Evidence of Gap Anisotropy in Superconducting YNi_2B_2C Using Directional Point-Contact Spectroscopy

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We present a study of the anisotropy in the superconducting energy gap in a single crystal of YNi_2B_2C ($T_c \sim 14.6$ K) using directional point-contact spectroscopy. The superconducting energy gap at 2.7 K, when measured for $I||c$, is 4.5 times larger than that for $I||a$. The energy gaps in the two directions also have different temperature dependences. Our results support a scenario with $s + g$ like symmetry.

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The determination of the symmetry of the order parameter is a central step in understanding the pairing mechanism of any superconducting system. Conventional superconductors are characterized by an isotropic energy gap with s-wave pairing symmetry. The interest in the pairing symmetry has revived with the discovery of new classes of superconductors, where the pairing is highly anisotropic, with the gap function going to zero for certain k directions [1]. These are the high T_c cuprates [2], the triplet superconductor [3] Sr_2RuO_4, organic superconductors [4,5], and several heavy Fermion compounds [6,7]. Since a zero in the gap function can arise only from a nontrivial representation of the symmetry group, such gap structures point towards unconventional pairing interactions. Superconductivity in these materials is widely believed to originate from interactions of purely electronic origin [1].

In this work, we focus our attention on one member of another class of novel materials, namely, the quaternary borocarbide superconductor, YNi_2B_2C. Ten years after superconductivity was reported in this compound [8,9], the symmetry of the order parameter in YNi_2B_2C has still remained an outstanding issue. Early studies on this compound suggested an s-wave symmetry [10] mediated by conventional electron-phonon interaction. However, in recent years, several experimental studies such as thermal conductivity [11,12], specific heat [13], tunneling spectroscopy [14], photoemission spectroscopy [15], and ultrasonic attenuation [16] have not only provided evidence of a large anisotropy but also the existence of nodes in the superconducting gap function. Furthermore, the angular variation of various physical properties such as thermal conductivity [11], ultrasonic attenuation [16], etc. show a robust fourfold anisotropy in the a–b plane in the superconducting state, while the normal state properties remain almost isotropic [17]. These results provide evidence of a strong anisotropy in the superconducting order parameter, and have been interpreted based on either anisotropic s-wave ($s + g$ wave) [18] with point nodes or d-wave symmetry [19] with line nodes. However, most of the angle resolved measurements on gap anisotropy carried out so far probe the quasiparticle excitation spectrum at $T \ll T_c$, from which the shape of the gap function is inferred. Considering that d and $s + g$ wave symmetries are likely to have their origins from very different pairing interactions, a direct measurement of the temperature dependence of the superconducting energy gap along different crystallographic directions is highly desirable. Furthermore, since for $s + g$ symmetry, the amplitudes of s and g component of the order parameter can have different temperature dependences [20], it is important to investigate the temperature dependence of the superconducting energy gap through a probe capable of probing the gap in different crystal directions over a wide temperature range.

Directional point contact spectroscopy, i.e., where conductance spectra (dI/dV versus V) are recorded by injecting current through a ballistic point contact along different crystallographic directions in the superconductor, is a powerful tool to investigate the gap anisotropy in unconventional superconductors [21]. This technique allows a direct determination of the gap along various directions in the crystal over a wide temperature range. In this Letter, we report the directional point contact measurements in a high quality single crystal of YNi_2B_2C. The spectra were recorded by injecting the current either along c or along a, thereby measuring the gap along these two directions in the temperature range 2.6–15 K. Since the structure of the gap function for $s + g$ symmetry and d-wave symmetry would be different along these two directions, the above measurements allow us to distinguish between these two symmetries. Our results provide evidence of sharp minima in the gap structure of YNi_2B_2C in the basal plane, consistent with the $s + g$-wave scenario. Furthermore, the normalized energy gaps along different crystallographic directions have different temperature dependences, providing com-

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pelling evidence that the ratio of the amplitudes of s and g in the order parameter is temperature dependent.

Directional point contact measurements were carried out on two YNi_2B_2C single crystals both grown by traveling solvent floating zone method using an image furnace. The larger of the two crystals was cut into a rectangular parallelepiped of size 0.5 mm $\times$ 0.5 mm $\times$ 2 mm with the long axis along a. In this Letter we will primarily concentrate on the measurement carried out on this crystal (which had relatively large well oriented facets on the [100] and [001] planes) though both the gap anisotropy as well as its temperature variation was verified on both crystals [22]. The $T_c \sim 14.6$ K for this crystal was determined from ac susceptibility measured at 15 kHz. Under the application of a dc magnetic field, $H||c$, the signature of a "peak effect," i.e., a dip in the real part of the ac susceptibility (χ') associated with an order-disorder transformation of the vortex lattice [23], was observed down to 1000 Oe. Since the intervortex spacing for this field (~ 1500 Å) is larger than the penetration depth [24] ($\lambda \sim 1000$ Å), this points towards the very low defect density in the crystal. The crystal quality was further confirmed from the observation of de Haas–van Alphen (dHvA) oscillations [25]. Resistivity measurement on similar crystals showed the residual resistivity, $\rho_0 \sim 4\ \mu\Omega$ cm, corresponding to a mean free path, $l \sim 110$ Å, at low temperatures [26]. The crystal facets were polished to a mirror finish prior to the point contact measurement. For the point contact measurement, a mechanically cut fine tip made of 0.25 mm thick gold wire was brought in contact with the [100] or [001] facet (for $I||a$ and $I||c$, respectively) of the crystal using a differential screw arrangement in a liquid He cryostat. To establish a ballistic contact, the tip was first engaged on the sample and then gradually withdrawn in small steps until a ballistic contact was established [27]. For all the spectra reported in this Letter, the point contact resistance (R_N) in the normal state was in the range 10–20 Ω, from which the point contact diameter (d) was estimated to be [28] $d = \{\frac{4}{3\pi}(\frac{\rho l}{R_N})\}^{1/2} \sim 30$–$40$ Å. Therefore, our measurements were well into the ballistic limit ($d < l$) of the point contact. A four-probe modulation technique was used to directly measure the differential resistance ($R_d = (dV/dI)$) as a function of voltage from which the differential conductance ($G = 1/R_d$) was calculated.

Figures 1(a) and 1(b) show two sets of point contact spectra for $I||a$ and $I||c$, respectively, measured in the temperature range 2.7 K to 15 K. A gap related feature is clearly discernible in the spectra in both the directions at the lowest temperature. However, even a visual inspection shows that the gap value is much larger for $I||c$ than for $I||a$. For $I||c$, the gap feature in the spectra can be observed up to 14 K. However, for the "small gap" direction $I||a$, no feature was resolved in the conductance curve for $T > 7$ K [29]. The conductance curves were fitted with the usual Blonder-Tinkham-Klapwijk (BTK) model [30] (solid lines) using the superconducting energy gap Δ, the barrier height coefficient Z, and the broadening parameter [31] Γ as fitting parameters [32].

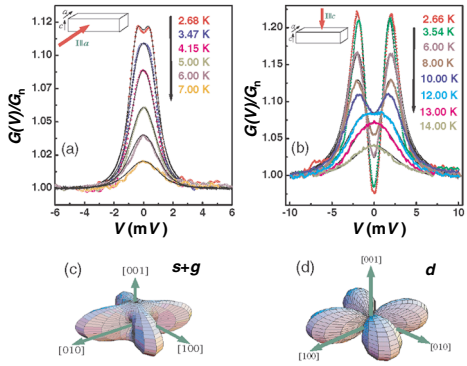

FIG. 1 (color online). Point contact spectra at different temperatures for (a) $I||a$ and (b) $I||c$. Open circles are experimental data and solid lines are BTK fits to the spectra. The conductance curves are normalized by their respective values at high bias. (c) and (d) show the gap functions corresponding to $s + g$ and d-wave symmetry, respectively, where the radial distance from the origin is proportional to the magnitude of the gap in that k direction.

We first concentrate on the G-V curves at the lowest temperature (e.g., 2.68 K). From the best fit parameters, the superconducting gaps in the two directions were determined to be $\Delta_{I||c} = 1.8 \pm 0.1$ meV and $\Delta_{I||a} = 0.415 \pm 0.08$ meV, respectively. This corresponds to a gap anisotropy of $\Delta_{I||c}/\Delta_{I||a} \sim 4.5$. However, it is important to note that for a ballistic contact, when I is injected along a particular direction $\hat{n}$, the current results from an average over the entire Fermi surface, though dominant contribution comes from Fermi surface regions close to k_{Fn}, while the contribution from the regions perpendicular to $\hat{n}$ is zero [33]. Therefore, the maximum ($\Delta_{\max}$) and the minimum ($\Delta_{\min}$) values of the gap are actually larger and smaller than $\Delta_{I||c}$ and $\Delta_{I||a}$, respectively. Thus, $\Delta_{I||c}/\Delta_{I||a}$ gives a lower limit of the gap anisotropy on the Fermi surface. The relative broadening of the spectra, characterized by Γ/Δ in the two directions is also different: $(\Gamma/\Delta) \sim 0.32$ for $I||c$ and $(\Gamma/\Delta) \sim 0.53$ for $I||a$.

We can now compare these results with the two order parameter symmetries proposed for this compound, namely, d and $s + g$ [18,19]. The gap functions corresponding to these two symmetries for a 3D Fermi surface in polar coordinates are $\Delta(k) = \Delta_0[\sin^2\theta \sin(2\phi)]$ and $\Delta(k) = (\Delta_0/2)[1 - \sin^4\theta \cos(4\phi)]$, where the convention for θ and ϕ are chosen such that the nodes are along [100] and [010] directions [11] [Figs. 1(c) and 1(d)]. For the d-wave symmetry, $\Delta(k)$ has line nodes perpendicular to the basal plane, extending to the poles. Therefore, $\Delta(k)$ has nodes both in the basal plane along [100] and [010] as well as along [001] directions. For $s + g$ symmetry (with equal amplitude of s and g), on the other hand, the gap is fully formed close to the poles and has point nodes only along [100] and [010]. Though our point contact measure-

ment cannot unambiguously identify a node in the $\Delta(k)$ due to Fermi surface averaging described before, the large value of $\Delta_{I||c}/\Delta_{I||a}$ observed at low T suggests that the gap function has sharp minima in the basal plane and a fully gapped nature close to the poles, consistent with the $s + g$ symmetry.

We now look at the anisotropy in Γ/Δ in the two directions. Though Γ is commonly attributed to the quasiparticle lifetime limited broadening of the spectrum [31], in a superconductor with an anisotropic gap function, a broadening in the point contact spectrum is also expected to arise from the averaging over the superconducting energy gap. The latter, though physically distinct in origin from the former, is indistinguishable within experimental errors. To illustrate this point, we have simulated a set of spectra using a distribution of superconducting energy gaps, keeping the mean value of the gap $\langle\Delta\rangle = 0.6$ meV and setting $\Gamma = 0$. The G-V curves are computed from $I = \sum_i I_{BTK}(Z = 0.4, T, \Delta_i, \Gamma = 0, V)$, where I_{BTK} is the well-known BTK expression for the current [30] and the sum runs over a distribution of gap values. Four G-V curves (normalized with respect to dI/dV for $V \gg \Delta$) with varying distribution of gap values are shown in Fig. 2. All the curves could be fitted (solid lines) using a single BTK function, when the broadening parameter Γ is used as an additional fitting parameter. The deviation of the fitted curve from the original curve is smaller than our level of experimental accuracy. Furthermore, the fitted value of Γ/Δ increases monotonically with the standard deviation of the distribution over Δ, i.e., $\sigma(\Delta) = \sqrt{\sum_i(\Delta_i - \langle\Delta\rangle)^2}$, showing that Γ/Δ is a measure of the variation in gap values (see the inset in Fig. 2). Therefore, the larger value of $(\Gamma/\Delta)_{I||a}$ compared to $(\Gamma/\Delta)_{I||c}$ in our measurements suggests that the gap function has a larger variation in the basal plane along [001] than close to the poles. Since in the $s + g$ symmetry, $\Delta(k)$ is "flat" close to the poles but has a sharp variation from zero close to the point nodes along [100], the larger Γ/Δ value for $I||a$ further supports $s + g$ scenario [34,35].

Finally, we concentrate on the temperature dependence of $\Delta_{I||c}$ and $\Delta_{I||a}$. The temperature variation of the gap for both $I||a$ and $I||c$ (Fig. 3) deviates from the expected temperature variation for an isotropic BCS superconductor, though the deviation is more pronounced for $I||a$. The gap decreases faster [36] than the BCS prediction at low T, consistent with the existence of gap zeros [21]. However, the striking observation is difference in the temperature dependence of the normalized energy gap in the two directions (inset of Fig. 3). Even taking into account the fact that a small gap could get smeared due to thermal broadening at higher temperatures, the rapid decrease in Δ for $I||a$ from the low temperature value is beyond any experimental error. This cannot be rationalized for a gap function of the form $\Delta(k) = \Delta_0 f(k)$, where the temperature dependence comes from Δ_0 alone, and therefore should be same for all k. It is pertinent to recall here that in the $s + g$ model, the amplitudes of the s and g are fine-tuned to be equal to obtain point nodes along [100] and [010] directions. There is, however, no symmetry reason why the amplitudes of inequivalent representations like s and g should be so close [18]. Experimentally, on the other hand, the node in $\Delta(k)$ at $T \ll T_c$ is a robust feature, with the lower bound of $\Delta_{\max}/\Delta_{\min}$ estimated to be [11,12] between 10–100. It is, however, possible that a state with equal amplitudes of s and g at $T = 0$ evolves with temperature and the amplitudes do not remain equal [37]. This would give rise to a $\Delta(k)$ of the form $\Delta(k) = \Delta_{0s}[1 + (\Delta_{0g}/\Delta_{0s})g(k)]$ where an additional temperature dependence would come from the temperature dependence of Δ_{0g}/Δ_{0s}. In such a situation, the shape of the gap function would be temperature depen-

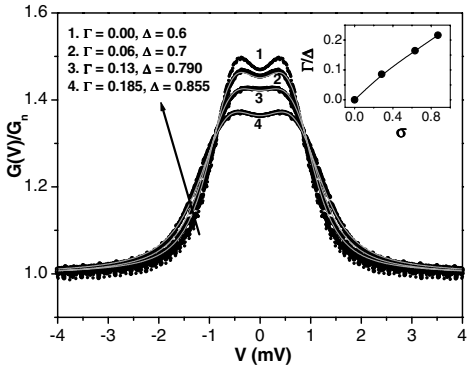

FIG. 2. Simulated spectra at 2.7 K (solid circles) assuming different distribution of Δ. For (1) $\Delta_i = 0.6$. For (2) $\Delta_i = 0.4$, 0.6, 0.8 meV, for (3) $\Delta_i = 0.2$, 0.4, 0.6, 0.8, 1.0 meV, and for (4) $\Delta_i = 0.0$, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2 meV, respectively. Simulated curves are fitted (solid lines) with BTK theory with broadening parameter Γ included. The best fit parameters for Δ and Γ are also shown in the figure. Inset: evolution of Γ/Δ with $\sigma(\Delta)$.

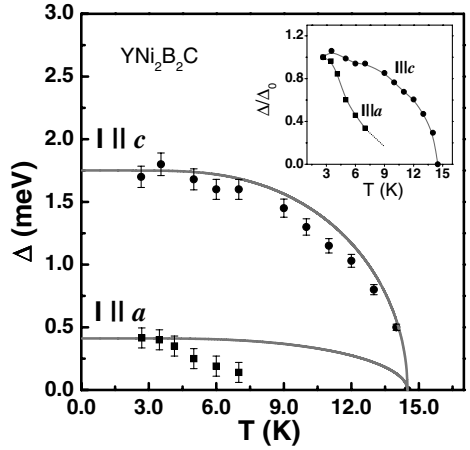

FIG. 3. Temperature dependence of $\Delta_{I||c}$ (solid circles) and $\Delta_{I||a}$ (solid boxes). Solid lines show the expected temperature variation from BCS theory for an isotropic gap. Inset: Temperature variation of Δ/Δ_0 (Δ_0 is the gap value at 2.7 K) for $I||c$ and $I||a$.

dent, giving rise to different temperature dependence of the gap along different directions.

In conclusion, directional point contact spectroscopy in YNi_2B_2C reveals a pronounced anisotropy in the superconducting energy gap with a fully gapped structure along the c direction and sharp minima in the basal plane, consistent with the $s + g$ symmetry. Furthermore, the temperature dependence of the energy gaps in different directions suggests that the ratio of amplitudes of s and g component in the order parameter is temperature dependent.

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