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Non-Fermi-liquid scaling in heavy-fermion UCu$_{3.5}$Al$_{1.5}$ and UCu$_3$Al$_2$

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We report on specific-heat, magnetic-susceptibility, high-field-magnetization, electrical-resistivity, and neutron-diffraction results on UCu$_{3.5}$Al$_{1.5}$ (polycrystal) and UCu$_3$Al$_2$ (polycrystal and single crystal). Our results indicate that both compounds crystallize in the hexagonal CaCu$_5$ structure with ordered UCu$_2$ planes separated by planes containing a statistical distribution of Al along with the remaining Cu atoms. At low temperatures, the specific heat and the magnetic susceptibility of both compounds are enhanced, but their temperature dependences are found to be distinct from expectations of Fermi-liquid theory. UCu$_{3.5}$Al$_{1.5}$ does not order magnetically, and the low-temperature specific heat and magnetic susceptibility show scaling behavior ($C/T \propto \ln(T)$ and $\chi \propto T^{-1/3}$) reminiscent of non-Fermi-liquid materials. For UCu$_3$Al$_2$, on the other hand, the low-temperature scaling of bulk properties is masked by an anomaly around 8–10 K, which is presumably of magnetic origin. Single-crystal studies of UCu$_3$Al$_2$ reveal a huge magnetic anisotropy with very different in-plane response compared to the $c$-axis response. Our data provide evidence that any temperature dependence of the magnetic susceptibility and electrical resistivity of polycrystalline material may be due to averaging anisotropic response over all crystallographic directions. The results are discussed in the context of findings from other non-Fermi-liquid materials.

I. INTRODUCTION

Heavy-fermion behavior found in a number of Ce-, Yb-, and U-based compounds has been studied extensively for almost two decades. For most heavy-fermion materials, the low-temperature properties are well described in terms of Fermi-liquid theory. In the limit $T \to 0$, the Fermi-liquid theory predicts large contributions to the specific heat ($\gamma \propto T$), the Pauli-like spin susceptibility ($\chi_0$), and the electrical resistivity ($\rho \propto T^2$) with temperature-independent parameters $\gamma$, $\chi_0$, and $A$. In general, heavy-fermion behavior may occur due to two different mechanisms: (a) the “screening” of a magnetic moment due to the Kondo effect and (b) magnetic-correlation effects. The former mechanism causes mass renormalization in a local-moment system, and the latter mechanism is applied to bandlike magnets (itinerant magnetism). Most heavy-fermion compounds are located at the borderline between local-moment and itinerant magnetism, and it is on that borderline where deviations from the Fermi-liquid behavior may be found. Recently, a number of materials, which display the so-called “non-Fermi-liquid behavior,” have attracted much attention. The hallmark for non-Fermi-liquid behavior is a divergence in the specific heat, i.e., $C/T \propto -\ln(T/T_0)$, but divergences are also expected in other bulk properties.

Up to now, non-Fermi-liquid behavior was achieved mainly in dilute systems, where some kind of disorder is introduced onto the crystal lattice. The role of disorder dif-
fers for the various scenarios (ranging from single-ion two-channel Kondo mechanism to collective effects) proposed for the occurrence of non-Fermi-liquid behavior.

The presently known non-Fermi-liquid materials fall into two categories: (a) the f-electron sublattice is dilated, and (b) the f-ion sublattice is kept intact, but its surrounding is changed by controlled substitutions. Examples of the former category are (U,Y)Pd$_3$ compounds\textsuperscript{3,5} and the (U,Th)Ru$_4$Si$_2$ system,\textsuperscript{6} while Ce(Cu,Au)$_6$ compounds\textsuperscript{7} and U(Cu,Pd)$_4$ representatives\textsuperscript{8} fall in the latter category. Non-Fermi-liquid scaling has been proposed for some compositions in all of the above systems, though sometimes different mechanisms have been proposed for its occurrence. Furthermore, while a logarithmic divergence of the specific heat is common to all of the above systems, quite different scaling behavior has been observed for UCu$_3$.5$Al$_{1.5}$ by neutron powder diffraction.

Recently, we have reported on the large enhancements in the low-temperature specific heat of a number of UCu$_{x}$Al$_{5-x}$ compounds,\textsuperscript{10} but little consideration was given to the origin of such enhancements. In the present paper, we argue whether the bulk properties of two members of this family, namely, UCu$_{3.5}$Al$_{1.5}$ and UCu$_3$Al$_2$, display a temperature behavior expected for non-Fermi-liquid materials.

In contrast to the cubic U(Cu,Pd)$_4$ compounds, UCu$_{x}$Al$_{5-x}$ compounds crystallize in the hexagonal CaCu$_4$ structure for 2.9\(\leq\)x\(\leq\)3.5. Therefore, magnetic (and transport) properties are expected to be anisotropic. Single-crystal studies of UCu$_3$Al$_2$ indeed reveal a huge magnetic anisotropy,\textsuperscript{11} and its consequences will be discussed here. For this compound, antiferromagnetic ordering below 8–10 K has been suggested on the basis of anomalies of the bulk properties at this temperature.\textsuperscript{10,11}

Our previous neutron-diffraction studies\textsuperscript{11} revealed that for UCu$_3$Al$_2$ the U atoms occupy the 1$a$ positions of the CaCu$_4$ structure and the 2$c$ positions are occupied by Cu atoms only, while a random distribution of Cu and Al atoms is found on the 3$g$ sites. The resultant structure, which is the same as reported for the two heavy-fermion superconductors UNi$_2$Al$_3$ and UPd$_2$Al$_3$,\textsuperscript{12} is shown in Fig. 1 and the structural parameters are given in Table I. Therefore, in UCu$_3$Al$_2$, perfectly ordered UCu$_3$ planes are separated by planes of statistically distributed Cu and Al atoms which exist in a Kagomé net.

Finally, we also present neutron diffraction on single-crystalline UCu$_{3}$Al$_{1.5}$ to gain some insight regarding the magnetic ground state, i.e., to clarify the origin of the anomaly around 8–10 K which is visible in the bulk properties.

### II. SAMPLE PREPARATION AND CHARACTERIZATION

Polycrystalline samples of UCu$_3$Al$_2$ and UCu$_{3.5}$Al$_{1.5}$ were prepared by arc melting stoichiometric amounts of the constituents with a purity of at least 99.9%. The buttons were encapsulated in quartz tubes under Ar atmosphere and were subsequently annealed for 2 months at 600 °C. For both samples, all reflections in the x-ray-diffraction patterns were indexed in the proper CaCu$_4$ structure. The absence of any unindexed peaks indicates an upper limit of impurity phases of about 5% for both samples. Electron microprobe analysis, however, revealed a small amount of a Cu-rich secondary phase in both samples, which was later identified as U$_2$Cu$_4$Al by means of neutron diffraction (see Sec. IV). The main phases, on the other hand, were found to exhibit compositions very close to the intended stoichiometry (within 3% of the elemental fractions).

In the case of UCu$_{3}$Al$_{1.5}$, we also tried to grow a single crystal using the Czochralski tri-arc method. We obtained an ingot, in which some almost single-crystalline parts with a small twinning were found. These ‘‘single crystals’’ were extracted from the material and subsequently annealed. Our best crystal, approximately 50 mg in mass, was checked by neutron diffraction on the Single Crystal Diffractometer (SCD) at the Intense Pulsed Neutron Source at Argonne National Laboratory. At room temperature, almost all of the observed reflections (more than 200) of that crystal were indexed in the appropriate CaCu$_4$ structure. However, we also found about 10 relatively weak unindexed reflections, which may indicate a small amount of an impurity phase to be present in the crystal. In addition, we found a large broadening for most reflections, and thus prevented a determination of the distribution of Cu and Al on the 2$c$ and 3$g$ sites due to the poor quality of our single crystal. A closer inspection, however, showed that crystal imperfections are mainly due to a large mosaicity within the hexagonal basal plane (with an angular spread of about 5$^\circ$), while the $c$-axis orientation is well defined. This does allow separation of the magnetic
contributions to the basal-plane and c-axis response. The crystal was used to check the magnetic properties and for the single-crystal neutron-diffraction experiment.

### III. BULK STUDIES

We studied the specific heat, the magnetic susceptibility, the high-field magnetization, and the electrical resistivity on polycrystals of UCu$_{3.5}$Al$_{1.5}$ and UCu$_3$Al$_2$. Furthermore, we report on the magnetic properties of single-crystalline UCu$_3$Al$_2$.

#### A. Specific heat

Specific-heat measurements between 300 mK and 1.2 K were performed in a $^3$He cryostat using the relaxation-time method. Between 1.2 and 50 K, the specific heat was measured using a semiadiabatic method in a different setup equipped with a superconducting 5-T coil.

The temperature dependences of the specific heat of UCu$_{3.5}$Al$_{1.5}$ and UCu$_3$Al$_2$ are shown in Fig. 3 as $C/T$ vs log $T$. For UCu$_{3.5}$Al$_{1.5}$, we find a logarithmic dependence of $C/T$ below 6 K. Such a dependence is usually taken as a signature of non-Fermi-liquid scaling. The low-temperature scaling of the specific heat of UCu$_3$Al$_2$, on the other hand, is masked by a maximum, which occurs around 8 K. The maximum may indicate the onset of magnetic correlations in UCu$_3$Al$_2$ at this temperature. Above 1.2 K, there was no change in either specific heat upon application of a magnetic field.

#### TABLE I. Refined structural parameters of UCu$_{3.5}$Al$_{1.5}$ and UCu$_3$Al$_2$.

<table>
<thead>
<tr>
<th></th>
<th>UCu$<em>{3.5}$Al$</em>{1.5}$</th>
<th>UCu$_3$Al$_2$</th>
</tr>
</thead>
<tbody>
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<td>Space group</td>
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<tr>
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<tr>
<td>$y$</td>
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<td>0</td>
</tr>
<tr>
<td>$z$</td>
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<td>0.33</td>
</tr>
<tr>
<td>fraction a</td>
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<td>1.00</td>
</tr>
<tr>
<td>U(1a)</td>
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<td></td>
</tr>
<tr>
<td>Cu(2c)</td>
<td>1/3</td>
<td>1/3</td>
</tr>
<tr>
<td>Cu(3g)</td>
<td>1/2</td>
<td>1/2</td>
</tr>
<tr>
<td>Al(3g)</td>
<td>1/2</td>
<td>1/2</td>
</tr>
<tr>
<td>$a$ (Å)</td>
<td>5.090(4)</td>
<td>5.145(4)</td>
</tr>
<tr>
<td>$c$ (Å)</td>
<td>4.159(3)</td>
<td>4.154(3)</td>
</tr>
<tr>
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<td>$R_p$</td>
<td>6.32%</td>
<td>3.60%</td>
</tr>
<tr>
<td>Reduced $\chi^2$</td>
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<td>4.698</td>
</tr>
<tr>
<td>$\chi^2$</td>
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<td>4.1515(1)</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>4.1611(1)</td>
<td>4.1515(1)</td>
</tr>
</tbody>
</table>

$^a$Fractions have been fixed to the exact stoichiometry for a better comparison.

$^b$X-ray data (taken from Ref. 10).

$^c$Neutron data obtained at the NIST research reactor (taken from Ref. 11).

![FIG. 2. Variation of the lattice parameters $a$ (○) and $c$ (△) vs copper content in UCu$_{3-x}$Al$_{x-3}$ compounds (after Ref. 10). Note that two CaCu$_5$-type phases appear in the diffraction pattern of UCu$_{3.3}$Al$_{1.7}$ with different sets of lattice parameters (open and solid symbols). The lines are guides to the eye.](image1)

![FIG. 3. Temperature dependence of the specific heat of UCu$_{3.5}$Al$_{1.5}$ (○) and UCu$_3$Al$_2$ (+). Note the logarithmic temperature scale. The dashed line is a straight-line fit to the low-temperature part of $C/T$ of UCu$_{3.5}$Al$_{1.5}$ and indicates the logarithmic temperature dependence.](image2)
field of 5 T. For higher temperatures ($T>15$ K), $C/T$ of UCu$_{3.5}$Al$_{1.5}$ is enhanced by about 70 mJ/K$^2$ mol compared to UCu$_3$Al$_2$. This may indicate a larger electronic contribution to the specific heat in the former compound.

**B. Magnetic susceptibility**

Between 1.4 and 300 K, the magnetic response of UCu$_{3.5}$Al$_{1.5}$ and UCu$_3$Al$_2$ in fields up to 1.3 T was measured by means of a pendulum magnetometer. At all temperatures, linear magnetization curves were found and we can therefore identify the magnetic susceptibility as the slope of the $M$ vs $H$ curve.

The results are shown in Fig. 4. UCu$_3$Al$_2$ exhibits a broad maximum slightly above 10 K, which is close to the temperature of the specific-heat maximum. For UCu$_{3.5}$Al$_{1.5}$, we find a flattening of the susceptibility around 20 K, which is followed by a strong divergence at lower temperatures. Above 50 K, we find Curie-Weiss behavior for both compounds with effective moments close to the free-ion values of $U^{3+}$ or $U^{4+}$ ($=3.6 \mu_B$). We have checked the field dependence of the magnetization of UCu$_{3.5}$Al$_{1.5}$ up to 18 T, at various temperatures, using a vibrating-sample magnetometer in the 20-T superconducting magnet at the Pulsed Field Facility of the NHMFL at Los Alamos National Laboratory. Up to the highest field applied, we find linear magnetizations at all temperatures. The $M/H$ values at 18 T of UCu$_{3.5}$Al$_{1.5}$ have been included as solid circles in Fig. 4.

Using a log-log representation in Fig. 5, we show the magnetic susceptibility of both polycrystals UCu$_{3.5}$Al$_{1.5}$ and UCu$_3$Al$_2$ (symbols in Fig. 5) and the single-crystal results on UCu$_3$Al$_2$ (solid lines in Fig. 5). We find that the low-temperature part of the susceptibility of UCu$_{3.5}$Al$_{1.5}$ is well described by a function of the form $a + b T^{-1/3}$ (dashed line in Fig. 5). Scaling of $\chi \propto T^{-1/3}$ was reported also for the non-Fermi-liquid compound UCu$_{3.5}$Pd$_{1.5}$. Here, however, we find that the low-temperature susceptibility consists out of temperature-independent and temperature-dependent contributions. This may indicate that both Fermi-liquid and non-Fermi-liquid contributions occur in the polycrystalline average. The magnetic susceptibility of polycrystalline UCu$_3$Al$_2$, on the other hand, does not show a temperature dependence expected for non-Fermi-liquid materials. However, comparison with the single-crystal results on UCu$_3$Al$_2$ clearly shows that any temperature dependence seen in polycrystals may be due to averaging anisotropic response over all crystallographic directions. While magnetic interactions dominate the response within the hexagonal basal plane and give rise to the maximum in the magnetic susceptibility, we find very different behavior for fields applied along the $c$ axis. The $c$-axis susceptibility is not only much weaker, but also shows very different behavior at low temperatures. In fact, we find that the $c$-axis susceptibility of UCu$_3$Al$_2$ diverges at low temperatures. This might imply that the $c$-axis susceptibility of UCu$_3$Al$_2$ shows traces of non-Fermi-liquid scaling, while magnetic correlations dominate the in-plane response. Note that only the interplanar interactions in this compound are affected by structural disorder, which might indicate that disorder is an essential ingredient for non-Fermi-liquid behavior in these compounds.

**C. High-field magnetization**

High-field-magnetization measurements on UCu$_{3.5}$Al$_{1.5}$ and UCu$_3$Al$_2$ were performed in the Amsterdam High-Field Facility. At this facility, controlled high-field pulses allow measurements of the magnetic response at any desired field shape within the fairly broad design limitations. Magnetization measurements up to 35 T are usually done in stepwise pulses, where fields are kept constant (within 3 mT) for at least 80 ms. In this way, the effect of eddy-current shielding in metallic samples can be minimized.

The magnetizations of UCu$_{3.5}$Al$_{1.5}$ and UCu$_3$Al$_2$ were measured on powdered particles (with a size smaller than...
100 μm) both free to be oriented by the applied field and in random orientations fixed by frozen alcohol. The former result ("free powder") is believed to represent the magnetic response along the easy magnetization direction, while the latter result ("fixed powder") simulates an "ideal" polycrystal. The difference between the free-powder and fixed-powder magnetizations can be taken as a measure of the magnetic anisotropy.

In Fig. 6, the free-powder and fixed-powder results for UCu$_{3.5}$Al$_{1.5}$ and UCu$_3$Al$_2$ at 4.2 K in fields up to 35 T are shown. While the magnetization curves of UCu$_3$Al$_2$ display a pronounced upturn at fields above 15 T, the opposite tendency is observed for UCu$_{3.5}$Al$_{1.5}$ above 30 T. At somewhat higher fields, some slight saturation tendency has been observed also for UCu$_3$Al$_2$, but, even in 50 T, no full saturation is achieved in either compound UCu$_{3.5}$Al$_{1.5}$ and UCu$_3$Al$_2$. For all fields, a higher response of the free-powder magnetization is seen in UCu$_{3.5}$Al$_{1.5}$ compared to UCu$_3$Al$_2$, which may indicate a larger saturated moment for the former compound. For both compounds, we find that the ratios of $M_{\text{fix}}/M_{\text{free}}$ at 35 T are larger than 0.8, which is indicative of multiaxial-type anisotropy in both compounds.

The results of the high-field-magnetization experiments (up to 38 T) on single-crystalline UCu$_3$Al$_2$ confirm a multiaxial type of anisotropy (see Fig. 7). At 4.2 K, the magnetization exhibits a slight S shape for fields within the basal plane, similar to the results for the heavy-fermion superconductor UPt$_3$. At the highest field (38 T), the magnetization is a little greater than 1 $\mu_B$/f.u. The c-axis response is much weaker, and we find values slightly above 0.3 $\mu_B$/f.u. in 38 T. Furthermore, there is no S-shape behavior along this direction.

**D. Electrical resistivity**

Between 300 mK and 300 K, the electrical resistivities were measured on two bar-shaped polycrystals of UCu$_{3.5}$Al$_{1.5}$ and UCu$_3$Al$_2$ using the standard four-point ac technique. The contacts were established using silver paint. As some small cracks were present in both samples, no accurate determination of absolute resistivity values was possible. Therefore, the resistivity values were normalized to the room-temperature values. The relative temperature dependences of the electrical resistivity of UCu$_{3.5}$Al$_{1.5}$ and UCu$_3$Al$_2$ are shown in Fig. 8 plotted against log T. Both are very unusual. Upon cooling from room temperature, the electrical resistivity of UCu$_{3.5}$Al$_{1.5}$ first increases with lowering temperature; then, it goes through a maximum around 30 K. At low temperatures, there is no evidence for a linear temperature dependence, the form that is often found in non-Fermi-liquid materials. Fermi-liquid behavior, on the other hand, is expected to display a $T^2$ dependence, which is clearly not observed. As shown in Fig. 8, fitting of the low-temperature part of $\rho(T)$ for UCu$_{3.5}$Al$_{1.5}$ implies a $T^{2/3}$ temperature scaling. One should, however, not overinterpret the exponent of 2/3 as the polycrystalline average of the anisotropic properties may, as was argued for the magnetic susceptibility, result in a peculiar temperature dependence.
Down to about 10 K, the overall shape of the electrical resistivity of UCu$_3$Al$_2$ is very similar to that of UCu$_{3.5}$Al$_{1.5}$. At this temperature, a minimum occurs in the electrical resistivity, and this coincides with the maxima in the temperature dependences of the specific heat and the magnetic susceptibility. Upon further lowering of the temperature, some saturation tendency is observed, but around 800 mK there is a sudden drop in electrical resistivity. At present, we have little idea about the origin of this anomaly. However, there is no evidence of an anomaly at this temperature in other bulk properties e.g., in the specific heat, and therefore we doubt that it is intrinsic to UCu$_3$Al$_2$. It might be due to some small amount of some impurity phase ~U$_2$Cu$_9$Al or elemental Al!.

IV. NEUTRON-DIFFRACTION RESULTS

Our previous neutron-diffraction studies were restricted to powders of UCu$_3$Al$_2$, and the results gave the crystal structure shown in Fig. 1. At low temperature, no additional magnetic peaks were observed, and an upper limit of 0.4$\mu_B$ for the size of any ordered moment at low temperatures was estimated.

In this paper we discuss the crystal structure of UCu$_{3.5}$Al$_{1.5}$ measured by neutron powder diffraction, and we also looked for magnetic moments smaller than 0.4$\mu_B$ in UCu$_3$Al$_2$ by neutron diffraction on a single crystal.

A. Neutron powder diffraction on UCu$_{3.5}$Al$_{1.5}$

For the neutron-diffraction experiments, about 7 g of UCu$_{3.5}$Al$_{1.5}$ were ground and enclosed under He atmosphere in a sealed vanadium can. This can was mounted on the cold finger of a diplex refrigerator, which in turn was mounted on the Neutron Powder Diffractometer (NPD) at the Manuel Lujan Jr. Neutron Scattering Center, Los Alamos National Laboratory. The NPD currently has four banks of detectors at $\pm 90^\circ$ and $\pm 148^\circ$. Data were taken at 300 and 12 K, and we collected data for about 12 h at each temperature. The diffraction patterns were analyzed using the Rietveld refinement program GSAS, which allows simultaneous refinement of multiple phases.

Our data rule out complete disorder of Cu and Al atoms ~reduced $x=6.991$ as opposed to $x=4.768$ for the structure in Fig. 1!, which had previously been proposed for this compound. As in UCu$_3$Al$_2$, we found for UCu$_{3.5}$Al$_{1.5}$ that the 2$c$ positions are occupied by Cu atoms only, while a statistical distribution of Al and the remaining Cu atoms is found on the 3$g$ sites. Not only do we find a lower $x^2$ for this structure, but refining the fractional occupancies on the 2$c$ and 3$g$ positions converges to Cu and Al occupancies close to those given in Table I, though a somewhat higher Al fraction (~0.56$\pm$0.02) is derived for the 3$g$ sites. We also checked for slight distortions and displacements of the atoms involving a cell doubling, but the absence of any superlattice reflections does not support this. Therefore, the diffraction patterns of UCu$_{3.5}$Al$_{1.5}$ are well described assuming the same crystal structure as for UCu$_3$Al$_2$ ~see Fig. 1!.

A few reflections in the diffraction pattern remain unindexed if one assumes that UCu$_{3.5}$Al$_{1.5}$ is the only phase. As can be seen in Fig. 9, the diffraction pattern is fully described if the refinement includes some 2% vol. of the Cu-rich ternary, U$_2$Cu$_9$Al ~space group P6$_3$/mmc!, which allows simultaneous refinement of multiple phases.

Our data rule out complete disorder of Cu and Al atoms ~reduced $x^2=6.991$ as opposed to $x^2=4.768$ for the structure in Fig. 1!, which had previously been proposed for this compound. As in UCu$_3$Al$_2$, we find for UCu$_{3.5}$Al$_{1.5}$ that the 2$c$ positions are occupied by Cu atoms only, while a statistical distribution of Al and the remaining Cu atoms is found on the 3$g$ sites. Not only do we find a lower $x^2$ for this structure, but refining the fractional occupancies on the 2$c$ and 3$g$ positions converges to Cu and Al occupancies close to those given in Table I, though a somewhat higher Al fraction (~0.56$\pm$0.02) is derived for the 3$g$ sites. We also checked for slight distortions and displacements of the atoms involving a cell doubling, but the absence of any superlattice reflections does not support this. Therefore, the diffraction patterns of UCu$_{3.5}$Al$_{1.5}$ are well described assuming the same crystal structure as for UCu$_3$Al$_2$ (see Fig. 1). A few reflections in the diffraction pattern remain unindexed if one assumes that UCu$_{3.5}$Al$_{1.5}$ is the only phase. As can be seen in Fig. 9, the diffraction pattern is fully described if the refinement includes some 2% vol. of the Cu-rich ternary, U$_2$Cu$_9$Al (space group P6$_3$/mmc). The least-squares refinements including all four banks yield lattice parameters and $R$ factors as given in Table I.

B. Neutron diffraction on single-crystalline UCu$_3$Al$_2$

We also performed neutron-diffraction experiments on a single crystal of UCu$_3$Al$_2$ in order to clarify the origin of an anomaly, which appears near 10 K, in the temperature dependencies of the magnetic susceptibility, the electrical resistivity, and the specific heat. For this purpose, we have

![Figure 8](image-url)  
**FIG. 8.** Temperature dependences of the electrical resistivities of UCu$_{3.5}$Al$_{1.5}$ and UCu$_3$Al$_2$ normalized to their room-temperature values. Note the logarithmic temperature scale. The dashed line represents a fit of the low-temperature resistivity of UCu$_{3.5}$Al$_{1.5}$ to a function of the form $a + bT^{2/3}$.

![Figure 9](image-url)  
**FIG. 9.** Observed and calculated nuclear structure profile of UCu$_{3.5}$Al$_{1.5}$ at 300 K, as measured on the +90$^\circ$ bank of NPD. Starting from the bottom, the reflection markers denote UCu$_{3.5}$Al$_{1.5}$ (with parameters as given in Table I) and U$_2$Cu$_9$Al. The difference of measured and calculated intensities is shown by the solid line below. The intensities have been divided by the incident spectrum.
collected diffraction patterns on the Single Crystal Diffractometer (SCD) at the Intense Pulsed Neutron Source at Argonne National Laboratory. The single crystal of UC\textsubscript{3.5}Al\textsubscript{1.5} was mounted on the sample holder of a Heli-Tran Liquid Transfer Refrigeration System, which allows measurements in the temperature range between 2 and 300 K. Data were taken at 20 K (5 histograms) and 6 K (11 histograms), above and below the presumed magnetic-ordering temperature. Each histogram was counted for about 3 h.

Compared to the 20-K data, there are no additional peaks at 6 K, which would be of magnetic origin. Also a triangular coplanar configuration of the moments, which gives magnetic contributions on the nuclear Bragg reflections only, is not supported by our data. Assuming a variety of different magnetic configurations, our data indicate that any ordered moment must be less than 0.1\(\mu_B\).

**V. CONCLUSIONS**

At low temperatures, the bulk properties of neither UC\textsubscript{3.5}Al\textsubscript{1.5} nor UC\textsubscript{3}Al\textsubscript{2} show the temperature dependences predicted by Fermi-liquid theory. The specific heat of UC\textsubscript{3.5}Al\textsubscript{1.5} diverges logarithmitically, which is evidence for non-Fermi-liquid scaling. The other properties are somewhat ambiguous in their temperature dependences because the magnetic anisotropy contributes differently to different crystallographic directions. Nevertheless, if the anisotropy effects are taken into account correctly, one may check for internal consistency of the critical exponents. Given the exponent of \(-1/3\) in \(\gamma(T)\), multichannel impurity models give an exponent of \(1/3\) for \(\rho\), while spin-fluctuation theory provides some mechanism that correctly predicts the observed exponent of \(2/3\) in \(\rho\). This may support the idea that the \(T=0\) phase transition in question is three dimensional in character (and not impuritylike as in UC\textsubscript{5}Pd\textsubscript{3}). UC\textsubscript{3}Al\textsubscript{2} behaves similar to UC\textsubscript{3.5}Al\textsubscript{1.5}, albeit with the superposition of an anomaly at around 8–10 K.

The present neutron-diffraction results show no difference in the crystal structures of UC\textsubscript{3.5}Al\textsubscript{1.5} and UC\textsubscript{3}Al\textsubscript{2}, which is surprising given the regular composition dependence of the lattice parameters (see Fig. 2). Very small displacements and/or distortions cannot be excluded on the basis of our powder diffraction data, and single-crystal studies are needed to confirm this conclusion. On the other hand, intensity-analysis results clearly exclude a completely random distribution of Cu and Al atoms for both compounds. Randomness in UC\textsubscript{3.5}Al\textsubscript{1.5} and UC\textsubscript{3}Al\textsubscript{2} is restricted to the 3g positions located on the intermediate planes between U-containing planes of the CaCu\textsubscript{5} structure. Therefore, only interplanar interactions are affected by the disorder. This provides a new perspective on non-Fermi-liquid scaling because structural randomness is an essential ingredient in many scenarios suggested for the understanding of non-Fermi-liquid behavior. Non-Fermi-liquid scaling due to a distribution of Kondo temperatures because of disorder has been invoked, e.g., in U(Cu,Pd)\textsubscript{3} compounds, and this disorder is believed to be a direct consequence of the random distribution of Cu and Pd atoms.

The origin of the anomalies in the bulk properties of UC\textsubscript{3.5}Al\textsubscript{2} remains a mystery. No magnetic Bragg peaks have been observed, and an upper limit for the ordered moment of 0.1\(\mu_B\) has been estimated. At present, we do not know whether the observed anomalies in bulk investigations reflect long-range order of even smaller magnetic moments or whether they should be attributed to other correlation effects, e.g., spin-glass behavior. The proximity to a spin-glass state has been argued for many non-Fermi-liquid systems, and there is indeed strong evidence for a spin glass in compounds with a diluted f-electron sublattice, for example, in U\textsubscript{0.2}Y\textsubscript{0.4}Pd\textsubscript{3}. In UC\textsubscript{3}Al\textsubscript{2}, however, there is no randomness on the f-electron sublattice. Such a periodic arrangement of magnetic atoms is not a favorable situation for formation of a spin-glass state. The huge observed magnetic anisotropy may be taken as further evidence against a three-dimensional spin glass. On the other hand, interactions between the planes are driven by a Kagome\textsuperscript{3} net of statistically distributed Cu and Al atoms. If interplane interactions are dominant compared to intraplane interactions, this might indeed lead to a complex arrangement of the moments in two dimensions. Sensitive local probes like muon spin resonance (\(\muSR\)) might be able to clarify this.

Up to now, most of the non-Fermi-liquid materials known in the literature have not been studied in single crystalline form. Our single-crystal studies on UC\textsubscript{3}Al\textsubscript{2} indicate that a huge magnetic anisotropy is present in the U(Cu,Al)\textsubscript{3} system. The role of possible magnetic anisotropy is ambiguous for non-Fermi-liquid materials which form in low-symmetry crystallographic structures, like (U,Th)Ru\textsubscript{2}Si\textsubscript{2} and (U,Th)Pd\textsubscript{2}Al\textsubscript{3}.

For an appropriate account of the anisotropy in such systems, single crystals are indispensable. Therefore, we intend to concentrate on single crystals for future studies of the U(Cu,Al)\textsubscript{3} system.

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14 The term ‘Kagomé’ comes from the Japanese art of folding paper, origami. It refers specifically to a certain type of two-dimensional lattice constructed from corner-shared triangular units [see, for example, J. N. Reimers, A. J. Berlinsky, and A. C. Shi, Phys. Rev. B 43, 865 (1991)]. Such Kagomé lattices are prone to highly frustrated magnetic behavior [see, for example, G. Aeppli et al., Physica B 213&214, 142 (1995)].


22 J. Chappert, in Magnetism of Metals and Alloys, edited by M. Cyrot (North-Holland, Amsterdam, 1982).