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Upper critical fields and de Haas–van Alphen oscillations in UNi_2Al_3

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Abstract

The upper critical field B_{c2} in UNi_2Al_3 is determined as a function of temperature for $B \parallel a$ and c from ac susceptibility measurements on a single crystal. $B_{c2}(0)$ is estimated at 0.93 ($\parallel a$) and 0.76 T ($\parallel c$). It is argued that B_{c2} is dominated by orbital effects. De Haas–van Alphen oscillations with $F = 3.29$ T and $m^* = 8.3 \pm 0.1\ m_e$ (m_e = free electron mass) are observed for $B \parallel c$. It is shown that the observed orbit most likely involves the magnetic breakdown. The orbit is compared to the UPd_2Al_3 β orbit.

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UNi_2Al_3 and UPd_2Al_3 have the same crystal structure and are 'isoelectronic' in the sense that Ni and Pd lie in the same column of the periodic table. Their magnetic and superconducting properties are, however, fairly contrasting [1]. UPd_2Al_3 orders into a simple antiferromagnetic structure with a substantial magnetic moment $\sim 0.8\,\mu_B$/U below $T_N = 14.3$ K and then exhibits a spin-singlet superconductivity below $T_c \sim 2$ K. UNi_2Al_3 enters an incommensurate SDW state with a much reduced magnetic moment amplitude $\sim 0.2\,\mu_B$/U below $T_N = 4.5$ K and becomes superconducting below $T_c \sim 1$ K, where recent NMR Knight shift measurements strongly suggest that spin-triplet paring takes place [2]. Comparative studies of the electronic structures in the two compounds may help elucidate where these differences come from.

We here report AC susceptibility (χ_{AC}) and de Haas–van Alphen (dHvA) oscillation measurements at temperatures T down to 0.03 K and in magnetic fields B up to 20 T performed on a high-quality (RRR ~40) single crystal of UNi_2Al_3 grown by the Czochralski method [3].

Fig. 1 shows the upper critical fields B_{c2} for $B \parallel a$ and c determined from χ'' vs. B curves at different temperatures. The present critical fields are much less anisotropic than previously determined from resistive transitions in single crystals [3]. The extrapolated $B_{c2}(0)$'s are 0.93 and 0.76 T for $B \parallel a$ and c, respectively. From these numbers, we may estimate the coherence lengths parallel and perpendicular the c-axis to be $\xi_{//} = 17$ nm and $\xi_{\perp} = 21$ nm. Linear fits to data near T_c (dotted lines) give $T_c = 0.89$ K and $-dB_{c2}/dT\big|_{T_c} = 1.4$ T/K for $B \parallel a$ and $T_c = 0.88$ K and $-dB_{c2}/dT\big|_{T_c} = 1.1$ T/K for $B \parallel c$. The orbital critical fields $B^*_{c2} = -0.727\ \left(dB_{c2}/dT\big|_{T_c}\right)\ T_c$ (clean limit) [4] are estimated to be 0.92 T ($\parallel a$) and 0.73 T ($\parallel c$), while the paramagnetic critical field $B_{po} = 1.84\ T_c$ [Tesla] [5] is 1.6 T.

The near equality between B^*_{c2} and $B_{c2}(0)$ indicates that the upper critical field in UNi_2Al_3 is dominated by the orbital effects. This conclusion is consistent with Ref. [3]. However, it conflicts with Ref. [6], which reported that B_{c2} vs. T curves measured on epitaxial thin films exhibited pronounced convex curvature near T_c and a steep slope $-dB_{c2}/dT\big|_{T_c} > 5$ K and concluded that the paramagnetic pair-breaking effects were not negligible in UNi_2Al_3.

Fig. 2(a) shows dHvA oscillations observed for $B \parallel c$. The Fourier transform (inset) shows a single peak at $F = 3.29$ T, which corresponds to the orbit area A of

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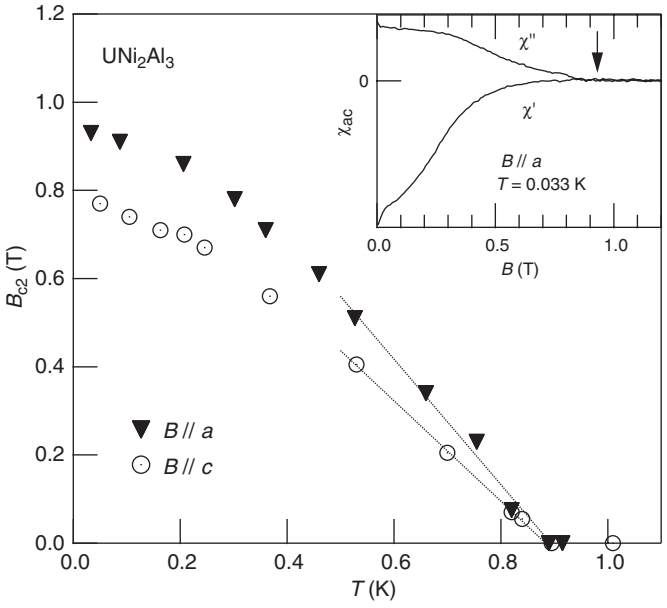

Fig. 1. Upper critical fields B_{c2} of UNi_2Al_3 as functions of temperature T for the magnetic field $B \parallel a$ and c, determined from the onset of χ'' signal in ac susceptibility χ_{AC} vs. B measurements at different temperatures (inset). The dotted lines are linear fits to data above $T = 0.5$ K.

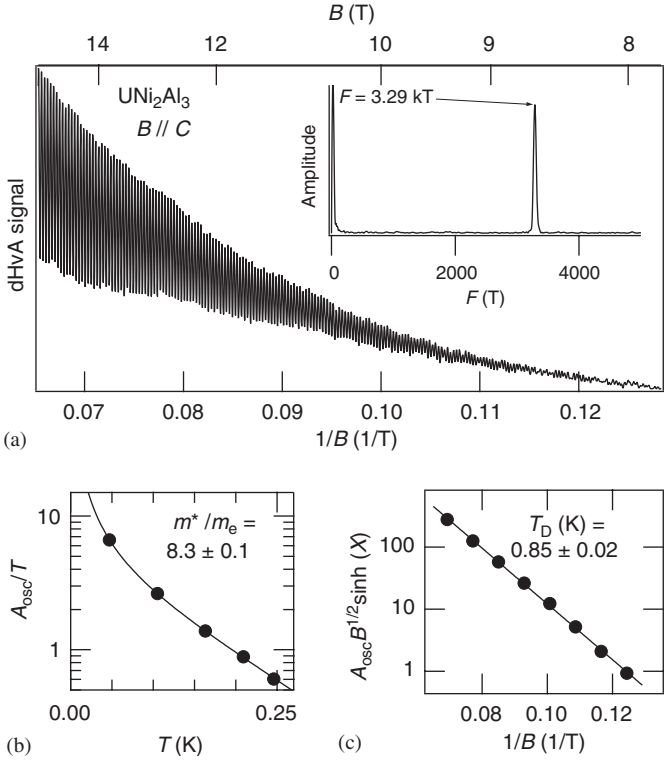

Fig. 2. (a) dHvA oscillations in UNi_2Al_3 measured with the magnetic field B parallel to the c-axis. The inset shows the corresponding Fourier spectrum. (b) and (c) Temperature and magnetic-field dependences of the oscillation amplitude A_{osc}. The solid curves are fits to the Lifshitz–Kosevich formulas, which give the estimates of the effective mass m^* and Dingle temperature T_D. $X = -K(m^*/m_e)T/B$ with $K = 14.69$ T/K.

$31.4\,\mathrm{nm}^{-1}$. The effective mass m^* and Dingle temperature T_D associated with the orbit are estimated from the temperature and magnetic-field dependences of the oscillation amplitude to be $m^* = 8.3 \pm 0.1\ m_e$ (m_e = free electron mass) and $T_D = 0.85 \pm 0.02$ K, respectively (Figs. 2(b) and (c)). Using the formulas, $A = \pi k_F^2$, $\hbar k_F = m^* v_F$, and $\tau = /2\pi k_B T_D$, where k_B is the Boltzmann constant, τ relaxation time of electrons, and the other symbols as usual, we may calculate the electron mean free path $l = \tau v_F$ at 63 nm, indicating that the sample is a clean superconductor ($l > \xi$).

The orbit area A is 18.7% of the cross section of the paramagnetic Brillouin zone (BZ). The magnetic-field-angle dependence of the frequency (not shown) indicates that the orbit is on an approximately cylindrical sheet of the Fermi surface (FS). This orbit in UNi_2Al_3 has a strong resemblance to the β orbit in UPd_2Al_3 [7]. The β orbit occupies 18.6% of the paramagnetic BZ for $B \parallel$ c and is attributed to a nearly cylindrical FS sheet.

We may estimate the Fermi wave vector to be $k_F = 3.16\,\mathrm{nm}^{-1}$, assuming that the orbit is a circle, i.e., $A = \pi k_F^2$. The wave vector characterizing the SDW is $Q_\pm = (1/2 \pm \tau, 0, 1/2)$ with $\tau = 0.11$ [8] and the basal-plane component of $\boldsymbol{Q}_-$ is $q_- = 5.44\,nm^{-1}$. Since $2k_F > q_-$, the approximately cylindrical FS sheet shifted by $\boldsymbol{Q}_-$ most likely intersects the original one and energy gaps open there. It then follows that the present observation of the orbit on the original FS sheet is due to the magnetic breakdown.

In conclusion, we determined B_{c2} in UNi_2Al_3 using a high-quality single crystal. The anisotropy of B_{c2} is much less than previously reported. No influence of the paramagnetic limitation is observed, as opposed to the thin-film data [6]. We observed dHvA oscillations in UNi_2Al_3 for the first time. The observed orbit most likely entails the magnetic breakdown. The orbit seems to correspond to the β orbit in UPd_2Al_3.

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