Low Energy Quasiparticle Excitation in the Vortex State of Borocarbide Superconductor YNi$_2$B$_2$C

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We have measured the low temperature heat capacity $C_p$ and microwave surface impedance $Z_s$ in the vortex state of YNi$_2$B$_2$C. In contrast to conventional s-wave superconductors, $C_p$ shows a nearly $\sqrt{H}$-dependence. This $\sqrt{H}$-dependence persists even after the introduction of the columnar defects which change the electronic structure of the vortex core regime dramatically and strongly disturb the regular vortex lattice. On the other hand, flux flow resistivity obtained from $Z_s$ is nearly proportional to $H$. Taken together, these results indicate that the vortex state of YNi$_2$B$_2$C is fundamentally different from the conventional s-wave counterparts, in that the delocalized quasiparticle states around the vortex core play a much more important role, similar to d-wave superconductors.

74.70.Dd, 74.60.Ec, 74.25.Nf, 74.25.Jb

The borocarbide superconductors LnNi$_2$B$_2$C where Ln=(Y, Lu, Tm, Er, Ho and Dy) exhibit a rich variety of interesting physical properties. In particular, the occurrence of superconductivity at elevated temperatures, the competition and coexistence of the antiferromagnetic ordering and superconductivity, and the transition between a triangular and square vortex lattice have attracted much attention. In spite of extensive studies on these subjects, however, one of the most fundamental properties of the superconducting state, namely the quasiparticle (QP) structure in the vortex state, is still controversial. In fact, recent measurements of low temperature heat capacity $C_p$ on YNi$_2$B$_2$C and LnNi$_2$B$_2$C in the vortex state have shown that $C_p$ clearly indicates the presence of the $\sqrt{H}$-term. In the conventional s-wave superconductors, $C_p$ should increase linearly with $H$ because all the QPs are trapped within the vortex core with the radius of the coherence length $\xi$, and hence the QP density of states (DOS) $N(H)$ is proportional to the number of vortices; $N(H) \propto N_F \xi^2 H$ where $N_F$ is the DOS at the Fermi level in the core. Thus, the observed $\sqrt{H}$-dependence of $C_p$ is strikingly in contrast to the ordinary s-wave superconductors. The $\sqrt{H}$-dependence of $C_p$ has been reported in some of the unconventional superconductors with gap nodes in the QP energy spectrum such as high-$T_c$ YBa$_2$Cu$_3$O$_7$ and heavy fermion UPt$_3$ superconductors. Nonlinear $H$-dependence close to the $\sqrt{H}$ of $C_p$ is also observed in some s-wave clean superconductors such as CeRu$_2$$_{13}$ and NbSe$_2$$_{14}$.

Although the unusual $H$-dependent $C_p$ of borocarbide superconductors has been discussed in terms of several intriguing models, the issue is still far from being settled. For instance, several authors proposed the shrinking of the vortex core with $H$ [14 13], but the physical origin behind this phenomenon is unclear. Another group ascribed it to the field-induced gap nodes [8], but this scenario is beyond the applicability of the original argument [12]. Moreover, the extended QP states outside the vortex core owing to a presupposed $d$-wave symmetry have been invoked [13]. There is, however, no corroborative evidence for $d$-wave pairing. Therefore, the experimental clarification of the QP structure in the vortex state of YNi$_2$B$_2$C is very much needed. Further, it is crucial for understanding the vortex lattice structure. If a substantial portion of the QPs extend in specific directions well outside the core, they should play an important role in determining the superconducting properties, including the vortex lattice structure, magnetization $M(H)$, upper critical field $H_{c2}$, etc. Nevertheless, these properties have been discussed in terms of an ordinary s-wave superconductor with an anisotropic Fermi surface with the use of the nonlocal London theory, without taking into account the effect of the extended QPs.

We stress that we can extract detailed information about the QP spectrum only when we measure both the heat capacity and the surface impedance $Z_s$ for the same sample. In superconductors with gap nodes, $C_p$ is essentially determined by the QPs excited in the node directions [14]. Energy dissipation in the flux flow state, on the other hand, occurs mainly in the “normal regions” created by the vortices. Thus, the dissipative response is dominated by Andreev bound states localized within vortex cores; those states have momenta whose directions lie away from the nodes [17]. Therefore, the measurement of $Z_s$ is complementary to the heat capacity. In this Letter, we report measurements for both $Z_s$ and $C_p$ in the vortex state of YNi$_2$B$_2$C. We have also examined the effect of introducing columnar defects (CD) on $C_p$: since the diameter of CD is comparable to $\xi \sim 70$ A of YNi$_2$B$_2$C...
and the inside of CD is semiconducting [18], they should strongly influence the electronic structure of the vortices. As we shall discuss below, these results provide strong evidence that the $\sqrt{\Phi}$-term in $C_p$ originates mainly from the Doppler shift of the delocalized QP spectrum due to the superfluid electrons surrounding the vortex cores [10]. This suggests that a strongly anisotropic $s$-wave state most likely applies to YNi$_2$B$_2$C.

Single crystals of YNi$_2$B$_2$C with $T_c = 13.4$ K were grown by the floating zone method. In all measurements, dc magnetic fields $H$ were applied parallel to the $c$ axis. The microwave surface impedance $Z_s = R_s + iX_s$, where $R_s$ and $X_s$ are the surface resistance and the reactance, respectively, were measured by the cavity perturbation technique. We used a cylindrical Cu cavity with $Q \sim 3 \times 10^4$ operated at 28.5 GHz in the TE$_{011}$ mode. The sample was placed at the center of the cavity which is the antinode of the microwave magnetic field $H_{ac}$ that is parallel to the $c$-axis of the sample ($H_{ac} \parallel H \parallel c$). In this configuration, the vortex lines along the $c$ axis respond to oscillatory driving currents within the $ab$ plane induced by $H_{ac}$. We measured $C_p$ by the thermal relaxation method. Several single crystals nearly one millimeter in size and $\sim 100\mu m$ in thickness along the $c$ axis were irradiated at GANIL (Caen, France) with a 6.0-GeV Pb-ion beam aligned parallel to the $c$-axis. The samples were irradiated to the fluence of $5 \times 10^{10}$ and $1 \times 10^{11}$ ions/cm$^2$, corresponding to a dose-equivalent flux density of $B_0=1$ T and 2 T, respectively. The resulting damage consisted of a random array of amorphous columns, about 60-70Å in diameter and continuous throughout the thickness of the crystal, which we confirmed by the transmission electron microscope image. The CD act as strong pinning centers of the vortices; at $B \lesssim B_0$, a substantial portion of the vortices are trapped inside the CD. Particularly below $\sim 0.2B_0$, almost all vortices are expected to be trapped [1]. The CD do not, however, act as strong scattering centers of the electrons, unlike magnetic impurities or point defects. In fact, after the irradiation, $M(H)$ showed a broad peak at $B \sim B_0$ due to the trapping of the vortices by the CD (inset of Fig.1), but the increase in the resistivity was very small (less than 10%) and the $T_c$ did not change.

Figure 1 plots $C_p/T$ as a function of $T^2$ for the pristine YNi$_2$B$_2$C. We will first make a remark on the $T$-dependence of $C_p$. Obviously, the normal state in Fig. 1 ($C_p/T$ vs $T^2$) that occurs as the superconductivity is suppressed by magnetic fields deviates from a linear dependence. Though this deviation may be attributed to the low-energy optical phonons, it is not clear where they originate from [20]. Moreover, recent inelastic neutron scattering experiments demonstrated an anomalous phonon branch which strongly couples to the electronic excitation in the superconducting state [21]. Therefore, the quantitative analysis of the $T$-dependence of the electronic contribution obtained by subtracting the phonon terms from the total heat capacity is precarious.

![Figure 1](image_url)

**FIG. 1.** $C_p/T$ versus $T^2$ for the pristine YNi$_2$B$_2$C. All measurements have been done in the field cooling conditions. Inset: $M-H$ curves for pristine and irradiated ($B_b=2$ T) crystals at 5 K. While in the pristine crystal $M(H)$ is reversible in a wide $H$-range, showing very weak pinning centers, $M(H)$ show a broad peak at $B = B_b$ in the irradiated crystal.
At a low field, assuming that \( \lambda \) flux flow state, two characteristic length scales, namely \( \lambda \) and \( \delta \), are given as \( \lambda \approx (\mu_0 H \rho_n)^{1/2} \) and \( \delta \approx (\mu_0 H \rho_n \omega \Lambda)^{1/2} \), respectively, in the normal state and \( \delta \) is replaced by \( \delta_f \). In \( \text{YNi}_2\text{B}_2\text{C} \), this crossover occurs at a very low field \( (\mu_0 H) \sim 20 \text{ mT} \). According to Coffey and Clem [23], \( Z_s \) in the flux flow state is expressed as

\[
Z_s = \frac{i \mu_0 \omega \lambda_L}{1 - (i/2) \delta_f^2/\lambda_L^2} \left[ 1 + 2i\lambda_L^2/\delta_{qp}^2 \right]^{1/2},
\]

where \( \delta_{qp} = \sqrt{2 \rho_n/\mu_0 \omega} \) with the QP resistivity \( \rho_{qp} \) is the normal-fluid skin depth. We analyzed the data by means of Eq. (1). We considered two different \( H \)-dependences of \( N(H) \), namely \( N(H) \propto H \) (case I) and \( N(H) \propto \sqrt{H} \) (case II). Case I corresponds to the conventional Bardeen-Stephen relation, \( \rho_f = (H/H_{c2}) \rho_n \) and \( \lambda_L^2(H) = \lambda_L^2(0)/(1 - H/H_{c2}) \), while case II corresponds to the vortex core shrinking, \( \rho_f \sim \sqrt{H/H_{c2}} \rho_n \) and \( \lambda_L^2(H) = \lambda_L^2(0)/(1 - \sqrt{H/H_{c2}}) \). In both cases we used \( \lambda_L(0) = 500 \text{ Å} \) [24]. The solid and dashed lines represent the theoretical calculations of \( R_s \) and \( X_s \) by Eq. (1), respectively. Comparing the two cases, case I obviously describes the data much better than case II. Small deviations of the fits from the data in case I may be due to the fact that \( \rho_f \) is not strictly linear in \( H \), as suggested by the time-dependent Ginzburg-Landau theory [25].

The results of \( Z_s \) and \( \Delta C_p \) for the pristine and irradiated \( \text{YNi}_2\text{B}_2\text{C} \) offer important clues for understanding the QP structure. Figure 3 shows that the linear \( H \)-dependent Bardeen-Stephen relation yields a more consistent fit to the data than another model does. Since the QPs localized in the core mainly contribute to the flux flow dissipation, this fact shows that the number of the QPs trapped within each core is independent of \( H \). Therefore, the scenario of the core shrinking with \( H \)
as an origin of nonlinear $H$-dependent $C_p$ proposed by several groups is completely excluded. In addition and more importantly, the fact that the existence of the CD with a comparable radius with $\xi$ little affects the $\Delta C_p$ implies that the QPs within the core radius $\xi$ are not important for the total heat capacity in the pristine YNi$_2$B$_2$C. On the basis of these results, we are led to conclude that in YNi$_2$B$_2$C the extended QP states around the vortex core play an important role in determining the superconducting properties, similar to d-wave superconductors.

Moreover, the effect of the CD on the $\Delta C_p$ provides another important piece of information about the microscopic origin of $\sqrt{H}$-dependence. It has been pointed out that in the presence of line nodes there are two sources for the $\sqrt{H}$-dependent $N(H)$, namely, the contributions from localized and delocalized fermions, but which of the two dominates has thus far been left unquestioned. Here we shall attempt to address this issue. One arises from the localized QPs in the node directions. Since the extended QP wavefunction in the node directions is cut off by its adjacent vortices, the area per a single vortex is proportional to the intervortex distance $R \propto 1/\sqrt{H}$. Then $N(H)$ is given as $N(H) \propto N_F \xi RH \propto \sqrt{H}$. The other arises from the delocalized QPs. In the presence of the supercurrent flow with velocity $v_s$, the energy spectrum of the delocalized QPs is shifted by the Doppler effect as $E(p) \rightarrow E(p) + v_s \cdot p$. In superconductors with line nodes such as d-wave symmetry where DOS has a linear energy dependence in the bulk $(N(E) \propto E)$, the Doppler-shifted QPs give rise to the finite DOS at the Fermi level. Then $N(H)$ is obtained by integrating the vortex lattice cell $N(H) \propto R^{-2} \int_{\xi}^{H} v_s(r) \cdot p \cdot r \, dr \propto \sqrt{H}$, where $|v_s(r)| = \hbar/2mr$ is the velocity of the circulating supercurrents. The very weak influence of the CD on $\Delta C_p$ elucidates the fact that the Doppler shift of the delocalized QPs is mainly responsible for the $\sqrt{H}$ dependent $C_p$, because the contribution from the localized QPs in the node directions should diminish when the vortex lattice structure is destroyed.

At low fields ($H < 70 \text{ mT} \approx H_{cr}$), the $\Delta C_p/T$ vs. $\sqrt{H}$ curve shows an upward curvature. There are two origins for the deviation from the $\sqrt{H}$-behavior. The first one is the lower critical field $H_{c1} \sim 30 \text{ mT}$, which is in the same order of $H_{cr}$. The second one is the crossover from high field to low field scaling. Generally, the heat capacity of superconductors with line nodes is proportional to $\sqrt{H}$ only at high fields where the number of the Doppler-shifted QPs exceeds that of thermally excited QPs. The heat capacity at low fields should be described by the zero-field scaling $C_p/(\gamma_n T) \sim k_B T/\Delta$, where $\gamma_n$ and $\Delta$ are the Sommerfeld coefficient in the normal state and superconducting energy gap, respectively. The crossover field from high field scaling to low field scaling roughly estimated from the relation $\sqrt{H}/H_{c2} \sim k_B T/\Delta$ with $\mu_0 H_{c2} = 5.5 \text{ T}$, $T_c = 13.4 \text{ K}$ and $T = 1.5 \text{ K}$ is $\sim 24 \text{ mT}$, which is also in the same order of $H_{cr}$. It should be noted that this behavior is also reported in YBa$_2$Cu$_3$O$_7-\delta$ with d-wave symmetry.

The present experiments strongly suggest that the influence of the extended QPs, which has been ignored by many authors, should be taken into account when discussing the vortex lattice structure, $H_{c2}$ and $M(H)$. In YNi$_2$B$_2$C, de Haas-van Alphen oscillations are observed as low as $H_{c2}/5$. This unusual phenomena may be related to the extended QPs. It is tempting to relate the observed relevance of the delocalized QPs to a three-dimensional d-wave superconductivity. However, recent doping studies on YNi$_2$B$_2$C show that the superconductivity survives even in the dirty limit. This robustness of the superconductivity against impurities makes a d-wave state unlikely. Therefore, we believe that a strongly anisotropic s-wave state in which $(N(E) \propto E)$ is similar to a d-wave state is most likely for YNi$_2$B$_2$C.

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