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Small superconducting gap on part of the Fermi surface of YNi_2B_2C from the de Haas–van Alphen effect

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The de Haas–van Alphen oscillation coming from a small electron pocket in the borocarbide superconductor YNi_2B_2C ($H_{c2}=8.8$ T) has been observed in the vortex state down to a surprisingly low field of 2 T. The oscillation amplitude is strongly suppressed in a field region immediately below H_{c2} but recovers at lower fields. The observed amplitude at low fields is much larger than theoretical predictions based on a literature value of the superconducting gap. It is argued that the gap opening on this particular Fermi surface is much smaller than the gap on other parts of the Fermi surface. [S0163-1829(97)04534-7]

The de Haas–van Alphen (dHvA) effect, quantum oscillations of magnetization arising from the Landau quantization of the electron energy, is the most direct and powerful tool to probe the Fermi surface (FS) and related properties of metals. Recently another field to be studied with the dHvA effect has opened up: the dHvA effect in the vortex (V) state of type-II superconductors. The first observation was reported by Graebner and Robbins for $NbSe_2$ in 1976.[1] Recent experiments carried out on several type-II superconductors such as $NbSe_2$,[2,3] V_3Si,[4,5] Nb_3Sn,[6] κ-$(ET)_2Cu(NCS)_2$,[7] and YNi_2B_2C (Refs. 8–10) have confirmed that the dHvA oscillation can be observed deep in the V state and showed that the superconductivity brings about an extra damping to the dHvA oscillation amplitude but no change in the dHvA frequency.

These observations have stimulated theoretical studies of the Landau level (LL) structure in the V state,[11–19] and it is widely accepted that the extra damping of the amplitude can be related to the magnitude of the superconducting (SC) gap. Since the dHvA effect can probe each piece of the FS separately, an exciting possibility emerges that the SC gap and its anisotropy may be determined for each piece of the FS. This direction of research has been pursued by Harrison *et al.*[6] They have examined the extra damping for four different dHvA frequencies in the V state of Nb_3Sn and shown that for all the frequencies the damping can be accounted for by a single value of the SC gap which is consistent with the thermodynamically determined one.

The borocarbide superconductor YNi_2B_2C ($T_c=15.6$ K) (Refs. 20 and 21) is a feasible compound for detailed studies of the dHvA effect in the V state. Because of the moderate upper critical field H_{c2} of about 9 T, comparison between the dHvA oscillations in the V and normal (N) states can be done with the same experimental setup. In the present study, the dHvA oscillation coming from a small ellipsoidal electron pocket, α, has been observed in a wide magnetic field range from the N state down to 2 T in the V state without interruption. In contrast with the results of Nb_3Sn, our data will show that the observed damping of the oscillation amplitude is much weaker than theoretically expected for a literature value of the SC gap. Accordingly, we will argue that the SC gap on the α FS is much smaller than the SC gap on other pieces of the FS and thus present evidence of an anisotropic SC gap of different pieces of the FS.

Single crystals of YNi_2B_2C were grown by a floating zone method. The crystals were carefully examined by SEM, EPMA, and x-ray-diffraction technique and found to be of high quality without any secondary phase.[22] The dHvA effect measurements at temperatures T down to 0.05 K and magnetic fields H parallel to the c axis up to 14 T were carried out using the low-frequency (67.1 Hz) field modulation technique. The dHvA oscillation was detected at the second harmonic of the modulation frequency and hence the efficiency of signal detection varies with H according to the Bessel factor $J_2(2\pi Fh/H^2)$, where J_2, F, and h are the second-order Bessel function, the dHvA oscillation frequency, and the modulation amplitude, respectively. An appropriate modulation amplitude was chosen between 3.8 and 8.9×10^{-3} T depending on the range of each field sweep and kept constant during one sweep. The same experimental setup was used to measure the ac susceptibility, from which the upper critical field $H_{c2}\|c$ at 0.05 K was estimated to be 8.8 ± 0.2 T. After the dHvA effect measurements, the heat capacity C of the sample was measured. The SC transition was observed at 14.9 K (onset) with a transition width of 0.9 K. The value of C/T at 0.6 K in the SC state ($H=0$ T) is less than 2% of the N-state value ($H=11$ T), confirming that the sample is fully superconducting.

The dHvA oscillation in normal metals is well described by the standard Lifshitz-Kosevich theory.[23] The T and H dependence of the oscillation amplitude A is given by

$$A\propto H^{1/2}R_TR_D. \tag{1}$$

The temperature reduction factor R_T is given by $R_T=X/\sinh(X)$ with $X=2\pi^2k_BT/\hbar\omega_c$, where the cyclotron frequency ω_c is given by eH/m^*c. The Dingle reduction factor R_D, which describes the effect of the LL broadening due to the finite scattering time τ of the conduction carrier, is

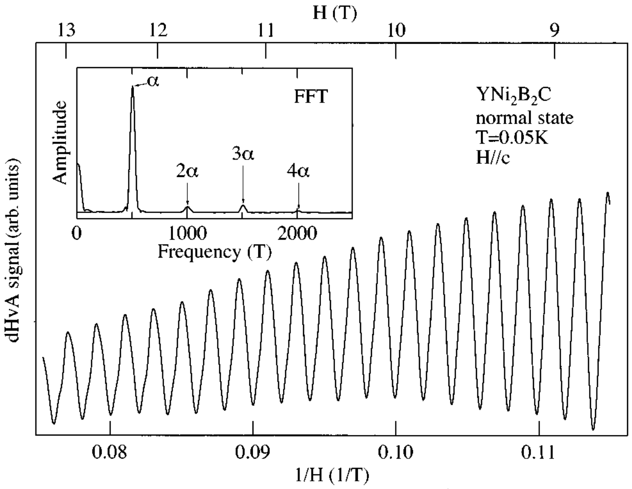

FIG. 1. dHvA oscillations in the normal state and Fourier spectrum (inset).

given by $R_D = \exp(-2\pi\Gamma/\hbar\omega_c)$. Here Γ is a measure of the level broadening defined as $\hbar/2\tau$. In normal metals Γ is dominated by the disorder or impurity scattering and hence is magnetic-field independent.

Figure 1 shows the dHvA oscillation in the N-state measured at 0.05 K. The apparent decrease in the oscillation amplitude with increasing H is due to decrease in the Bessel factor. The α frequency is seen at 504 T in the Fourier spectrum together with its harmonics (Fig. 1 inset). The fact that the second harmonic is smaller than the third one is probably ascribed to the spin-splitting factor.[23] The cyclotron effective mass m^* of α for $H \| c$ was determined from the T dependence of the amplitude between 0.05 and 2 K, and to be 0.35 $(\pm 0.03) m_0$, m_0 being the free-electron mass.

Figure 2(a) shows the dHvA oscillation at 0.05 K in the field range where the strong peak effect (PE) is observed. While the oscillations are somewhat unclear in the raw data because of the large background due to the PE, they clearly manifest themselves after substraction of the background and it is found that the oscillation exhibits a node at about 6.2 T. Figure 2(b) shows the dHvA oscillation at lower fields. The oscillation persists down to a surprisingly low field of 2 T $(\sim 0.23 H_{c2})$. The Fourier spectrum shows a sharp peak corresponding to the α frequency [Fig. 2(b) inset]. The T dependence of the oscillation amplitude in the field range from 3.55 to 4.76 T was examined between 0.05 and 2.0 K and confirmed to follow the same factor R_T as the N state. The cyclotron effective mass of α in the V state was determined to be 0.347 (± 0.004) m_0, i.e., the same as that in the N state.

Several field sweeps were made to cover the wide field range from 14 to 2 T, and the data were digitally filtered to eliminate the harmonics. By plotting the peak number against $1/H$, we have confirmed that the dHvA oscillation continues from the N state to the V state without phase shift and that the frequency is constant at 502 T (within an experimental error of about 1%), which is consistent with the Fourier spectra shown in Figs. 1 and 2(b). After correcting the oscillation amplitude for the Bessel factor, we examined its field dependence. Figure 3 shows the reduced amplitude $A/H^{1/2}R_T$ on a logarithmic scale against $1/H$. In the N state, the logarithm of the reduced amplitude varies linearly with

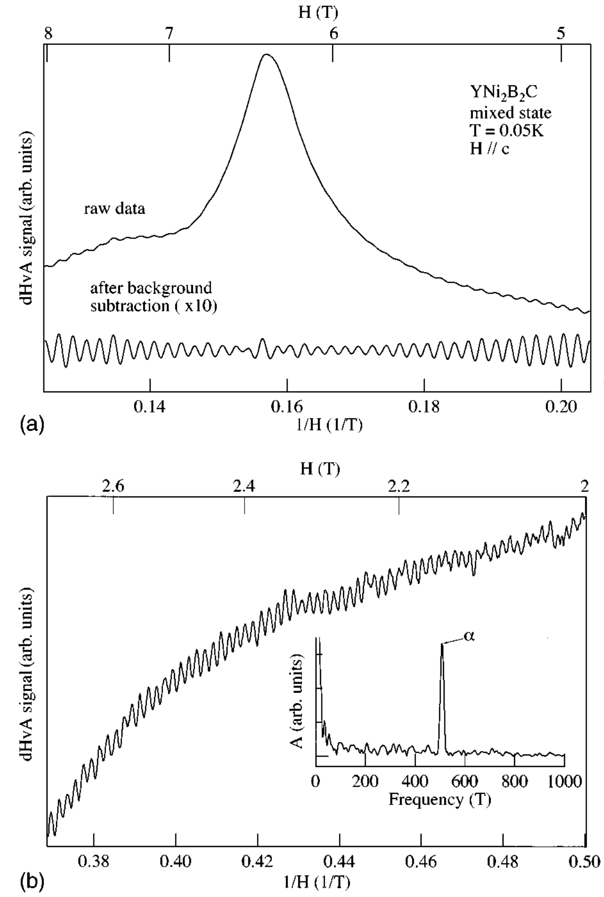

FIG. 2. (a) dHvA oscillations in the peak effect region. (b) dHvA oscillations at the lowest fields down to 2 T and Fourier spectrum (inset).

$1/H$ as is expected from R_D with a constant Γ, which is determined to be 0.53 meV. The amplitude is strongly suppressed in the PE region immediately below H_{c2} and the maximum reduction amounts to about 90% at around 6.2 T. However, it recovers at lower fields and remains as large as about 30–40% of that extrapolated from the N state.

Before comparing the observed damping of the amplitude with theoretical predictions, it is necessary to consider spatial

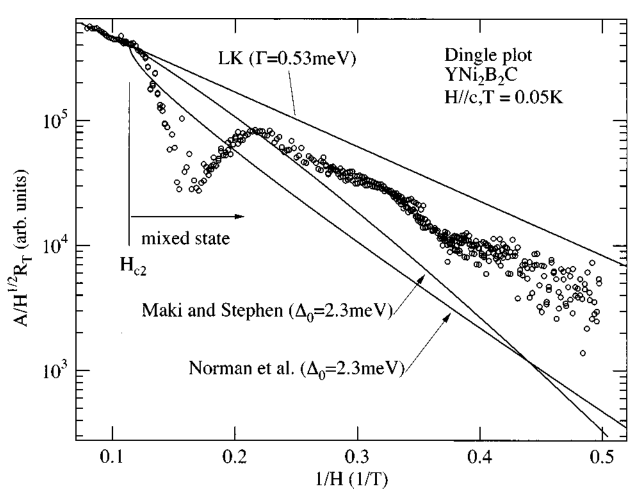

FIG. 3. Reduced amplitude vs inverse field $1/H$ (so-called Dingle plot).

variation of the magnetic field inside a sample, which may reduce the oscillation amplitude. The magnetic field whose variation is to be considered here is not the microscopic local field varying over the vortex spacing but its average over the cyclotron radius. Since even at 2 T the cyclotron radius (407 nm) is much larger than the vortex spacing (34.6 nm), the average field in a pin-free sample is nearly completely homogeneous. Therefore the amplitude reduction occurs only when pinning causes a macroscopic field variation in a sample. Two mechanisms must be considered: phase smearing of the dHvA oscillation due to the inhomogeneous field and shielding of the modulation field. Hirata *et al.* carried out detailed magnetization measurements of a single crystal cut from the same ingot as the present sample and found prominent hysteresis in the PE region, which is an indication of strong pinning.[24] We estimated numerically the amplitude reduction due to both mechanisms using their magnetization data and concluded that the observed amplitude reduction of 90% in the PE region is mostly explained by these two mechanisms arising from the strong pinning. On the other hand, the magnetization data show that there extends a wide reversible region between the PE region and the lowest-field irreversible region near H_{c1}.[24] Our ac susceptibility data also show that both real and imaginary parts are relatively small in the field region from 2 T to about 4 T. Both facts indicate that the pinning force is relatively weak in this field region. Therefore, it is worthwhile comparing the low-field data with theoretical predictions of the amplitude damping in the *V* state.

In the *V* state the SC gap modifies the LL structure and hence the dHvA oscillation. In the early works of Maki[11] and Stephen,[12] they examined the dHvA effect in the *V* state neglecting the detailed structure of the vortex lattice and based on an approximate quasiparticle Green's function. On the other hand, recently Dukan and Tešanović[16] and Norman *et al.*[17] have considered the quasiparticle band structure in the magnetic Brillouin zone due to the vortex lattice. Both approaches lead to the conclusion that the superconductivity brings about the extra damping of the oscillation amplitude without modifying the dHvA frequency.

In the theories of Maki, Stephen, and Norman *et al.*, the extra damping may conveniently be expressed as $\exp(-2\pi\Gamma_{\rm ex}/\hbar\omega_c)$ by introducing a magnetic-field-dependent level broadening $\Gamma_{\rm ex}$ due to the SC gap. Maki[11] and Stephen[12] estimate the level broadening $\Gamma_{\rm ex}$ as

$$\Gamma_{\rm ex}=\frac{\sqrt{\pi}}{2}\,\frac{\Delta^2}{\sqrt{\varepsilon_F\hbar\omega_c}}, \tag{2}$$

while, based on numerical calculations for a two-dimensional model system, Norman *et al.*[17] propose a different expression:

$$\Gamma_{\rm ex}=0.6\Delta\left(\frac{\varepsilon_F}{\hbar\omega_c}\right)^{-1/4}. \tag{3}$$

Here Δ is the average SC gap in a magnetic field and can be estimated from the zero-field SC gap Δ_0 using the standard BCS equation

$$\Delta^2=\Delta_0{}^2\left(1-\frac{H}{H_{c2}}\right). \tag{4}$$

In the cases of V_3Si (Ref. 5) and Nb_3Sn,[6] the extra damping in the *V* state is well accounted for by using Eq. (2) together with the thermodynamically obtained value of the SC gap. However, the extra damping in $NbSe_2$ is two or three times smaller than theoretically expected.[3]

Dukan and Tešanović emphasize the existence of the ''gapless'' region in the magnetic Brillouin zone where the SC gap is zero or relatively small compared with the temperature or disorder broadening.[16] The contribution A^G of this gapless region to the dHvA oscillation amplitude in the *V* state is given by $A^G=GA$, where A is the same as the oscillation amplitude in the *N* state except that the level broadening Γ in the *N* state must be replaced with the self-consistent level broadening Γ^* in the *V* state, which is calculated as $\Gamma^*=\sqrt{\Gamma\Delta/2}$. The coefficient G is the fraction of the gapless region and is given by $G=2[C\max(T/\Delta,\Gamma/\Delta)]^2$, C being a parameter of order of unity. The contribution of the rest of the FS, the ''gapped'' region, is usually negligibly small.

The zero-field SC gap of YNi_2B_2C has been reported to be 2.3 meV from tunneling measurements by Ekino *et al.*[25] and this value is consistent with previous specific-heat measurements.[26] By using this value, we have evaluated theoretical damping factors of Maki and Stephen [Eq. (2)], and of Norman *et al.* [Eq. (3)] as shown in Fig. 3. The experimentally observed amplitude is roughly one order of the magnitude larger than the theoretical predictions at the lowest fields. That is, the extra damping is much smaller than that theoretically expected from Δ_0 of 2.3 meV. We also note that the experimental data points in the *V* state go almost parallel to the high-field extrapolation at low fields where the theories predict a much steeper descent. We also tried the Dukan-Tešanović theory. However, even if we keep the coefficient G unity by assuming that the whole FS is gapless, the estimated amplitude is smaller than the observed one because of the larger Γ^*. This conclusion disagrees with Goll *et al.*[10] They have measured the dHvA oscillation in YNi_2B_2C down to 4 T using a torque method and concluded that the field dependence of the oscillation amplitude can be well fitted by the Dukan-Tešanović theory using Δ_0 of 2.5 meV. The discrepancy may be ascribed to the following. First, their Dingle plot in the *N* state shows a strange bend at about 13 T, which is much higher than H_{c2}, and hence their determination of Γ in the *N* state involves some ambiguity. Second, we have observed that the oscillation amplitude recovers at low fields after the strong suppression due to the PE. It is possible that the oscillation amplitude in the sample of Goll *et al.* recovers below the lowest field of their measurements.

The fact that the experimentally observed extra damping is much smaller than the theoretical predictions seems to indicate that the SC gap on this particular FS, α, is much smaller than the SC gap on other parts of the FS. If we assume Δ_0 of the α surface is 2.3 meV, the average SC gap Δ is already larger than the LL spacing at about 5 T and becomes about three times larger at 2 T. An observation of the dHvA effect at fields where the SC gap overwhelms the

LL spacing seems unlikely. This intuitive argument is in line with a recent theoretical study by Norman and MacDonald.[19] They have carried out a numerical study on the dHvA oscillation in the *V* state, especially concentrating on the crossover regime, a field range where the SC gap becomes comparable to the LL spacing. They have concluded that no clear dHvA oscillation survives in this regime but that the field variation of the magnetization is aperiodic. Note that our conclusion above does not conflict with the results of the tunneling spectroscopy, nor the specific-heat measurements, which determine a ''density-of-states weighted'' average SC gap over all the pieces of the FS. Since the α surface is very small, enclosing only 0.3% of the first Brillouin zone, and contributes little to the density of states, it would hardly influence the average SC gap.

In summary, we have observed the dHvA oscillation in the *V* state of YNi_2B_2C down to 2T. The dHvA oscillation continues from the *N* state to the *V* state without phase shift. The frequency and the cyclotron effective mass are confirmed to be the same in both states. The oscillation amplitude is largely suppressed in the PE region due to the strong pinning but recovers at lower fields. The observed extra damping at the lowest fields is much weaker than the theoretical estimations based on the thermodynamic value of the zero-field SC gap. Accordingly, we have argued that the SC gap on the α FS is much smaller than the SC gap on other parts of the FS.

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