Specific heat in a magnetic field: A probe of the magnetic ground-state properties of heavy-fermion $Ce(Ru_{2-x}Rh_x)Si_{2-y}Ge_y$

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Specific-heat data up to 12.5 T are presented for $CeRu_2Si_2$, $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$, and $CeRu_2Si_{1.8}Ge_{0.2}$. The behaviors with field of the specific heats are compared, also with susceptibility data. The possibility that the maximum in C/T, or γ, at $H_{\text{metamagnetic}}=8$ T in $CeRu_2Si_2$ corresponds to an increase in m^* at the metamagnetic transition is discussed. Similar data for CeB_6 are compared.

I. INTRODUCTION

The nearness of heavy-fermion systems (HFS's) to magnetic behavior has long been clear.[1] Inverse magnetic susceptibility versus temperature above 100 K behaves linearly for HFS's, i.e., follows a Curie-Weiss behavior, giving evidence for an $\sim 3\mu_B$ local moment. This moment is, for HFS's, at least partially compensated during the formulation of the high-effective-mass heavy-fermion ground state at lower temperatures. Some HFS's actually order antiferromagnetically, e.g., UCd_{11} (Ref. 2) and U_2Zn_{17},[3] while UPt_3 displays evidence[4,5] of (antiferromagnetic) spin fluctuations as does (Ref. 6) $CeCu_6$. Doping leads to magnetic ordering in both UPt_3 (Refs. 7–9) and $CeCu_6$ (Refs. 10–12) at low temperatures. This connection between magnetism and the heavy-fermion ground state has been exploited in order to manufacture pseudobinary heavy-fermion systems near in composition to magnetic order, e.g., $U(In,Sn)_3$.[13]

In all of these systems, the strong nearly magnetic behavior of UPt_3 coupled with its bulk superconductivity[4] at 0.5 K has remained a focus of interest. UPt_3 can, with good reason, be called the most nearly magnetic of all known HFS's based not only on its spin fluctuation ground state,[4] its[5] nonzero frequency ordered magnetic moment of $0.02\mu_B$, and its rapid conversion to a magnetically ordered ground state with doping,[7–9] but also based on the metamagnetic transition at ~ 20.5 T applied field. Recently, another system has been discovered with very similar properties, except for superconductivity. $CeRu_2Si_2$, according[14] to neutron scattering measurements, has short-range magnetic correlations that become fully established below 15 K, undergoes[15] a metamagnetic transition at ~ 8 T, has[16] a large γ at low temperatures of 385 mJ/mol K^2 (versus 450 mJ/mol K^2 for UPt_3), and orders antiferromagnetically upon doping on any of the three sites [$Ce_{0.9}La_{0.1}Ru_2Si_2$ orders[17] at 2.7 K, $Ce(Ru_{0.4}Rh_{0.6})_2Si_2$ orders[18] at 11 K, and $CeRu_2Si_{1.5}Ge_{0.5}$ orders[19] at 8 K]. We report here measurements of dc magnetic susceptibility in fields up to 5.5 T and, for the first time, low-temperature specific-heat measurements in fields up to 12 T on polycrystalline $CeRu_2Si_2$, $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$ (where[18] $\gamma=550$ mJ/mol K^2), and $CeRu_2Si_{1.8}Ge_{0.2}$ (where[20] $\gamma=600$ mJ/mol K^2) in order to more fully understand this metamagnetic transition, and possibly, the reasons for the occurrence of superconductivity in UPt_3. Comparison of these data will be made with our recent 18 T specific-heat data[21] on single-crystal UPt_3, which are being extended to 23 T by several groups.

II. EXPERIMENTAL RESULTS AND DISCUSSION

The samples were prepared by arc melting together high-purity starting materials using the highest available purity Ce, that from Ames Laboratory. We have found large differences in sample properties, particularly in the dc magnetic susceptibility, even using Reacton™ grade Ce from Johnson Matthey. The Ru, Rh, Si, and Ge were all from Johnson Matthey and were 99.99% purity or better.

The question of preferential orientation of these polycrystalline samples is of importance. Previous work[22] on single-crystal tetragonal $CeRu_2Si_2$ shows $\chi(4.2\text{ K})\simeq 35\times10^{-3}$ emu/mol for H along the c axis, while $\chi(4.2\text{ K})\simeq 2.6\times10^{-3}$ emu/mol for H perpendicular to the c axis. Additionally, there is[22] a slight $([\chi^{\text{peak}}-\chi(4.2\text{ K})]/\chi^{\text{peak}}\simeq 1\%)$ peak in χ at ~ 10 K for H parallel to c, with no such feature for H perpendicular to c. Our polycrystalline $CeRu_2Si_2$ sample shows some preferential alignment, with a slight peak in χ at 10 K visible for all orientations of the polycrystalline sample and a factor of 2 difference (9 versus 20×10^{-3} emu/mol) in χ at 1.8 K obtainable for different orientations. Preferred orientation is also apparent in our susceptibility measurements on $CeRu_2Si_{1.8}Ge_{0.2}$ and $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$. Thus, where changes in the magnitude of χ or C with field occur, in this work they will be less accentuated than in single-crystal results. In the cases where no change with field occurs, the results of this work are of general applicability. As will be seen later, the magnitude of the change of a property with field (unless there is *no* change) will not play a central role in understanding these systems.

A. Susceptibility data

In general, $CeRu_2Si_2$, $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$, and $CeRu_2Si_{1.8}Ge_{0.2}$ have already been characterized by oth-

ers[15,18–20,22] via dc magnetic susceptibility measurements. Thus, we present susceptibility data here for our samples primarily as an introduction to the central issues addressed by the specific-heat data discussed in the following. One of the motivations for doping $CeRu_2Si_2$ is to vary the metamagnetic transition. Pure $CeRu_2Si_2$ has[22] an M versus H behavior that, in the H parallel to c direction, is linear below 6 T and again above 12.5 T, while there is a steep increase in the slope of M versus H ($=\chi$) in between whose steepest slope is at 8 T. Magnetoresistance measurements[22] show a peak in $[\rho(H)-\rho(0)]/\rho(0)$ also at 8 T. (This may be compared to UPt_3, where the steepest part of the M versus H transition[23] and the peak in the magnetoresistivity are[24] at 20.5 T in one measurement, with some sample dependence, i.e., ρ peak is at 18.5 T, more recently reported.[21])

Upon doping with Ge, but below the Ge concentration where antiferromagnetism begins to occur, we observe not one but two steps in M versus H (see Fig. 1), with the first transition narrower in field. (Similar results on $CeRu_2Si_{2-y}Ge_y$ have already been reported.[20]) The fields at which these transitions occur in $CeRu_2Si_{2-x}Ge_x$ are, of course, composition dependent. We have arbitrarily chosen to focus on $CeRu_2Si_{1.8}Ge_{0.2}$, since at this composition both transitions are just in the range of the upper field (5.5 T) of our Quantum Design dc magnetometer. Upon increasing doping, the transitions occur at lower fields but become less pronounced and broader.

In addition to depressing the field H^* where the metamagnetic transition occurs in pure $CeRu_2Si_2$, we have found that Ge doping also depresses the temperature where the peak in the magnetic susceptibility occurs (10 K in the parent compound versus 7 K for Ge=0.2), accentuates the peak,

$$[\chi(7\text{ K})-\chi(1.8\text{ K})/\chi(1.8\text{ K})=32\%$$

in our polycrystalline sample, and raises the magnitude of χ in our polycrystalline specimens versus pure $CeRu_2Si_2$ by a factor of 2 (see Fig. 2). This may be precursor fluctuations setting in before the long-range magnetic order

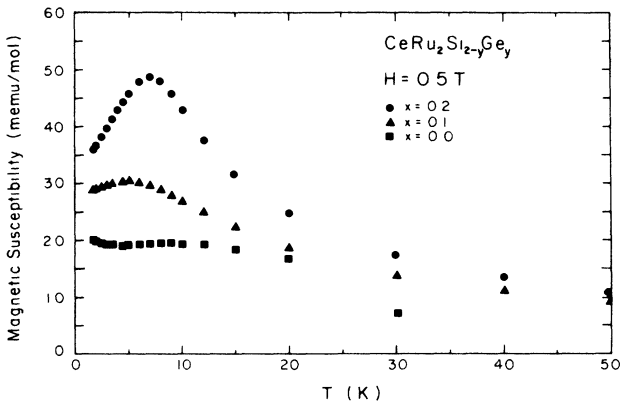

FIG. 2. Susceptibility χ vs temperature for polycrystalline $CeRu_2Si_{2-y}Ge_y$. Note the accentuation of the slight peak at 10 K for $y=0$ upon addition of Ge. The magnitude of χ for $CeRu_2Si_{1.8}Ge_{0.2}$ is larger than that of pure $CeRu_2Si_2$, even allowing for uncertainties in alignment of our polycrystalline sample.

at 7.5 K reported[25] for pure $CeRu_2Ge_2$.

The reason that $Ce(Ru_{2-x}Rh_x)Si_2$ is of interest is that (1) the γ has been reported[18] to be quite large, ~600 mJ/mol K^2, and (2) neutron scattering data[18] imply that $Ce(Ru_{0.4}Rh_{0.6})_2Si_2$ is an ordered antiferromagnet with a local moment of $0.65\mu_B$ and $T_N=11$ K, while these neutron data show no magnetic behavior for $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$. ($CeRh_2Si_2$ is antiferromagnetic at 36 K). Such a large γ near, in "composition space," to magnetism is similar to the behavior[13] of U(In,Sn)$_3$, and although our M versus H data show no transition up to 5.5 T, and there is no peak in χ versus T (see Fig. 3), investigating the behavior of the specific heat with field of a large γ system related to $CeRu_2Si_2$ might shed further light on the magnetic properties of this parent system.

B. Specific heat

Presented here are specific heat divided by temperature (C/T) data for 0 and 12 T for $CeRu_2Si_2$ (Fig. 4) and for

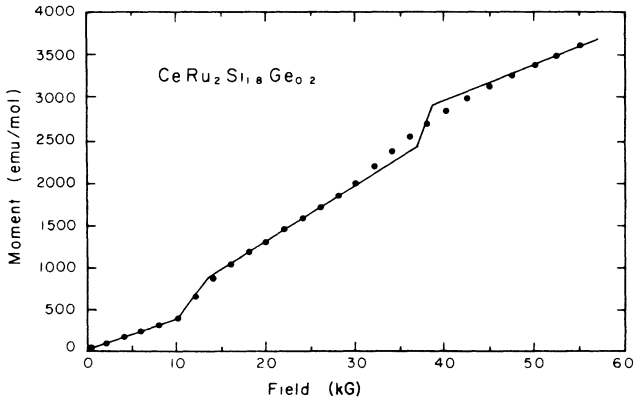

FIG. 1. Magnetization vs field for $CeRu_2Si_{1.8}Ge_{0.2}$. There are two increases in M as a function of H, the one at lower field being sharper and easier to discern. The line is a guide to the eye.

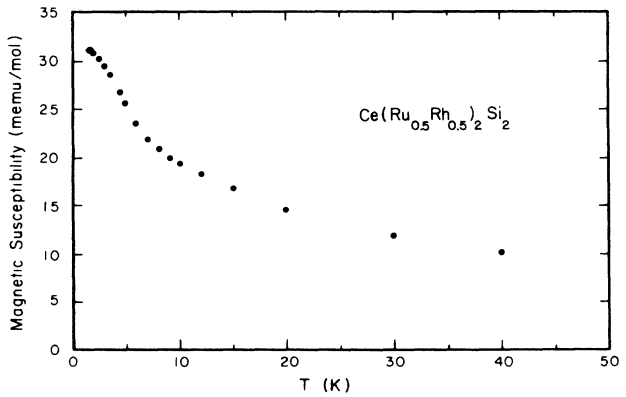

FIG. 3. χ vs T for $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$. Rather than a peak in χ vs T, as seen in Figs. 1 and 2, a change in slope occurs at around 7 K.

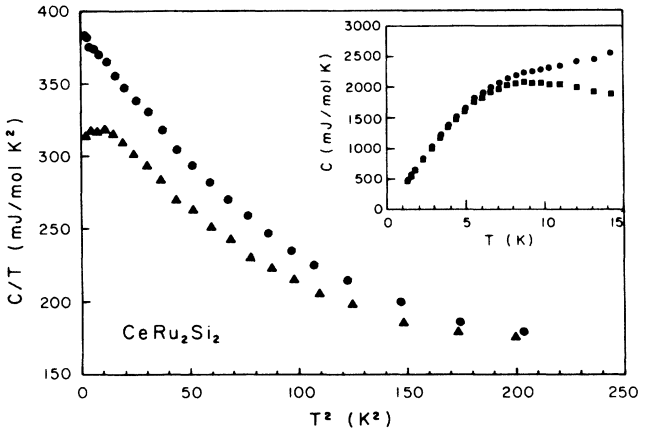

FIG. 4. Specific heat divided by temperature vs temperature squared for $CeRu_2Si_2$ in 0 (circles) and 12 T (triangles). The zero-field data agree with the literature. The inset shows specific heat as a function of temperature for $CeRu_2Si_2$ (circles) and $CeRu_2Si_2$, with the specific heat of $LaRu_2Si_2$ subtracted (squares).

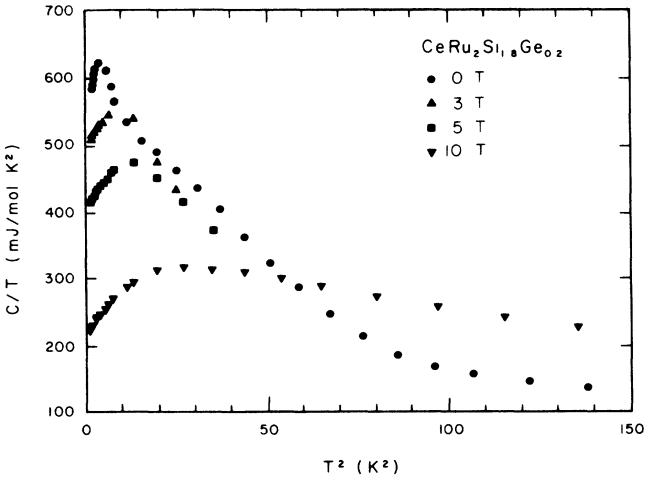

FIG. 6. Specific heat divided by temperature vs temperature squared of $CeRu_2Si_{1.8}Ge_{0.2}$ as a function of magnetic field. The peak seen in C/T at around 2 K moves up in temperature and broadens with increasing field. Clearly, field has a much stronger effect on C/T for $CeRu_2Si_{1.8}Ge_{0.2}$ than for $CeRu_2Si_2$ and $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$.

$Ce(Ru_{0.5}Rh_{0.5})_2Si_2$ (Fig. 5), with an inset for the zero-field C versus T plot. Figure 6 shows C/T versus T^2 data for several fields between 0 and 10 T for $CeRu_2Si_{1.8}Ge_{0.2}$, while Fig. 7 shows the same data plotted as C versus T. We will present the behavior of C/T at low temperature (1.5 K) as a function of field with much finer gradations in H. The only specific-heat data already present in the literature on these systems, to our knowledge, for comparison are zero field up to 7.5 T specific-heat data (i.e., to just below the metamagnetic transition) for single-crystal $CeRu_2Si_2$ (Ref. 26) and zero-field, low-temperature ($T<2$ K) data[18] for $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$. These data are in agreement with that of this work, except for the size of the change in γ with field for $CeRu_2Si_2$ due to preferential orientation effects discussed earlier.

Can these specific-heat results shed light on the cause of the various peaks in magnetic susceptibility discussed above? Clearly, the very slight peak at 10 K in χ for $CeRu_2Si_2$ does not correspond to magnetic order—neutron measurements[14] show nothing, as is the case for the C/T versus T^2 plot of our data in Fig. 4. A C versus T plot, inset to Fig. 4, with the specific heat[15] of $LaRu_2Si_2$ subtracted, does show a peak that is consistent with the presence of short-range magnetic correlations below 15 K indicated by the neutron scattering experiment.[14] [That

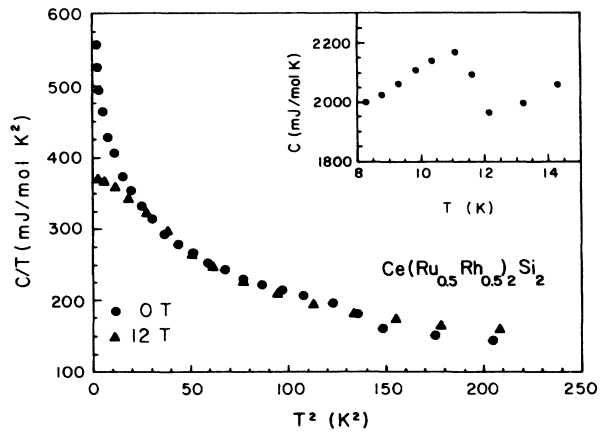

FIG. 5. Specific heat divided by temperature vs temperature squared for $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$ at 0 (circles) and 12 T (triangles). Note the agreement of the 0 and 12 T data above 5 K, in contrast to both $CeRu_2Si_2$ and $CeRu_2Si_{1.8}Ge_{0.2}$. The insert show C vs T for $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$. Note the anomaly at 11 K.

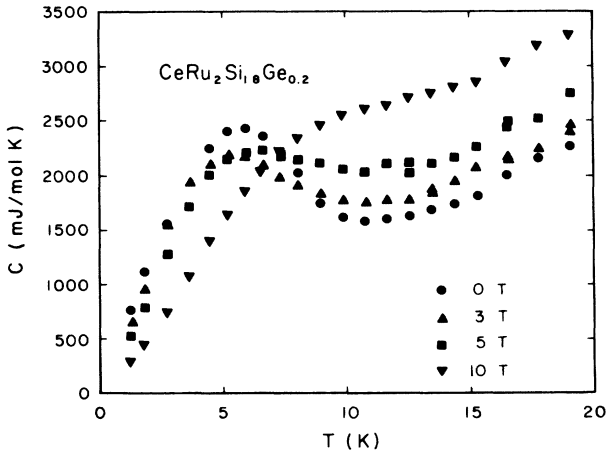

FIG. 7. Specific heat vs temperature as a function of field for $CeRu_2Si_{1.8}Ge_{0.2}$. The shift of the peak at 6 K in C vs T is only slightly downward in temperature with 3 T and only slightly upward in temperature with 5 T, whereas 10 T shifts the peak up to ~ 10 K.

is, magnetic correlations appear more weakly in the specific heat than magnetic order. Magnetic order contributes an entropy, which requires an anomaly in C/T since $S=\int(C/T)dT$. Magnetic correlations may have an energy of formation (where $C=dE/dT$) that is temperature dependent as the magnetic exchange overcomes the thermal energy of disorder.]

The claim that $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$ is nonmagnetic is likely correct (although neutron scattering experiments may not detect small local moment ordering); however, there is a small anomaly in the C versus T data (inset, Fig. 5) at the same tempearture, 11 K, as where neutron scattering measurements[18] find a local moment of significant size, $0.65\mu_B$, in $Ce(Ru_{0.4}Rh_{0.5})_2Si_2$. [It is not actually clear in Ref. 18 if neutron scattering measurements were performed on the $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$ composition.] This small specific-heat anomaly does not correspond to any peak in the susceptibility of $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$, but instead our χ data (see Fig. 3) show a shoulder beginning at about 8 K.

It remains then to discuss our specific-heat data between 0 and 10 T for $CeRu_2Si_{1.8}Ge_{0.2}$ and to try to present a coherent picture that will link these data to those already discussed for $CeRu_2Si_2$ and $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$. The C/T versus T^2 data for $CeRu_2Si_{1.8}Ge_{0.2}$ are presented in Fig. 6, while the C versus T data are shown in Fig. 7. Although similiar in magnitude to the specific heat of $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$, the occurrence of a peak in C versus T around 6 K and the decrease of C/T below some temperature in high field in the Ge-doped sample finds similar behavior in the pure $CeRu_2Si_2$. Since the peak in C versus T for $CeRu_2Si_2$ appears to be connected to the magnetic correlations observed via neutron scattering,[14] and since the peak in the specific-heat data, Fig. 7, for the Ge-doped sample is more pronounced than that for the pure $CeRu_2Si_2$, it is tempting to predict that $CeRu_2Si_{1.8}Ge_{0.2}$ will be found to display stronger magnetic correlations in a similar temperature range when neutron scattering experiments are performed on this material. This is consistent with the lower field needed ($\sim$1.2 T) to induce a metamagnetic transition in the Ge-doped magnetization data than the $\sim$8 T required in $CeRu_2Si_2$.

It is thus these stronger magnetic correlations in $CeRu_2Si_{1.8}Ge_{0.2}$ that cause the greater decrease of γ at low temperature with field observed compared with $CeRu_2Si_2$; Figs. 8 and 9: a 54% decrease in the Ge-doped material by 10 T versus only a 17% decrease in $CeRu_2Si_2$ by 12 T and a 29% decrease in $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$, Fig. 10. A concomitant observation is that it is then these magnetic correlations that cause the large γ for $CeRu_2Si_{1.8}Ge_{0.2}$ of 590 mJ/mol K^2 at low temperature compared with 376 mJ/mol K^2 for $CeRu_2Si_2$.

Before we discuss the behavior of the low-temperature γ versus H through the metamagnetic transition field, what is the explanation of the peak at 2 K in C/T for the Ge-doped sample, Fig. 6? In previously published zero-field specific-heat data[27] for pure $CeRu_2Si_2$ down to 0.1 K, no sign of any peak was observed. With field, this peak in C/T in $CeRu_2Si_{1.8}Ge_{0.2}$ moves to higher temperatures and broadens (see Fig. 6). Thus, it is unlikely to be a Fermi-liquid effect of highly correlated Ce $4f$ electrons (these create[1] a peak in C/T at 0.35 K in $CeAl_3$ which is not qualitatively nearly so field dependent). A magnetic order explanation is unlikely—no anomaly in C versus T is observed, plus the peak temperature in C/T increases with field, which would be some sort of ferrimagnetic or ferromagnetic coupling. Therefore, some saturation effect of the stronger magnetic-correlation-induced increase in the effective mass present in $CeRu_2Si_2$ doped with Ge may be a possible explanation.

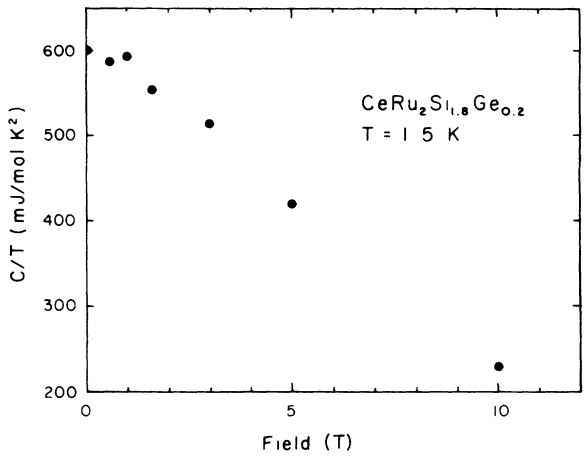

FIG. 8. Specific heat divided by temperature at $T=1.5$ K vs H for $CeRu_2Si_{1.8}Ge_{0.2}$ Within 2%, our precision in the present type of measurement, no structure in γ is seen until the first (see Fig. 1) field (1.2 T), where a metamagnetic transition occurs, whereupon γ begins to drop sharply with increasing field.

γ versus H. Figures 8, 9, and 10 detail the behavior of C/T at 1.5 K for each sample as a function of field.

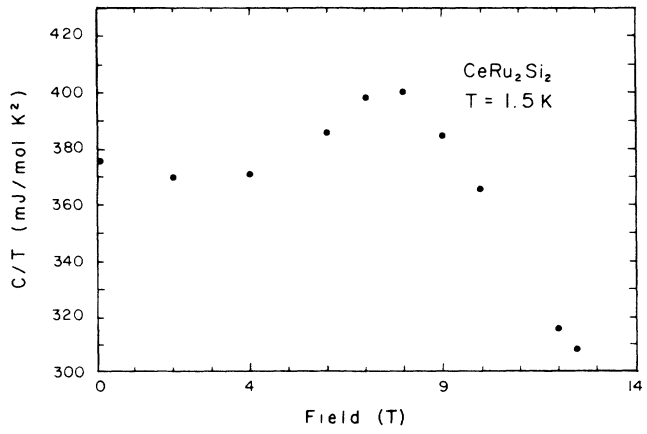

FIG. 9. Specific heat divided by temperature at $T=1.5$ K vs H for $CeRu_2Si_2$. The 6% rise in γ between 0–8 T would be (Ref. 26) more pronounced in a single crystal with H in the C direction. The fall off of γ in $CeRu_2Si_2$ above 8 T is reported here for the first time.

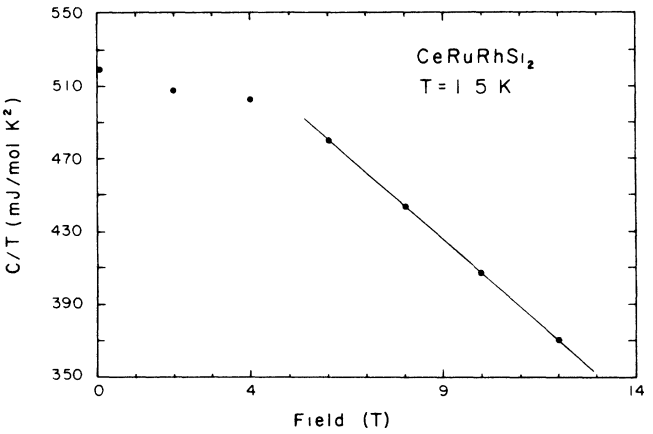

FIG. 10. Specific heat divided by temperature at $T=1.5$ K vs H for $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$. Note that, although no anomaly in M vs H is observed for this alloy, again two regions of behavior are observed: at low H, γ is $\sim$ constant, while above 5 T γ falls sharply. Although the low temperature C/T values for $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$ and $CeRu_2Si_{1.8}Ge_{0.2}$ are comparable, the rate of the fall off of C/T with H is approximately a factor of 2 different.

These field data (γ versus H) in related systems that have variously one ($CeRu_2Si_2$), two ($CeRu_2Si_{1.8}Ge_{0.2}$), or no [$Ce(Ru_{0.5}Rh_{0.5})_2Si_2$] metamagnetic transitions up to 5.5 T were the primary goal of this work. [The higher fields (>20 T) required to examine γ versus H through such a transition in UPt_3 have thus far[21] (coupled with the vagaries of reliability of such very high-field normal-state magnets) prevented us from such a study]. We see immediately from Figs. 8–10 several correlations. At the metamagnetic transitions at 8 T in $CeRu_2Si_2$ (Fig. 9) and at 1.2 T in $CeRu_2Si_{1.8}Ge_{0.2}$ (Fig. 8), a sharp drop in γ at higher fields is observed. The larger and sharper the anomaly in M versus H, the greater is the change in behavior of γ through the transition. Thus, referring to Figs. 1 and 8, we see that the broad anomaly in M versus H at 3.7 T for $CeRu_2Si_{1.8}Ge_{0.2}$ does not produce a (visible) corresponding γ versus H anomaly. Further, the much more distinct M versus H anomaly in $CeRu_2Si_2$ actually corresponds to a distinct *peak* in γ versus H at the same field (Fig. 9). This peak, whose onset up to 7.5 T has been reported,[26] is evidence of the complexity of this system.

If one adopts the simple antiferromagnetic correlation picture as being the important cause of magnetic field effects [and also of the peak in the specific heat of $CeRu_2Si_2$ (Fig. 4, inset) at ~ 8 K], then the explanation of the γ versus H data in Fig. 9 is straightforward. The entropy due to these antiferromagnetic correlations is suppressed in temperature with increasing field. As the anomaly and its associated entropy pass (however broadened) through 1.5 K, "γ" ($\equiv C/T$) is increased. At higher fields, the antiferromagnetic correlations are totally suppressed, and γ falls precipitously. Thus, by this model γ at low temperatures is not really tracking m^*, the electron effective mass, since a broadened anomaly in the specific heat due to the entropy of antiferromagnetic correlations is the (at least partial) source of the variation in C/T. The analog of this behavior is the peak in C versus T at 2 K in UBe_{13}. The entropy under this as yet not understood anomaly is substantial (Ref. 1), ~ 1 J/mol K. This peak moves[28] upon doping the U site; thus, measuring C/T in a heavy-fermion system at some low temperature may not give a clean determination of m^* ($\propto \gamma_{\text{electronic}}$) due to the admixture of an additional specific-heat contribution. Since the magnetic-correlation entropy observed in $CeRu_2Si_2$ at $T\sim 9$ K (see inset, Fig. 4) can, under suppression by magnetic field, have a finite contribution to the specific heat at arbitrarily low temperature, it is premature to conclude that m^*, as would be measured by $dHvA$, first increases and then decreases as H is varied through a metamagnetic transition. Since $dHvA$ measurements are difficult to achieve at this low (8 T) a field, the question of the real behavior of m^* through the metamagnetic transition in $CeRu_2Si_2$ is likely to remain moot.

This view, that m^* versus H may be difficult to determine from the specific heat of a heavy-fermion system due to non-m^*-producing specific-heat contributions which mask the real γ value, is not universally held. The cause of the creation of the large m^* in heavy-fermion systems is still an open question. Magnetic fluctuations have been experimentally proven to[5,6] exist in heavy-fermion systems and, indeed, in (Ref. 14) $CeRu_2Si_2$, via neutron scattering experiments, and are visible in other measurements as well, including specific heat and susceptibility. Theoretically, it has been proposed[29] that such fluctuations actually are partially responsible for the creation of a large m^* at low temperatures. Thus, in $CeRu_2Si_2$ it has been proposed[30] that the increase in C/T at $T=0.4$ K seen[26] up to 7.5 T, (which mirrors our own 1.5 K results; Fig. 9) is in fact proof of an increasing m^*, due to an "increase of the ferromagnetic coupling." At higher fields above the metamagnetic transition, then this model would have m^* fall as the fluctuations are eventually suppressed with ever-increasing field. For comparison, $dHvA$ are available[31] for CeB_6 above 13 T, and field data for C/T of CeB_6 are available[32] up to 22 T. In the region where both kinds of measurement overlap ($H\geq 13$ T), the determination of γ from the measured m^* from the $dHvA$ data agrees well with the measured specific heat. C/T data well below 0.4 K are necessary[33] to determine γ in CeB_6, however, due to the strong influence on C/T (there is still curvature in C/T at 0.4 K in $H=0$) from the large anomaly in C at 2.3 K from the antiferromagnetic transition. It is not clear, *a priori*, to how low a temperature C/T must be measured in $CeRu_2Si_2$ to avoid distortion due to the magnetic fluctuation peak in C at 9 K and $H=0$. The peak broadens as it is suppressed with field and is difficult to identify.

In any case, no measurable rise in C/T at low temperatures is observed at the metamagnetic transitions in $CeRu_2Si_{1.8}Ge_{0.2}$. A slight rise in C/T at 0.4 K versus H is observed[17] in $Ce_{0.9}La_{0.1}Ru_2Si_2$. However, the data of Ref. 17 show very clearly that this rise is due to a peak in C/T at 2 K becoming more pronounced in height and shifting to lower temperature with increasing field.

In summary, $CeRu_2Si_2$ is an interesting high-γ system which, upon doping either the Ru or the Si site, has an increasing γ and, eventually, magnetic order. Specific-heat measurements in field of $Ce(Ru_{2-x}Rh_x)Si_{2-y}Ge_y$ show very strong suppression of C/T ($T=1.5$ K) by field in $CeRu_2Si_{1.8}Ge_{0.2}$ (54% by 10 T) and a peak in C/T versus H at 8 T in $CeRu_2Si_2$, where M versus H data show an anomaly. However, no such peak in γ versus H is observed in $CeRu_2Si_{1.8}Ge_{0.2}$ despite the existence therein of two anomalies in M versus H (so-called "metamagnetic" transitions).

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[1]G. R. Stewart, Rev. Mod. Phys. **56**, 755 (1984).
[2]Z. Fisk, G. R. Stewart, J. O. Willis, H. R. Ott, and F. Hulliger, Phys. Rev. B **30**, 6360 (1984).
[3]H. R. Ott, H. Rudigier, P. Delsing, and Z. Fisk, Phys. Rev. Lett. **52**, 1551 (1984).
[4]G. R. Stewart, Z. Fisk, J. O. Willis, and J. L. Smith, Phys. Rev. Lett. **52**, 679 (1984).
[5]G. Aeppli, A. Goldman, G. Shirane, E. Bucher, and M.-Ch. Lux-Steiner, Phys. Rev. Lett. **58**, 808 (1987).
[6]G. Aeppli, H. Yoshizawa, Y. Endoh, E. Bucher, J. Hufnagl, Y. Onuki, and T. Komatsubara, Phys. Rev. Lett. **57**, 122 (1986).
[7]A. de Visser, J. C. P. Klaase, M. van Spang, J. J. M. Franse, A. Menovsky, and T. T. M. Palstra, J. Magn. Magn. Mater. **54-57**, 375 (1986).
[8]G. R. Stewart, A. L. Giorgi, J. O. Willis, and J. O'Rourke, Phys. Rev. B **34**, 4269 (1986).
[9]A. P. Ramirez, B. Batlogg, E. Bucher, and A. S. Cooper, Phys. Rev. Lett. **57**, 1072 (1986).
[10]A. K. Gangopadhyay, J. S. Schilling, E. Schuberth, P. Gutsmiedl, F. Gross, and K. Andres, Phys. Rev. B **38**, 2603 (1988).
[11]G. Fraunberger, B. Andraka, J. S. Kim, U. Ahlheim, and G. R. Stewart, Phys. Rev. B **40**, 4735 (1989).
[12]A. German, A. K. Nigam, J. Dutzi, A. Schröder, and H. v. Löhneysen, J. Phys. (Paris) Colloq. **49**, C8-755 (1988); A. Germann and H. v. Löhneysen, Europhys. Lett. **9**, 367 (1989).
[13]C. L. Lin, L. W. Zhou, J. E. Crow, R. P. Guertin, and G. R. Stewart, J. Magn. Magn. Mater. **54–57** 391 (1986).
[14]L.-P. Regnault, W. A. Erkelens, J. Rossat-Mignot, P. Lejay, and J. Flouquet, Phys. Rev. B **38**, 4481 (1988).
[15]M. J. Besnus, J. P. Kappler, P. Lehmann, and A. Meyer, Solid State Commun. **55**, 779 (1985).
[16]J. D. Thompson, J. O. Willis, C. Godart, D. E. MacLaughlin, and L. C. Gupta, J. Magn. Magn. Mater. **47–48**, 281 (1985).
[17]C. Marcarat, R. A. Fisher, N. E. Phillips, and J. Flouquet, J. Magn. Magn. Mater. **76–77** 115 (1988).
[18]B. L. Loret, B. Chevalier, B. Buffat, J. Etourneau, S. Quezel, A. Lamharrar, J. Rossat-Mignot, R. Calemczuk, and E. Bonjour, J. Magn. Magn. Mater. **63–64**, 85 (1987).
[19]C. Godart, A. M. Umarji, L. C. Gupta, and R. Vijayaraghavan, J. Magn. Magn. Mater. **63–64**, 326 (1987).
[20]J. Rossat-Mignot (private communication).
[21]G. R. Stewart, Z. Fisk, J. L. Smith, J. J. M. Franse, A. Menovsky, and B. L. Brandt, J. Magn. Magn. Mater. **76–77**, 484 (1988).
[22]J. Flouquet, P. Haen, F. Lapierre, D. Jaccard, and G. Remenyi, J. Magn. Magn. Mater. **54–57**, 322 (1986).
[23]P. H. Frings, J. J. M. Franse, F. R. de Boer, and A. Menovsky, J. Magn. Magn. Mater. **31–34**, 240 (1983).
[24]J. J. M. Franse, P. H. Frings, A. de Visser, and A. Menovsky, Physica **126B**, 116 (1984).
[25]A. Böhm, R. Caspary, U. Habel, L. Pawlak, A. Zuber, F. Steglich, and A. Loidl, J. Magn. Magn. Mater. **76–77**, 150 (1988).
[26]R. A. Fisher, N. E. Phillips, C. Marcenat, J. Flouquet, P. Haen, P. Lejay, and J. Rossat-Mignot, J. Phys. (Paris) Colloq. **49**, C8-759 (1988).
[27]F. Steglich, U. Rauchschwalbe, U. Gottwick, H. M. Mayer, G. Sparn, N. Grewe, U. Poppe, and J. J. M. Franse, J. Appl. Phys. **57**, 3054 (1985).
[28]J. S. Kim, B. Andraka, C. S. Jee, S. Roy, and G. R. Stewart (unpublished).
[29]M. R. Norman, J. Magn. Magn. Mater. **76–77**, 513 (1988), and references therein.
[30]J. Flouquet, J. Magn. Magn. Mater. **76–77**, 666 (1988).
[31]W. Joss, J. M. van Ruitenbeek, G. W. Crabtree, J. L. Tholence, A. P. J. van Deursen, and Z. Fisk, Phys. Rev. Lett. **59**, 1609 (1987).
[32]T. Müller, W. Joss, J. M. van Ruitenbeek, U. Welp, P. Wyder, and Z. Fisk, J. Magn. Magn. Mater. **76–77**, 35 (1988).
[33]C. D. Bredl, J. Magn. Magn. Mater. **63–64**, 355 (1987).