Anisotropic superconductivity in NbSe$_2$ probed by magnetic penetration depth

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Abstract

NbSe$_2$ shows coexistence of a charge density wave ($T_{CDW} \sim 32$ K) with a superconducting state below $T_c = 7.2$ K. Recent ARPES measurements revealed different values of the superconducting gap on the main sheets of the Fermi surface. These results suggest a multigap superconductivity such as in MgB$_2$. The temperature dependence of the magnetic penetration depth ($\kappa(T)$) down to $T_c/16$ has been measured on high quality single crystals in the Meissner state. A strong increase of the in-plane penetration depth is observed, signaling the presence of low lying excitations. Given the relative contributions of each Fermi surface sheet, these measurements indicate that a reduced gap is not necessarily only found on the small Se sheet as suggested by the ARPES measurements. These results are discussed in a framework of multigap superconductivity.

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The hexagonal dichalcogenides NbSe$_2$ has attracted a large interest in the last few decades for the coexistence of an incommensurate charge density wave with a superconducting state below $T_c = 7.1$ K [1]. Furthermore, the superconducting state shows unusual properties, which can not be explained by an isotropic BCS weak coupling model. For example, the electronic specific heat has already shown the presence of a reduced energy gap [2]. Recently, NbSe$_2$ has been revisited in the light of multigap superconductivity. ARPES measurement suggested that the low energy excitation gap is due to the Se p-band which has a small electron–phonon coupling constant [3]. A directional probe combined to the particular anisotropy of the Fermi Surface of NbSe$_2$ allows us to test the excitation gap on the different sheets.

In this paper, we present high sensitivity measurements of the change of the in-plane and c-axis temperature dependence of the magnetic penetration depth in the Meissner state (respectively $\Delta \kappa_a$ and $\Delta \kappa_c$). The detailed results are published elsewhere [4].

1. Experimental method

$\Delta \kappa_i$ ($i = a$ or $c$) was measured with a LC circuit driven by a tunnel diode operating at 14 MHz. The very low AC field probe ($\sim$10 $\mu$T) and the screening of any DC magnetic field ensured that the sample was kept in the Meissner state. The frequency shift of the LC oscillator is directly proportional to $\Delta \kappa$.

Single crystals from three sources (Lausanne, Tsukuba, Bell Lab) have been measured in three different laboratories (Grenoble, Bristol, Urbana-Champaign respectively). Crystals of thickness $t$ were grown with large flat layers.
perpendicular to the \( c \)-axis. Each side of the samples were cut. Samples from different batches have a RRR between 33 and 70 (see inset Fig. 1). No drastic change with sample quality has been observed.

When the magnetic field is applied along the \( c \)-axis, the supercurrents are flowing only in the basal plane. However, for a magnetic field applied perpendicular to the basal plane, both, a and \( c \)-axis directions are probed. For a sample of rectangular shape with a section \( \frac{a}{2} \times t \times w \), the frequency shift is proportional to \( D_k a + \frac{t}{2} D_k c \). To extract the out-of-plane penetration depth the aspect ratio of a sample is changed by cutting.

2. Results

In Fig. 1 the low temperature dependence of the in-plane penetration depth is shown. All the curves are fitted with the approximated expression (valid for \( kT < T_c/3 \)):

\[
\Delta \lambda_i(T) \simeq \lambda_i(0) \sqrt{\frac{\pi D_0}{2T}} \exp\left(-\frac{D_0}{T}\right)
\]

where \( D_0 \) is the superconducting gap at \( T = 0 \) K. We find \( D_0 = 1.1 \pm 0.1kT_c \), less than the value expected for a weak coupling BCS gap (~1.76\( kT_c \)). In Fig. 2 the low temperature dependence of the \( c \)-axis penetration depth is fitted for \( T < 2 \) K with the same expression. A gap of \( D_0 = 1.3 \pm 0.1kT_c \) is measured.

The experimental results have to be compared with the calculated Fermi surface. The Fermi surface of \( \text{NbSe}_2 \) is formed of two cylinders along the \( c \)-axis from the 4d-electrons of the Nb and also a small flat pancake around the center of the Brillouin zone from the p-electron of the Se. This sheet contributes only to 2% to the total in-plane superfluidity but 85% to the out-plane superfluidity [5]. So the reduced energy gap measured by in-plane penetration depth is on one or more of the quasi-2D Nb sheets. Moreover, \( \Delta \lambda_c \) shows that the superconducting gap associated to the Se sheet is not smaller than the smallest gap of the quasi-2D Nb band. These results are in strong contrast with previous measurements [3].

References