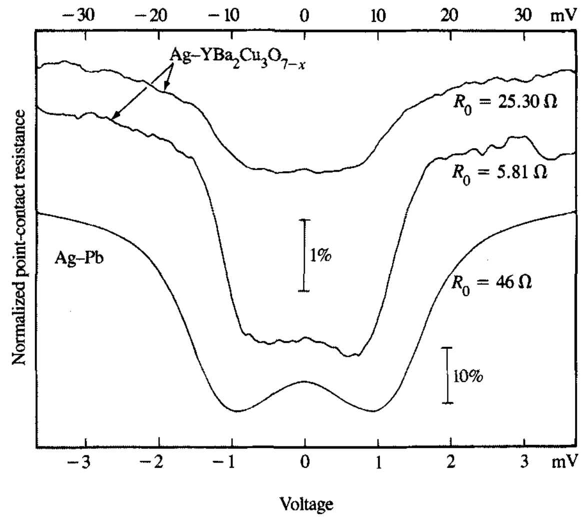


Figure 3

Measurements of Andreev reflection (upper two curves) on Ag–$YBa_2Cu_3O_{7-\delta}$ film at 1.2 K. The normalized resistances of two point contacts with a resistance of 25.30 and 5.81 Ω (top and middle curve, respectively) versus voltage are shown. The lowest curve (taken from [7]) gives the result for a Ag–Pb interface for comparison. Note the different scales.

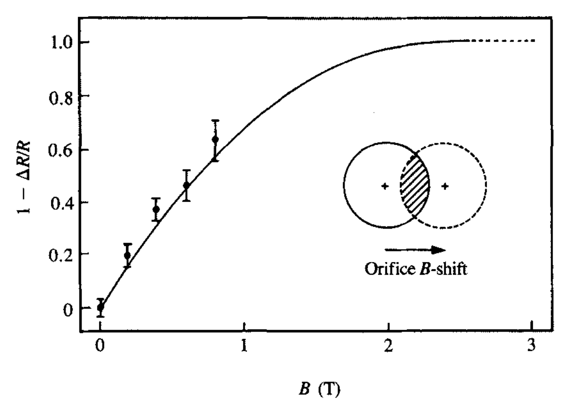


Figure 4

Magnetic field dependence of the normalized decrease in the point-contact resistance due to the Andreev reflected holes. The solid curve is a calculation based on the deflection of the charge carriers in a magnetic field, as indicated in Figure 1 and the inset of this figure.

hampered by the short mean free path of the normal metal, so only a minimum value of 12.5 meV could be found.

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References

1. G. Bednorz and K. A. Müller, *Z. Phys. B* **64,** 189 (1986).
2. A. F. Andreev, *Zh. Eksp. Teor. Fiz.* **46,** 1823 (1964) [*Sov. Phys.-JETP* **19,** 1228 (1964)].
3. G. E. Blonder, M. Tinkham, and T. M. Klapwijk, *Phys. Rev. B* **25,** 4515 (1982).
4. G. E. Blonder and M. Tinkham. *Phys. Rev. B* **27,** 112 (1983).
5. Yu. V. Sharvin, *Zh. Eksp. Teor. Fiz.* **48,** 984 (1965) [*Sov. Phys.-JETP* **21,** 655 (1964)].
6. P. A. M. Benistant, A. P. van Gelder, H. van Kempen, and P. Wyder, *Phys. Rev. B* **32,** 3351 (1985).
7. P. C. van Son, H. van Kempen, and P. Wyder, *Phys. Rev. Lett.* **59,** 2226 (1987).
8. S. I. Bozkho, V. S. Tsoi, and S. E. Yakovlev, *Pis'ma Zh. Eksp. Teor. Fiz.* **36,** 123 (1982) [*JETP Lett.* **36,** 153 (1982)].
9. P. A. M. Benistant, H. van Kempen, and P. Wyder, *Phys. Rev. Lett.* **51,** 817 (1983).
10. G. Deutscher and K. A. Müller, *Phys. Rev. Lett.* **59,** 1745 (1987).
11. P. C. van Son, H. van Kempen, and P. Wyder, *Phys. Rev. B* **37,** 5015 (1988).
12. A. J. G. Schellingerhout, R. H. M. van de Leur, D. Schalkoord, D. van der Marel, and J. E. Mooij, *Z. Phys. B,* to be published.
13. H. F. C. Hoevers, P. J. M. van Bentum, L. E. C. van der Leemput, H. van Kempen, A. J. G. Schellingerhout, and D. van der Marel, *Physica C* **152,** 105 (1988).
14. A. G. M. Jansen, F. Mueller, and P. Wyder. *Phys. Rev. B* **16,** 1325 (1977).

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