Anomaly of quasi-particle density of states in the vortex state of $NbSe_2$

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Abstract

Magnetic field H dependence of the electronic specific heat coefficient γ was measured in various $NbSe_2$ crystals in the vortex states. With increasing residual resistivity ratio, $\gamma(H)$ changed from conventional $\gamma \propto H$ behavior to the strongly sublinear function of H. The sublinear H dependence of γ is similar to that of nodal superconductors, while $NbSe_2$ is a nodeless superconductor. From measurements on the sample containing columnar defects, we found that the γ anomaly is brought by quasi-particle states *outside* of the vortex cores. This result suggests that excess quasi-particle states are generated by Doppler energy shift caused by supercurrent around vortices.

Key words: vortex state; electronic specific heat coefficient; $NbSe_2$;

1. Introduction

In conventional isotropic s-wave superconductors, all the quasi-particles (QP's) in the vortex states are confined in the vortex cores. However, in a superconductor with nodes in the superconducting gap (SG), excess QP's can be excited *outside* of the core, since low energy states near the gap nodes are Doppler shifted to the Fermi energy ϵ_F by the supercurrent around vortices [1]. Because of this effect, QP density of states at ϵ_F or the electronic specific heat coefficient γ of nodal superconductors varies proportionally to $\sqrt{H}$, which is quite different from conventional H-linear behavior. Such an enhancement of γ has really been observed and is regarded as an evidence of the gap nodes [2,3].

On the other hand, small but clear enhancement of γ is also observed in clean $NbSe_2$ of which SG is nodeless [4]. To make clear the origin of this peculiar behavior of γ, we performed systematic γ measurements on various $NbSe_2$ crystals with different residual resistivity ratios (RRR's). Moreover, we examined the effects of columnar defects on the enhancement of γ. From these experiments, we show that the enhancement of γ is brought by QP's *outside* of the vortex core.

2. Experimental

$NbSe_2$ single crystals were grown by iodine vapor transport technique. By changing the growth conditions and doping Ta instead of Nb, we succeeded in growing various crystals with RRR ranging from 3 to 100. Columnar defects, of which dose equivalent field B_ϕ =1 T, were introduced to the crystal with RRR=60 by the irradiation of 6 GeV Pb ions. Specific heat C was measured by thermal relaxation method. In all the measurements, magnetic fields were applied along the c-axis under field-cooled conditions.

3. Results and Discussion

Figure 1 shows the H dependence of γ of various $NbSe_2$ crystals. Here, H and γ are normalized by the upper critical field H_{c2} and the Sommerfeld constant

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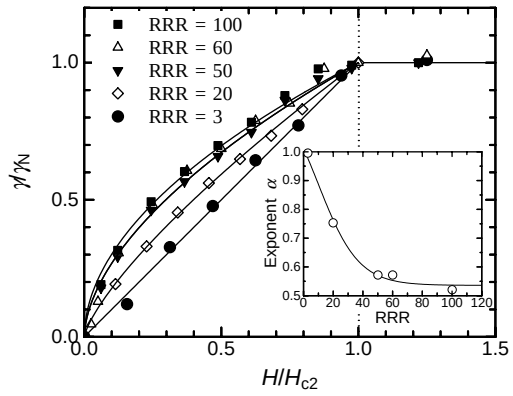

Fig. 1. H/H_{c2} dependence of γ/γ_N of $NbSe_2$ crystals. Lines denote the fitted results by exponential functions. In the sample with RRR=3, 20% of Nb were substituted by Ta. inset: RRR dependence of the exponent α. Line is a guide for the eye.

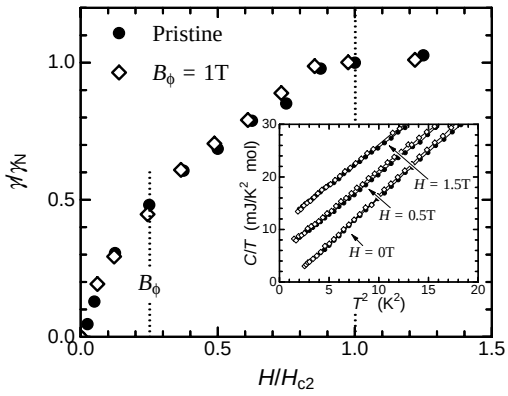

Fig. 2. H/H_{c2} dependence of γ/γ_N of a $NbSe_2$ crystal before and after the introduction of columnar defects. RRR of the pristine sample was 60. inset: C/T vs. T^2 plot of the pristine and irradiated crystals.

γ_N measured above H_{c2}, respectively. It is apparent that the enhancement of γ becomes large with increasing RRR. We found that γ in the vortex state can be fitted by $\gamma/\gamma_N = (H/H_{c2})^\alpha$. The RRR dependence of the exponent α, which is a measure of the enhancement of γ, is shown in the inset of Fig. 1. With increasing RRR, the exponent decreases from 1 (linear in H) and saturates to about 0.5 above RRR$\sim$50 where QP mean free path is more than 10 times longer than the coherence length. This result means that the enhancement of γ in clean enough $NbSe_2$ is not small but almost same as that of a nodal superconductor.

One may consider that the appearance of gap nodes in clean enough $NbSe_2$ is the origin of the γ enhancement, since gap anisotropy increases with decreasing QP scattering rate or increasing RRR in s-wave superconductors [5]. However, even in our cleanest $NbSe_2$, temperature dependence of the electronic specific heat shows thermally activated behavior, which means that the SG of our cleanest $NbSe_2$ is still nodeless.

Another RRR-dependent change of the electronic state may occur in the vortex core. In clean superconductors, QP bound states inside the vortex core [6] become well-defined. To examine the relation between vortex core state and the enhancement of γ, we measured γ of the sample containing columnar defects produced by heavy ion irradiation. Since vortices are pinned along the columnar defects, electronic states of the vortex core can be modified selectively. Therefore, if the electronic state of the vortex core is responsible for the enhancement of γ, introduction of the columnar defects should affect γ. This method was applied to YNi_2B_2C by Izawa *et al.* [7].

Figure 2 shows H/H_{c2} dependence of the normalized γ measured before and after the irradiation. Surprisingly, not only γ but also C itself were not affected by the irradiation as shown in the inset of Fig. 2. We confirmed the enhancement of the critical current after the irradiation, which indicates that the columnar defects actually act as pinning centers.

Insensibility of γ to the introduction of columnar defects means that the enhancement of γ is originated from QP states *outside* of the core, as in the case of nodal superconductors. However, unlike nodal superconductors, the SG of $NbSe_2$ is finite over the Fermi surface. Even in this case, Doppler energy shift may generate QP states at ϵ_F, if the Doppler energy shift exceed the SG at somewhere on the Fermi surface. To realize such a situation, SG and/or the Doppler energy shift should be anisotropic in the momentum space. Some anisotropy of SG in $NbSe_2$ is actually suggested [8] although its origin still remains to be solved.

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References

[1] G. E. Volovik, JETP Lett. **58** (1993) 469.

[2] K. A. Moler *et al.*, Phys. Rev. Lett. **73** (1994) 2744.

[3] M. Nohara *et al.*, Physica C **341-348** (2000) 2177.

[4] M. Nohara *et al.*, J. Phys. Soc. Jpn. **68** (1999) 1078.

[5] L. S. Borkowski, P. J. Hirschfeld, Phys. Rev. B **49** (1994) 15404, R. Fehrenbacher, M. R. Norman, *ibid.* **50** (1994) 3495. 8

[6] C. Caroli, P. G. de Gennes, J. Matricon, Phys. Lett. **9** (1964) 307.

[7] K. Izawa *et al.*, Phys. Rev. Lett. **86** (2001) 1327.

[8] N. Hayashi, M. Ichioka, K. Machida, Phys. Rev. Lett. **77** (1996) 4074.