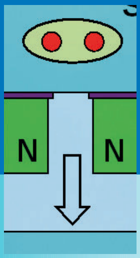

Spatial structure of Cooper electronic pairs from current noise measurements

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Measuring the fluctuations of electrical current has recently proved a way to obtain new information on mesoscopic devices. In a superconductor attached to two normal metallic leads, the cross-correlation of the currents flowing in each of them is shown to provide information on the spatial structure of the Cooper pairs.

Il a été récemment prouvé que la mesure des fluctuations du courant électrique permet d'obtenir de nouvelles informations sur des dispositifs mésoscopiques. Nous montrons que, pour un supra-conducteur relié à deux électrodes métalliques normales, la corrélation croisée des courants circulant dans chaque électrode fournit des informations sur la structure spatiale des paires de Cooper.

Tunnel junctions are formed with two pieces of normal metal separated by a thin oxide layer. They are named after the quantum tunnelling of single electrons which allows electrical current to flow through the insulating barrier. When one of the electrodes becomes superconducting, the conduction electrons attract each other into Cooper pairs. A gap in the energy spectrum hinders single electron excitations. As a result, the standard tunnelling of single electrons is barred. Instead, Andreev reflection - a process involving two electrons - is observed. It allows a Cooper pair from the superconductor to be transferred into two electrons on the other side of the junction. Equivalently, it can be viewed as the reflection of an incident quasi-hole from the normal electrode into a quasi-particle in the same electrode. This process is expected to take place on a characteristic distance of about the size of the Cooper pairs.

In principle, it should be possible for the electrons to be transmitted in two different normal terminals provided that the distance between the contacts is comparable with the size of the pairs. This process, called the crossed Andreev reflection (CAR), could be useful to probe the spatial structure of the Cooper pair directly, but how can it be detected? It was first suggested to perform conductance measurements on multi-terminal devices like the one represented in Fig. 1. Indeed, applying a voltage to lead B would affect the current flowing between the superconductor and lead A if the normal leads were close enough. However this procedure has two main drawbacks. First, CAR comes along with elastic co-tunnelling (EC), the transfer of an electron from one normal lead to the other one, via the superconductor, see Fig. 2. Second, CAR and EC contributions to the average currents are dominated by direct Andreev reflection in each normal lead, i.e. by the current associated

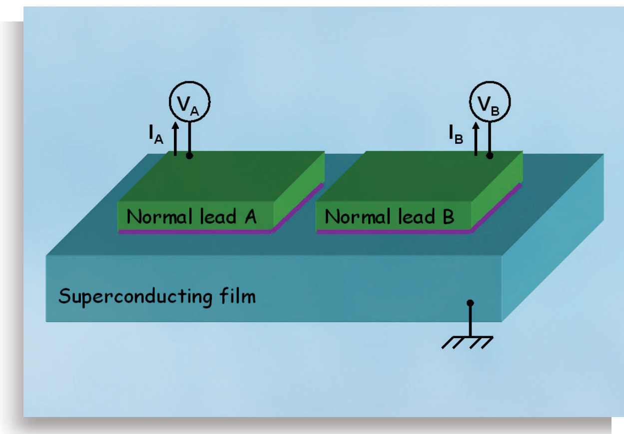

Figure 1: Schematic representation of the three-terminal device.

with the transfer of a Cooper pair of the superconductor into two electrons in the same lead. Alternatively, we found that the CAR or the EC contribution can be picked up directly by measuring the cross-correlation of the currents flowing in each normal lead [1].

As a matter of fact, due to the discrete nature of the electric charges, current fluctuates in time around its mean value. It is characterised by the current noise, $S_{\alpha\beta}=2\int dt\,\delta I_\alpha(t)\delta I_\beta(0)$, where $\delta I_\alpha(t)=I_\alpha(t)-I_\alpha$ describes the fluctuations of the instantaneous current, $I_\alpha(t)$, around its mean value, I_α, and α, β stand for any normal lead A,B. Current noise measurement revealed a powerful probe for electronic devices. In two-terminal junctions, the equilibrium noise is simply proportional to the temperature T and the conductance G of the junction, $S=4k_BTG$, according to the fluctuation-dissipation theorem. By contrast, at vanishing temperature, the non-equilibrium noise is proportional to the current and the absolute electric charge q, transferred through the junction. In the case of rare and uncorrelated charge transfers, like in quantum tunnelling, $S=2qI$ was predicted. As a result of the Andreev reflection, which involves two electrons, this noise is doubled in a hybrid superconducting/normal metallic tunnel junction ($q=2|e|$) compared to a completely normal device ($q=|e|$). Such doubling of the noise was first observed in our laboratory [2].

The cross-correlation, S_{AB}, in the three-terminal hybrid structure represented in Fig. 1 also deserved some attention. Indeed, it was predicted not only to differ by a numerical factor, but also to show a sign change with respect to normal metallic structures [3]. A simplified explanation of this effect is the following. If electrons in the two leads are emitted from one Cooper pair, a positive correlation is expected, since both electrons appear at the same time in each lead. By contrast, in the normal structure, electrons arriving one by one at the barriers are transmitted either in one or the other lead, leading to a negative correlation.

We find that CAR contributes to the cross-correlation with a positive sign, while EC contributes with a negative sign, and there is no contribution at all from direct Andreev reflection. The CAR and EC contributions can be selected independently by tuning the voltages of the normal terminals. In particular, only CAR contributes when the voltages are the same in each normal electrode, while only EC contributes when the voltages are opposite. Cross-correlation in tunnelling systems thus provides a direct way (i) to probe both CAR and EC and (ii) to measure the sign change of the correlations.

Our quantitative estimates of these effects show that their observation may be within the reach of present technology. The characteristic size for the Cooper pairs gives the important scale to be achieved in the real device: a few tens of nanometres for standard materials. Then the overall amplitude of the signal to be measured would compare with the resolution already achieved in the experiment [2]. The main difficulty of the experiment is to make the contacts as close as possible, without short-circuiting them. We hope that the experiment can be performed soon in our laboratory to compare with our predictions.

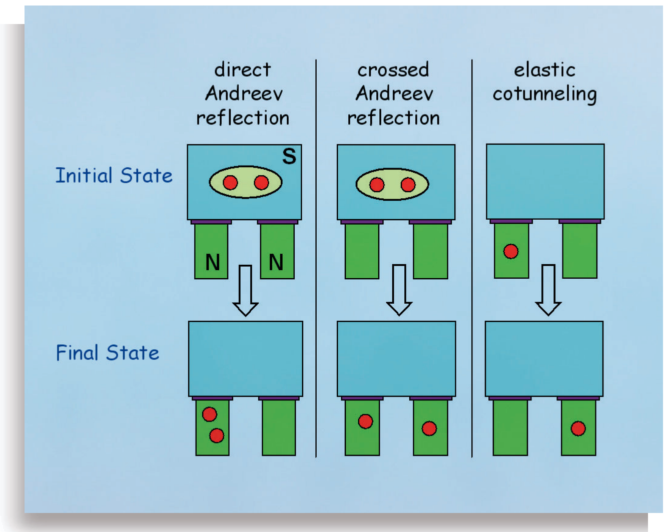

Figure 2: Three processes for charge transfer.

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