Magnetic order of UPt_3 under uniaxial pressure

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The weak antiferromagnetic order of the heavy fermion superconductor UPt_3 has been investigated by elastic neutron-scattering measurements under applied uniaxial pressure up to 6 kbars along the *a* and *c* axes of the hexagonal crystal structure. For $p||c$ the small antiferromagnetically ordered moment of 0.02 μ_B/U atom shows a nonlinear decrease for increasing pressures and is still not completely suppressed at the maximum applied pressure of 6 kbars. For $p||a$ a significant increase in the magnetic Bragg peak intensity is observed, which suggests an incomplete domain repopulation and confirms the presence of a single-*k* structure. The Néel temperature of $T_N=6$ K does not substantially change with uniaxial pressure. The results are discussed in relation to the understanding of the unconventional superconducting phase diagram.

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I. INTRODUCTION

One of the central problems in the understanding of the heavy fermion superconductors is the role of the antiferromagnetic order. The magnetic interactions in most heavy fermion systems are governed by a hybridization of the *f* electrons and the conduction electrons that lead to a competition between the Kondo screening and the indirect exchange (Ruderman-Kittel-Kasuya-Yosida) interaction of the *f* electrons. As a consequence, a strong enhancement of the quasiparticle mass at low temperatures, and a rich variety of magnetic structures, is observed. The relation of the antiferromagnetic order to the superconductivity, and their coexistence at low temperatures, is one of the major issues yet to be resolved experimentally and theoretically.

For UPt_3, elastic neutron-scattering measurements[1] revealed the onset of antiferromagnetic order below $T_N=6$ K with an unusually small ordered moment of $m=0.02\mu_B/(\text{U atom})$. The antiferromagnetic order has a propagation vector of $\mathbf{k}=(1/2,0,0)$ with the ordered moment along the propagation vector in the basal plane of the hexagonal close-packed crystal structure (space group $P6_3/mmc$). The magnetic Bragg peaks are not resolution limited but show a Lorentzian broadening that corresponds to a finite correlation length of the order of $\xi\approx250-500$ Å. The weak antiferromagnetic order, observed by neutron-scattering measurements, has only been observed by two other techniques, namely magnetic x rays[2] and muon-spin rotation in magnetic field.[3] Recent elastic neutron-scattering experiments at low temperatures[4] showed a considerable narrowing of the antiferromagnetic Bragg peak below 50 mK, and a resolution limited peak was observed below 20 mK. The onset of long-range antiferromagnetic order below 20 mK was earlier suggested by a low-temperature anomaly in the specific heat[5] and later supported by magnetization measurements.[6] The proximity to a magnetic instability of UPt_3 is nicely demonstrated by the effect of doping with small concentrations of Pd,[7,8] which causes a substantial increase in the size of the ordered moment with a maximum value of $0.6\mu_B/(\text{U atom})$ for 5% Pd doping. Recently, Fomin and Flouquet[9] and Okuno and Miyake[10] have proposed models for an alternative scenario that ascribes the weak magnetic contribution, observed in elastic neutron-scattering measurements below 6 K, to the development of magnetic fluctuations. These fluctuations are sufficiently slow to *appear* static on the time scale of neutron and x-ray scattering experiments.

At low temperatures, UPt_3 shows unique unconventional superconducting properties. The superconducting transition at $T_c^+=0.55$ K is followed by a second superconducting transition at $T_c^-=0.50$ K. As a function of magnetic field and temperature, an exotic superconducting phase diagram[11–13] is observed with three different superconducting phases that meet at a tetracritical point. Neutron-scattering[2,4,14] and magnetic x-ray-diffraction[2] measurements at low temperatures revealed that the superconductivity coexists with the antiferromagnetic order. Combined elastic neutron-scattering[15] and specific-heat measurements[16] under hydrostatic pressure showed a direct relation between the size of the weak ordered moment and the splitting of the superconducting transition temperatures $\Delta T_c = T_c^+ - T_c^-$. By applying a pressure of 3–4 kbars, the antiferromagnetic order is fully suppressed and the two superconducting transition temperatures merge. In order to describe the exotic superconducting phase diagram, several scenarios have been proposed.[17–20] In most scenarios[17–19] the double transition is caused by a symmetry-breaking field that lifts the degeneracy of the components of a vector order parameter within a single symmetry representation. The most likely candidate for the symmetry-breaking field is the weak antiferromagnetic order, as the magnetic order lowers the symmetry of the system. Recent small-angle neutron scattering measurements[21] of the superconducting flux-line lattice in an applied magnetic field along the *c* axis demonstrated the unconventional nature of the superconductivity and assigned the symmetry of the superconducting gap function to the E_{2u} representation.

In view of the important implications to the understanding of the superconductivity, Lussier *et al.*[22] studied the effect of an applied magnetic field within the basal plane on the antiferromagnetic order. Their elastic neutron-scattering measurements at $T = 1.8$ K showed no change in the antiferromagnetic order and, in particular, no significant domain repopulation for applied magnetic fields up to 3.2 T ($B||a$), which includes the entire field range of interest for the superconductivity ($B_{c2} = 2.2$ T).[11–13] In order to explain the absence of domain repopulation for magnetic fields within the basal plane ($B||a$), Lussier *et al.*[22] proposed the existence of a triple-*k* structure. The question whether the magnetic order corresponds to a single-*k* or a triple-*k* structure is crucial for the understanding of the unconventional superconductivity because the magnetic order determines the symmetry of the system. Additional elastic neutron-scattering measurements in applied magnetic fields up to 12 T ($B||a$ and $B||c$) (Ref. 23) did not show a significant change in the magnetic structure or the ordered moment. This is compatible with a triple-*k* structure but does not exclude a single-*k* structure since the energy gain of a domain repopulation is relatively small for ordered moments of $0.02\mu_B$/(U atom).

An alternative method to study whether the magnetic order corresponds to a single-*k* or a triple-*k* structure is to apply uniaxial pressure in the hexagonal plane. A triple-*k* structure is expected to be rather insensitive to applied uniaxial pressure,[24] while a single-*k* structure is expected to show a domain repopulation for uniaxial pressure in the basal plane. Due to the small size of the ordered moment, its pressure dependence is difficult to measure and has only been determined by elastic neutron-scattering measurements under hydrostatic pressure.[15]

In order to study the uniaxial pressure dependence of the weak antiferromagnetic order, we performed elastic neutron-scattering measurements under pressure up to 6 kbars for $p||a$ and $p||c$. The applied pressure along the *a* axis allows us to study a possible domain repopulation and possibly distinguish a single-*k* structure from a triple-*k* structure. If a sizable domain repopulation is indeed observed for applied pressure along the *a* axis, a triple-*k* structure can be excluded for the antiferromagnetic order with important implications for the unconventional superconductivity.

II. EXPERIMENTAL PROCEDURE

The neutron-scattering experiments were performed on two high quality single crystals prepared under ultrahigh vacuum by the Czochralski technique and annealed for 5 days at a temperature of 950 °C. The first sample, used for pressure experiments along the *c* axis, was a cube of $5\times5\times5$ mm^3 with a mass of 3 g. The second sample, used for pressure experiments along the *a* axis, had a thickness of 1.7 mm, a surface area of 30 mm^2, and a mass of 1 g. For both samples the surfaces, where the uniaxial pressure was applied, were parallel within 0.1°. Resistivity measurements confirmed the good crystal quality, with a residual resistance ratio of RRR≈600 for an electrical current along the *c* axis in both samples. The superconducting transition temperature of both samples was $T_c^+ = 0.55$ K.

The antiferromagnetic order in UPt_3 was studied by elastic neutron-scattering measurements on the cold triple-axis spectrometer IN14 of the ILL. Pyrolytic graphite (002) planes were used as both monochromator and analyzer. We used an initial wave vector of $k_i = 1.48$ Å^{-1}, a collimation of 37′-40′-40′-60′ in the horizontal scattering plane, and a beryllium filter before the sample. The crystals were mounted in a uniaxial pressure cell and aligned with, respectively, the *a* axis (1-g sample) and the *c* axis (3-g sample) along the vertically applied uniaxial pressure. The sample was placed between two stainless steel spacers with a similar surface area as the sample.

The uniaxial stress was applied with a hydraulic press (at room temperature) via a stainless steel rod and a knee-joint placed at low temperature to the faces of the sample. This system allows for changing the pressure without heating the pressure cell. During the experiment the force applied by the hydraulic press was measured continuously with a calibrated piezoelectric sensor. After each change of force, a small pressure drift was observed, which remained within 4% of the total force during all measurements. In order to reduce the background, care was taken to avoid that the direct beam hit any of the pillars of the pressure cell or the vertical faces of the spacers, using cadmium where necessary.

III. RESULTS

Measurements of the magnetic Bragg-peak intensity were performed under applied pressures up to 6 kbars for $p||a$ and $p||c$. In both cases the uniaxial pressure is applied perpendicular to the scattering plane (**a***-**c*** for $p||a$ and **a***-**b*** for $p||c$). For pressures along the *c* axis scans through the magnetic Bragg peak at $\mathbf{Q} = (3/2,-1/2,0)$ along $\mathbf{k} = (1/2,-1/2,0)$ and perpendicular to **k** were performed. In Fig. 1, such scans along **k** are shown for applied pressures along the *c* axis of $p = 0.37$ and 2.54 kbars at $T = 1.6$ K. Under a pressure of 2.54 kbars the Bragg peak intensity, which is proportional to the square of the ordered moment, is strongly suppressed. Similar scans through the magnetic Bragg peak at $\mathbf{Q} = (0,1/2,2)$ along **c*** have been performed for pressure along the *a* axis at $T = 1.7$ K.

The pressure dependence of the integrated intensity of the magnetic Bragg peak is shown in Fig. 2 for $p||a$ and $p||c$.

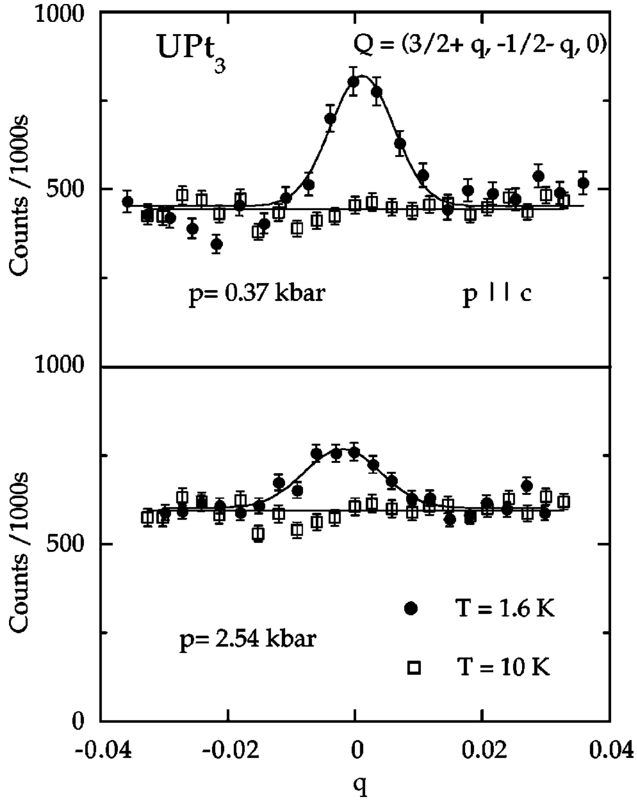

FIG. 1. Magnetic Bragg peak intensity at $\mathbf{Q}=(3/2+q,-1/2-q,0)$ as a function of q under an applied pressure of $p=0.37$ and 2.54 kbars for $p||c$ at $T=1.6$ K. For comparison, high-temperature scans ($T>T_N$) are also shown.

The integrated intensity of the magnetic Bragg peak was normalized to the weak nuclear Bragg reflection at $\mathbf{Q}=(1,1,0)$ for $p||c$ and $\mathbf{Q}=(1,0,1)$ for $p||a$. For applied pressures along the c axis the magnetic Bragg peak intensity at $\mathbf{Q}=(3/2,-1/2,0)$ along $\mathbf{k}=(1/2,-1/2,0)$ shows a nonlinear decrease for increasing pressure and remains finite up to the maximum applied pressure of $p=5.70$ kbars. Similar results have been obtained for the scans perpendicular to $\mathbf{k}$. In order to make sure that all three magnetic domains show the same pressure dependence for $p||c$ we have performed scans through the magnetic Bragg peaks at $\mathbf{Q}=(3/2,-1/2,0)$, (1,1/2,0), and (1/2,1,0) along their respective $\mathbf{k}$ vectors at $p=0.37$ and 4.10 kbars. For applied pressures along the a axis a significant increase in the relative integrated intensity is observed. The observed pressure dependence is nonlinear and the increase does not reach a factor 3 at the maximum applied pressure of $p=6.10$ kbars along the a axis, as would be expected for a complete domain repopulation and a constant moment. For comparison the data from earlier elastic neutron-scattering measurements[15] under hydrostatic pressure are shown in Fig. 2. For pressures up to 2 kbars the pressure dependence of the relative integrated intensity for hydrostatic pressure is similar to the uniaxial pressure dependence along the c axis, while for higher pressures a stronger suppression is observed for hydrostatic pressure.

In Fig. 3 the full width at half maximum of the scans through the magnetic Bragg peaks at $\mathbf{Q}=(0,1/2,2)$ and $\mathbf{Q}=(3/2,-1/2,0)$ is shown as a function of applied pressure for respectively $p||a$ and $p||c$. The scans were performed along $\mathbf{c}^*$ at $\mathbf{Q}=(0,1/2,2)$ and along $\mathbf{k}=(1/2,-1/2,0)$ at $\mathbf{Q}=(3/2,-1/2,0)$. It is interesting to note that the full width at

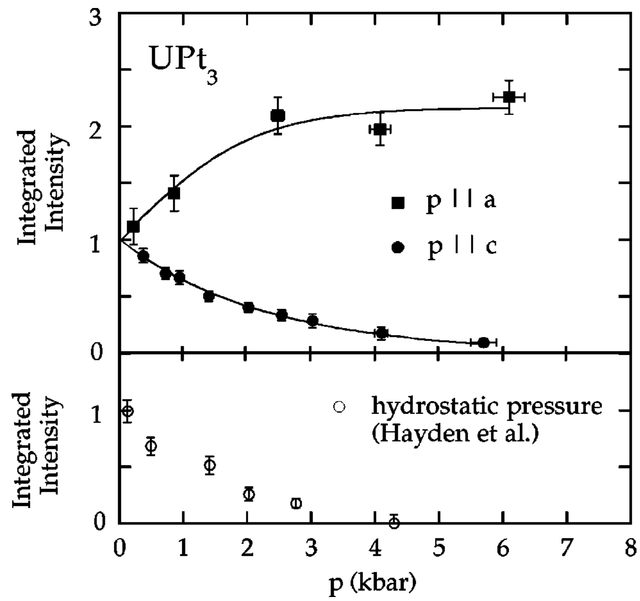

FIG. 2. Relative integrated intensity of the magnetic Bragg peaks at $\mathbf{Q}=(3/2,-1/2,0)$ and $\mathbf{Q}=(0,1/2,2)$ as a function of applied pressure for $p||c$ and $p||a$, respectively. The data points for $p||a$ (solid squares) and $p||c$ (solid circles) are normalized to the extrapolated zero-pressure value and compared with the earlier measurements under hydrostatic pressure (open circles) of Hayden *et al.* (Ref. 15). The lines are fits to Eqs. (2) and (3) for $p||c$ and $p||a$, respectively. The error bars for the pressure ($p||a$ and $p||c$) are a measure for the maximum drift during the experiment.

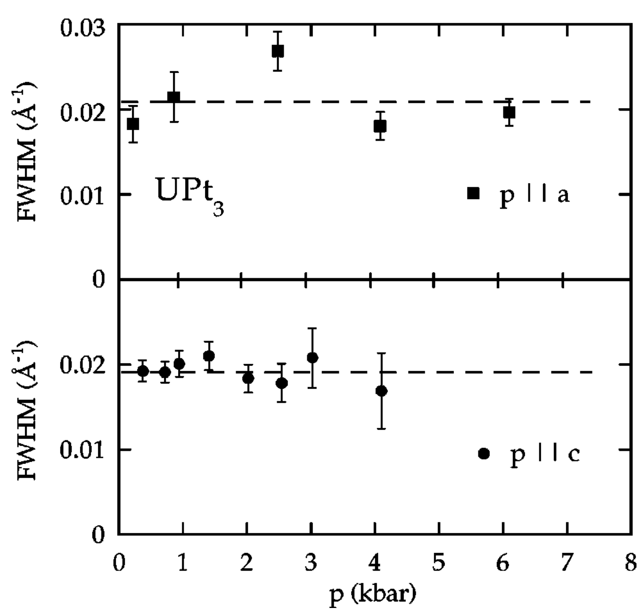

FIG. 3. Full width at half maximum of scans though the magnetic Bragg peaks at $\mathbf{Q}=(3/2,-1/2,0)$ along $\mathbf{k}=(1/2,-1/2,0)$ and at $\mathbf{Q}=(0,1/2,2)$ along $\mathbf{c}^*$ as a function of applied pressure for $p||c$ and $p||a$, respectively.

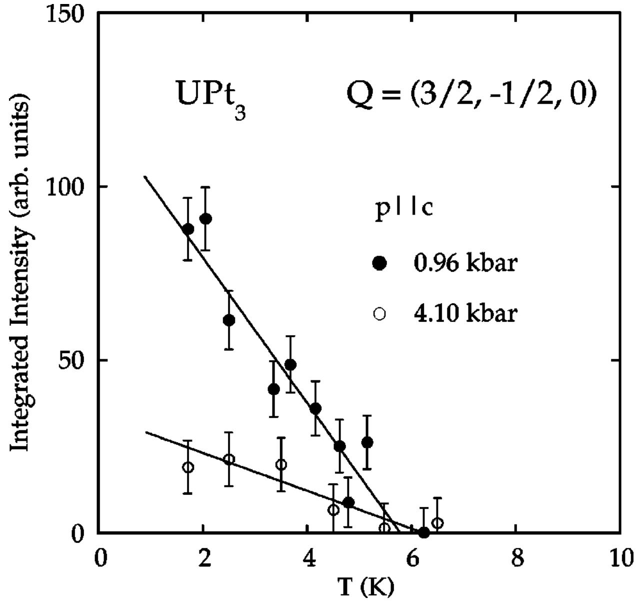

FIG. 4. Temperature dependence of the integrated intensity of the magnetic Bragg peak at $\mathbf{Q}=(3/2,-1/2,0)$ under an applied pressure of $p=0.96$ and 4.10 kbars along the c axis.

half maximum, and therefore the finite correlation length for the antiferromagnetic order of $\xi \approx 250$–500 Å, is insensitive to the applied pressure for $p||a$ and $p||c$. Additional scans through the magnetic Bragg peak at $\mathbf{Q}=(3/2,-1/2,0)$ perpendicular to **k** confirm that the full width at half maximum is insensitive to applied pressure along the c axis.

The temperature dependence of the integrated intensity of the magnetic Bragg peak at $\mathbf{Q}=(3/2,-1/2,0)$ is shown in Fig. 4 for applied pressures of $p=0.96$ and 4.10 kbars along the c axis. Although a significant decrease in intensity is observed with increasing pressure, the Néel temperature is hardly affected by the applied pressure. The values of the Néel temperature derived from temperature scans such as those shown in Fig. 4 are listed in Table I for $p||a$ and $p||c$. The absence of a significant pressure dependence of T_N is in good agreement with the results of earlier elastic neutron-scattering measurements under hydrostatic pressure[15] and was also found for measurements in magnetic fields up to 12 T.[23]

IV. ANALYSIS AND DISCUSSION

In Fig. 2 our present result for the uniaxial pressure dependence of the magnetic Bragg peak intensity is compared with the data from earlier elastic neutron-scattering measurements under hydrostatic pressure.[15] It is important to note that the observed hydrostatic pressure dependence of the magnetic Bragg peak intensity ($I \propto m^2$) cannot be derived from the present results of the uniaxial pressure dependence along the a and the c axes via the expression $d[\ln(m^2)]/dp = 2d[\ln(m^2)]/dp_a + d[\ln(m^2)]/dp_c$, which would be valid for an isotropic pressure dependence of the ordered moment m in the basal plane. Apparently, the magnetic domain structure is significantly modified by an applied pressure along the a axis as the uniaxial pressure breaks the sixfold symmetry in the basal plane. For pressures up to 2 kbars the pressure dependence of the relative integrated intensity for hydrostatic pressure is similar to the uniaxial pressure dependence along the c axis ($d[\ln(m^2)]/dp \approx d[\ln(m^2)]/dp_c$). This clearly indicates that the pressure dependence of the magnetic Bragg peak intensity along the a axis is mainly caused by the induced symmetry breaking in the basal plane.

The pressure dependence of the magnetic Bragg peak for $p||c$ shows an unusual strongly nonlinear suppression for increasing pressure (Fig. 2). If we assume a linear pressure dependence for the ordered moment up to a critical pressure p_{cr} of the form $m(p)=m(0)[1-p/p_{cr}]$, then the magnetic Bragg peak intensity $I(p) \propto m(p)^2$ is described by

$$I(p)=I(0)[1-p/p_{cr}]^2. \qquad (1)$$

A fit of the relative integrated intensity $I(p)/I(0)$ for $p||c$ yields a critical pressure of $p_{cr}=7.3(5)$ kbars, which is beyond the maximum applied pressure of $p=5.70$ kbars. A much better fit is however obtained if we assume an exponential pressure dependence for the ordered moment m of the form $m(p)=m(0)\exp(-\alpha p)$. The magnetic Bragg peak intensity $I(p)$ is then described by

$$I(p)=I(0)\exp(-2\alpha p). \qquad (2)$$

In Fig. 2(a) fit of the relative integrated intensity $I(p)/I(0)$ for $p||c$ is shown with a value of $\alpha=0.22(1)$ kbars^{-1}. An exponential pressure dependence for the ordered moment would imply that the weak antiferromagnetic order does not show a critical pressure for the suppression of the ordered moment.

In order to check that the observed nonlinear pressure dependence for $p||c$ does not originate from an inhomogeneous pressure distribution inside the sample we have performed finite-element calculations. In these calculations we have assumed elastic deformations and an infinite surface friction (fixed surface). As a consequence of the infinite surface friction enhanced stresses develop in a small region around the surface edges. The regions within 0.5 mm from the surface are, however, shielded in our experiment by cadmium in order to reduce the background. In the remaining volume of the sample the variation in stress along the c axis remains within 20% of the average value and cannot cause a significant nonlinear pressure dependence of the magnetic Bragg peak intensity as a function of the applied pressure.

TABLE I. Pressure dependence of the Néel temperature T_N of the weak antiferromagnetic order of UPt_3 for $p||a$ and $p||c$.

$p\|\|a$ (kbars)	$p\|\|c$ (kbars)	T_N (K)
	0.37	6.3(4)
	0.96	5.8(4)
	4.10	6.1(7)
4.08		5.6(5)

Although the pressure dependence of the relative integrated intensity of the magnetic Bragg peak is qualitatively the same for $p||c$ and hydrostatic pressure in the low-pressure region, the situation at higher pressures is less clear. Hayden *et al.*[15] reported that the magnetic order was completely suppressed at a hydrostatic pressure of 4 kbars, while our present results for $p||c$ indicate a significantly higher critical pressure. The experimental results of Hayden *et al.* do, however, not exclude a higher critical pressure in case of a nonlinear hydrostatic pressure dependence, as neutron-scattering measurements under hydrostatic pressure have limited sensitivity.

A comparison of the hydrostatic pressure dependence of the magnetic Bragg peak intensity $I \propto m^2$, measured by elastic neutron scattering,[15] and the splitting in the superconducting transition temperatures ΔT_c, measured by specific-heat measurements[16] indicated a direct relation ($\Delta T_c \propto m^2$). This relation was later qualitatively supported by combined elastic neutron-scattering and specific-heat experiments on single-crystalline UPt_3 doped with small concentrations of Pd.[25] For small concentrations ($<0.6\%$) of Pd doping both the magnetic Bragg peak intensity and the splitting in the superconducting transition temperatures increase for increasing Pd concentrations, but show some deviation from the simple $\Delta T_c \propto m^2$ relation.

It is interesting to compare our present experimental data of m^2 under pressure along the c axis with measurements of ΔT_c under pressure along the c axis assuming a direct proportionality between ΔT_c and m^2. Specific-heat[26,27] and sound-velocity[13] measurements for $p||c$ indicate a suppression of ΔT_c for increasing pressure with a critical pressure of $p_{cr} \approx 2$ kbars. These experiments are, however, rather insensitive for small values of ΔT_c as the width $\delta T_c^{\pm}$ of each of the superconducting transitions T_c^+ and T_c^- is relatively large compared to the initial splitting in T_c: $\delta T_c^{\pm} \approx 10$ mK and $\Delta T_c \approx 55$ mK at $p=0$ kbars.[26,27] When the magnetic Bragg peak intensity is reduced by a factor 3 with respect to its value at zero pressure the two superconducting transitions at T_c^+ and T_c^- cannot be distinguished individually. It can therefore not be excluded that the critical pressure is significantly higher for a nonlinear pressure dependence.

Our present experimental data for the magnetic Bragg peak intensities for $p||c$ indicate a nonlinear pressure dependence of m^2 with a critical pressure beyond the maximum applied pressure of 5.70 kbars. This has important consequences for our understanding of the superconducting phase diagram. It can either imply that the critical pressure for ΔT_c is in fact much higher than the established value of $p_{cr} \approx 2$ kbars, or that the weak antiferromagnetic order is not the origin for the splitting in T_c. Due to the weak sensitivity of both specific-heat and sound-velocity measurements to resolve a small splitting in T_c, the most likely scenario is that the critical pressure for ΔT_c is much higher than the established value of $p_{cr} \approx 2$ kbars. The excellent fit of the experimental data in Fig. 2 to an exponential pressure dependence [Eq. (2)] even suggests the absence of a critical pressure and a continuous suppression of ΔT_c for increasing pressure along the c axis. This would also imply that in zero field the low-temperature phase ($T<T_c^-$) remains stable for all pressures along the c axis and does not show a transition to the high-field phase at the critical pressure. This phase transition was deduced from sound-velocity measurements in magnetic field under uniaxial pressure ($B||p||c$).[13]

For applied pressures along the a axis the magnetic Bragg peak intensity in Fig. 2 shows an initial increase at low pressure and a saturation at high pressure, which can either be ascribed to an increase in the ordered moment or by a repopulation of magnetic domains. From a comparison of the uniaxial and hydrostatic pressure dependence of the magnetic Bragg peak intensity we concluded that the observed pressure dependence along the a axis is mainly due to the induced symmetry breaking in the basal plane. If we further assume that $m^2 \propto \Delta T_c$ and recall that according to specific-heat experiments[26] ΔT_c is independent of pressure for $p||a$, we can conclude that the ordered moment is insensitive to pressure along the a axis. As a consequence, the large increase in the relative Bragg peak intensity is not related to an increase in the ordered moment but suggests a repopulation of magnetic domains for applied pressure along the a axis. Unfortunately, this repopulation cannot be proven since for an applied pressure along the a axis and perpendicular to the scattering plane, the magnetic Bragg peaks of the other two domains are not accessible in our experimental setup.

For a complete domain repopulation and a constant moment, a factor 3 increase in the integrated intensity is expected at the maximum applied pressure of $p=6.10$ kbars. The domain population for the energetically most favorable domain is given by $a_o = 1/[1+2\exp(-\Delta E/k_B T)]$, where ΔE is the energy difference between the domains, k_B the Boltzmann factor, and T the temperature. For an incomplete domain repopulation with $\Delta E = \epsilon p$, the relative magnetic Bragg peak intensity $I(p)$ can be expressed as

$$I(p) = I(0)\,\frac{3}{(1+\delta)+(2-\delta)\exp(-\beta p)}, \tag{3}$$

where δ and $\beta = \epsilon/k_B T$ are phenomenological constants. A fit of the experimental data for $p||a$ in Fig. 2 gives $\delta = 0.38(8)$ and $\beta = 1.0(3)$ kbars^{-1}. The saturation value of the relative intensity for the incomplete domain repopulation corresponds to $I(\infty)/I(0) = 3/(1+\delta) = 2.2(1)$, while the energy difference between the domains per unit pressure is given by $\epsilon = \Delta E/p = \beta k_B T = 0.14(4)$ meV/kbar at $T = 1.6$ K. For an applied pressure along the a axis the crystal structure is slightly distorted and the hexagonal symmetry is broken. The in-plane distortion of the crystal structure, which is governed by the compressibilities s_{11} and s_{12}, lifts the degeneracy of the three magnetic domains and causes a domain repopulation.

The presence of an incomplete domain repopulation for $p||a$ has consequences for the magnetic structure of UPt_3. The antiferromagnetic order of UPt_3 determined by elastic neutron-scattering measurements in zero pressure[2,14] has three equivalent propagation vectors: $\mathbf{k} = (1/2,0,0)$, $(0,1/2,0)$, and $(-1/2,1/2,0)$. The magnetic structure is therefore in principle consistent with three different scenarios: a single-k, double-k, and triple-k structure. Both the single-k and double-k structures have three magnetic domains, while a triple-k structure does not have magnetic domains. As the triple-k structure is rather insensitive to applied uniaxial pressure[24] the most likely scenario is the presence of a single-k structure with three magnetic domains (although the double-k structure cannot be excluded).

One of the main questions related to the weak antiferromagnetic order of UPt_3 is whether the magnetic peaks observed in elastic neutron scattering describe static moments with a finite correlation length or slow fluctuations. In the case of static magnetic moments the long-range antiferromagnetic order would be limited to a finite correlation length by a relatively large density of structural defects which act as pinning sites for the magnetic domain walls. Transmission-electron microscopy[28,29] and x-ray-diffraction[28] measurements have indeed shown a relative large density of stacking faults which can take up to 3% of the sample volume of single-crystalline samples. A subsequent transmission-electron microscopy (TEM) study[30] even reported the presence of an incommensurate structural modulation. Similar effects have also been reported in a more recent TEM investigation on whiskers.[31] A serious problem with the reported incommensurate structural modulation is, however, that one cannot exclude the possibility that it is induced by the sample preparation for the TEM studies.[31] Recent small-angle neutron scattering measurements along the c axis of a high-quality single crystal[21] showed a strong defect scattering along the $\mathbf{a}^*$ axes. All the experimental evidence indicates that the presence of structural defects is inherent to the system and also exists in the highest quality samples. The absence of a domain repopulation in elastic neutron-scattering measurements in applied magnetic fields in the basal plane[22] has been claimed to prove a strong pinning of magnetic domain walls. For an applied pressure in the basal plane we have observed a significant increase in the magnetic Bragg peak intensity, which can be related to a domain repopulation. This domain repopulation does, however, not lead to a change in the magnetic correlation length as shown in Fig. 3.

If the magnetic signal below 6 K is in fact not static, but corresponds to slow magnetic fluctuations, as recently proposed by Fomin and Flouquet[9] and Okuno and Miyake,[10] then a weak pressure and field dependence is expected as only the excitation spectrum of the fluctuations is modified. The strongest support for slowly fluctuating moments is that no sign of antiferromagnetic order has been observed in nuclear magnetic resonance[32] and muon-spin resonance measurements in zero field.[3] Both techniques are extremely sensitive to small magnetic moments, but on longer time scales than neutron scattering. High-resolution neutron spin-echo measurements could in principle distinguish between slowly fluctuating and static moments, but have not yet been successful for UPt_3.[33] The scenario of slow fluctuations is supported by the observation that the onset temperature of the magnetic signal (T_N) is insensitive to hydrostatic pressures up to 4 kbars (Ref. 15) and magnetic fields up to 12 T.[23]

In our present experiments we confirm that T_N is also insensitive to uniaxial pressures for $p||a$ and $p||c$, as indicated in Fig. 4 and Table I. Further, we find that the magnetic correlation length is insensitive to applied uniaxial pressure for $p||a$ and $p||c$. Even the incomplete domain repopulation observed for $p||a$ does not lead to an enhancement in the magnetic correlation length, as would be expected for static order. In high magnetic fields the magnetic correlation length also remained constant up to 10 T for $B||a$ and $B||c$.[23] In addition, the pressure (Fig. 2) and temperature[1,2,7] dependence of the magnetic Bragg peak intensity is rather unusual for static order. The observed anomalous behavior, which strongly deviates from the magnetic response for static order, can be regarded as indirect evidence for the presence of slowly fluctuating moments.

Additional support for the existence of slow fluctuations is found in elastic neutron-scattering measurements at low temperatures,[4] which show a decrease in the width of the magnetic Bragg peak below 50 mK until it becomes resolution limited below 20 mK. This can be favorably interpreted as a transition from slow fluctuations to static long-range antiferromagnetic order. Recent nuclear magnetic resonance measurements at low temperatures[34] indeed show an anomaly below 50 mK, suggesting a slowing down of the antiferromagnetic fluctuations, but indicate also that the antiferromagnetic order is not yet static down to 15 mK. Recent muon-spin resonance experiments[3] have shown that the clear sign of weak antiferromagnetic order observed in applied magnetic field vanishes in zero field. This can be explained by the presence of slowly fluctuating moments. One cannot, however, exclude the existence of static order when the local dipolar magnetic field at the stopping site for the muon is canceled by the symmetry of the surrounding magnetic moments. In either case an applied magnetic field causes a distortion of the magnetic structure, which then produces a local dipolar magnetic field. Further low-temperature muon experiments ($T<50$ mK) are desirable to clarify the situation. In the scenario with static moments where the finite correlation length for the antiferromagnetic order is caused by structural defects, the pinning of the magnetic domain walls would need to become less effective below 50 mK in order to explain the increase in magnetic correlation length. It is difficult to imagine what the origin for such a weakening of the magnetic domain-wall pinning would be without assuming drastic changes in the magnetic structure at low temperatures. The most likely scenario for the magnetic structure of UPt_3 is therefore the presence of slowly fluctuating moments which fluctuate with frequencies in the range between those of nuclear magnetic resonance (~ 1 MHz) and neutron-scattering (~ 1 GHz) measurements.

V. CONCLUSIONS

In conclusion, we have measured the weak ordered moment of UPt_3 using elastic neutron scattering under uniaxial pressures up to 6 kbars for $p||a$ and $p||c$. For $p||c$ the small antiferromagnetically ordered moment of 0.02 μ_B/U atom shows a nonlinear decrease for increasing pressures and is still not completely suppressed at the maximum applied pressure of 6 kbars. For $p||a$ a significant increase in the magnetic Bragg peak intensity is observed, which suggests an incomplete domain repopulation and confirms the presence of a single-*k* structure. The nonlinear pressure dependence of the antiferromagnetic order along the *c* axis has direct consequences for the superconducting phase diagram when the weak antiferromagnetic order acts as a symmetry-breaking field. While direct measurements of the splitting in the superconducting transition ΔT_c seem to indicate a critical pressure of about 2 kbars for pressure along the *c* axis, our present results suggest that the two superconducting transition temperatures do not merge for pressures up to 6 kbars.

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[1] G. Aeppli, E. Bucher, C. Broholm, J.K. Kjems, J. Baumann, and J. Hufnagl, Phys. Rev. Lett. **60**, 615 (1988).
[2] E.D. Isaacs, P. Zschack, C.L. Broholm, C. Burns, G. Aeppli, A.P. Ramirez, T.T.M. Palstra, R.W. Erwin, N. Stücheli, and E. Bucher, Phys. Rev. Lett. **75**, 1178 (1995).
[3] A. Yaouanc, P. Dalmas de Réotier, F.N. Gygax, A. Schenk, A. Amato, C. Baines, P.C.M. Gubbens, C.T. Kaiser, A. de Visser, R.J. Keizer, A. Huxley, and A.A. Menovsky, Phys. Rev. Lett. **84**, 2702 (2000).
[4] Y. Koike, N. Metoki, N. Kimura, E. Yamamoto, Y. Haga, Y. Onuki, and K. Maezawa, J. Phys. Soc. Jpn. **67**, 1142 (1998).
[5] E.A. Schuberth, B. Strickler, and K. Andres, Phys. Rev. Lett. **68**, 117 (1992).
[6] S. Schöttl, E.A. Schuberth, K. Flachbart, J.B. Kycia, J.I. Hong, D.N. Seidman, W.P. Halperin, J. Hufnagl, and E. Bucher, Phys. Rev. Lett. **82**, 2378 (2000).
[7] R.J. Keizer, A. de Visser, A.A. Menovsky, J.J.M. Franse, B. Fåk, and J.M. Mignot, Phys. Rev. B **60**, 6668 (1999).
[8] R.J. Keizer, A. de Visser, A.A. Menovsky, J.J.M. Franse, A. Amato, F.N. Gygax, M. Pinkpank, and A. Schenck, J. Phys.: Condens. Matter **11**, 8591 (2000).
[9] I.A. Fomin and J. Flouquet, Solid State Commun. **98**, 795 (1996).
[10] Y. Okuno and K. Miyake, J. Phys. Soc. Jpn. **67**, 3342 (1998).
[11] S. Adenwalla, S.W. Lin, Q.Z. Ran, Z. Zhao, J.B. Ketterson, J.A. Sauls, L. Taillefer, D.G. Hinks, M. Levy, and B.K. Sarma, Phys. Rev. Lett. **65**, 2298 (1990).
[12] N.H. van Dijk, A. de Visser, J.J.M. Franse, and L. Taillefer, J. Low Temp. Phys. **93**, 101 (1993).
[13] M. Boukhney, G.L. Bullock, B.S. Shivaram, and D.G. Hinks, Phys. Rev. Lett. **73**, 1707 (1994).
[14] G. Aeppli, D. Bishop, C. Broholm, E. Bucher, K. Siemesmeyer, M. Steiner, and N. Stüsser, Phys. Rev. Lett. **63**, 676 (1989).
[15] S.M. Hayden, L. Taillefer, C. Vettier, and J. Flouquet, Phys. Rev. B **46**, 8675 (1992).
[16] T. Trappmann, H.v. Löhneysen, and L. Taillefer, Phys. Rev. B **43**, 13 714 (1991).
[17] J. Sauls, Adv. Phys. **43**, 113 (1994).
[18] R. Joynt, Phys. Rev. Lett. **71**, 3015 (1993).
[19] K. Machida and M. Ozaki, Phys. Rev. Lett. **66**, 3293 (1991); K. Machida, T. Ohmi, and M. Ozaki, J. Phys. Soc. Jpn. **62**, 3216 (1993).
[20] D.-C. Chen and A. Garg, Phys. Rev. Lett. **70**, 1689 (1993); A. Garg and D.-C. Chen, Phys. Rev. B **49**, 479 (1994).
[21] A. Huxley, P. Rodière, D.McK. Paul, N. van Dijk, R. Cubitt, and J. Flouquet, Nature (London) **406**, 160 (2000).
[22] B. Lussier, L. Taillefer, W.J.L. Buyers, T.E. Mason, and T. Petersen, Phys. Rev. B **54**, R6873 (1996).
[23] N.H. van Dijk, B. Fåk, L.P. Regnault, A. Huxley, and M.-T. Fernández-Díaz, Phys. Rev. B **58**, 3186 (1998).
[24] J. Rossat-Mignod, G.H. Lander, and P. Burlet, in *Handbook on the Physics and Chemistry of Actinides*, edited by A.J. Freeman and G.H. Lander (Elsevier, Amsterdam, 1984), Vol. 1, p. 415.
[25] R.J. Keizer, A. de Visser, M.J. Graf, A.A. Menovsky, and J.J.M. Franse, Phys. Rev. B **60**, 10 527 (1999).
[26] D.S. Jin, S.A. Carter, B. Ellman, T.F. Rosenbaum, and D.G. Hinks, Phys. Rev. Lett. **68**, 1597 (1992).
[27] D.S. Jin, A. Husmann, T.F. Rosenbaum, T.E. Steyer, and K.T. Faber, Phys. Rev. Lett. **78**, 1775 (1997).
[28] M.C. Aronson, R. Clarke, B.G. Demczyk, B.R. Coles, J.L. Smith, A. de Visser, T. Vorenkamp, and J.J.M. Franse, Physica B **186-188**, 788 (1993).
[29] B.G. Demczyk, M.C. Aronson, B.R. Coles, and J.L. Smith, Philos. Mag. Lett. **67**, 85 (1993).
[30] P.A. Midgley, S.M. Hayden, L. Taillefer, B. Bogenberger, and H.v. Löhneysen, Phys. Rev. Lett. **70**, 678 (1993).
[31] B. Ellman, A. Zaluska, and L. Taillefer, Physica B **205**, 346 (1995).
[32] H. Tou, Y. Kitaoka, K. Asayama, N. Kimura, Y. Onuki, E. Yamamoto, and K. Maezawa, Phys. Rev. Lett. **77**, 1374 (1996).
[33] B. Fåk, B. Farago, and N.H. van Dijk, Physica B **259-261**, 644 (1999).
[34] Y. Kitaoka, H. Tou, K. Ishida, N. Kimura, Y. Onuki, E. Yamamoto, Y. Haga, and K. Maezawa, Physica B **281-282**, 878 (2000).