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Physica C 408–410 (2004) 727–728
PHYSICA C
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Multi-band superconductivity in $NbSe_2$ from heat transport

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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.

Keywords: 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 Δ. The difference of Δ on different sheets of the Fermi surface, or multi-band 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 Δ 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 κ of pure samples of $NbSe_2$ (residual resistivity $\rho_0 = 3$ μΩ cm) was measured upon warming in a magnetic field ($H \| c$ axis) [4]. In Fig. 1, κ is presented as κ/T vs T^2, enabling a separation of the electronic contribution, $\kappa_0 \sim T$, and the phononic contribution, $\kappa^g \sim T^3$. In zero field, κ_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, κ_0/T rapidly increases (Fig. 2, main panel) up to H_{c2}, following closely the increase of the electronic specific heat γ [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 γ with H) is not followed by an increase of κ_0. This is shown for V_3Si in the upper panel of Fig. 2 [6,7].

A closer examination of the field dependence of κ_0 and of γ at fields close to H_{c1} is consistent with the presence of localized states, another indication of a gap

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0921-4534/$ - see front matter
doi:10.1016/j.physc.2004.03.055

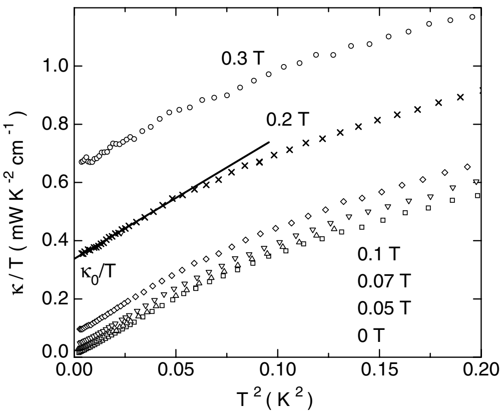

Fig. 1. κ/T vs T^2 for $NbSe_2$. The line shows the $T \to 0$ extrapolation which yields the electronic contribution κ_0/T. In zero field, $\kappa_0/T = 0$, as expected for a superconductor without nodes in the gap anywhere on the Fermi surface.

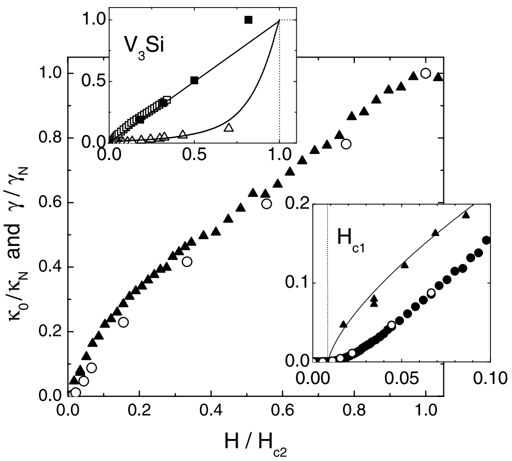

Fig. 2. Field dependence of thermal conductivity (circles for $NbSe_2$ and empty triangles for V_3Si) and specific heat (filled triangles for $NbSe_2$ and squares for V_3Si) in $NbSe_2$ (main panel and lower inset) and V_3Si (upper inset). The filled circles come from a field sweep at 100 mK. Both quantities are normalized to the values in the normal state.

without nodes. Indeed, in a limited field range, κ_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 κ and γ by plotting the ratio κ_0/γ. In a rough sense, it represents the "mobility" of quasiparticle excitations in the vortex state. It is clear that the field dependence of κ_0/γ 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_3Si by using $H^* \sim H_{c2}/9$.

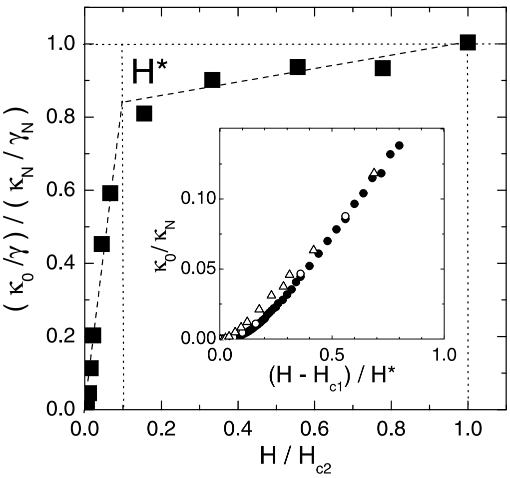

Fig. 3. Field dependence of κ_0/γ (main panel). The inset shows the field dependence of thermal conductivity for $NbSe_2$ (circles) and V_3Si (triangles), plotted as a function of $(H - H_{c1})/H^*$ where $H^* = H_{c2}/9$ for $NbSe_2$ and $H^* = H_{c2}$ for V_3Si.

While ξ is associated with the upper critical field ($\xi^2 = \Phi_0/2\pi H_{c2}$), a second length scale ξ^* must be associated with H^*. The crossover between ξ and ξ^* 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 Δ 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.

This work was supported by the Canadian Institute for Advanced Research and funded by NSERC.

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