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Spectroscopic measurements of Zeeman splitting of the density of states in high temperature superconducting tunneling junctions

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We report *c*-axis tunneling spectroscopy investigations in high magnetic fields (*I*-*V* characteristics and tunneling conductance dI/dV) of high quality planar junctions fabricated from *c*-axis oriented NdBa₂Cu₃O_{7-δ}/PrBa₂Cu₃O_{7-δ}/NdBa₂Cu₃O_{7-δ} thin film multilayers. The tunneling conductance in a parallel magnetic field reveals Zeeman splitting of the quasiparticle density of states. In the presence of spin-orbit interactions, our measurements for the tunneling density of states and the tunneling conductance show a spin splitting of $g\mu_B H$ in energy space of the density of states peak. Here the quantity μ_B is the Bohr magneton, g is the g factor of the electron, and H is the applied magnetic field. The magnitude of the splitting is attributed to the magnetic moment of the quasiparticles. The spin splitting of the density of states in HTS multilayer tunneling junctions could be used as a very powerful technique to determine the relative spin polarization in magnetic materials. © 2006 American Institute of Physics. [DOI: [10.1063/1.2177407](https://doi.org/10.1063/1.2177407)]

A magnetic field applied to a thin superconducting film will act on the spins of the electrons as well as on their orbits. At temperatures $T < T_C$, the thermal broadening is sufficiently reduced that a Zeeman “shift” can be resolved. In this case the quasiparticle spectrum will be then given by $E_{\uparrow,\downarrow} = (\epsilon^2 + \Delta^2)^{1/2} \pm \mu_B H$, where the spectrum has simply been split and shifted in energy by a Zeeman term. In the presence of a magnetic field the tunneling density of states would therefore consist of the addition of two BCS-type density of states curves shifted in voltage by $\pm \mu_B H/e$ with respect to the curve in the absence of field. This behavior has been observed experimentally in the low T_c superconductors.¹ The splitting of the superconducting density of states into up and down spin states has been used in a way to determine experimentally the polarization of electron spin in ferromagnetic metals. In remarkable experiments high field tunneling between aluminium and ferromagnetic metals has been used to obtain the relative density of states of majority and minority spin electrons at the Fermi surface of Fe, Co, Ni, and Gd.²⁻⁴ The influence of the Zeeman splitting alone on a supercurrent was studied first for the superconductor/*F*/superconductor junction.⁵ (*F* denotes a ferromagnetic metal.) It was shown that the spin splitting suppresses the critical current and produces its oscillations over the intrinsic magnetic field localized within the *F* layer. Spin polarized tunneling data on La_{2/3}Sr_{1/3}MnO₃/Al junctions have been

analyzed in terms of numerical solutions to Maki’s equations which include the effects of orbital depairing, the Zeeman splitting of the spin states, and spin-orbit scattering.⁶

The spin-orbit interaction in heterojunctions and two-dimensional (2D) quantum Hall systems has attracted continuing theoretical and experimental attentions. Zeeman splitting combined with a strong spin-orbit coupling gives rise to noble classes of coherent phenomena, e.g., the spontaneous Aharonov-Bohm effect.⁷ The role of electron spin in energy spectra of nanostructures has been the subject of much experimental⁸ and theoretical⁹ interests. Spin manifests itself differently in different types of structures. Spin effects have been observed in nanostructures including metallic nanoparticles¹⁰ and carbon nanotubes.¹¹ Understanding the role of spin in nanostructures is important for potential applications ranging from spin-based electronics to quantum computers.¹²

We have investigated manifestations of spin effects on the energy spectra of NdBa₂Cu₃O_{7-δ}/PrBa₂Cu₃O_{7-δ}/NdBa₂Cu₃O_{7-δ} (NBCO/PBCO/NBCO) tunneling junctions when a tunneling current flows across those tunneling structures. We used tunneling and Coulomb blockade spectroscopy measurements in a magnetic field oriented parallel to the plane of the sample. By noting the shift of successive Coulomb blockade peaks upon application of a parallel field, we are able to observe the behavior consistent with spin effects while minimizing the influence of the magnetic field on

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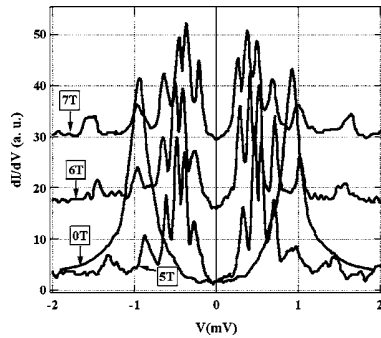


FIG. 1. Tunneling conductance curve at 11 K for a NBCO/PBCO/NBCO trilayer junction in 0, 5, 6, and 7 T fields, respectively. The curves corresponding to 5, 6, and 7 T reveal the spin split of the superconducting density of states. The curves at 6 and 7 T have been displaced vertically.

electrons' spatial states. Our observations support the presence of spin splitting by a magnetic field in the laboratory range.

For the fabrication of high temperature superconducting (HTS) tunneling junctions, very high quality thin films with atomically flat surfaces and interfaces are required. There has not been a method of fabricating high T_C superconductor/insulator/superconductor (SIS) structures. Because of the close lattice match and growth conditions with respect to NBCO superconductors, a very promising approach is to grow epitaxially nonsuperconducting PBCO thin films on a lattice matched superconducting NBCO films and vice versa. Field effect experiments in HTS have been successfully studied in NBCO/PBCO bilayers.¹³

The NBCO/PBCO/NBCO trilayer junctions used in this study were fabricated by the pulsed laser deposition (PLD) method. Single thin film deposition is described elsewhere.¹⁴ Very high crystal orientation (c axis) was shown from x-ray diffractometer (XRD) and Rutherford backscattering spectrometer (RBS) analyses. Atomic force microscopy (AFM) studies showed very smooth surface morphology with a few angstrom roughness.¹⁵ Transmission electron microscopy (TEM) and transport data on a variety of multilayers and trilayers demonstrated that virtually atomic perfection of the interfaces between NBCO/PBCO/NBCO was achieved.¹⁴ Planar junctions with widths varying from 1 to 10 μm were fabricated from those c -axis oriented NBCO/PBCO/NBCO thin film multilayers. All the devices were contacted with Au bonding pads. The junctions were placed in the center of a superconducting solenoid with a maximum field of 7 T. The tunneling junctions were fabricated using standard photolithographic and ion milling techniques.¹⁶

We have observed experimentally the anomalous Zeeman splitting for high T_C superconductors, as shown in Figs. 1 and 2. We used a standard experimental approach to measure the tunneling conduction through the PBCO barrier via two NBCO electrodes as a function of the voltage applied between the upper and lower electrodes. The conductance dI/dV is plotted versus the voltage V for $H=0, 5, 6$, and 7 T, respectively. The 2Δ value is 0.930 ± 0.050 meV at 11 K. This low value of Δ for this experiment indicates that the energy gap in ultrathin NBCO films decreases with thickness, however, there is not enough published information to

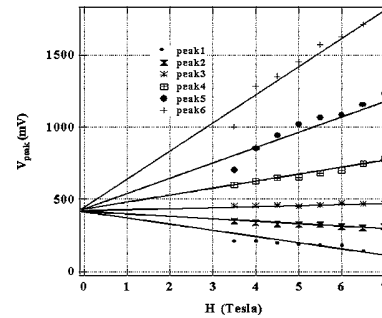


FIG. 2. Voltage corresponding to the spin splitting of the quasiparticle density of states curves determined from Fig. 1. The solid lines are guide for the eyes.

make comparisons at this point. In zero field the usual superconductor-insulator-superconductor tunneling characteristic is obtained. For lower values of H up to 3 T the peaks appearing in the dI/dV are noticeably broadened. As H increases this broadening develops into six resolved peaks at fields above 3 T, revealing Zeeman splitting of the quasiparticle density of states. The splitting occurs at six peaks for all fields in a series of Coulomb blockade conductance peaks of the tunneling junction as the bias current is swept. Figure 2 shows how the Coulomb blockade peaks shift in position with in plane magnetic field H . The position of each peak is determined by the energy necessary to add additional electrons to the tunneling barrier. This energy has components originating from both Coulomb charging and spatial quantization.

It is clear from Fig. 3 that the addition energy is altered by magnetic field: as the magnetic field is increased up to 7 T, the emerging peaks develop into two principal components depending upon their intensity. This configuration provides information on how electron spin and orbital effects combine to determine the ground state energy of the tunneling structure. We interpret the intensity of the peaks as due to a Zeeman contribution to the tunneling junction ground state energy, a consequence of the electron spin. The Zeeman contribution to the peak position is negative when the electron added is spin up and positive when the electron added is spin down. Spin up means the spin state whose direction is parallel to the field.

Figures 2 and 4 provide evidence for the role of electron

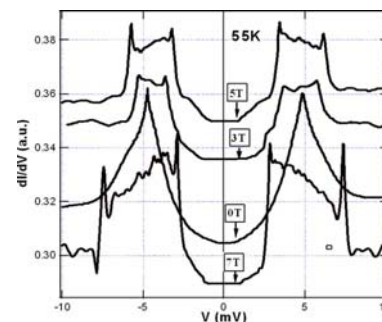


FIG. 3. Tunneling conductance curve at 55 K for a NBCO/PBCO/NBCO trilayer junction in 1, 5, 6, and 7 T fields, respectively. The curves corresponding to 3, 5, and 7 T reveals the spin split of the superconducting density of states. The curves have been displaced vertically.

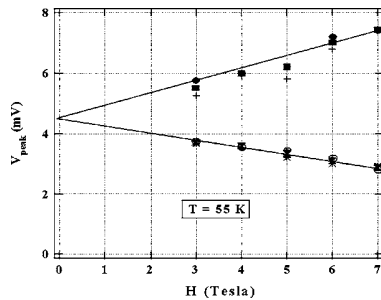


FIG. 4. Voltage corresponding to the spin splitting of the quasiparticle density of states curves determined from Fig. 3. The solid lines are guide for the eyes.

spin in the addition energy. Those figures show the voltage values measured for the peaks as a function of field and they exhibit the Zeeman splitting. In order to explain our data we use the following relation: $eV = \Delta \pm \mu_B g_L M_j H$, where M_j is the total momenta and g_L is the Landé electron g factor. We assume that the stationary states of the electrons in these tunneling structures are mixtures of states with different M_j values. There are upper and lower states with g_L varying between 1 and 6. In the presence of the magnetic field the tunneling density of states consists of the addition of six and two peaks in voltage for the samples 1 and 2, respectively, implying energy shifts of magnitude $\pm \Delta + \mu_B g_L M_j H$ and $\pm \Delta - \mu_B g_L M_j H$ with respect to the curve in the absence of field. The g factor will, in general, increase for a decreasing density of states at the Fermi energy E_F . The expected g value at zero temperature is approximately 1.

It is already well known that spin splittings are strongly affected by electron-electron exchange which gives rise to the exchange-enhanced g factor,¹⁷ and it has been observed experimentally¹⁸ that the g -factor enhancement can become extremely large whenever the Fermi level lies between spin-split Landau levels.

The calculations presented above have an experimental error of about $\pm 5\% - 10\%$. This is due to several factors that make the experiment difficult. First, one needs a very thin film (30–40 nm), such that the upper critical field is determined by the Pauli paramagnetic condition. Second, the spin-orbit scattering has to be small. Third, the splitting of the peaks in the density of states can only be observed at temperatures T such that $T/T_C \ll 1$. Fourth, to get a good separation of the peaks large magnetic fields of the order of a few tesla are needed.

The magnetic field splitting of the quasiparticle energy states in superconducting NBCO thin films has been observed in tunneling experiments. The magnitude of the splitting is attributed to the magnetic moment of the quasiparticles in these structures. These tunneling structures have

sufficiently small spin-orbit scattering rates to make the splitting effect observable. High enough fields can separate states that are degenerate in the absence of the field by energies typically of the order of $58 \mu\text{eV/T}$ and therefore gives rise to the possibility of spectroscopic investigations in the microwave regions of the spectrum, in which transitions are induced between the split levels in high T_C superconductors. Our conclusion is that the stationary states of the electrons in these NBCO/PBCO/NBCO tunneling structures are mixtures of states with different M_j values. The spin splitting of the density of states in HTS multilayer tunneling junctions could be used as a very powerful technique to determine the relative spin polarization in magnetic materials.

The characteristics shown in Figs. 2 and 4 lead to a strikingly simple conclusion. The Zeeman splitting scale varies with field as $eV = \Delta \pm \mu_B g_L M_j H$. Furthermore, the Zeeman splitting implies that the orbital contribution is very small and hence that the tunneling junctions are of high quality.

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