Multiband superconductivity in NbSe$_2$ from heat transport

E. Boaknin$^a$, M. A. Tanatar$^{a,1}$, J. Paglione$^a$, D. G. Hawthorn$^a$, R. W. Hill$^a$, F. Ronning$^a$, M. Sutherland$^a$, L. Taillefer$^{a,*2}$, J. Sonier$^b$, S. M. Hayden$^c$, J. W. Brill$^d$

$^a$Department of Physics, University of Toronto, Toronto, Canada M5S 1A7
$^b$Department of Physics, Simon Fraser University, Burnaby, Canada V5A 1S6
$^c$H. H. Wills Physics Laboratory, University of Bristol, United Kingdom
$^d$Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky, USA 40506-0055

Abstract

The thermal conductivity of the layered $s$-wave superconductor NbSe$_2$ was measured down to $T_c/100$ throughout the vortex state. With increasing field, we identify two regimes: one with localized states at fields very near $H_{c1}$ and one with highly delocalized quasiparticle excitations at higher fields. The two associated length scales are most naturally explained as multi-band superconductivity, with distinct small and large superconducting gaps on different sheets of the Fermi surface.

Key words: multi-band superconductivity, NbSe$_2$, thermal conductivity

In the classical theory of superconductivity all electrons on the Fermi surface contribute equally to the superconducting pairing, giving a constant superconducting gap $\Delta$. The difference of $\Delta$ on different sheets of the Fermi surface, or multiband superconductivity (MBSC), considered theoretically back in the 50s [1], has emerged recently as a possible explanation for the unusual properties of MgB$_2$ [2]. Based on the observation of a sizable difference of $\Delta$ on two Fermi surface sheets by angle resolved photoemission spectroscopy, it has been suggested that the layered superconductor NbSe$_2$ is also host to MBSC [3]. However, these surface-sensitive measurements were performed only down to 5.3 K, close to $T_c=7.0$ K. We present evidence of bulk MBSC at low temperatures in this compound.

The thermal conductivity $\kappa$ of pure samples of NbSe$_2$ (residual resistivity $\rho_0=3 \, \mu\Omega \text{cm}$) was measured upon warming in a magnetic field ($H \parallel c$ axis) [4]. In Fig. 1, $\kappa$ is presented as $\kappa/T$ vs $T^2$, enabling a separation of the electronic contribution, $\kappa_0 \sim T$, and the phononic contribution, $\kappa^p \sim T^3$. In zero field, $\kappa_0/T$ goes to zero in the $T=0$ limit as expected for $s$-wave superconductors, thus ruling out the possibility of nodes in the gap at any point on the Fermi surface. With the application of a magnetic field, $\kappa_0/T$ rapidly increases (Fig. 2, main panel) up to $H_{c2}$, following closely the increase of the electronic specific heat $\gamma$ [5]. This behavior is very different from that expected for conventional superconductors. There, electronic quasiparticles remain localized inside the vortex cores, such that the increase in quasiparticle density (seen as an increase of $\gamma$ with $H$) is not followed by an increase of $\kappa_0$. This is shown for V$_3$Si in the upper panel of Fig. 2 [6,7].

A closer examination of the field dependence of $\kappa_0$ and of $\gamma$ at fields close to $H_{c1}$ is consistent with the presence of localized states, another indication of a gap without nodes. Indeed, in a limited field range, $\kappa_0$ shows an activated increase in field whereas the specific heat increases rapidly above $H_{c1}$ (lower inset in Fig. 2).

In Fig. 3, we show a more detailed comparison of $\kappa$ and $\gamma$ by plotting the ratio $\kappa_0/\gamma$. In a rough sense, it represents the “mobility” of quasiparticle excitations.

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nodes in the gap anywhere on the Fermi surface.

Fig. 1. $\kappa/T$ vs $T^2$ for NbSe$_2$. The line shows the $T \to 0$ extrapolation which yields the electronic contribution $\kappa_0/T$. In zero field, $\kappa_0/T=0$, as expected for a superconductor without nodes in the gap anywhere on the Fermi surface.

Fig. 2. Field dependence of thermal conductivity (circles for NbSe$_2$ and empty triangles for V$_3$Si) and specific heat (filled triangles for NbSe$_2$ and squares for V$_3$Si) in NbSe$_2$ (main panel and lower inset) and V$_3$Si (upper inset). The filled circles come from a field sweep at 100 mK. Both quantities are normalized to the values in the normal state.

In the vortex state, it is clear that the field dependence of $\kappa_0/\gamma$ shows a strong change of slope at $H^* \sim H_{c2}/9$, supporting the existence of a field scale which plays the same role for quasiparticle localization as $H_{c2}$ does in standard s-wave superconductors. In the inset of Fig. 3, we show that the low field behavior of NbSe$_2$ can be matched to that of V$_3$Si by using $H^* \sim H_{c2}/9$.

While $\xi$ is associated with the upper critical field ($\xi^2 = \Phi_0/2\pi H_{c2}$), a second length scale $\xi^*$ must be associated with $H^*$. The crossover between $\xi$ and $\xi^*$ with $H$ can naturally explain the shrinking of the vortex cores observed by muon spin relaxation in NbSe$_2$ [8]. Moreover, the superconducting coherence length is related to $\Delta$ via $\xi \sim v_F/\Delta$, where $v_F$ is the Fermi velocity. In NbSe$_2$, $v_F$ is approximately the same for different sheets of the Fermi surface, such that the ratio $\xi^*/\xi \sim 3$ gives a ratio of associated superconducting gaps $\Delta^*/\Delta \sim 3$. This value is consistent with previous heat capacity and tunneling results [5,9,10].

In conclusion, we have identified the anomalous evolution of thermal conductivity in NbSe$_2$ versus magnetic field with the existence of two length scales in the superconducting state. This finds a natural explanation in a model of multi-band superconductivity, assuming a ratio of larger gap to smaller gap of about 3.

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