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Scanning tunneling spectroscopy of the vortex state in $NbSe_2$ using a superconducting tip

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Abstract

The vortex electronic structure in the multiband superconductor $NbSe_2$ is studied by means of scanning tunneling spectroscopy (STS) using a superconducting tip. The use of a superconducting tip (Pb) as a probe provides an enhancement of the different features related to the DOS of $NbSe_2$ in the tunneling conductance curves. This use allows the observation of rich patterns of electronic states in the conductance images around the vortex cores in a wide range of temperature, as well as the simultaneous acquisition of Josephson current images in the vortex state.

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1. Introduction

It is widely recognized that scanning tunneling spectroscopy (STS) is a powerful tool to obtain the local density of states (LDOS) of conducting materials, even at atomic scale. The obtained information is a convolution of the DOS of both electrodes, tip and sample. Since the initial works by Hess et al. [1] on $NbSe_2$, this technique has been used to investigate the electronic density of states in the vortex state in a variety of materials. Improvements in this technique have produced results evolving from the initial observations of the Abrikosov vortex lattice, to detailed conductance maps at selected energies, showing features like electronic bound states at and around the vortex core.

The most detailed results about the symmetry and patterns presented by these bound states (i.e.: sixfold in $NbSe_2$ [1,2], fourfold in $YBa_2Cu_3O_7$ [3], $Bi_2Sr_2CaCu_2O_{8-d}$ [4] and YNi_2B_2C [5]) were obtained at low temperatures. There is a great interest in this type of measurements due to the fact that the symmetry of the bound states around the vortex core is related to the symmetry of the order parameter.

Very low temperature is therefore a requisite in order to prevent the thermal smearing of the features associated to the bound states, which typically have an energy width below 0.1 meV. The experiments by Hess et al. [1] and Pan et al. [2] on $NbSe_2$ at 300 mK showed a wealth of patterns associated to the electronic bound states that cannot be obtained at higher temperatures using normal metal tips.

In the recent years there is also a renewed interest in the topic of multiband superconductivity (MBSC), boosted by the discovery of the superconducting properties of MgB_2 [6]. Results obtained by different techniques on $NbSe_2$ [7] indicate that this material is also a multiband superconductor. In a previous work [8], we studied the evolution of the distribution of gap values in $NbSe_2$ as a function of temperature. The results of these tunnel spectroscopy measurements, from 300 mK up to the critical temperature (7.2 K),

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were interpreted as an example of MBSC with small interband scattering.

We were able to observe this behavior by using a superconducting tip (Pb) as counter electrode. This allowed the enhancement of any feature associated with a superconducting gap (due to the convolution of the divergences in the DOS at the gap edges in both electrodes) in all the temperature range.

Therefore, it seems straightforward to investigate the possibilities of using a STM with a superconducting tip to study the electronic bound states around the vortex core at different temperatures. Its evolution up to T_C will add information about the possible variations of the order parameter in the different bands of a MBSC like $NbSe_2$.

Recently, Kohen et al. [9] have used a superconducting tip (Nb) to perform STS on $NbSe_2$ in the vortex state at 2.3 K and 4.5 K. Their results show variations of the conductance spectra due to the presence of vortices, but the smearing of the curves prevents the observation of the above mentioned bound states and its sixfold symmetry around the vortex core.

In this article we present STS measurements on $NbSe_2$ using a superconducting tip. The electronic bound states and its sixfold pattern can be observed in a large temperature range from 300 mK to 6 K, and for magnetic fields in the range of 1000 G. The in situ method of preparation of the tip [8,10] produces atomically sharp tips with stable and reproducible superconducting properties, capable of atomic scale topographic resolution. This is of crucial importance in order to obtain high resolution conductance maps, preventing an undesired average of features appearing in the local DOS at the nanoscale [11].

2. Experimental

We have used a home built STM, whose sample holder can move in a controlled way millimetric distances in the x and y directions, with nanometric precision. The STM is installed in an Oxford ^{3}He refrigerator, with automatic thermal control. Three different materials are located on the sample holder: lead, gold and $NbSe_2$. The lead nanotip is fabricated and characterized on the lead substrate as indicated in a previous work [8]. This process is done at 300 mK, and once we have verified the quality of the superconducting DOS of the tip and its atomic scale resolution by scanning the $NbSe_2$ surface, we proceed to characterize its behavior under magnetic field.

The tip is located on the lead sample in tunneling regime. Well defined superconducting–superconducting spectra are obtained as the magnetic field is increased from zero up to the lead critical field (800 G at 300 mK), when the sample becomes normal. At higher fields we obtain normal-superconducting spectra because the nanotip remains superconducting due to its small dimensions compared to the superconducting coherence length and magnetic field penetration depth. Depending on the sharpness of the tip achieved in the fabrication process, the critical field of the nanotip can be as high as 20 kG at 300 mK [10]. For the values of the magnetic field used to investigate the vortex states (around 1 kG) the tip presents a superconducting DOS with a well defined gap.

After the characterization of the tip we proceed with the study of $NbSe_2$. The STS measurements consist of 128 × 128 or 256 × 256 points topographic images, with an I–V tunneling curve taken at each topographic point. Depending on the number of points of the I–V curve (from 512 to 2048) and the number of topographic points, the acquisition time of the full STS image ranges from 15 to 75 min. The use of a software controlled feedback loop in the constant current scanning mode allows faster and more versatile scanning than the usual analog feedback.

The scanning range is set depending on the applied magnetic field, in order to allow for a clear imaging of the triangular Abrikosov vortex lattice, ensuring the quality of the results. The bias voltage in the I–V curves is ramped between +5 and −5 mV, to permit the determination of the normal state conductance well above the total gap (tip + sample) in the DOS. These I–V curves are numerically derivated to obtain the conductance curves (G–V) used to produce the conductance images at a given voltage, $G(x, y, V)$. As a routine, small range topographic images are taken in the studied areas to ensure that the superconducting tip keeps its atomic resolution capability.

3. Results and discussion

The results obtained during the process of fabrication and characterisation of the superconducting nanotip, both in the absence and in presence of magnetic field, were described in previous articles [8,10]. In Fig. 1 we present several conductance curves corresponding to a series used to characterize the behaviour of the lead nanotip under

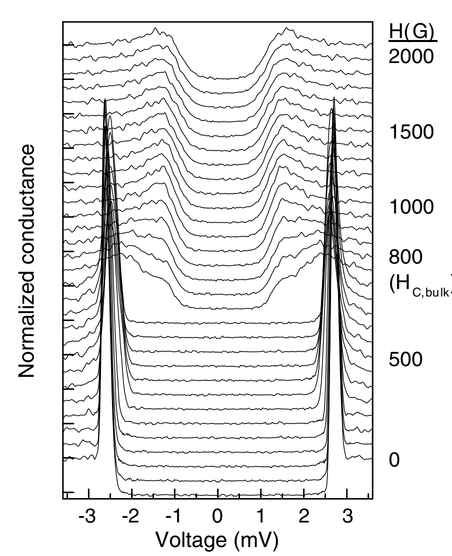

Fig. 1. Pb–Pb conductance curves taken at 300 mK in tunneling regime ($R_N = 10\ M\Omega$) as the magnetic field is varied from 0 to 2000 G. This particular nanotip presented a critical field of 9 kG.