Excess quasiparticles outside the vortex cores in $Y(Ni_{1-x}Pt_x)_2B_2C$

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Abstract

The in-plane magnetic penetration depth λ and vortex core radius ρ_v in $Y(Ni_{1-x}Pt_x)_2B_2C$ ($x = 0.0$ and 0.2) have been determined by μSR. It is demonstrated by the magnetic field dependence of the penetration depth λ that quasiparticle excitations exist not only in the vortex cores but also their outside in both samples.

Key words: penetration depth; vortex core radius; quasiparticle excitations; borocarbide

The physics of flux-line lattice (FLL) phase has been drawing much interest in recent years because the recent studies of the FLL state in presumably conventional s-wave superconductors have revealed that the electronic structure of vortices is much more complicated than that of a simple array of rigid cylinders containing normal electrons. One of the unexpected phenomena within this conventional model is the non-linearity in the magnetic field dependence of the Sommerfeld constant $\gamma(H)$ (electronic specific heat coefficient) observed in $CeRu_2$[1], $NbSe_2$[2], and YNi_2B_2C[2]. According to the above simple model where the quasiparticle excitations are confined within the cores of vortices (with a radius ξ) in s-wave superconductors, one would expect that $\gamma(H)$ is proportional to the number of vortices per unit cell and thus to the applied magnetic field H. However, experiments have revealed that this is not the case for any of the above compounds [1,2]. Instead, they find a field dependence like $\gamma(H) \propto \sqrt{H}$ which is expected for d-wave superconductors having more extended quasiparticle excitations along nodes in the energy gap. The recent study on the effect of doping in YNi_2B_2C and $NbSe_2$ indicates that the anomalous field dependence is observed only in the clean limit[2], suggesting the importance of nonlocal effects in understanding the field dependence of $\gamma(H)$. Moreover, it has been reported that the vortex core radius depends on applied magnetic field and shrinks at higher fields in $NbSe_2$ [3] and in $CeRu_2$ [4].

In order to elucidate the structure of the quasiparticle excitations, we have performed μSR measurements in $Y(Ni_{1-x}Pt_x)_2B_2C$, where the magnetic field dependence of the penetration depth λ, vortex core radius ρ_v and the angle of the FLL θ were measured [6–8]. The single crystals of $Y(Ni_{1-x}Pt_x)_2B_2C$ ($x = 0.0, 0.2$) used in these experiments had surface area of ~ 64 mm^2. The superconducting transition temperature T_c and the upper critical field $H_{c2}(0)$ determined from resistivity and specific heat measurements were 15.4 K and 8.0 T in $x = 0.0$ sample and 12.1 K and 4.3 T in

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x = 0.2, respectively [2]. μSR experiments were performed on the M15 and M20 surface muon beamlines at TRIUMF.

The analysis based on the London model with non-local corrections [5] in YNi_2B_2C shows that the FLL has changed from hexagonal to square with increasing magnetic field H, and the magnetic penetration depth λ increases linearly in H [7]. At low fields the vortex core radius $\rho_v(H)$ decreases with increasing H much steeper than what is expected from the $\sqrt{H}$ behavior of the Sommerfeld constant $\gamma(H)$, strongly suggesting that the anomaly in $\gamma(H)$ primarily arises from the quasiparticle excitations outside the vortex cores [7]. On the other hand, λ in $Y(Ni_{1-x}Pt_x)_2B_2C$ ($x = 0.2$) behaves as a constant under $H \leq 0.4H_{c2}$, suggesting that the superconducting gap is effectively isotropic, while ρ_v decreases with increasing H [8].

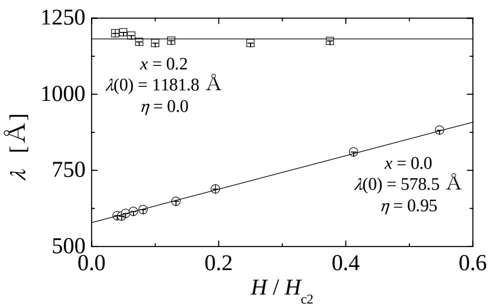

Fig. 1. The H/H_{c2} dependence of the λ in $Y(Ni_{1-x}Pt_x)_2B_2C$. Solid lines are fitting results by Eq. (1).

Fig. 1 shows the magnetic penetration depth λ in $Y(Ni_{1-x}Pt_x)_2B_2C$ ($x = 0.0$ and 0.2) versus normalized external field. A fit to the relation

$$\lambda(h) = \lambda(0)[1 + \eta h] \quad (h = H/H_{c2}) \tag{1}$$

provides a dimensionless parameter η that represents the strength of the pair-breaking effect. We obtain η = 0.95(1) with $\lambda(0)$ = 578.5(2.0) Å and η = 0.0 with $\lambda(0)$ = 1181.8(5.1) Å in clean sample (x = 0.0) and dirty (x = 0.2), respectively. We expect the conventional s-wave superconductors to be $\eta = 0.0$ because quasiparticles exist only within the vortex cores. The H-linear behavior of λ in clean sample suggests the presence of excess quasiparticle excitations outside the vortex cores. On the other hand, λ in the dirty sample does not depend on H, taking a value about 1182 Å. The disappearance of the field dependence in λ can be ascribed to that of the gap anisotropy as inferred from the photoelectron result [9]. However, the value of $\lambda(0)$ in dirty sample is considerably larger than that in the clean sample. The enhancement of λ due to impurity effect is evaluated by the following equation,

$$\lambda_{\mathrm{eff}}(l,T) = \lambda_L(T)\left(\frac{\xi_0}{\xi}\right)^{1/2} = \lambda_L(T)\left(1+\frac{\xi_0}{l}\right)^{1/2}, \tag{2}$$

where λ_L is the London penetration depth. The estimated effective penetration depth λ_{eff} is

$$\lambda_{\mathrm{eff}} = 1.612 \times \lambda_{x=0}. \tag{3}$$

Using the above Eq. (3), the λ_{eff} is deduced to be 932.5 Å which is about 0.79 times smaller than λ in the dirty sample, suggesting that the enhancement is explained not only by impurity effect but also by the existence of quasiparticles outside the vortex cores. In contrast to λ, ρ_v decreases with increasing H in both samples. The difference in the field dependence of ρ_v between that deduced from μSR and from specific heat in clean sample [2] is again explained by the predominant contribution of quasiparticle excitations outside the vortex cores for the specific heat measurement. A similar situation is suggested in dirty sample by the extremely large value of $\lambda(0)$ in $x = 0.2$ compared with that in $x = 0.0$. In this way, our study has revealed that the anomalies of the quasiparticle excitations in $Y(Ni_{1-x}Pt_x)_2B_2C$ ($x = 0.0, 0.2$) are related with the anisotropic order parameters.

In conclusion, we have found that the superconducting gap has changed from anisotropic to effectively isotropic one upon doping of Pt. However, λ in the sample with $x = 0.2$ is about 1.27 times larger than that estimated by impurity effect, suggesting that the quasiparticles also exist not only inside the vortex cores but outside like pure YNi_2B_2C.

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