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Field-induced non-Fermi-liquid behavior in Ce_2IrIn_8

J. S. Kim,[1] N. O. Moreno,[2] J. L. Sarrao,[2] J. D. Thompson,[2] and G. R. Stewart[1]
[1]*Department of Physics, University of Florida, Gainesville, Florida 32611-8440, USA*
[2]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

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In zero field, Ce_2IrIn_8 obeys Landau's Fermi-liquid model, with a constant C/T of about 700 mJ/Ce mol K^2 below 0.7 K and a susceptibility that is constant to $\pm 4\%$ below 4 K. In applied magnetic field, however, Ce_2IrIn_8 shows definite non-Fermi-liquid (nFl) behavior at ~ 13 T, with $C/T \sim \ln T$ between 0.3 and 6 K, $\chi \sim \ln T$, and $\rho = \rho_0 + AT^1$. At fields of 17 T and higher there is a strong divergent upturn in C/T below 0.7 K that is approximately field independent and the susceptibility becomes again constant (Fermi-liquid like) below 6 K and decreases in magnitude at low temperature compared to χ (13 T). These results imply that a quantum critical point may exist in Ce_2IrIn_8 at ~ 13 T. The magnetization at low temperature as a function of field of Ce_2IrIn_8 between 0.1 and 30 T shows no sign of an increase, or jump, near 13 T, but rather a change from $M \sim H$ at lower fields to a more saturated behavior above 13 T. Thus, unlike previous field-induced nFl behavior, where the magnetic interactions responsible for the nFl behavior either came (i) at the field, H_{metamag}, where the magnetization showed a step at a metamagnetic transition (e.g., in UPt_3 or in $Sr_3Ru_2O_7$), or (ii) at the field where $T_{\mathrm{Néel}}$ in an antiferromagnet was *suppressed* to $T=0$ by the field (e.g., in $CeCu_{6-x}Ag_x$), the present measurements point to a different kind of behavior. Thus the nFl behavior in Ce_2IrIn_8 may be describable as due to quantum criticality at the point in the phase diagram where field *induces* magnetism. Comparisons to other nFl systems, both field-induced and those which display an anomalous upturn in C/T at low temperatures, are made.

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I. INTRODUCTION

Recently, a new family of Ce-based heavy fermion compounds, including two heavy fermion superconductors ($CeIrIn_5$ and $CeCoIn_5$), have been discovered.[1] These $Ce_nT_mIn_{3n+2m}$ compounds grow with a tetragonal unit cell that is made from *n* layers of $CeIn_3$ arranged along the *c* axis followed by *m* layers of TIn_2. Ce_2IrIn_8 has been reported[1] to have a specific heat γ (defined as the specific heat *C* divided by the temperature *T* as $T \rightarrow 0$) of 700 mJ/Ce mol K^2, qualifying it to be classified as a heavy fermion system. The present work was initially planned around specific-heat measurements up to 25 T and down to 0.3 K in order to determine the $\gamma(H)$ behavior of this new heavy fermion compound (as has been done for a number of heavy fermion systems[2,3]) and to look for possible new behavior. Our initial high-field specific heat results for Ce_2IrIn_8 led to additional measurements of the magnetization, the ac magnetic susceptibility, and the resistivity in high fields to further characterize the behavior revealed by the specific-heat data.

High quality (as determined by single-crystal structural analysis[4] of similar samples grown in the same laboratory) single crystals of Ce_2IrIn_8 were grown using an In flux technique described elsewhere.[5] Specific-heat measurements down to 0.3 K and in high magnetic fields were made using established methods[2,6,7] while resistivity measurements were made using a standard four-wire technique. The magnetization was measured using the VSM facility at the NHMFL, Tallahassee.

II. RESULTS AND DISCUSSION

The specific heat of single-crystal Ce_2IrIn_8 was measured in 0 and applied magnetic fields with the field oriented both perpendicular to, as well as in, the basal plane. Data in 0, 13, and 24.5 T (corrected for the lattice contribution as well as the magnetic field and quadrupolar moment splitting of the nuclear levels[8]) for $H\perp$ basal plane are shown in Fig. 1. C/T is approximately constant (i.e., Fermi-liquid like) at low temperatures in zero field, but follows $C/T \sim \ln T$ in 13 T (13-T data for $H\parallel$basal plane, not shown, are identical within the error bars) between 0.3 and 6 K—a standard[9] temperature dependence observed in many non-Fermi-liquid (nFl) materials. Specific-heat data taken in 10 T (not shown) over the same temperature range in both field directions show approximately the same standard deviation for a fit of the data to a $\ln T$ behavior, i.e., the critical field for nFl behavior is in the 10–13-T field range in both field directions. In contrast to the observed[10] behavior in UPt_3, where C/T at low temperatures *decreases*[11] for fields above H_{metamag} after following $C/T \sim \ln T$ at H_{metamag} (=20.5 T for UPt_3), C/T at low temperatures for Ce_2IrIn_8 increases strongly above the $\ln T$ behavior for higher fields as shown in Fig. 1. In order to better follow the strong upturn in C/T for fields above 13 T, field data for $H\perp$ basal plane for 13, 17, 20, and 24.5 T and, for comparison, for $H\parallel$basal plane, $H=24.5$ T (corrected for the lattice contribution and the magnetic field and quadrupolar moment splitting of the nuclear levels[8]) are shown in Fig. 2. Rather than higher fields inducing a transition that then increases in size and transition temperature with increasing field as observed[12] in $CeIrIn_5$, the upturn in C/T in Ce_2IrIn_8 for fields above H_{nFl} appears to be almost field independent.

To further examine this field-induced upturn in Ce_2IrIn_8, we examined the temperature dependence of the upturn in C/T above the log behavior in 24.5 T and below 0.7 K in Fig. 2. This upturn is extremely divergent and is fit reasonably well by $C/T \sim T^{-11}$. This is much more divergent than,

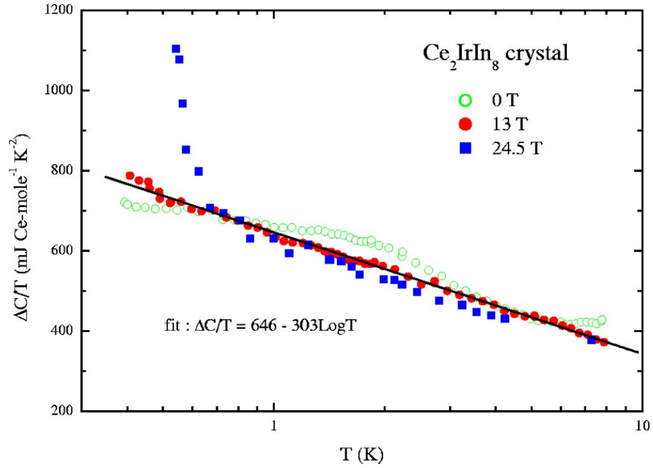

FIG. 1. (Color online) Specific heat C divided by temperature T of Ce_2IrIn_8 corrected (see, e.g., Ref. 8) for the contributions to the specific heat from the lattice specific heat (approximated from the lattice specific heat (Ref. 8) of $CeIrIn_5$), as well as the quadrupolar and magnetic field splitting (Ref. 8) of the nuclear energy levels, vs $\log_{10} T$ for $H=0$, 13, and 24.5 T applied perpendicular to the basal plane. The quadrupolar contribution to the specific heat is essentially negligible in the measured temperature range; the contribution to C/T from the nuclear hyperfine Schottky anomaly due to the field splitting behaves as $1/T^3$ and is less than 6% at the lowest temperature of measurement in 24.5 T and is only 1.5% at the lowest temperature in 13 T. The lattice contribution is ~20% of the total measured specific heat at 7 K. Note that the 13-T data follow the fit of C/T to $\ln T$ quite well between 0.3 and 6 K and that the divergence of C/T below 0.7 K in 24.5 T is quite rapid.

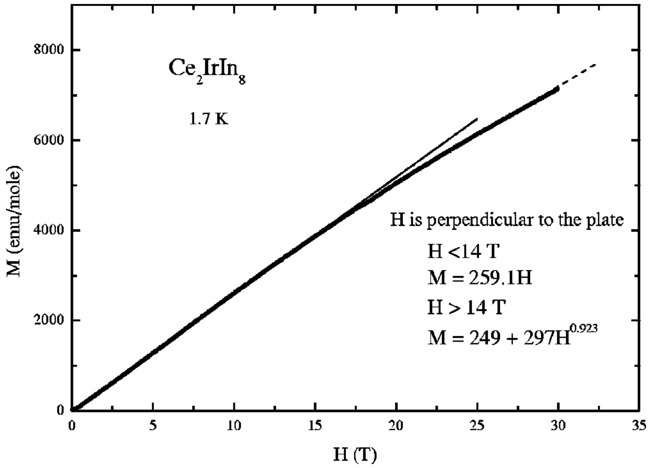

FIG. 3. Magnetization as a function of field up to 30 T measured at 1.7 K for field perpendicular to the basal plane in Ce_2IrIn_8. There is no sign of a metamagnetic jump anywhere in these data, rather the data behave linearly with field up to ~14 T and then show a slight tendency towards saturation at higher fields. Data for field in the basal plane (not shown) show essentially the same result.

e.g., the upturn[9] in C/T for $U_{0.2}Y_{0.8}Pd_3$ below 0.25 K, which approximately fits the temperature dependence of a Scottky anomaly, $C/T \sim T^{-3}$, or the upturn in C/T on the high-temperature side of the field-induced transition in $CeIrIn_5$. Additionally, the field-induced transition which starts at ~26 T in $CeIrIn_5$ shows a strong field dependence, in stark contrast to the behavior shown in Fig. 2. The quasi-field-independent nature (once it is induced for $H \geqslant 17$ T) of the transition shown in Fig. 2 for Ce_2IrIn_8 would be more consistent with a field-induced crossing of energy levels than of a single-particle field alignment of spins picture. Thus above a certain field a state that is magnetically ordered at ~0.7 K becomes the ground state in Ce_2IrIn_8. Further, this field-induced ordered state has an ordering temperature that is, as observed,[13] e.g., for antiferromagnetic $CePd_2Si_2$, rather unaffected by applied field.

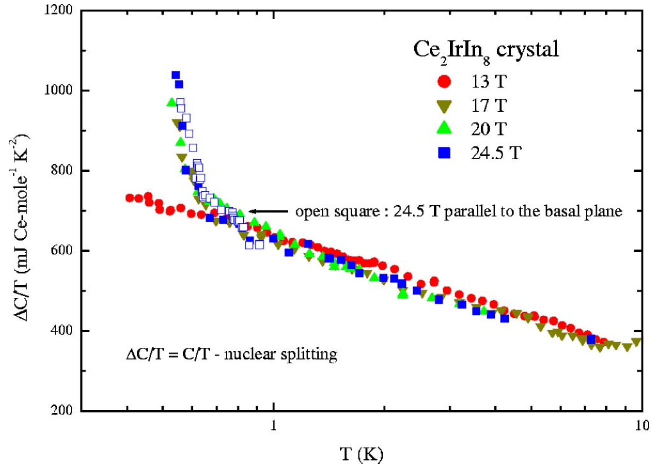

FIG. 2. (Color online) C/T vs $\log_{10} T$ of Ce_2IrIn_8 (corrected as in Fig. 1) for 13, 17, 20, and 24.5 T applied perpendicular to the basal plane, as well as for 24.5 T applied in the basal plane (open squares). Note the essentially field independent C/T upturn for $H \geqslant 17$ T below 0.7 K, and the good agreement between the 24.5-T data in the two field directions.

To investigate if Ce_2IrIn_8 has an increase, or jump, in M vs H (the defining property for "metamagnetism") at around 13 T, as do both UPt_3 and $Sr_3Ru_2O_7$ at the field (20.5 and 7.7 T, respectively) where $C/T \sim \ln T$, we measured M vs H at 1.7 K up to 30 T. The data are shown in Fig. 3, and show merely a decrease below linear $M \sim H$, or saturation behavior, above ~14 T. Thus the field-induced nFl behavior in the specific heat of Ce_2IrIn_8 at 13 T is unlike similar behavior observed in UPt_3 and $Sr_3Ru_2O_7$. (In order to compare with the field-induced transition in $CeIrIn_5$ as regards its magnetization as a function of field, we would have to measure M vs H for Ce_2IrIn_8 below its ordering temperature of 0.7 K which is below the lowest measurement temperature for the VSM at the NHMFL.)

Thus, in order to gain some further knowledge of the magnetic transition, we measured χ_{ac} for Ce_2IrIn_8 in 0- and 24.5-T applied dc fields down to 0.6 K; the data are shown in Fig. 4. Although there is no clear indication of a transition at 0.7 K, by plotting the difference between the 24.5- and 0-T data in the lower part of the figure on an expanded vertical scale we see that there may be, obscured by the scatter in the high-field data, a feature at around 0.7 K in χ_{ac}. Certainly, there is no strong magnetic indication where the specific-heat anomaly occurs, which is consistent with a rather field-independent antiferromagnetic transition and definitely in-

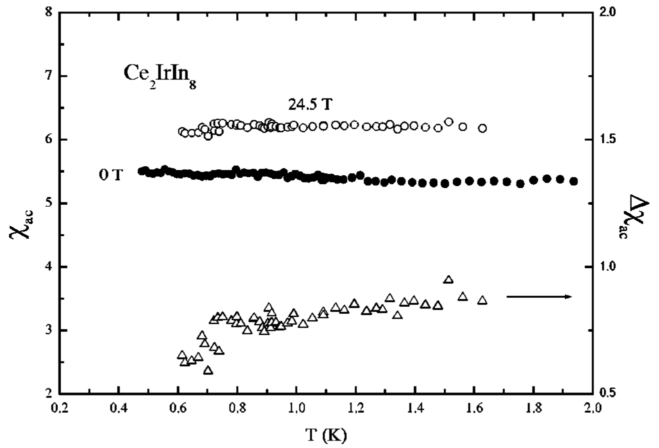

FIG. 4. ac susceptibility at 0 (filled circles) and 24.5 T (open circles) applied dc field between 0.5, 0.6 and 2 K, respectively. The slight feature in 24.5 T around 0.7 K is shown accentuated on an expanded scale in the lower part of the figure by plotting the difference (open triangles) between the 0- and the 24.5-T data. There may be a slight feature at 0.7 K, however, this is mostly obscured by scatter in the high-field data.

consistent with a ferromagnetic transition.

Considering now the dc susceptibility χ between 1.7 and 10 K in 0.1 T (shown in the inset in Fig. 5), χ_{dc} has a slight peak at ~3 K and is approximately constant at 14.5 m emu/Ce mol below 4 K. In order to look further for nFl behavior at 13 T, χ vs T at 13 T, field perpendicular to the basal plane, is shown in Fig. 5. These data rise ~10% between 10 and 2 K and can be fit approximately equally well (see Fig. 5) to the nFl temperature dependences $\chi \sim T^{-0.06}$ or $\chi \sim \ln T$. In any case, these χ (13 T) vs temperature data are not independent of temperature at low temperature, i.e., are not Fermi-liquid like in character. As shown in Fig. 5, a further increase of the field to 24.5 T results in an essentially constant χ below 6 K, with a further decrease of the magnitude of χ (2 K). (In UPt$_3$ χ (2 K) continues to increase[10] as field is increased.) Thus the temperature dependence of the dc susceptibility in field agrees with the results for the specific heat: at low fields Ce$_2$IrIn$_8$ exhibits Fermi-liquid behavior, while at 13 T there is non-Fermi-liquid behavior. In higher fields, C/T exhibits evidence for an upturn at low temperatures while the dc susceptibility shows again Fermi-liquid behavior, both of which contrast with what is measured[10] above H_{metamag} in UPt$_3$.

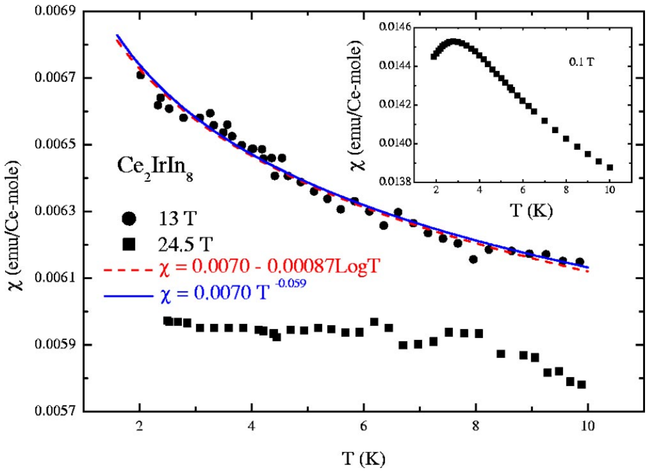

FIG. 5. (Color online) Susceptibility vs temperature in 0.1 (inset), 13, and 24.5 T applied perpendicular to the basal plane in Ce$_2$IrIn$_8$. Both the power-law (solid line) and log (dashed line) fits to the 13-T data are shown. Taking into consideration the expanded scales for both the inset and the main figure, the data in 0 and 24.5 T are essentially constant at low temperatures.

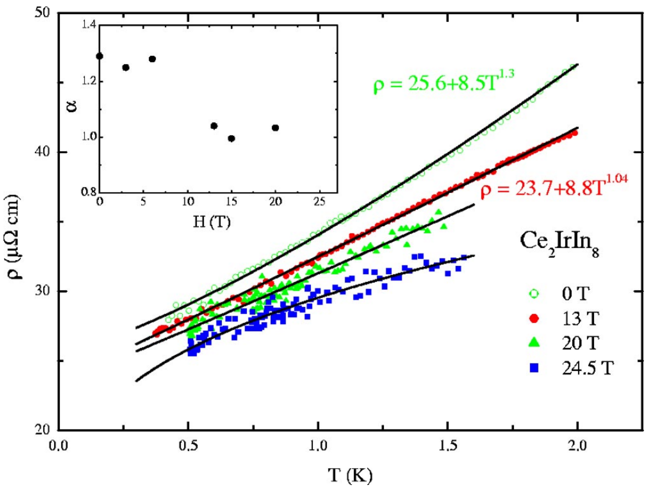

FIG. 6. (Color online) Resistivity vs temperature in 0, 13, 20, and 24.5 T applied perpendicular to the basal plane in Ce$_2$IrIn$_8$, with current in the basal plane. Fits of the data to $\rho = \rho_0 + AT^{\alpha}$ for each field are shown as solid lines through the data. (Fit parameters for 0 and 13 T are shown next to the respective curves.) The inset shows the temperature dependence exponent α as a function of field.

As a further probe of the evolution of the behavior in Ce$_2$IrIn$_8$ with increasing field, Fig. 6 shows the resistivity in 0, 13, 20, and 24.5 T down to 0.3 K (0.5 K for $H > 13$ T). Data (not shown) for the resistivity in 15 T are essentially identical to the 13-T data. Similar to the χ_{ac} vs T data discussed above, the ρ data shown in Fig. 6 show no indication of the transition observed in the specific heat at 0.7 K. In 0 field, the resistivity follows[14] $\rho = \rho_0 + AT^{1.3}$, i.e., the temperative dependence is significantly different[15] than the T^2 expected from Fermi-liquid behavior. At 13 T, $\rho = \rho_0 + AT^{1.04}$, where linear T dependence is[9] a standard nFl temperature dependence. 15-T data (not shown) have a resistivity temperature dependence of $T^{1.00}$. Thus the temperature dependence of the resistivity data (see inset to Fig. 6) is in qualitative agreement with the C/T and χ data which show a change to nFl behavior at a critical field of 13 T. However, as has been seen[9] in other systems where field induces nFl behavior, e.g., UPt$_3$, the exponent α in $\rho = \rho_0 + AT^{\alpha}$ does not fully recover back to the Fermi-liquid value of $\alpha \approx 2$ over any appreciable temperature range even by 24.5 T (see Fig. 6). Rather, the 24.5-T data appear to be describable as the lower half of an S-shaped curve: $\rho \sim \rho_0 + AT$ at low temperatures over a more limited temperature range, ~0.5–0.75 K, than at 13–20 T—as expected as the field moves the system away from the quantum critical point, followed by negative curvature at higher temperatures. It should be stressed that the value of ρ_0 observed in the single crystal reported here ($\sim$26 $\mu\Omega$ cm) is characteristic of high quality crystals without evidence for In inclusions (see Ref. 4) and is less[4] than the value of ρ_0 found for high quality Ce_2RhIn_8 ($\rho_0 = 55\ \mu\Omega$ cm) which becomes superconducting (certainly a sign of sample quality) at 2 K under 25 kbar pressure.

III. SUMMARY AND CONCLUSIONS

Ce_2IrIn_8 appears to be a new example of field-induced non-Fermi-liquid behavior, with $H_{\mathrm{nFl}} \sim 13$ T. The temperature dependences of C/T and χ show Fermi-liquid behavior in 0 field, and C/T, χ, and ρ all show standard nFl temperature dependences ($\ln T$, $\ln T$ or $T^{-\alpha}$, and T^1, respectively) in the vicinity of 13 T. At higher fields, the susceptibility shows a return to Fermi-liquid behavior, while C/T shows an approximately field-independent upturn below 0.7 K. (Lower temperature C/T data in high field, currently outside of our measurement range, could well exhibit Fermi-liquid behavior below the magnetic transition.) The source of the long-range interactions responsible for the nFl behavior are likely related to this field-induced upturn in C/T, the nature of which requires further investigation. The low-temperature magnetization as a function of field up to 30 T, as well as differences in C/T and χ for fields above 13 T from what is observed[10] in UPt_3 above H_{metamag} (plus the lack of any long range antiferromagnetic order to suppress with the applied field) indicate that the field-induced non-Fermi-liquid behavior in Ce_2IrIn_8 is not comparable to that of the other known[9] field-induced non-Fermi-liquid systems such as UPt_3 or $CeCu_{6-x}Ag_x$, but rather is due to non-Fermi-liquid behavior at a quantum critical point where the quantum criticality is due to the *inducement* of a magnetic transition by applied field.

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[14] A number of samples of Ce_2IrIn_8 show this $\rho \sim T^{1.3}$ behavior in zero field, including results by R. Movshovich (private communication).

[15] Reference 10 reports $\rho \sim T^{1.7}$ at 0 field for Fermi liquid UPt_3; thus it is not unknown that a system that shows Fermi-liquid behavior in its specific heat and susceptibility at low temperatures does not show $\rho \sim T^2$ above 0.3 K.