FERMI SURFACE STUDIES OF THE FERROMAGNETIC SUPERCONDUCTOR UGe_2 UNDER HIGH PRESSURE*

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We report de Haas–van Alphen effect measurements on UGe_2 at pressures P up to ∼18 kbar, which exceeds the critical pressure P_c ∼16 kbar for the suppression of ferromagnetism. Particular attention is given to the complicated pressure dependence of the Fermi surface and effective mass in an intermediate pressure region from ∼11 kbar to P_c.

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UGe_2 is an itinerant-electron ferromagnet with the Curie temperature T_C of 52 K at ambient pressure [1]. The magnetic anisotropy is extremely strong, and the easy axis is the a axis. The Curie temperature T_C decreases with pressure P and vanishes at the critical pressure P_c near 16 kbar [2–6]. Superconductivity is observed in a limited pressure range, ∼10–16 kbar, on the ferromagnetic side of P_c [4–6]. There is another anomaly occurring below T_C in the ferromagnetic state [3,5,6]. Its characteristic temperature T_x also decreases with pressure and vanishes at the pressure P_x near 12–13 kbar. In order to study the pressure dependence of quasiparticle properties, we have

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performed de Haas–van Alphen (dHvA) effect measurements up to ∼18 kbar ($> P_c$), for the magnetic field B along the hard b axis [7] and along the easy a axis [8]. In this paper, we focus on the b-axis results in an intermediate pressure range from just bellow P_x to P_c.

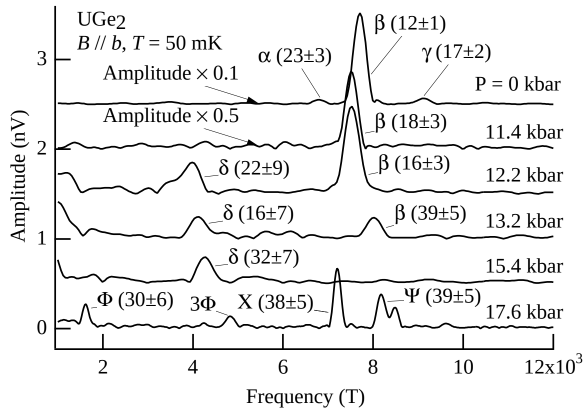

Fig. 1. Fourier spectra of dHvA oscillations in UGe_2 for selected pressures. The dHvA frequencies, or orbits, are labeled by Greek letters. The numbers in the parentheses indicate the effective masses in the unit of the free electron mass. The data windows for the Fourier transformations are $B = 16$–17.75 T for $P = 0$ and 11.4 kbar, 17.8–19.6 T for 12.2, 13.2 and 15.4 kbar, and 15–17.8 T for 17.6 kbar. The experimental signal is the emf in a pickup coil, and hence the unit of the vertical axis is Volts. The spectra are vertically shifted for clarity. Note that the $P = 0$ and 11.4 kbar spectra are scaled by 1/10 and 1/2, respectively.

Figure 1 shows the Fourier spectra of dHvA oscillations at selected pressures for $B \parallel b$. The strongest frequency β at 0 kbar corresponds to an orbit occupying 29 % of the cross-section of the Brillouin zone and is probably ascribed to the majority-spin quasi-two-dimensional Fermi surface (FS) sheet predicted by band-structure calculations [9]. Pressure effects are not very significant below ∼11 kbar: only slight changes in the dHvA frequencies and effective masses are observed. In the intermediate pressure range from ∼11 kbar to P_c, the pressure causes successive changes in quasiparticle properties: (1) The pressure coefficient of the frequency β changes form negative to positive near ∼11 kbar. (2) The oscillation amplitude of β is anomalously reduced. Comparing the amplitudes at $T = 70$ mK and $B = 17$ T, those at 11.4, 12.2 and 13.2 kbar are 1/7, 1/20 and less than 1/40 of that at 0 kbar, respectively. (3) The effective mass of β jumps from $16 \pm 3\ m_e$ at 12.2 kbar to $39 \pm 5\ m_e$ at 13.2 kbar, where m_e is the free electron mass. (4) The new frequency δ suddenly appears at 12.2 kbar. We also mention that the superconductivity is observed in this intermediate pressure regime: the sample exhibits superconductivity at 11.4, 12.2 and 13.2 kbar. As the pressure is further increased from 15.4 to 17.6 kbar, *i.e.*, on entering the paramagnetic phase, the FS abruptly changes. The discontinuous change of the FS is in favor of the view that the ferromagnetic transition is first order at pressures near P_c [5, 7].

In order to interpret the complicated behavior of quasiparticle properties in the intermediate pressure regime, we need to locate P_x. One can determine T_x as a function of P by measuring resistivity or magnetization vs temperature curves at various pressures. Such measurements show $12 < P_x < 13$ [5], $\sim 11.5 < P_x < 12.6$ [6], or $11.8 < P_x < 12.1$ [10] (P_x in the unit of kbar). Since the T_x anomaly can be induced by magnetic fields along the easy a axis at pressures higher than P_x, one can also determine P_x from the pressure where the field-induced T_x anomaly goes to zero field. With this method, we have obtained $12.3 < P_x < 14.0$ for another sample [8]. The errors in the pressure values are $\sim\pm 0.3$ kbar in our case and are probably of similar magnitude in other cases. Considering these data, we seem to have two possibilities in Fig. 1: $11.4 < P_x < 12.2$ and $12.2 < P_x < 13.2$. We here note that the T^2 coefficient of resistivity sharply increases as P_x is crossed [5, 6]. Relating this with the mass jump between 12.2 and 13.2 kbar, we assume that $12.2 < P_x < 13.2$. A further support to this assumption comes from heat capacity data [11]. Although P_x was not determined in those measurements, it can safely be located by identifying the steep increase in the electronic specific heat coefficient γ between 11 and 12 kbar with the increase in the T^2 coefficient. The data indicate that the coefficient γ at pressures just above P_x is about three times larger than that at 0 kbar. This compares favorably with the fact that the mass of β just above P_x, *i.e.*, at 13.2 kbar is about three times larger than that at 0 kbar. With the assumption that $12.2 < P_x < 13.2$, we may attribute the appearance of δ at 12.2 kbar to the pressure-induced modification of a FS sheet that already exists at lower pressures: *i.e.*, the sheet is continuously modified by pressure, and an extremal orbit happens to appear on it at 12.2 kbar. Since the frequency β smoothly varies from 11.4 to 12.2 kbar, the appearance of δ can not be taken as a sign of such a radical change of the electronic structure that a new band crosses the Fermi level to form a new FS pocket. The suppression of dHvA oscillation amplitudes in the intermediate pressure regime remains difficult to explain within the framework of the Lifshitz–Kosevich theory [7].

Finally, we consider two alternative explanations. Firstly, one might argue that β at 12.2 and 13.2 kbar may be the second harmonic of δ. The frequency β is close to twice the frequency δ, and, because of the large error, it seems difficult to exclude the possibility that the mass of β is also twice the mass of δ. However, the comparison of the amplitudes indicates that β can not be the second harmonic of δ. Within the Lifshitz–Kosevich theory, the ratio of the amplitude of the second harmonic to that of the fundamental is given by $2^{-3/2}C\exp(-K\mu^*x/B)\cosh^{-1}(K\mu^*T/B)$, where $K = 14.7$ T/K, $\mu = m^*/m_e$, and x is the Dingle temperature. The factor C depends on the detection method of dHvA oscillations and is 2 for the present case. Note that, since we deal with exchange-split FS's, the spin-splitting factor is irrelevant. The equation shows that the amplitude of a second harmonic can never be larger than $1/\sqrt{2}$ of the fundamental. Secondly, one might assume that the low-pressure and high-pressure ferromagnetic phases may coexist in some pressure interval near P_x. The frequencies β and δ would be attributed to the low- and high-pressure phases, respectively. This assumption is tempting since it could naturally explain the anomalous amplitude reduction of the β oscillation as a result of the reduced volume of the low-pressure phase. With this interpretation, the coexistence region would be expected to range from below 11.4 kbar to above 13.2 kbar, since the anomalous damping of β is already noticed at 11.4 kbar. However, such a wide coexistence region has never been observed in the aforementioned resistivity and magnetization measurements. Especially in the case of magnetization measurements by Tateiwa *et al.* [10] the transition from the low- to high-pressure phases occurs in a narrow pressure range between 11.8 and 12.1 kbar.

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