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Anomalous magnetic torque in UBe_{13}: Evidence for a field-induced magnetic phase transition

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Measurements of the magnetic force and magnetic torque acting upon single-crystal and polycrystal samples of the heavy-fermion superconductor UBe_{13} have been made at temperatures from 60 mK to 30.0 K and in magnetic fields to 23 T using a capacitive magnetometer. The magnetic susceptibility deduced from the magnetic force is in reasonably good agreement with measurements using conventional techniques. We find that a large, anomalous contribution to the magnetic torque (AMT) appears in fields above 3–5 T at low temperature and at temperatures below about 7–12 K in high fields. The AMT coexists with the superconducting state at low temperature. We propose that the AMT reflects the existence of a field-induced magnetic phase transition. The presence of such a phase transition is consistent with specific-heat, thermopower, magnetoresistance, and Hall-effect measurements.

I. INTRODUCTION

The delicate interplay between superconductivity and magnetism is one of the more fascinating aspects of heavy-fermion physics.[1] For most heavy-fermion superconductors the onset of magnetic order (at T_N) precedes the onset of superconductivity (at T_c) as the temperature falls. Such is the case for UPt_3,[2] URu_2Si_2,[3] UNi_2Al_3,[4] and UPd_2Al_3.[5] In $U_{0.97}Th_{0.03}Be_{13}$ the order is reversed,[6] and in $CeCu_2Si_2$, T_N and T_c virtually coincide.[7] Field-induced magnetic phase transitions have also been observed in heavy-fermion superconductors at low temperature,[8] some within the superconducting state itself.[9]

This paper is concerned with the remaining heavy-fermion superconductor, UBe_{13}. Here the situation with regards to magnetic phase transitions is less well defined than in those systems mentioned above. Structure in the magnetostriction of a single-crystal sample has been presented as evidence for an antiferromagnetic phase transition near $T_N = 8.8$ K,[10] well above $T_c \sim 0.9$ K, however, similar measurements on another single crystal did not show such structure.[11] Further, μSR measurements on a polycrystal sample show no signs of magnetic order.[12] On the other hand, a break in the slope of the thermal conductivity with temperature near 9 K of a polycrystal has been interpreted as an increase in the characteristic length of antiferromagnetic correlations[13] (these authors also point out that the μSR data of Ref. 12 is rather sparse near 9 K).

A maximum in the temperature-dependent thermopower of UBe_{13} under high pressures (near 4 K at 67 kbar) has been presented as evidence for pressure-induced magnetic order.[14] The appearance of a second peak in the temperature-dependent specific heat of a polycrystal (below that at T_c) in high magnetic fields (near 150 mK at 6 T) may reflect field-induced magnetic order.[15] Measurements of the field-dependent specific heat of a polycrystal sample reveal a (nearly) temperature-independent phase boundary within the superconducting state near 2 T, extending to at least 0.5 K.[16] Attempts to correlate these results are hampered by the sample-to-sample variations one might expect along with aging effects which result from α decay of the U atoms, aging effects which can be nontrivial.[17] In addition, the behavior of single-crystal samples can be qualitatively different from polycrystal samples [e.g., the upper critical field H_{c2} (T) (Ref. 18)]. One would therefore like reports of new phenomena to include measurements on several samples, both crystalline and polycrystalline.

We have previously reported what appear to be two kinks in H_{c2} (T), of both single-crystal and polycrystal samples of UBe_{13}.[19] In this earlier work we allude to an anomalous magnetic torque (AMT) which correlates with the warmer of the two kinks in H_{c2} (T). In this paper we describe this phenomenon in detail and argue that it is associated with an intrinsic field-induced magnetic phase transition in UBe_{13}. Our proposed magnetic phase coexists with the superconducting state at low temperatures and extends into the normal state up to temperatures of 7–12 K in high fields.

II. EXPERIMENTAL DETAILS

Several samples, both crystalline and polycrystalline, have been studied. Sample No. 1 is a polycrystal sample prepared by arc-melting appropriate quantities of the constituent elements in an argon arc furnace (the details are given elsewhere[20]) and has a superconducting onset temperature of 0.94 K. Sample No. 2 is a polycrystalline sample prepared similarly[21] in another laboratory using different starting materials, with a superconducting onset temperature of 0.97 K. Sample No. 3 is a single crystal, grown from pre-arc-melted UBe_{13} embedded in Al flux as described elsewhere,[22] with a superconducting onset temperature of 0.89 K.

Our choice for thermometry depended upon the tem-

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perature range in which a particular data set was taken: For data taken between 0.06 and 1.3 K, the temperature is determined by a Speer 220 carbon resistor calibrated against the susceptibility of cerium magnesium nitrate and corrected for magnetoresistance.[23] For data from 0.5 to 1.2 K we used the vapor pressure of ^{3}He and from 1.2 to 4.2 K, we used the vapor pressure of ^{4}He. From 4.0 to 30.0 K we used a commercial carbon-glass resistor, with the manufacturers calibration (no correction for magnetoresistance was made, $\Delta T/T < 3\%$ for this particular resistor in fields below 12 T in this temperature range).

The magnetization M, and magnetic susceptibility $\chi = M/H$, are derived from measurements of the magnetic force F and magnetic torque τ acting upon the sample. These measurements are made with a capacitive, cantilever magnetometer, or $C_{\rm MAG}$, described in detail elsewhere.[24] Briefly, the sample is suspended by fine wires over a silvered glass plate forming a capacitor in which the sample itself is one capacitor plate. This assembly is positioned at or near the magnetic center of a normal or superconducting magnet. We model the sample as an oblate spheroid with all of its dimensions of comparable length.[24] If the sample is not at magnetic center it experiences a force proportional to the strength of the field gradient, one can show that, to leading order in χ, $F \propto \chi H^2$. For a nonspherical sample one can show that, to leading order in χ, shape effects result in a torque $\tau \propto \chi^2 H^2$. If the magnetic susceptibility is isotropic and independent of H [as is approximately the case for $\rm UBe_{13}$ to about 24 T at 1 K (Ref. 25)] then one expects $F \propto \tau$ in isothermal sweeps of H. One can also show that both F and τ contribute to the change in capacitance, $\Delta C(T,H) \equiv C(T,H) - C(T,0)$, linearly if the relative change in capacitance is small (i.e., $\Delta C/C \ll 1$):

$$\Delta C = A_F F + A_\tau \tau \; , \tag{1}$$

where A_F and A_τ are constants or slow functions of H and/or T. The force is separated from the torque contribution to ΔC at a particular temperature T by measuring $\Delta C(H)$ at and away from magnetic center (at which only τ contributes to ΔC) and subtracting the two data sets. This technique has been demonstrated on polycrystal samples of $\rm URu_2Si_2$ and $\rm UPt_3$.[24] If the susceptibility is not isotropic (as for many single-crystal samples) then an additional contribution to the torque can arise from a transverse (with respect to H) component of the magnetization $M_\perp$ given by $\tau = M_\perp H$.

In this paper we shall use the term "run" to denote data taken on a particular sample in a particular experimental setup ($C_{\rm MAG}$, magnet, refrigerator, etc.). Generally the $C_{\rm MAG}$ is completely reconstructed (new wires, glue, etc.) when samples are changed or when moving from one experimental station to another. The sample-$C_{\rm MAG}$-magnet combination in a particular run is characterized by specific values of A_F and A_τ from Eq. (1). Data from different runs cannot be compared quantitatively unless the magnetometer has been calibrated for each run in a fashion described elsewhere.[24] However, we have found that data from the different runs described in this paper always agree qualitatively.

III. MAGNETIC FORCE AND TORQUE

The temperature and field dependence of the magnetic susceptibility χ deduced from the magnetic force is in reasonably good agreement with χ as measured with a conventional magnetometer. This agreement is illustrated in Fig. 1, where $C_{\rm MAG}$ data from a run with polycrystal sample No. 1 are compared with data taken on a commercial superconducting quantum interference device (SQUID)-based magnetometer. The SQUID data, shown as solid circles, were taken at 0.5 T. The open circles represent χ derived from the magnetic force as a function of field at fixed temperature, scaled to the SQUID data at 4.2 K. The solid and dashed lines represent χ derived from the magnetic force as a function of temperature at fixed fields of 2.5 and 10.0 T, respectively, scaled to the SQUID data at 4.2 K. [Recall that the magnetic susceptibility of $\rm UBe_{13}$ is approximately independent of field to about 24 T (Ref. 25).] Susceptibilities derived from the magnetic force agree with the SQUID data to better than 5% over the full temperature range (4.2–30.0 K) of this run. The systematic deviation between the SQUID and $C_{\rm MAG}$ data sets at higher temperatures may be related to the temperature dependence of the elastic properties of the copper wire used in the $C_{\rm MAG}$.

We find that the temperature dependence and field dependence of the magnetic torque, contrary to our earlier results on $\rm URu_2Si_2$ and $\rm UPt_3$,[24] do *not* agree with the magnetic susceptibility results summarized above. Measurements of the magnetic torque (from the same run as the force data shown in Fig. 1) are shown in Fig. 2. The

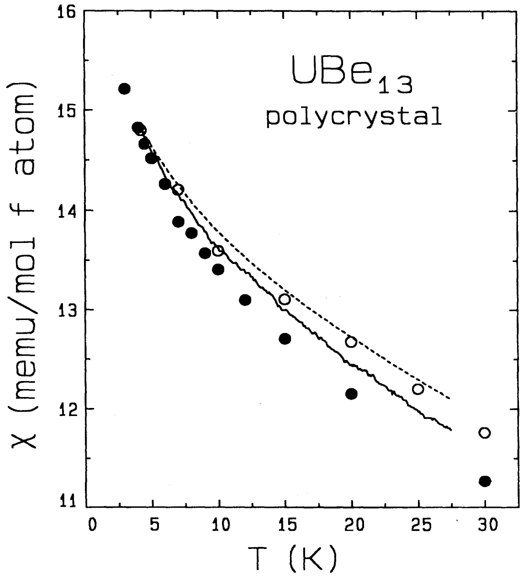

FIG. 1. The magnetic susceptibility χ of $\rm UBe_{13}$ polycrystal sample No. 1. Solid circles are measurements from a commercial SQUID magnetometer. Open circles are measurements deduced from the magnetic force as a function of field at fixed temperature. The solid and dashed lines are measurements deduced from the magnetic force as a function of temperature at fixed fields of 2.5 and 10.0 T, respectively.

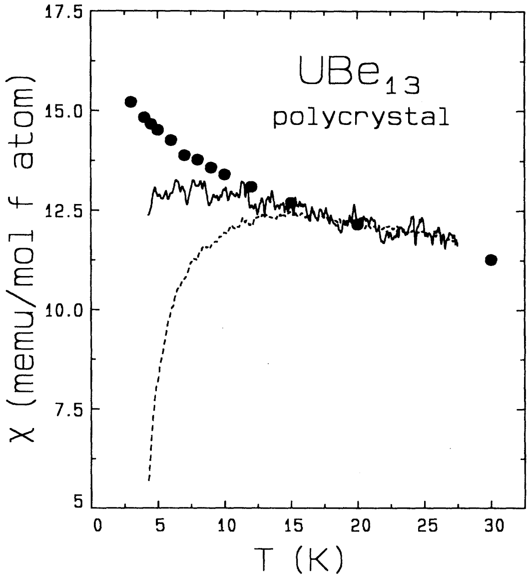

FIG. 2. The magnetic susceptibility χ of UBe$_{13}$ polycrystal sample No. 1. Solid circles are measurements from a commercial SQUID magnetometer. The solid and dashed lines are measurements deduced from the magnetic torque as a function of temperature at fixed fields of 5.0 and 10.0 T, respectively.

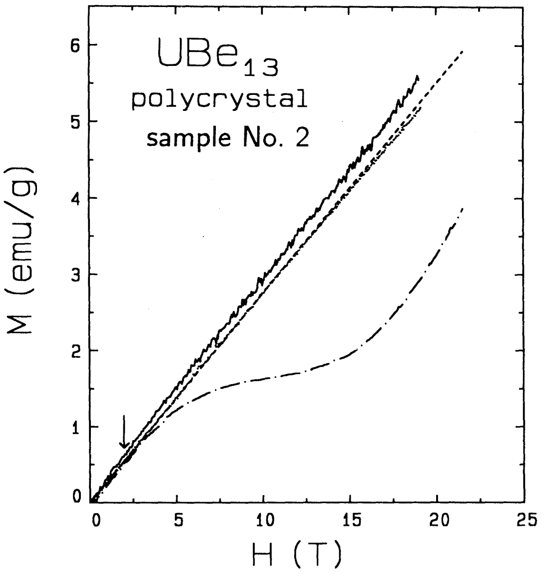

FIG. 3. The magnetization of UBe$_{13}$ polycrystal sample No. 2 as a function of field at fixed temperature. The dotted line and solid line represent vibrating sample magnetometer measurements at 4.2 and 1.3 K, respectively. The dashed line and dash-dot line represent measurements derived from the capacitive magnetometer at 4.5 and 1.4 K, respectively (see text). The large arrow shows the position of a peak in the specific heat (see text).

SQUID data of Fig. 1 are reproduced in Fig. 2 as the solid circles. The susceptibility is derived from the magnetic torque under the assumption that it arises from shape effects as discussed above (i.e., $\tau \sim \chi^2 H^2$). The torque data are scaled to the SQUID data at 20.0 K. The resultant $\chi(T)$ at fixed fields of 5.0 and 10.0 T are shown as solid and dashed lines, respectively. At temperatures above 12 K the agreement between our data and the SQUID data is within the experimental noise (a result partially due to our choice of scaling temperature, and partially to the smaller amplitude of the torque response in this temperature range as discussed below). Below 12 K, however, the high-field data strongly diverges from the SQUID data, a trend which is also apparent (though smaller) in the 5-T data. One might expect such a strong divergence in the capacitance if the two capacitor plates of the magnetometer were almost in contact with each other (i.e., $C \rightarrow \infty$ as $d \rightarrow 0$, since $C \sim 1/d$, where d is the distance between the capacitor plates). However, the maximum change in capacitance for this torque data is nearly 200 times *smaller* than that for the force data shown in Fig. 1. The decrease in magnitude of $\tau(T)$ is strong enough to suggest that τ changes sign with decreasing T, in spite of the fact that $\tau \sim \chi^2 H^2$ for shape effects (see Sec. II). Indeed, as shown below, τ does change sign with decreasing T. This is the onset of the anomalous magnetic torque (AMT).

In Fig. 3 we compare high magnetic field C_{MAG} data containing both force and torque contributions to ΔC with high-field measurements made with a vibrating sample magnetometer (VSM). Both measurements were made on sample No. 2. Recall that, if the magnetic torque on the sample is due to shape effects, then τ as well as F will be proportional to H^2 since χ is independent of field, we therefore expect isothermal measurements of $\Delta C(H)$ to be proportional to H^2 [Eq. (1)]. For this data the C_{MAG} is calibrated by assuming the magnetization as a function of field, $M(H)$ is linear at 4.5 K;[25] the results are scaled to the VSM data at 10 T. The same calibration and scaling are applied to the C_{MAG} data at 1.4 K. In Fig. 3 the dotted line and solid line depict the VSM data at 4.2 and 1.3 K, respectively; the dashed line and dash-dot line represent the C_{MAG} data at 4.5 and 1.4 K, respectively. (The VSM and C_{MAG} data near 4 K are virtually superimposed.) For comparison purposes we consider the data at 15 T: Whereas the VSM data increase by 7% on cooling from 4.2 to 1.3 K, the C_{MAG} data decrease by 53%. The enormous depression of the C_{MAG} data in high field dwarfs the modest increase in the VSM data, an increase consistent with the SQUID data discussed above. Note that there appears to be a minimum field for the onset of this depression. This anomalous behavior is consistent with the strong, high-field depression of τ shown in Fig. 2 (the AMT), overpowering the contribution of F to $\Delta C(H)$.

In Fig. 4(a), we show C_{MAG} data on polycrystal sample No. 1, containing both F and τ contributions, calibrated assuming $M(H)$ to be linear with H at 4.2 K. A depression of $M(H)$, qualitatively similar to the AMT observed for sample No. 2 (see Fig. 3) is observed. The smaller magnitude of the high-field depression may be attributed to any of the following origins: (1) a different ratio A_F/A_τ [see Eq. (1)] for the two runs, (2) different field

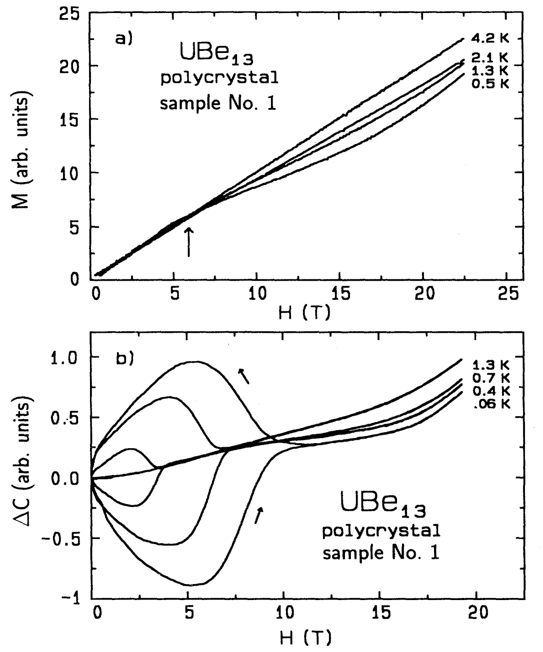

FIG. 4. (a) The magnetization of UBe_{13} polycrystal sample No. 1 as a function of field at several fixed temperatures. The magnetic hysteresis of the superconducting state is not shown. The large arrow shows the position of a kink in the upper critical field (see text). (b) Change in capacitance of UBe_{13} polycrystal sample No. 1 as a function of field at several fixed temperatures. The small arrows denote the path the capacitance follows as the field is increased and decreased.

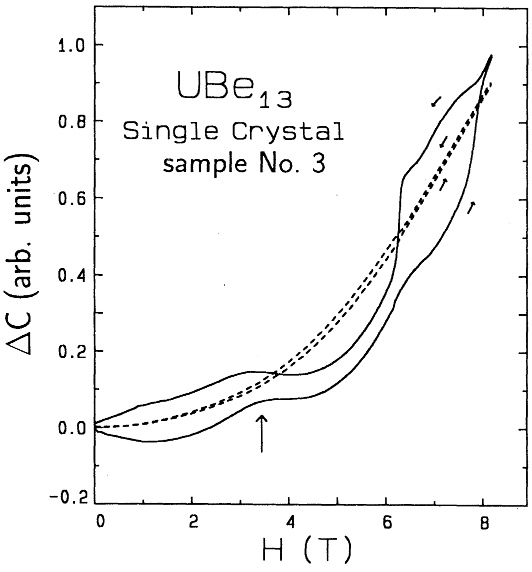

FIG. 5. Change in capacitance of UBe_{13} single-crystal sample No. 3 as a function of field at 1.3 K (dashed line) and 0.23 K (solid line). Small arrows show the direction in which the hysteresis loop is traversed. The large arrow shows the position of a kink in the upper critical field (see text).

profiles of the Bitter magnets used in each run (affecting the relative magnitudes of the field itself and the field gradient), and (3) sample-to-sample variations as discussed in the Introduction. As with the data in Fig. 3, an onset field for the AMT is suggested by this data (albeit at a higher field). In Fig. 4(a), we have removed the large magnetic hysteresis resulting from flux-pinning effects in the superconducting state for clarity. This hysteresis remains in the data shown in Fig. 4(b), which is plotted as the change in the capacitance $\Delta C(H)$. The small arrows denote the path the capacitance follows as the magnetic field is increased and decreased. (The sense in which the hysteresis loop is traversed is the same for all the data shown.) The AMT is clearly visible in fields above the superconducting state. The magnitude of the AMT continues to increase with decreasing temperature, even below 100 mK.

It is not clear from the data of Fig. 4(b) if an onset field, similar to that in Figs. 3 and 4(a), exists. Such an onset field is, however, apparent in Fig. 5 where we show data, similar to that of Fig. 4(b), on single-crystal sample No. 3. In Fig. 5 the dashed and solid lines represent C_{MAG} data taken at 1.3 and 0.25 K, respectively. The small arrows denote the path the capacitance follows as H is increased and decreased. For this sample, the flux-pinning effects are smaller than those of Fig. 4, allowing the anomalous behavior to be clearly visible. [The high-field structure in the magnetic hysteresis amplitude itself is known as a "peak effect," a phenomenon in type-II superconductors which can arise from several sources (Ref. 26).]

Next we show data taken over a wide range of fields and temperatures with the C_{MAG} placed at magnetic center where only τ contributes to ΔC. These data were taken as a function of field at several fixed temperatures on single-crystal sample No. 3. Shown in Fig. 6 is representative data covering the range from 0.5 to 30 K, in fields to 23 T. The arrows denote the path the capacitance follows as the field is increased and decreased at 0.5 K. The magnetic oscillations are discussed elsewhere.[27] Here we point out that, in high fields, τ changes sign as the temperature falls below about 10 K, a behavior suggested by the data in Fig. 2. The strong temperature dependence of the high field τ suggested by the data of Figs. 3 and 4 is also apparent. Note that at low temperatures and in high fields, τ varies linearly with H.

The low-temperature behavior of τ shown in Fig. 6 is consistent with the data shown in Figs. 3, 4, and 5. We interpret the shape of $\Delta C(H)$ in these latter figures as follows: At all fields $F \propto H^2$, in agreement with our model. In low fields (or at temperatures above about 10 K), $\tau \propto H^2$ resulting from shape effects. Above a threshold field of 2–5 T (depending upon the sample and/or T) $\tau(H)$ decreases much faster than $F(H)$ increases, depressing the magnitude of $\Delta C(H)$. In high fields and at low temperature, τ varies linearly with H leading to the upturn of $\Delta C(H)$, since $F \propto H^2$. Therefore, data from different runs, on both single-crystal and polycrystal samples, fabricated in different labs using starting material from different sources, display the *same* AMT behavior. We assert that this AMT is an intrinsic aspect of UBe_{13}.

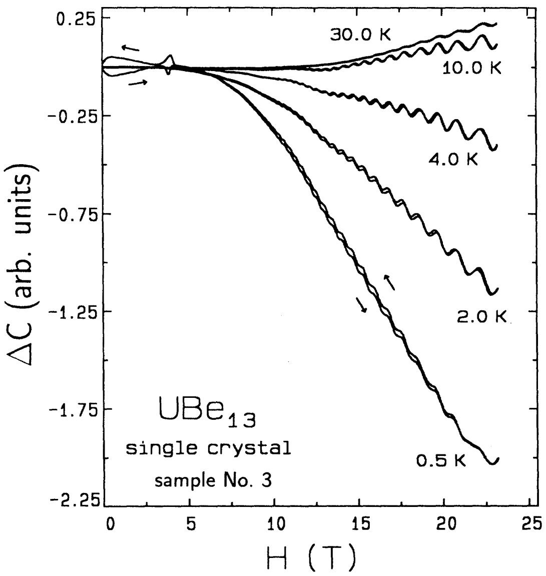

FIG. 6. Change in capacitance of UBe$_{13}$ single-crystal sample No. 3 (proportional to the magnetic torque here) as a function of field at several fixed temperatures. The small arrows denote the path the capacitance follows as the field is increased and decreased.

IV. DISCUSSION

The fact that τ changes sign with decreasing temperature in high fields (Fig. 6) suggests that there is a second contribution to τ, a contribution responsible for the AMT. The fact that this second contribution is large suggests that it is due to the appearance of an $M_\perp$ rather than additional shape effects (such as rotation about the long axis of the sample). Recall that shape effects contribute to the torque as $\tau \propto \chi^2 H^2$ and $M_\perp$ will contribute as $\tau \propto \chi_\perp H^2$, where $\chi_\perp$ is the transverse magnetic susceptibility; since $\chi \ll 1$ the effect of an $M_\perp$ can be much larger than that associated with shape effects. A transverse component of the magnetization could arise from the anisotropy associated with any magnetic phase transition. The presence of the AMT in polycrystal samples argues against such an interpretation as one would expect $M_\perp$ to average to zero. However, one requires not only random orientation of the individual grains of the polycrystal but for each of the grains to experience the same local magnetic field. Such would be the case if the samples were ellipsoidal but in our case the samples range from rectangular solids to significantly less regular shapes with cracks, pits, etc. (shape effects may also contribute to the sample-to-sample variations of the AMT).

The temperature dependence of $M_\perp$ in high fields of 10 T (squares), 15 T (triangles), and 20 T (circles) is shown in Fig. 7(a), a transition region between 5–10 K is evident. The field dependence of $M_\perp$ at 1.0 K is shown in Fig. 7(b), the high-field linearity of τ could be interpreted as the saturation of the transverse magnetization described by a Brillouin-like function offset along the H axis, or the step at the "top" of a broad metamagnetic transition. (Note that the shape effect contribution to τ has not been removed from the data shown in Fig. 7.) On the other hand, one would expect a sufficiently large external magnetic field to reduce $M_\perp$ (as in the spin-flop variety of metamagnetic transitions). Perhaps the behavior shown in Fig. 7(b) reflects the beginnings of such a process.

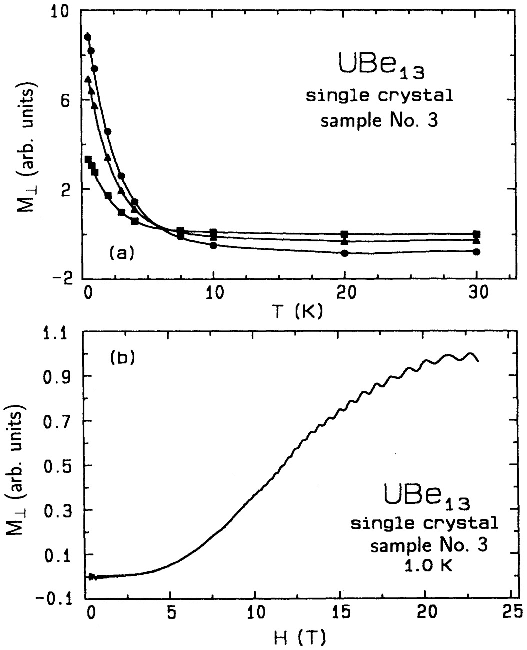

FIG. 7. (a) The transverse magnetization ($M_\perp$, see text) plotted as a function of temperature at fixed fields of 10 T (squares), 15 T (triangles), and 20 T (circles) for UBe$_{13}$ single-crystal sample No. 3. The solid lines are guides to the eye. (b) $M_\perp$ plotted as a function of field at 1.0 K.

We can estimate the magnitude of $M_\perp$ by calibrating the magnetometer under the assumption that the high-temperature data result from shape effects only. In the high-temperature region we model the sample as an oblate spheroid with a short axis a and a long axis c making an angle θ with respect to the direction of H. We have shown elsewhere that, to leading order in the (volume) susceptibility χ,

$$\tau = 4\pi\chi^2 H^2 \sin\theta \cos\theta (N_a - N_c) , \quad (2)$$

where N_a and N_c are demagnetization coefficients,[24] here τ is the torque per unit volume. We take θ from the orientation of the body diagonal of our rectangular sample and estimate N_a and N_c from the sample dimensions ($\theta = 76°$, $N_a = 9.4$, $N_c = 0.83$). We further assume that A_T [see Eq. (1)] is independent of both T and H. At low temperatures the torque is given by $\tau = M_\perp H$. Calibrating the magnetometer from ΔC observed at 20 K and 20 T, we find that, at 1 K and 20 T [the maximum value of $M_\perp$ in Fig. 7(b)], $M_\perp \sim 0.23$ emu/g (or about $0.015 \mu_B / U$ atom). $M_\perp$ is thus about 4% of the VSM magnetization shown in Fig. 3 (comparable to the noise in the VSM data at 1.3 K). Should the mechanism responsible for $M_\perp$ contribute as much to $M_\parallel$ it would be virtually invisible in the data shown in Fig. 3.

We have searched for the onset of an $M_\perp$ using a commercial SQUID-based magnetometer for measurements of the transverse magnetic moment as a function of H at 2.0 K using sample No. 3. Due to the difficulty of positioning the sample–pickup-coil geometry appropriately, we were unable to resolve an independent transverse moment to better than about 3% of the longitudinal moment at 5 T. However, given our estimate of the magnitude of $M_\perp$ this is not a negative result.

We propose that a field-induced magnetic phase transition is responsible for the AMT. Our proposed phase diagram for UBe_{13} in the H-T plane for single-crystal sample No. 3 is shown in Fig. 8, where T is plotted on a logarithmic scale. The small solid circles represent measurements of H_{c2} (T) reported elsewhere.[19] The large open circles denote the positions of potential sharp kinks in H_{c2} (T) which are too small to be easily visible in Fig. 8. The large closed circles represent the onset of the AMT as derived from data similar to that in Figs. 3 and 5, containing both F and τ contributions to $\Delta C(H)$. To estimate the onset field, $\Delta C(H)$ is plotted against H^2, we take the first deviation from linearity of such a plot to be the onset of the AMT. The solid line is a guide to the eye for the onset of the AMT behavior, this line also represents the phase boundary for our field-induced magnetic transition.

We now speculate on the origin of our proposed magnetic phase transition and show that the existence of such a phase transition is consistent with results from other groups: For an $M_\perp$ to exist one would like to invoke magnetic anisotropy in spite of the fact that UBe_{13} has cubic symmetry. However, the Be_{II} atoms in the UBe_{13} lattice do not occupy points of cubic symmetry and an anisotropic Knight shift has been observed at these sites.[28] Perhaps this transition is associated with the Be_{II} atoms. On the other hand, several aspects of our results and those of other workers are qualitatively consistent with the general characteristics of a metamagnetic transition.[29] In general a metamagnetic transition takes a low-spin to a high-spin state in high magnetic fields[30] and the appearance of an $M_\perp$ fits this general criterion. However, it seems clear that we are not observing the more common spin-flop variety of metamagnetic transition which would act to reduce $M_\perp$.

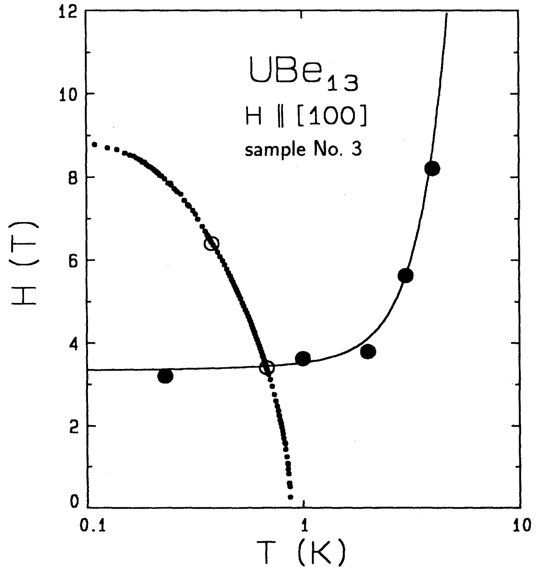

FIG. 8. The low-temperature phase diagram of UBe_{13} single-crystal sample No. 3 in the H-T plane. Small solid circles denote the upper critical field H_{c2} (T), large open circles show the positions of kinks in H_{c2} (T), large solid circles represent the onset of the anomalous magnetic torque (see text) for which the solid line is a guide to the eye. The solid line also represents the phase boundary of the proposed field-induced magnetic phase transition.

Although we do not find a sharp feature in any of the data presented in this paper (a characteristic of metamagnetic transitions), the onset of this behavior at low temperatures correlates quite well with other indications of phase transitions at low temperatures and in high magnetic fields: The vertical arrow in Fig. 3 denotes the position of the peak in specific-heat measurements[16] on another sample prepared from the same starting materials in the same laboratory as our sample No. 2. The vertical arrow in Fig. 4(a) denotes the position of a potential kink in the upper critical field of sample No. 1 which is discussed elsewhere.[19,31] The vertical arrow in Fig. 5 denotes the position of a potential (and much sharper) kink in H_{c2} (T) of sample No. 3, also discussed elsewhere.[19] The temperature separating the high-temperature behavior of the magnetic torque from the low-temperature anomalous behavior of our single-crystal sample No. 3 [about 7 K, see Fig. 7(a)] correlates with the (controversial) antiferromagnetic transition (at 8.8 K) (Ref. 10) and/or increased size of antiferromagnetic correlations (near 8–9 K) (Ref. 13) discussed above.

In a metamagnetic transition one expects a line of first-order phase transitions at a finite magnetic field, qualitatively independent of temperature, such as that reported in the specific heat[16] and consistent with the field independence of our onset field at low temperatures. One frequently finds an inflection point in the magnetoresistance at a metamagnetic transition.[32] A weak inflection point indeed develops in the magnetoresistance of UBe_{13} at temperatures below 4.2 K and has been interpreted as arising from the single-ion Kondo effect, an interpretation which requires a depression of $M(H)$ below linearity which is not observed.[33] If this inflection point in the magnetoresistance is due to a metamagnetic transition, a depression of $M(H)$ below linearity could be compensated by the increase in $M(H)$ associated with the transition.

This field-induced magnetic transition may be related to the magnetic order induced by high pressures mentioned in the Introduction.[14] Such a view requires that the application of magnetic fields and high pressures P, similarly affect the low-temperature magnetic properties of UBe_{13}, which is the case for both specific heat[34,35] and magnetic susceptibility.[36] In zero field and at ambient pressure there is a maximum in the electrical resistivity ρ 2.5 K well below which the heavy fermions scatter coherently.[37] This maximum occurs at higher temperatures and eventually broadens into a "shoulder" with the application of either P (Ref. 38) or H (Refs. 39 and 40).

At temperatures well below the maximum, the resistivity of $\mathrm{UBe_{13}}$ (as that of many heavy-fermion compounds) may be written as

$$\rho(T,H,P)=\rho_0(H,P)+A_\rho(H,P)T^2 . \qquad (3)$$

The application of either H or P depresses the residual resistivity ρ_0 and leads to a broad maximum in A_ρ.[38,39] The maximum in $A_\rho(H)$ occurs near 3 T in good agreement with our low-temperature onset field for the field-induced magnetic transition. The maximum in $A_\rho(P)$ occurs near 60 kbar, the threshold pressure above which magnetic order has been reported.[14] Such extrema have not been observed in $A_\rho(H,P)$ for several other heavy-fermion systems.[38] It is reasonable to expect a magnetic phase transition to influence A_ρ rather than ρ_0, since the former reflects interactions between the heavy quasiparticles, while the latter is related to incoherent scattering from imperfections and impurities.[41] Further, since the low-pressure magnetoresistance is dominated by the depression of ρ_0,[38] we would expect the influence of our proposed magnetic transition to be weak, as is the inflection point in the low-temperature magnetoresistance of $\mathrm{UBe_{13}}$.[42]

The field-induced magnetic phase transition may also be related to the unusual behavior of the Hall effect in $\mathrm{UBe_{13}}$. A broad maximum in the Hall voltage has been observed to develop at low temperatures by several groups.[43–45] The maximum has a temperature dependence consistent with our proposed phase diagram (Fig. 8). A similar maximum in the Hall voltage of $\mathrm{CeRu_2Si_2}$ has been interpreted as resulting from a metamagnetic transition.[46]

V. CONCLUSIONS

We have presented measurements of the magnetic force and magnetic torque acting upon single-crystal and polycrystal samples of the heavy-fermion superconductor $\mathrm{UBe_{13}}$. We have shown that the magnetic susceptibility deduced from the magnetic force is in good agreement with measurements using conventional techniques. We found that a large, anomalous contribution to the magnetic torque appears in fields above 3–5 T at low temperature and at temperatures below about 7–12 K in high fields. This anomalous torque coexists with the superconducting state at low temperature. We proposed that the anomalous torque reflects the existence of an intrinsic field-induced magnetic phase transition, and we have shown that the presence of such a phase transition is consistent with measurements of specific heat, magnetoresistance, thermopower, and Hall effect by other groups.

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