Quasiparticles in the Vortex State of V_3Si

R. Corcoran, N. Harrison, S. M. Hayden, P. Meeson, M. Springford, and P. J. van der Wel
H. H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol, BS8 1TL, United Kingdom
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Low-energy quasiparticle excitations in the vortex state of the superconductor V_3Si have been investigated using the de Haas–van Alphen effect. Quantum oscillations persist to surprisingly low values of $B_0/B_{c2} \sim 0.6$ and $T/T_c \sim 0.001$. The superconducting state introduces a field-dependent quasiparticle damping which has a value $\hbar\tau^{-1} \approx 0.25\Delta$ at the lowest fields investigated, considerably less than the superconducting gap Δ. Quantum oscillations are attributed to the presence of a gapless excitation spectrum and may be a universal characteristic of superconductors in the vortex state.

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The nature of the electronic excitations in the vortex state remains a fundamental problem in superconductivity [1]. The existence of low-energy excitations is supported by the observation of a field-dependent linear contribution $[C = \gamma(B_0)T]$ to the low-temperature specific heat [2], and by scanning tunneling microscopy measurements which reveal the presence of low-energy states $(E < 2\Delta)$ associated with the vortex cores [3]. However, measurements of Landau quantum oscillatory phenomena, such as the de Haas–van Alphen (dHvA) effect, provide, perhaps, the most direct probe of quasiparticle excitations in metals. It is nearly 20 years since the first observation by Graebner and Robbins [4], who reported both dHvA and magnetothermal oscillations in the layer compound 2H-$NbSe_2$ at magnetic fields below B_{c2}. The influence of Landau level quantization on the properties of superconductors has commanded much interest recently [5–11]. This has, to a large extent, been motivated by the prospect of observing the dHvA effect in the vortex state of strong type-II superconductors, and hence, in principle, of probing rather directly the magnitude and symmetry of the order parameter. Furthermore, dHvA oscillations have been reported in the $A15$ superconductor V_3Si [12] and in the high temperature superconductor $YBa_2Cu_3O_{7-\delta}$ [13–15].

We report here the unambiguous (high signal to noise) observation of the dHvA effect in the vortex state of V_3Si ($\lambda = 106$ nm, $\xi = 6.3$ nm, $\kappa = 17$ [16]). Results obtained by two experimental techniques on several crystals are internally consistent, but disagree with previously reported data [12]. We find that quantum oscillations persist deep into the superconducting state, at least to fields of $\sim 0.6B_{c2}$ and to temperatures of $\sim 0.001T_c$, although with an additional damping of the fermion quasiparticles compared to the normal state. In contrast, recent measurements [17] on 2H-$NbSe_2$ ($\lambda_{ab} \approx 250$ nm, $\xi_a \approx 8$ nm, $\kappa = 31$ [18]) also show oscillations deep into the superconducting state, down to fields of $\sim 0.3B_{c2}$ and to temperatures of $\sim 0.003T_c$, but with little additional damping in the vortex state. We attribute the origin of the quantum oscillations to the existence of a gapless quasiparticle excitation spectrum for wave vectors in planes normal to the applied magnetic field.

Single crystals of V_3Si were confirmed by x-ray analysis to be single phase and, from resistivity measurements, to have a $R_{RRR} = 47$ (extrapolated to $T = 0$) and $T_c = 17$ K. High field experiments in V_3Si were performed using a pulsed magnet system described elsewhere [19], with the sample temperature in the range 1.3–2.2 K. By employing magnetic fields extending to ~ 30 T, the dHvA effect could be investigated both above and below B_{c2}, which was at 18.5 T in these samples. The effects of eddy current heating of the samples in the rapidly changing magnetic fields have been extensively studied by us, but were effectively eliminated in the present experiments by using crystals of submillimeter dimensions. To make more sensitive measurements in the vortex state, a second experimental technique, using the field modulation method at low frequency (5 Hz), was employed in a dilution refrigerator, at temperatures down to 20 mK and magnetic fields up to 13.5 T.

The dHvA effect consists of an oscillatory variation of the magnetization $\tilde{\mathbf{M}}$ which is periodic in the inverse applied magnetic field $\mathbf{B}_0^{-1}$, where $\mathbf{B}_0 = \mu_0\mathbf{H}$. The frequency and amplitude of the oscillations provide information about the low-energy quasiparticles. In the standard Lifshitz-Kosevich theory [20], each extremal cross-sectional area A of the Fermi surface in the plane normal to the applied field $\mathbf{B}_0$ gives a fundamental oscillatory component of $\tilde{\mathbf{M}}$ with frequency $F = \hbar A/2\pi e$ given by

$$\tilde{\mathbf{M}} = a(B,T)\sin\left(\frac{2\pi F}{B_0} + \phi\right)$$
$$\propto B_0^{-1/2}\frac{T}{\sinh X}\sin\left(\frac{2\pi F}{B_0} + \phi\right)\cos\left(\frac{\pi g m^*}{2m}\right)$$
$$\times\exp\left(-\frac{\pi}{\omega_c\tau_0}\right), \qquad (1)$$

where $X = 2\pi^2 k_B T/\hbar\omega_c$, ω_c is the cyclotron frequency eB_0/m^*, and m^* is the appropriately averaged effective mass associated with the orbit around area A. Experimental records of the dHvA effect in V_3Si are shown in

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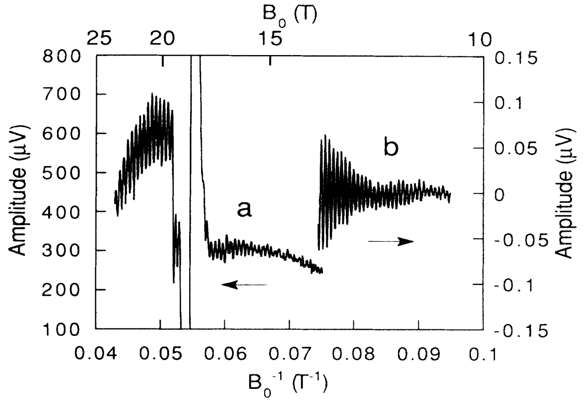

FIG. 1. dHvA oscillations in V_3Si, for the field along a direction 10° from [001], both above and below the critical field, $B_{c2}=18.5$ T. Trace (a) was obtained in a pulsed field experiment, at $T=1.3$ K, and shows an overloading of the detection system occurring close to B_{c2}. Trace (b) was obtained by the low frequency (5 Hz) field modulation method, at $T=20$ mK. The left- and right-hand scales refer to the signal voltages at the pickup coils in (a) and (b), respectively.

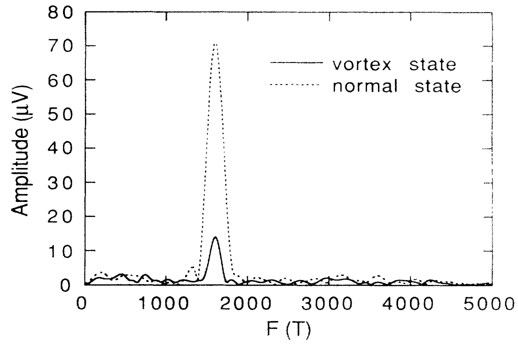

FIG. 2. Fourier spectrum of dHvA effect oscillations shown in Fig. 1(a) in V_3Si above (dotted line) and below (solid line) B_{c2} (18.5 T). The spectrum reveals a single frequency constant to within 0.1% above and below B_{c2}. Other minor features in the spectrum are irreproducible and are attributed to noise.

Fig. 1, in which quantum oscillations are seen in (a) from pulsed field measurements both above and below the upper critical field and, in (b), from field modulation experiments persisting to fields as low as ~ 10.5 T (i.e., $B_0/B_{c2}=0.57$). The disturbed region for magnetic measurements between 17.9 and 18.5 T is thought to be related to the creation or destruction of the flux lattice, and the step in the rate of change of magnetization in Fig. 1 at 19.2 T is of unknown origin. Spectral analysis, shown in Fig. 2, reveals the presence of a single prominent dHvA frequency. For $\mathbf{B}_0$ parallel to [001], $F=1570$ T, corresponding to an orbit with an average Fermi wave vector $k_F=2.1$ nm^{-1} and cyclotron radius $r_c=130$ nm. This frequency is unchanged to within 0.1% between the normal and vortex states. The results are closely reproducible in different crystals.

Given that band structure calculations and positron annihilation experiments [21] indicate that V_3Si has a complicated Fermi surface with several quasicylindrical features parallel to [001], it is surprising that we observe only a single dHvA frequency for $\mathbf{B}_0$ parallel to this direction, even in the normal state. We note, however, that calculations have only been performed for the cubic phase of V_3Si, above the martensitic phase transition (cubic to tetragonal) which occurs at $T\sim 21$ K. We have additionally performed angle-resolved measurements up to $\pm 35°$ from [001] which show that the frequency $F=1570$ T derives from a maximum extremal orbit symmetrical about [001]. In contrast, Mueller *et al.* [12] have reported observing two frequencies of 1490 T and 1980 T at this orientation.

The amplitude $a(T,B_0)$ of the quantum oscillations in Fig. 1 varies with temperature as $a(T)\propto T\sinh X$, in both the normal and superconducting regimes in accord with Eq. (1). From measurements in the temperature range $1.3\ \text{K}<T<2.2$ K, we find effective masses of $(1.6\pm 0.1)m_e$ and $(1.7\pm 0.3)m_e$ for $B_0=21.0\ \text{T}>B_{c2}$ and $B=16.0\ \text{T}<B_{c2}$, respectively. Quantum oscillations originate from the presence of quasiparticle excitations with the same effective mass, to within the experimental error, in the normal and superconducting regimes. The (Dingle) factor $\exp(-\pi/\omega_c\tau_0)$ in Eq. (1) arises from the effect of broadening of the Landau levels due, for example, to scattering by impurities. We can estimate this broadening from a plot of the measured $\ln[a\sinh(X)\times B_0^{1/2}T^{-1}]$ against B_0^{-1}, as shown in Fig. 3. The linear variation with B_0^{-1} for $B_0>B_{c2}$ corresponds to a scattering rate or broadening $\tau_0^{-1}=1.1\times 10^{12}$ s^{-1}. On passing

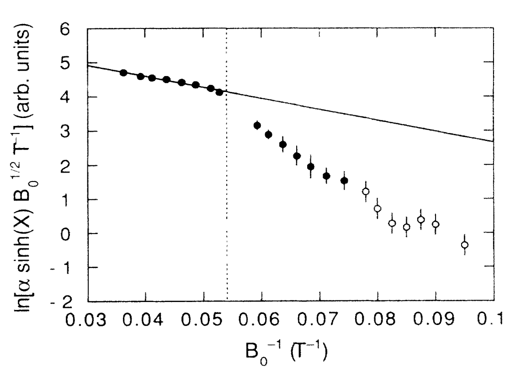

FIG. 3. Field dependence of $\ln[a\sinh(X)B_0^{1/2}T^{-1}]$ in V_3Si (sometimes referred to as a Dingle plot) showing the onset of an additional attenuation on passing from the normal to the superconducting state at $B_{c2}=18.5$ T (dotted line). The scattering (Dingle) temperature in the normal state is 1.6 K. Solid circles refer to the pulsed field experiments and open circles to the field modulation technique in a quasistatic field. Errors associated with the latter arise mainly from the need to combine the results of both experiments.

into the vortex state, an additional attenuation of the dHvA signal is observed relative to an extrapolation of Eq. (1) into the vortex state, which is ~ 2 at 17.4 T increasing to ~ 10 at 14.3 T, and is not approximately constant below B_{c2} as claimed by Mueller *et al.* [12]. The additional attenuation evident in Fig. 3 may be expressed as a field-dependent amplitude reduction factor, $R_s = \exp(-\pi/\omega_c \tau_s)$, where $\tau_s^{-1}(B_0)$ is an additional effective scattering rate experienced by the fermion quasiparticles in the superconducting state. Figure 4 shows this scattering rate as a function of the reduced magnetic field, B_0/B_{c2}, for both V_3Si and, from experiments, on 2H-$NbSe_2$ [17]. Over the field range studied, τ_s^{-1} is seen to be greater in V_3Si than in 2H-$NbSe_2$ by an order of magnitude.

The persistence of quantum oscillations into the mixed state could, in principle, be due to a small portion of the sample remaining normal. However, heat capacity measurements on the sample show a sharp superconducting anomaly at T_c of width $\Delta T = 0.1$ K and an extrapolated linear intercept $\gamma = C/T$ ($T \to 0$) of less than 0.5% of the normal state value. These values confirm that our sample is fully transformed.

In discussing the amplitude of quantum oscillations in the vortex state, an important consideration is the extent to which the inhomogeneous field induced by the spatially varying order parameter produces broadening of the Landau levels. Under the experimental conditions (e.g., $B_0 = 10.5$ T), $r_c = 130$ nm and the separation of the flux lines $a = 10$ nm. An estimate of the Landau level broadening [22] is $\tau^{-1} \approx v_F \delta k_F$, where δk_F is variation in radius of orbits cutting the same flux and v_F is the Fermi velocity. An upper bound for the variation in area δA of orbits cutting the same flux is $B_0 \delta A = B_0 2\pi r_c \delta r_c \approx \delta B 2 r_c a$, where δB is the extreme variation of the local field magnetic field $\mathbf{B}(\mathbf{r})$ in the sample due to the flux lattice. Thus $\delta k_F = \delta r_c (e B_0/\hbar) \approx a e \delta B/\pi\hbar$. Using the estimate [23] $\delta B \sim (B_{c2} - B_0)/\kappa^2$ and $v_F = (2\hbar e F)^{1/2}/m^* = 1.6\times 10^5$ m s^{-1}, we find, for $B_0 = 10.5$ T, $\tau^{-1} \approx 2\times 10^{10}$ s^{-1}. We conclude that damping arising from the inhomogeneous **B** field is unimportant compared with the observed additional damping. This conclusion differs from that of Mueller *et al.* [12].

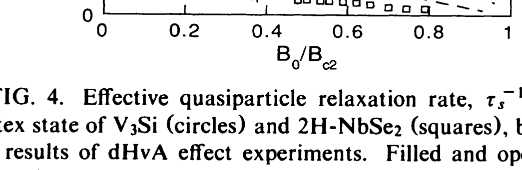

FIG. 4. Effective quasiparticle relaxation rate, τ_s^{-1}, in the vortex state of V_3Si (circles) and 2H-$NbSe_2$ (squares), based on the results of dHvA effect experiments. Filled and open symbols refer to pulsed field and field modulation experiments, respectively. The theoretical variation of τ_s^{-1}, based on Eqs. (2) and (3) in the text, is shown dotted for V_3Si [$\Delta(0)/\hbar = 2.6$ meV/$\hbar = 4.0\times 10^{12}$ s^{-1}] and dashed for 2H-$NbSe_2$ [$\Delta(0)/\hbar = 1.1$ meV/$\hbar = 1.7\times 10^{12}$ s^{-1}].

It is interesting to compare our results with calculations of the effect of superconductivity on the quasiparticles close to B_{c2}. In an extreme type-II superconductor, the resulting vortex lattice consists of highly overlapping flux tubes with an almost uniform magnetic field (see above). Within certain approximations [24], it is found that the spatial variation of the order parameter $\Delta(\mathbf{r})$ causes the quasiparticle excitation spectrum to vary from BCS-like to "gapless' as the quasiparticle momentum varies from being parallel to being perpendicular to the magnetic field. It is precisely the perpendicular momenta of quasiparticles that are probed in a dHvA experiment. Of the several recent theories relating to quantum oscillations in the vortex state, those by Maki [6] and Wasserman and Springford [10] are appropriate to the case of a fully three-dimensional superconductor such as V_3Si. Applicable, in principle, only for fields close to B_{c2}, both theories find that the main effect of superconductivity is to introduce an additional term into the dHvA amplitude which can be expressed as an additional *field-dependent* relaxation rate,

$$\tau_s^{-1} = \Delta^2 2\pi^{1/2} \Lambda/\hbar v_F , \tag{2}$$

in which Δ is the spatially averaged order parameter ($\Delta^2 = \overline{|\Delta|^2}$) appropriate to the particular extremal orbit and $\Lambda = (2\hbar e B_0)^{-1/2}$. Assuming that Δ evolves according to the expression [6]

$$\Delta^2 = \Delta^2(0)(1 - B_0/B_{c2}) , \tag{3}$$

the relaxation scattering rates are also plotted in Fig. 4. Given that the theory as expressed by Eqs. (2) and (3) is only expected to apply close to B_{c2}, the result is surprisingly good, and it reflects the difference between the two materials approximately correctly. This theory also predicts that the effective mass of the quasiparticle states probed by dHvA will be essentially unchanged on passing through B_{c2}, in agreement with our observations.

In summary, we have observed de Haas–van Alphen oscillations deep in the mixed state of V_3Si. The existence of quantum oscillations in the mixed state is thus not confined to strongly anisotropic systems such as 2H-$NbSe_2$. An additional suppression of the dHvA oscillations is observed in the mixed state, which cannot be explained by the effect of the inhomogeneous **B** field inside the superconductor associated with the spatially varying order parameter in the vortex state. We attribute the additional suppression to an effective scattering of quasiparticles in the superconductor due to the direct influence of the (orbitally averaged) order parameter. We note that the largest measured values of $\hbar\tau^{-1}$ (0.63 meV for V_3Si and 0.06 meV for 2H-$NbSe_2$) are considerably less than the gap parameters [$\Delta(0) = 2.6$ meV for V_3Si [25] and 1.1 meV for 2H-$NbSe_2$ [26]]. Finally, we note that the results in Fig. 4 refer to a particular region (extremal orbit) on the Fermi surface and so illustrate, in principle, how such experiments, made for a range of orientations, could be used to obtain information on the magnitude and symmetry of the order parameter rather directly. Such experimental work is in progress, but it is clear that we require a deeper theoretical understanding of quantum oscillations in the vortex state in the limit far from B_{c2} before they can be interpreted in detail.

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