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Search for antiferromagnetic order in UBe_{13} via magnetovolume effects

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The linear magnetostriction (λ) and the coefficient of linear thermal expansion (α) of a single-crystalline sample of the heavy-fermion compound UBe_{13} have been determined for elongation directions along and perpendicular to the applied magnetic field ($\mathbf{B}\|[100]$), in the temperature interval $0.3<T<12$ K and for fields $B<8$ T. We find neither evidence for antiferromagnetic order ($T_N=8.8$ K), nor for magnetostrictive oscillations, which were reported recently by Kleiman *et al.* [Phys. Rev. Lett. **64**, 1975 (1990)]. Instead λ varies proportional to B^2 as expected for a normal paramagnetic metal. The low-temperature normal-state electronic Grüneisen parameter is unusually large and drops rapidly in the superconducting phase ($T_c=0.85$ K). We also report magnetostriction measurements on UBe_{13} below T_c. The magnetovolume effects in the superconducting phase are strongly anisotropic and reveal a large hysteresis.

I. INTRODUCTION

In recent years it has become clear that the proximity of a magnetic instability is one of the major issues in understanding the heavy-fermion problem.[1] The proximity of the magnetic instability is hinted at by the occurrence of strong antiferromagnetic spin-fluctuation phenomena, which are evidenced by pronounced anomalies in the low-temperature magnetic properties, and is clearly demonstrated by specific subtle replacements of one of the constituents by another element that drive most (if not all) of the heavy-fermion systems towards a long-range-ordered antiferromagnetic groundstate, with fairly large values for the ordered moment ($|\mu|\sim 0.5\ \mu_B/f$ atom). Surprisingly, subsequent minute investigations[2-9] have revealed that some of the pure compounds exhibit long-range antiferromagnetism as well, though with very small ordered moments ($|\mu|\sim 0.01\ \mu_B/f$ atom). It is particularly intriguing that the weak long-range antiferromagnetic order has been reported especially for the superconducting heavy-fermion systems UPt_3,[2-4] URu_2Si_2,[5-7] and UBe_{13},[8] with the common feature $T_N\sim 10T_c$, while for $CeCu_2Si_2$ (Ref. 9) $T_N\sim T_c$ (T_N and T_c are the Néel and superconducting transition temperature, respectively). This general behavior for the U-based systems would strongly suggest a close connection between the energy scales for superconductivity and antiferromagnetism, and would lend further support for a superconducting pairing interaction mediated by antiferromagnetic spin fluctuations,[10] rather than by the conventional electron-phonon interaction. A detailed investigation of the weak antiferromagnetic order is therefore undoubtedly of principal importance.

Since only in URu_2Si_2 clear anomalies in the thermodynamic and transport properties accompany the transition to the ordered state,[11] convincing evidence for the weak antiferromagnetic order must generally be gathered from various microprobe techniques. In the case of URu_2Si_2 ($T_N=17.5$ K) neutron diffraction[5,6] and x-ray magnetic scattering[7] substantiate an ordered moment of $\sim 0.03\ \mu_B$/U atom. For UPt_3 ($T_N=5$ K), μSR experiments[2] and neutron diffraction[3,4] point to an ordered moment of $0.02\mu_B$/U atom, although long-range order has not been reported[4] for all samples investigated. NMR experiments[9] yield a Néel temperature of ~ 0.6 K for superconducting $CeCu_2Si_2$.

In the case of UBe_{13}, microprobe techniques (in particular careful μSR experiments[2]) have thus far been unsuccessful in demonstrating long-range magnetic order. Nevertheless, evidence for a transition to an antiferromagnetic state at $T_N=8.8$ K has recently been put forward by Kleiman *et al.*[8] The authors of Ref. 8 measured the magnetostriction of a single-crystalline sample using a field-modulation technique and observed an additional contribution at low temperatures, that was ascribed to antiferromagnetic ordering. In the same Letter[8] the authors reported pronounced hysteretic behavior and magnetostrictive oscillations, which were ascribed to de Haas-van Alphen oscillations due to an unusual aspect of the Fermi surface. However, our prior magnetostriction data,[12] taken in the same field and temperature interval, were not consistent with their results.

In view of the important implications of the conclusions presented in Ref. 8, we decided to reinvestigate the magnetostriction of our single-crystalline UBe_{13} sample. We performed an extensive magnetovolume study in the temperature interval $0.3<T<12$ K and in magnetic fields up to 8 T using a sensitive capacitance technique.

We report on a complete set of magnetostriction $\lambda(T,B)$, and thermal expansion $\alpha(T,B)$, measurements in field. The length variation of the sample was measured along and perpendicular to the applied magnetic field, in order to study the anisotropy in λ and α. As it will appear, we find neither evidence for antiferromagnetic order below 12 K nor for pronounced hysteretic or oscillatory behavior in the magnetostriction. We complete our magnetovolume data with specific-heat data, taken in the same temperature and field interval on the same sample, in order to perform a Grüneisen parameter analysis. Finally, we report a magnetovolume study of the superconducting phase of UBe_{13}.

II. EXPERIMENT

A single-crystalline UBe_{13} sample was shaped into a rectangular bar with edges of ~2, 4, and 6 mm, along the crystallographic (cubic) [100] directions. The single-crystalline nature of the sample was checked in a neutron-scattering experiment on the IN 20 triple-axis spectrometer at the Institute von Laue–Langevin (Grenoble). No magnetic ordering was observed and no impurity phases were detected. The width of the observed nuclear Bragg reflections is given by the instrumental resolution. In order to measure the linear magnetostriction $\lambda=[L(B)-L(0)]/L(0)$, and the coefficient of linear thermal expansion $\alpha=L^{-1}dL/dT$, the sample was mounted in a parallel-plate capacitance cell, machined of oxygen-free high-conductivity copper.[13] The length changes were always measured along the 4-mm edge, either parallel to the field ($\mathbf{B}\|[100]$), $\lambda_{\|}$, or perpendicular to the field, $\lambda_{\perp}$, by rotating the cell (with $\mathbf{B}$ along another [110] direction). In the perpendicular configuration the field was applied along the 6-mm edge, in order to minimize demagnetization effects. The length change was measured using a sensitive three-terminal capacitance method with a detection limit of 0.1 Å. The cell, equipped with a RuO_2 thermometer, calibrated in fields up to 8 T, and a heater, was thermally anchored to the cold plate of a ^3He cryostate.

The magnetostriction was measured by slowly sweeping the field at a typical rate of 0.1 T/min in order to prevent eddy current heating. While sweeping the field the temperature was controlled by the RuO_2 thermometer, but no correction was made for its magnetoresistance. However, as the magnetoresistance is small, the maximum temperature variation during one field sweep could be kept below 3%. The contribution of the cell to the magnetostriction signal, as obtained for a dummy oxygen-free high-conductivity (OFHC) copper sample, has carefully been measured and was found to be negligible.

The thermal expansion, in zero and in applied field, was measured stepwise, $\Delta T \geq 10$ mK, allowing cell and sample to reach thermal equilibrium after each temperature step. The data have been corrected for the cell effect, i.e., the contribution of the cell with a dummy OFHC copper sample. For a 4-mm sample the correction to α attains the typical values of 1.5×10^{-7} K^{-1} at 0.5 K, 0.7×10^{-7} K^{-1} at 1.5 K, and 0.4×10^{-7} K^{-1} at 10 K. The absolute accuracy of the cell amounts to ±3% and is mainly determined by the effective area of the parallel-plate capacitor that varies slightly for different mountings of the sample.

The proper functioning of this type of cell over a wide temperature ($0.1<T<270$ K) and field ($B<24$ T) range has been demonstrated in a number of magnetovolume studies on heavy-fermion systems among which UPt_3 (Ref. 14), URu_2Si_2 (Ref. 15), $CeCu_6$ (Ref. 16), and $CeRu_2Si_2$ (Ref. 17) (see also Refs. 12 and 18, and references therein).

Low-temperature specific-heat measurements ($0.3<T<1.2$ K) in fields up to 8 T have been performed with a relaxation technique. The sample was glued with silver paint to a sapphire support equipped with a heater and a RuO_2 thermometer. Specific-heat data in the temperature range $1.3<T<10$ K were taken in a different setup employing an adiabatic method. The maximum field in this case amounted to 5 T.

III. RESULTS

A. Magnetostriction

The magnetostriction of UBe_{13} has been measured up to 8 T at temperatures of 0.4, 0.5, 0.6, 1.25, 4.2, 6, 8, and 10 K. At all temperatures data have been taken along, $\lambda_{\|}$, and perpendicular to, $\lambda_{\perp}$, the field. In Fig. 1 we show some typical as-measured magnetostriction curves at 1.25, 4.2, and 10 K. Within the experiment error no hysteresis is observed in the normal phase. The linear magnetostriction is strongly anisotropic: the sample contracts along the field, while it expands perpendicular to the field. The volume magnetostriction is calculated from $\lambda_v=\lambda_{\|}+2\lambda_{\perp}$. In Fig. 1 we show $\lambda_v/3$. Strictly, the volume magnetostriction is only defined for a fixed field direction (i.e., the field always along the same edge of the sample). However, under the assumptions that the sample is perfectly homogeneous and that demagnetizing effects can be neglected (which is the case for our UBe_{13} sample) one may also obtain λ_v by changing the field

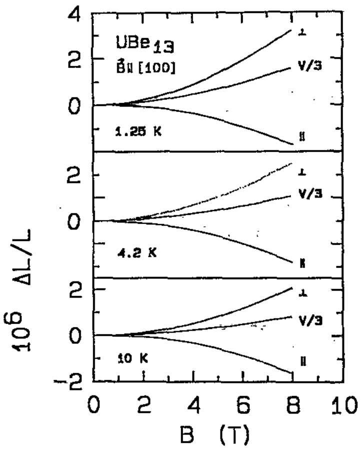

FIG. 1. The magnetostriction of UBe_{13} along (∥) and perpendicular (⊥) to the applied magnetic field ($\mathbf{B}\|[100]$) at temperatures indicated. Data for field sweeps up and down coincide. The curves labeled $v/3$ represent $\lambda_v/3$.

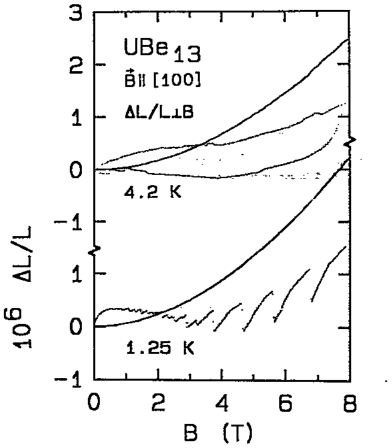

FIG. 2. Comparison of our magnetostriction results for $\lambda_\perp$ (solid lines) with the data of Kleiman *et al.* (Ref. 8) (dotted lines) at 1.25 and 4.2 K (upper dotted line, field up; lower dotted line, field down). We observe neither hysteresis effects nor oscillatory behavior.

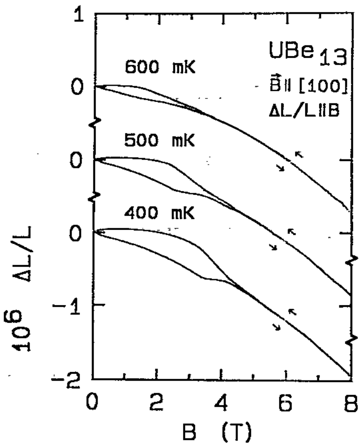

FIG. 4. $\lambda_\parallel$ of UBe$_{13}$ ($B\|[100]$) at 0.4, 0.5, and 0.6 K. The arrows indicate field sweeps up or down. A hysteresis loop opens in the superconducting phase.

direction, while keeping the dilation direction fixed.

The present data yield the same field variation as our earlier data[12] at 1.3 and 4.2 K, taken on the same sample at the Centre de Recherches sur les Très Basses Températures in Grenoble in a different setup, using another similar cell. However, a difference between both data sets appears in the absolute value of λ, which is about 15% smaller in the present experiments. The origin of this difference, which exceeds the absolute uncertainty (±3%), is not clear. Possibly, the not perfect plan-parallellity of our sample results in a larger uncertainty in the effective area of the capacitor than expected. As other possible error sources we mention (i) friction between the sample and the OFHC copper cell due to a mismatch of thermal-expansion coefficients at low temperatures giving rise to some irreproducibility and (ii) aging effects of the sample.

In Fig. 2 we compare our results at 1.25 and 4.2 K with the data obtained by Kleiman *et al.*[8] The different data sets are obviously at large variance with each other.

The magnetostriction in the superconducting phase has been measured at 0.4, 0.5, and 0.6 K. The data for field sweeps up and down are shown in Fig. 3 ($\lambda_\perp$) and Fig. 4 ($\lambda_\parallel$). Again the magnetostriction is strongly anisotropic. Furthermore a large hysteresis loop opens in the superconducting phase. Remarkably, the hysteresis loop is considerably smaller for $\lambda_\perp$ than for $\lambda_\parallel$.

B. Thermal expansion

The coefficient of linear thermal expansion of UBe$_{13}$ has been measured in zero and applied fields up to 8 T. In Fig. 5 we show the coefficient of volume expansion, $\alpha_v = \alpha_\parallel + 2\alpha_\perp$, that has been calculated after averaging and spline fitting $\alpha_\parallel$ and $\alpha_\perp$, for temperatures up to 12 K in zero and an applied field of 8 T. In Fig. 6 we focus on the superconducting transition. The thermal expansion of UBe$_{13}$ has a very unusual temperature dependence. Below 10 K it rises strongly with decreasing temperature, it then passes through a weak maximum at 1.3 K and drops sharply when the superconducting transition sets in at 0.85 K. The present zero-field data are in good agreement with our previous results.[19] Similar data have

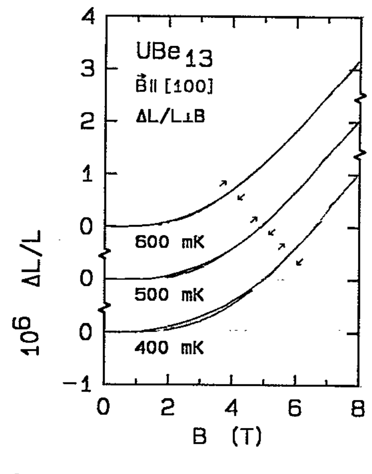

FIG. 3. $\lambda_\perp$ of UBe$_{13}$ ($\mathbf{B}\|[100]$) at 0.4, 0.5, and 0.6 K. The arrows indicate field sweeps up and down. A hysteresis loop opens in the superconducting phase.

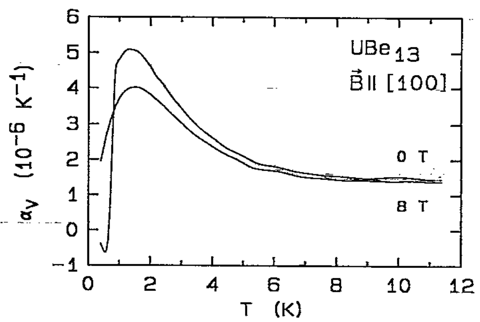

FIG. 5. Coefficient of volume thermal expansion, α_v, of UBe$_{13}$ in zero and an applied field of 8 T ($\mathbf{B}\|[100]$).

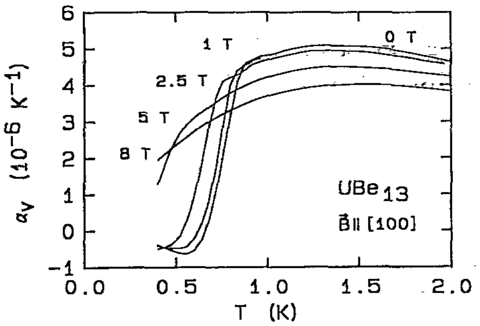

FIG. 6. Coefficient of volume thermal expansion, α_v, of UBe$_{13}$ at the superconducting transition for magnetic fields as indicated (**B**∥[100]).

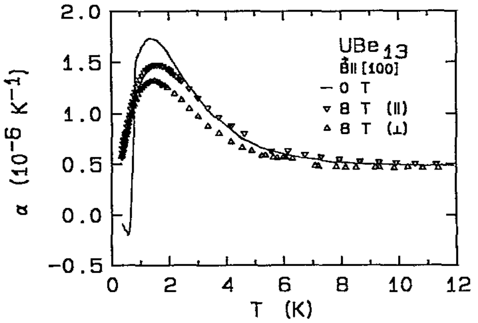

FIG. 7. Coefficient of linear thermal expansion of UBe$_{13}$ in zero field (solid line) and along (∇) and perpendicular (Δ) to a field of 8 T (B∥[100]). The data reveal a substantial anisotropy in α under the influence of a magnetic field.

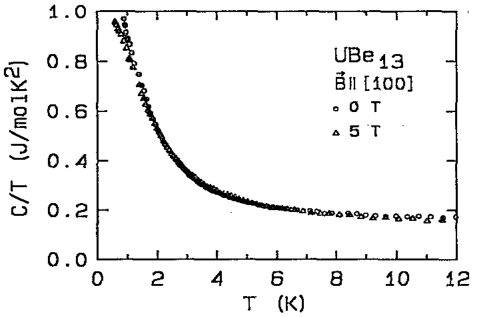

FIG. 8. Specific heat of UBe$_{13}$ in the normal phase plotted as c/T vs T, in zero and an applied field of 5 T.

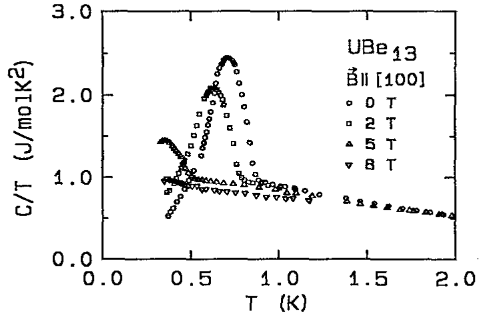

FIG. 9. Specific heat of UBe$_{13}$ at the superconducting transition in a plot of c/T vs T for fields as indicated.

been obtained by Ott.[20] By applying a magnetic field the normal-state thermal expansion is considerably suppressed in an anisotropic way. The suppression is largest for the parallel configuration (see Fig. 7). The position of the maximum in α_v increases with field at a modest rate of 30 mK/T, while a 20% reduction is achieved in its height by a field of 8 T.

C. Specific heat

The normal-state specific heat of our UBe$_{13}$ sample in zero and an applied field of 5 T is shown in a plot of c/T vs T in Fig. 8. For temperatures above 1.3 K the data were taken with the adiabatic method, while for $T<1.3$ K the relaxation technique was used. The agreement between both data sets is satisfactory. The influence of a magnetic field of 5 T becomes only visible below ~2 K. The large rise of c/T with decreasing temperature and the weak influence of a relatively large magnetic field is characteristic for heavy-fermion systems. In Fig. 9 we show the specific heat at the superconducting transition ($T_c=0.85$ K) obtained with the relaxation technique. The normal-state c/T value amounts to 1000 mJ/mol K^2 at the onset of the superconducting transition. An extrapolation of the zero-field c/T vs T curve to $T=0$ K in a nonlinear fashion as is indicated by the 5- and 8-T data, yields a γ value of ~1150 mJ/mol K^2. The jump in c/T at T_c amounts to 2.5 (Bardeen-Cooper-Schrieffer value 1.43) in agreement with previously obtained values.[21–23] In fact, the low-temperature specific heat of UBe$_{13}$ in zero and an applied field has been discussed before extensively.[21–23] The present data are in good agreement with previous studies, indicating the correct sample quality.

IV. ANALYSIS AND DISCUSSION

The discrepancy between our magnetostriction data and the data of Ref. 8 is most strikingly reflected in Fig. 2. Clearly hysteretic and oscillatory behavior are absent in our data. In order to search for the occurrence of long-range antiferromagnetism, we have plotted in Fig. 10 the temperature variation of the slope of the λ vs B curve in fields of 3, 5, and 7 T. For $\lambda_\perp$ (upper frame) the slope smoothly decreases with increasing temperature, while it remains roughly constant for $\lambda_\parallel$ (lower frame). We also compare in Fig. 10 our data with the data of Kleiman *et al.* obtained with the field-modulation technique in fields of 3 and 7 T (only data for the perpendicular configuration have been published). The abrupt increase in $\lambda_\perp'$ (with decreasing temperature) observed by Kleiman *et al.* at 7.7 K in 3 T and at 6.2 K in 7 T has been put forward as evidence for an antiferromagnetic transition. However, the interpretation of these experimental data is by no means clear cut. The slope was measured using a field-modulation technique with an amplitude of 0.1 T. It is likely that the reported unusually-field-induced hysteretic and oscillatory behavior, which is moreover strongly varying with temperature, influences in a nontrivial way the obtained slope. From Fig. 10 it is obvious that our data do not confirm the transition to a long-range-ordered antiferromagnetic state.

It is unlikely that the large discrepancy between our

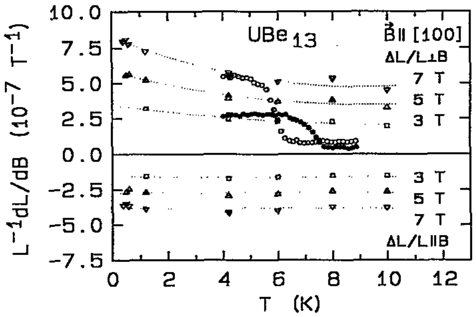

FIG. 10. $L^{-1}dL/dB$ vs temperature in fields of 3, 5, and 7 T, as determined from the data in Figs. 1–4. In the lower frame we show $\lambda'_{\parallel}$ and in the upper frame $\lambda'_{\perp}$. Dotted lines serve as a guide to the eye. The closed and open circles represent data for $L^{-1}dL/dB$ by Kleiman *et al.* (Ref. 8) taken with the field-modulation technique in fields of 3 and 7 T, respectively. We find no evidence for long-range antiferromagnetic order.

data and the data in Ref. 8 must be ascribed to an extreme sample quality dependence. The published data on the thermodynamic and the magnetic properties of various UBe_{13} samples yield in general consistent results, indicating a proper sample quality. The specific-heat data on our sample reveal that we have a sample of sufficient quality. Unfortunately such data have not been published for the sample investigated in Ref. 8. However, there are no particular reasons to believe that the sample used in Ref. 8 is "worse" or "better." It is remarkable that the magnetostrictive oscillations reported by Kleiman *et al.* have the largest amplitude at a temperature of 1.25 K, where also the maximum in the thermal expansion is found ($\alpha = 1.7\times10^{-6}$ K^{-1}). A temperature oscillation of, for instance, 0.1 K would induce an oscillation in $\Delta L/L$ with amplitude $\sim 1.7\times10^{-7}$, which is of the order of the reported values. Therefore, we suggest that an unusual temperature instability, possibly, induced by eddy current heating, might have caused the unusual λ vs *B* curves reported by Kleiman *et al.* As possible other sources for the oscillatory behavior we mention systematic errors that occur when the sample and/or coaxial cables are not immovably fixed while sweeping the field. Concurrently, one cannot exclude that the "evidence" for antiferromagnetism (Fig. 10) is an artifact of the experiment. Furthermore, we would like to draw attention to the fact that the authors of Ref. 8 are themselves unable to give a satisfactory explanation for the unusual observations.

Our magnetostriction data are thus in sharp contrast with the data of Ref. 8 and do not confirm a transition to the long-range-ordered state at $T_N = 8.8$ K in zero field for our UBe_{13} sample. Of course the data cannot exclude the occurrence of antiferromagnetism above 12 K (although this seems unlikely), or at very low temperatures. In this respect it is interesting to note that several indications of a phase transition, perhaps magnetic in origin, have been observed recently. Additional anomalies in the specific heat[23] in field were found at very low temperatures, possibly implying that UBe_{13} becomes antiferromagnetic below ~100 mK in strong magnetic fields. Also measurements of the thermoelectric power at very high pressure[24] (67 kbar) might indicate pressure-induced long-range order at a temperature of a few K.

The linear normal-state magnetostrictions, $\lambda_{\perp}$ and $\lambda_{\parallel}$, follow a quadratic field dependence. Consequently, $\lambda_v = bB^2$, as expected from the linear magnetization curves,[25] $M = \chi H$. Employing the thermodynamic relative $\partial M/\partial P = -\mu_0^{-1}\partial V/\partial H$, the relative hydrostatic pressure dependence of the molar magnetic susceptibility can be calculated from

$$\frac{\partial \ln\chi}{\partial P} = -V_m \mu_0 \chi^{-1} 2b \ . \tag{1}$$

Here χ is the molar susceptibility (in S.I. units) and V_m ($=8.13\times10^{-5}$ m^3/mol) is the molar volume. We deduce a value for $\partial\ln\chi/\partial P$ of -6.1 Mbar^{-1} at 4.2 K, where we used $b = 5.1\times10^{-8}$ T^{-2} and $\chi = 171\times10^{-9}$ m^3/mol (Ref. 25). This value should be compared with the experimental value of -10.3 Mbar^{-1} derived directly from pressure experiments.[26] Apparently, the initial pressure dependence of χ as probed by the magnetostriction technique is somewhat smaller than the one induced by pressures of several kbars, a feature often observed for heavy-fermion compounds.[12] The corresponding "magnetic" Grüneisen parameter, $\Gamma_m = \partial\ln\chi/\partial\ln V$, amounts to 5.7 at 4.2 K and to 6.9 at 1.25 K (utilizing the magnetostriction data), where we used a value for the compressibility of $\kappa = -V^{-1}\partial V/\partial P = 1.08$ Mbar^{-1}, calculated from the elastic constants derived from the phonon-dispersion curves[27] at 10 K. Note that the value for Γ_m evaluated by Kleiman *et al.*[8] is almost a factor 3 too large, because an isotropic magnetostriction was assumed, which is rarely the case.

In order to obtain a quantitative estimate of the volume dependence of the low-temperature energy scale, the thermal-expansion and the specific-heat data may be combined by means of a Grüneisen parameter analysis. In Fig. 11 we show the effective temperature dependent Grüneisen parameter, Γ_{eff},

$$\Gamma_{\text{eff}}(T) = \alpha_v(T) V_m / \kappa C(T) \ . \tag{2}$$

As follows from Fig. 11, Γ_{eff} rapidly increases with decreasing temperature, attains a maximum at T_c ($\Gamma_{\text{eff}} = 42$), and subsequently drops sharply to a negative value of -12 (at 0.3 K) in the superconducting state. Retaining only the linear electronic terms for $T \to 0$,

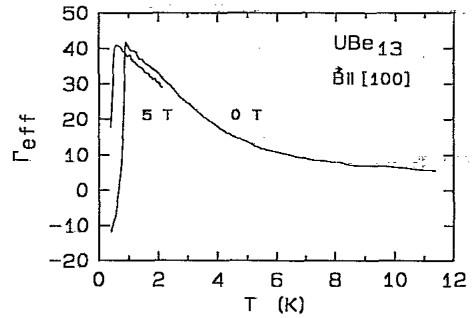

FIG. 11. The effective Grüneisen parameter of UBe_{13} vs temperature in zero and an applied field of 5 T.

$\alpha_v = 3aT$, and $c = \gamma T$, we obtain the heavy-fermion (HF) Grüneisen parameter

$$\Gamma_{\mathrm{HF}} = 3aV_m/\kappa\gamma = 50 \ . \tag{3}$$

The unusually large value for Γ_{HF} yields a strong suppression of the linear term in the specific heat with pressure at a rate of

$$\frac{d\gamma}{dP} = -\kappa\Gamma_{\mathrm{HF}}\gamma = -62 \ \mathrm{mJ/(mol\,K^2\,kbar)} \tag{4}$$

in agreement with the results obtained from specific-heat experiments under pressure.[28] In a magnetic field of 5 T, $\Gamma_{\mathrm{eff}}(T)$ is suppressed (Fig. 11), and $\Gamma_{\mathrm{HF}} = 45$.

A quantitative estimate of the suppression of the heavy-fermion state by the external magnetic field can be given from both the specific-heat and the thermal-expansion data. Comparing the specific-heat data in zero field and 8 T (Fig. 9), the field suppression of γ can be estimated at $d\gamma/dB \sim -31$ mJ/(mol K^{2}T), or $\partial \ln\gamma/\partial B \sim -0.027\ \mathrm{T}^{-1}$. Assuming that the temperature T_m, where the maximum in the thermal expansion is found is proportional to the Kondo lattice temperature, and thus $T_m \propto 1/\gamma$, a similar estimate can be made from the zero-field and 8 T data in Fig. 5: $dT_m/dB = 30$ mK/T or $\partial \ln T_m/\partial B = 0.024\ \mathrm{T}^{-1}$. This value is in good agreement with the negative value for $\partial \ln\gamma/\partial B$. Note that in order to perform this comparison we have assumed, in a first approximation, that γ and T_m vary linearly with the field.

The heavy-fermion state is strongly correlated with the volume via the Grüneisen parameter coupling,[12,28] whereas the volume plays only a minor role in the field dependence of the heavy-fermion state. In order to compare the effect of the volume change on the pressure and on the field dependence of γ, we remark that $\Delta V/V = -1.16\times10^{-3}$ for a pressure of 1 kbar, while $\Delta V/V$ amounts only to 4.8×10^{-6} for $B = 8$ T at a temperature of 1.25 K.

As a remarkable result from the Grüneisen parameter analysis we find that for UBe_{13}, $\Gamma_\gamma \equiv \Gamma_{\mathrm{HF}} \gg \Gamma_\chi \equiv \Gamma_m$, while for most other heavy-fermion systems[30] $\Gamma_\gamma \approx \Gamma_\chi$. This seems to indicate that in UBe_{13} the magnetic properties are partly decoupled from the electronic properties. Apparently, the basic microscopic interactions that form the heavy-fermion quasiparticles have a fundamentally different volume dependence in UBe_{13}.

At the onset of the superconducting transition, $\Gamma_{\mathrm{eff}}(T)$ drops sharply. Even at the lowest temperatures Γ_{eff} still varies rapidly with temperature. Clearly, measurements below 0.3 K are needed to investigate the Grüneisen parameter in the superconducting state in detail. The negative Γ value of about -12 indicates a rather strong suppression of T_c with pressure. Applying the Ehrenfest relation, $dT_c/dP = -V_m T_c \Delta\alpha_v/\Delta c$, where $\Delta\alpha_v$ and Δc are the jumps in the coefficient of volume expansion and the specific heat at T_c, the pressure dependence of T_c can be determined. However, the evaluation of $\Delta\alpha_v$ and Δc from the data is not straightforward as the transition is rather broad. Taking the overall jump heights we arrive at a rather large estimate for dT_c/dP of -38 mK/kbar and correspondingly $\partial \ln T_c/\partial \ln V = 41$, in agreement with a value of 48 derived from specific-heat experiments under pressure.[28] However, resistivity measurements[31] yield a much smaller value for dT_c/dP: -16 mK/kbar.

As $\Gamma_{\mathrm{eff}}(T = 0.85\mathrm{K}) = 42 \approx -\partial \ln T^*/\partial \ln V$, where we define T^* as the characteristic temperature for the heavy-fermion contribution ($T^* \sim T_m \propto \gamma^{-1}$), we infer from the thermodynamic properties

$$\frac{\partial \ln T^*}{\partial \ln V} \approx -\frac{\partial \ln T_c}{\partial \ln V} \approx -42 \ . \tag{5}$$

The correlation between T^* and T_c suggests a close connection between the Fermi liquid and the superconducting properties, and thus a pairing mechanism mediated by the antiferromagnetic interactions is anticipated. Note that a similar inverse correlation between the volume dependence of T_c and T^* has been found for the heavy-fermion superconductors UPt_3 and URu_2Si_2.[1,32,33]

The magnetostriction in the superconducting phase reveals a remarkable anisotropy (Figs. 3 and 4). The hysteresis loops are much larger for the parallel than for the perpendicular configuration, indicating that the field penetration and flux-pinning effects contribute the most to the length variation along the field. This complex behavior is not easy to understand and asks for further measurements. The field at which the hysteresis loop opens is in good agreement with the upper critical field as determined from the specific heat and thermal expansion.

In conclusion, we have investigated the magnetovolume effects of heavy-fermion UBe_{13} in the normal ($T < 12$ K) and superconducting state. The magnetostriction in the normal phase varies as expected for a normal paramagnetic metal. We find no evidence for magnetostrictive oscillations or long-range antiferromagnetism as reported recently by Kleiman *et al.* A quantitative estimate is deduced for the suppression of the heavy-fermion state with pressure and magnetic field. The effective Grüneisen parameter is unusually large in the normal state ($\Gamma_{\mathrm{HF}} = 50$) and inversely connected to the Grüneisen parameter for the superconducting phase, implying a close connection between T^* and T_c.

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