Magnetic structure of CeRhIn$_5$ as a function of pressure and temperature

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We report magnetic neutron-diffraction and electrical resistivity studies on single crystals of the heavy-fermion antiferromagnet CeRhIn$_5$ at pressures up to 2.3 GPa. These experiments show that the staggered moment of Ce and the incommensurate magnetic structure change weakly with applied pressure up to 1.63 GPa, where resistivity, specific heat and NQR measurements confirm the presence of bulk superconductivity. This work places new constraints on an interpretation of the relationship between antiferromagnetism and unconventional superconductivity in CeRhIn$_5$.

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I. INTRODUCTION

Heavy fermion (HF) materials provide an excellent opportunity to investigate the interaction between magnetism and unconventional superconductivity (SC). In most HF compounds the magnetic interactions are governed by the hybridization of the $f$ electrons and the conduction electrons. This leads to competition between the tendency to order magnetically, favored by the RKKY (Ruderman-Kittel-Kasuya-Yosida) indirect exchange interaction, and the tendency to have a spin-singlet ground state mediated by the Kondo interaction. In these systems, there is increasing experimental and theoretical evidence that antiferromagnetic (AFM) spin fluctuations mediate Cooper pairing and that anisotropic SC appears in the vicinity of a quantum-critical point. Several families of HF compounds are known where SC does coexist with weak magnetic order (e.g., UP$_3$, URu$_2$Si$_2$, UNi$_2$Al$_2$). However most of Ce-based heavy fermion superconductors (HFS) (CeIn$_3$, CeCu$_2$Ge$_2$, CePd$_2$Si$_2$, CeRh$_2$Si$_2$, CeRu$_2$Si$_2$) display an AFM ground state at ambient pressure and superconduct when external pressure is applied and $T_N$ is driven to 0 K.

A new family of Ce-based compounds: CeMIn$_5$ ($M=$Co,Ir,Rh) with Sommerfeld coefficients ($\gamma$) of 1000, 750 and 380 mJ mol$^{-1}$K$^{-2}$ respectively, has recently been added to the list of HFS. Several families of Ce-based heavy fermion superconductors (HFS) (CeIn$_3$, CeCu$_2$Ge$_2$, CePd$_2$Si$_2$, CeRh$_2$Si$_2$, CeRu$_2$Si$_2$) display an AFM ground state at ambient pressure and superconduct when external pressure is applied and $T_N$ is driven to 0 K.

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pressures below 2.0 GPa and that there is a steep increase in the cyclotron mass only above 1.6 GPa when SC develops. Additional X-ray diffraction studies confirm that the CeRhIn₅ crystal structure, except for a small decrease in the cell volume, remains unchanged for pressures up to 2.0 GPa. In this work, we have extended the pressure range over which electrical resistivity and neutron diffraction measurements have been performed on CeRhIn₅ in order to investigate the effect of pressure on the superconducting and magnetic transition temperatures and the evolution of the magnetic structure as it approaches and exceeds the critical pressure where the two phases meet.

II. EXPERIMENTAL DETAILS

Single crystals of CeRhIn₅ were grown using the In flux technique. Four-probe AC resistivity measurements, with the current flowing in the tetragonal basal plane, were made on bar-shaped single crystals. A clamp-type cell generated hydrostatic pressures to 2.3 GPa for resistivity measurements using silicon oil as the pressure medium.

Neutron diffraction experiments were carried out at the C5 and N5 spectrometers at the NRU reactor, Chalk River Laboratories (CRL) as well as at the 6T2 lifting detector diffractometer at Laboratoire Léon Brillouin, Saclay (LLB). A clamp-type Cu-Be cell was used in experiments performed at CRL with Fluorinert-75 as the pressure medium to generate up to 1.8 GPa. Bar-shaped single crystals (1.3 × 1.3 × 10 mm) were used to reduce neutron absorption by In and Rh nuclei at CRL. The longest dimension of the crystals was along the (110) crystallographic axis. The scattering plane was defined to be the (hhl). In this set-up, the applied pressure was determined, within ± 0.1 GPa, by measuring the lattice parameters of a graphite crystal placed behind the sample inside the cell at low temperature. Neutron beams with incident energy of Eᵢ = 35 meV were produced from a Ge(113) or Be(002) monochromator. Pyrolytic graphite (PG) filters with approximate thickness of 10 cm were placed in the scattered beam to reduce higher order reflections and occasionally a pyrolytic graphite analyzer was used to improve the signal to noise ratio.

At LLB, a gasketed sapphire anvil cell was used with a mixture of methanol and ethanol as the pressure transmitting medium for experiments at 0.63 and 1.1 GPa. Samples, with dimensions 1.3 × 1.3 × 0.2 mm, were aligned with the [001] crystallographic direction (shorted dimension) vertical. A thin layer of ruby powder was placed on the inner surface of the anvil in order to measure the applied pressure at room temperature using the standard ruby fluorescence technique. This was performed before and after thermal cycling to ensure that pressure was constant throughout the experiment. This technique allows determining the pressure at low temperatures within ± 0.15 GPa. Neutron beams of Eᵢ = 14.81 meV, were produced using a PG(002) monochromator. In both laboratories a top loading He-flow cryostat was used to cool down the pressure cell and sample. Results reported below were obtained on several different single crystals, in different pressure environments and at two neutron sources. The consistency of these results substantiate conclusions drawn from them.

III. RESULTS AND DISCUSSION

We measured electrical resistivity (ρ) on CeRhIn₅ single crystal at different applied pressures and temperatures from 300 mK to room temperature. This crystal has a resistivity ratio ρ(295 K)/ρ(1.5 K) = 280 that is about two times higher than that in a crystal studied by Hegger et al. The pressure-temperature (P-T) phase diagram constructed from these ρ(T) measurements is shown in Fig. 1. Our new results show that the magnetic

![Fig. 1: a) Temperature-pressure phase diagram for CeRhIn₅ determined by ρ(T) measurements. Open squares correspond to the Neél temperature and solid circles to the temperature at which the resistivity drops to zero. The lines are guides to the eye. b) Pressure evolution of the antiferromagnetic helical structure characterized by the propagation vector qₑ=(0.5,0.5,δ). c) Pressure evolution of the estimated Ce staggered moment at T=1.85 K of CeRhIn₅. Filled circles correspond to measurements performed at CRL, filled squares correspond to measurements performed at LLB Saclay and empty squares correspond to data reported by Bao et al.](image-url)
FIG. 2: Elastic $q$-scans through selected nuclear Bragg peaks at $T=1.8$ K and $P=1.15$ GPa.

FIG. 3: Elastic $q$-scans around some of the magnetic peaks at $T=1.8$ K and $P=1.15$ GPa.

to non-magnetic transition is smooth and reveals the existence of a large pressure region of coexisting long-range magnetic order and SC ($0.9$ GPa $\leq P \leq 1.75$ GPa). There is a slight increase of $T_N$ with pressure up to about $0.8$ GPa and for pressures above this value $T_N$ decreases and a SC ground state develops. This phase diagram is fully consistent with that determined by specific heat and NQR and departs from initially reported results.

To determine the pressure evolution of the magnetic structure of CeRhIn$_5$ and particularly the incommensurability parameter ($\delta$) of the magnetic structure ($q_m = (0.5,0.5,\delta)$) special attention has been paid to the precise alignment of the single crystal since $\delta$ depends critically on it. For this reason, systematic checks have been performed during the measurements using $\{1,1,2\}$, $\{0,0,3\}$ and $\{2,2,0\}$ nuclear Bragg reflections. Fig.2 shows typical $q$-scans around a series of $\{1,1,2\}$ reflections at $1.85$ K and $1.15$ GPa which attest to the quality of the crystal alignment. When changing pressure, the cell and sample were warmed to room temperature before the next pressure was applied. At each pressure, $q$-scans and rocking curves were measured at magnetic and nuclear peaks. Several magnetic reflections, including Friedel pairs, were measured to determine $\delta$ more accurately. A set of representative magnetic Bragg peaks are shown in Fig.3 for $P=1.15$ GPa and $T=1.85$ K. The absence of other commensurate reflections, like $(0.5,0.5,0.5)$, was also systematically verified. From data such as shown in Fig.3, we obtain the pressure dependence of $\delta$ plotted in Fig.1b. Our results show that there is no substantial change in the magnetic wave vector $(0.5,0.5,\delta)$ within the accuracy of these measurement up to pressures of $1.63$ GPa. This is qualitatively different from the result reported by Majumdar et al. At $1.8$ GPa, we do not detect any evidence for magnetic scattering for temperatures greater than $1.85$ K as shown in Fig.4. We speculate that the lack of magnetic long range order at this pressure can be due to the existence of a marginally higher pressure than $1.8$ GPa which would drive $T_N$ close to our lowest measuring temperature in which case the magnetic scattering would be not observable above background scattering from the Be-Cu pressure cell. The possibility that a dramatic change may occur in the magnetic structure between $1.63$ GPa and $1.8$ GPa giving no magnetic scattering along $(0.5,0.5,\ell)$ for the $\ell$ interval reported seems very unlikely but cannot be definitely ruled out.

The temperature dependence of the $(0.5,0.5,\delta)$ Bragg peak intensity which corresponds to the magnetic order parameter squared is shown in Fig.5 for $P=0.6$ GPa and $1.1$ GPa. It reveals that there is not a significant change in the development of the magnetic order at pressures above and below the pressure where SC starts developing. A tentative fit to $(1-T/T_N)^{2\beta}$ showed better agreement when $\beta = 0.25$ which is consistent with the results reported at ambient pressure.

To determine the magnetic moment at each pressure, magnetic Bragg peaks were measured at $1.8$ K with rocking scans at LLB-Saclay and with scans such as those in Fig.3 at CRL. Magnetic cross-sections are derived from integrated intensities with appropriate correction for
(0.5,0.5, Q) NQR is given by $A_{RhIn}$. Resistivity measurements ($T_N$ measured value of $dM$ decreases at 1.63 GPa compared to ambient pressure). The solid lines are fits to $(1-T/T_N)^{1/3}$ with $\beta = 0.25$.

resolution. They are normalized to nuclear Bragg peaks to yield values in absolute unit. The theoretical cross-section for the AFM spiral model is:

$$\sigma(q) = \left(\frac{\gamma_{iso}}{2}\right)^2(M_Q)^2 \frac{1}{4} |f(q)|^2 (1 + (\bar{q} \cdot \bar{c})^2) \tag{1}$$

where $f(q)$ is the Ce$^{3+}$ magnetic form factor \cite{40}, $\left(\frac{\gamma_{iso}}{2}\right)^2 = 0.07265$ barns/$\mu_B$ and $M_Q$ is the staggered moment of Ce ion. Fig. shows the staggered moment of Ce as a function of applied pressure. The staggered magnetic moment of Ce at ambient pressure, $M_Q = (0.8 \pm 0.1) \mu_B$/Ce, which is consistent with the previously reported value of $M_Q = (0.75 \pm 0.02) \mu_B$/Ce and is found to be about 20% smaller than the full moment obtained from crystal field calculations, which estimate $M_Q = 0.92 \mu_B$/Ce. We attribute the smaller measured value of $M_Q$ to partial Kondo compensation of the moment, an effect neglected in crystal field calculations. Fig. shows that there appears to be a slight tendency for $M_Q$ to decrease with pressure (less than 15% decrease at 1.63 GPa compared to ambient pressure).

An anomaly at $T_\gamma = 2.8$ K was found for $1.3<P<2.0$ GPa in earlier resistivity measurements on CeRhIn$_5$\cite{25}. This resistivity anomaly is not detected in the higher quality crystals used to construct the phase diagram in Fig. We have measured $q$-scans around $(0.5,0.5,\delta)$ at $P = 1.63$ GPa for different temperatures (Fig. and our results confirm that magnetic long range AFM helical order disappears below 2.25 and 2.75 K which is very close to values of $T_N$ obtained from resistivity measurements ($T_N$(1.6 GPa) = 2.8 K).

For the incommensurate magnetic structure of CeRhIn$_5$, the internal magnetic field sensed by $^{115}$In-NQR is given by $H_{int} \propto A_{ab}M_Q\sin(q_{ab}z)\cos(q_{ab}z)\hat{c}$, where $A_{ab}$ is the hyperfine coupling between the in-plane components and each of its four Ce nearest neighbors, $M_Q$ is the ordered moment and $q_0 = 2\pi\delta/\phi_2$. Our neutron diffraction experiments show that $\delta$ and $M_Q$ change by at most 10% and 15% respectively, as pressure is raised from atmospheric to 1.63 GPa (Fig. (b) and Fig. (c)). These relatively small changes in $\delta$ and $M_Q$ are unable by themselves to account for the 80% reduction of $H_{int}$ deduced by NQR measurements. If the Ce moments acquire a component out of the $ab$ plane as a function of pressure, an apparent decrease of $H_{int}$ would be also observed. In such a scenario, additional magnetic diffraction peaks corresponding to a propagation vector different from $(0.5,0.5,\delta)$ would appear and a subsequent reduction of the in-plane component would be observed. We did not observe a large reduction of the in-plane component nor any evidence of magnetic diffraction at (0.5,0.5,0.5) due to an AFM out of the $ab$ plane component but we cannot discard out magnetic intensity appearing at $(0.5,0.5,0)$. Taken together, our results would seem to rule out the canting scenario. An alternative, and more plausible, interpretation of the reduction of $H_{int}$ is that hyperfine coupling decreases with pressure. Irrespective of the magnitude of $H_{int}$, NQR measurements establish beyond reasonable doubt the coexistence of AFM and bulk SC in CeRhIn$_5$ at 1.75 GPa. Our diffraction results indicate that $M_Q \sim (0.67 \pm 0.04) \mu_B$/Ce at 1.6 GPa and 1.85 K. These results indicate that bulk SC coexists with relatively large-moment AFM order in CeRhIn$_5$ under pressure.

Unlike UPd$_2$Al$_3$, where the coexistence of AFM and unconventional SC has been ascribed to the partition of the three U 5f electrons into dual roles, magnetic and SC, CeRhIn$_5$ has only a single 4f electron that participates in creating both states. This situation in CeRhIn$_5$ is also distinctly different from other pressure-induced HFS based on Ce. CeIn$_3$, on which CeRhIn$_5$ is based is an example. In CeIn$_3$ the ordered moment\cite{40} and specific heat anomaly at $T_N$ decrease monotonically towards zero as the critical pressure is approached where SC appears\cite{40}. We do not understand presently how such a large-moment AFM can coexist with unconventional SC in CeRhIn$_5$. It is as if the 4f moments, in some way, also assumed dual character, perhaps purely in a dynamically as suggested by recent NMR studies\cite{27} or spatially segregating into AFM and SC domains. Such segregation, however, also could be dynamic since there is no evidence for additional NQR frequencies\cite{27,28}.

In summary, we have determined a P-T phase diagram from high quality CeRhIn$_5$ single crystals which shows a broad range of pressures where AFM and SC coexist. In addition, our single crystal magnetic neutron diffraction studies on CeRhIn$_5$ find only small changes in the incommensurate magnetic structure and ordered moment as pressure is increased up to 1.63 GPa. These results are consistent with specific heat measurements but inconsistent with estimates of $H_{int}$ determined by NQR, which we attribute tentatively to a pressure-induced change in the hyperfine coupling. We have not reproduced the observation of a significant change in $\delta$ and the absence of
AFM at 1.3 GPa reported earlier\textsuperscript{30}. Most importantly, we have found that compared to other heavy fermions, the relationship between AFM and unconventional SC is qualitatively different in CeRhIn\textsubscript{5} and will require the development of a new interpretative framework in which the 4f electron produces both long-range AFM order and heavy-quasiparticles that pair to form an unconventional SC state.

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1 N. D. Mathur, F. M. Grosche, S. R. Julian, I. R. Walker, D. M. Freye, R. K. W. Haselwimmer, and G. G. Lonzarich, Nature 394, 39 (1998).
2 N. K. Sato, N. Aso, K. Miyake, R. Shiina, P. Thalmeier, G. Varelogiannis, C. Geibel, F. Steglich, P. Fulde, and T. Komatsubara, Nature 410, 340 (2001).
3 Z. Fisk, H. R. Ott, and J. L. Smith, Nonlinearity in Condensed Matter. Proceedings of the Sixth Annual Conference, Los Alamos, NM, USA (1986).
4 K. Miyake, S. Schmitt-Rink, and C. M. Varma, Phys. Rev. B 34, 6554 (1986).
5 P. Monthoux, A.V. Balatsky, and D. Pines, Phys. Rev. Lett. 67, 3448 (1991).
6 P. Coleman and C. Pepin, Physica B 312-313, 383 (2002).
7 R. H. Effner and M. R. Norman, Comments on Condensed Matter Phys. 17, 361 (1996).
8 I. R. Walker, F. M. Grosche, D. M. Freye, and G. G. Lonzarich, Physica C 282-287, 303 (1997).
9 P. Morin, C. Vettier, J. Flouquet, M. Konczykowski, Y. Lassailly, J. M. Mignot, and U. Welp, J. of Low Temp. Phys. 70, 377 (1988).
10 D. Jaccard, H. Wilhelm, K. Alami-Yadri, and E. Vargoz, Physica B 259-261, 1 (1999).
11 D. Jaccard, K. Behnia, and J. Sierro, Phys. Lett. A 163, 475 (1992).
12 J. D. Thompson, R. D. Parks, and H. Borges, J. Magn. Magn. Mater. 54-57, 377 (1986).
13 F. M. Grosche, S. R. Julian, N. D. Mathur, and G. G. Lonzarich, Physica B 223-224, 50 (1996).
14 R. Movshovich, T. Graf, D. Mandrus, J. D. Thompson, J. L. Smith, and Z. Fisk, Phys. Rev. B 53, 8241 (1996).
15 H. Hegger, C. Petrovic, E. G. Moshopoulou, M. F. Hundley, J. L. Sarrao, Z. Fisk, and J. D. Thompson, Phys. Rev. Lett. 84, 4986 (2000).
16 C. Petrovic, R. Movshovich, M. Jaime, P. G. Pagliuso, M. F. Hundley, J. L. Sarrao, Z. Fisk, and J. D. Thompson, Europhys. Lett. 53, 354 (2001).
17 C. Petrovic, P. G. Pagliuso, M. F. Hundley, R. Movshovich, J. L. Sarrao, J. D. Thompson, Z. Fisk, and P. Monthoux, J. Phys: Condens. Matter 13, L337 (2001).
18 G.-q. Zheng, K. Tanabe, T. Mito, S. Kawasaki, Y. Kitaoka, D. Aoki, Y. Haga, and Y. Onuki, Phys. Rev. Lett. 86, 4664 (2001).
19 R. Movshovich, M. Jaime, J. D. Thompson, C. Petrovic, Z. Fisk, P. G. Pagliuso, and J. L. Sarrao, Phys. Rev. Lett. 86, 5152 (2001).
20 R. A. Fisher, F. Bouquet, N. E. Phillips, M. F. Hundley, P. G. Pagliuso, J. L. Sarrao, Z. Fisk, and J. D. Thompson, Phys. Rev. B 65, 224509 (2002).
21 P. G. Pagliuso, C. Petrovic, R. Movshovich, D. Hall, M. F. Hundley, J. L. Sarrao, J. D. Thompson, and Z. Fisk, Phys. Rev. B 64, 100503 (2001).
22 V. S. Zapf, E. J. Freeman, E. D. Baurer, J. Petricka, C. Sirvent, N. A. Frederic, R. P. Dickey, and M. B. Maple, Phys. Rev. B 65, 014506 (2002).
23 E. G. Moshopoulou, Z. Fisk, J. L. Sarrao, and J. D. Thompson, J. of Solid State Chemistry 158, 25 (2001).
24 N. J. Curro, P. C. Hammel, P. G. Pagliuso, J. L. Sarrao, J. D. Thompson, and Z. Fisk, Phys. Rev. B 62, R6100 (2000).
25 W. Bao, P. G. Pagliuso, J. L. Sarrao, J. D. Thompson, Z. Fisk, J. W. Lynn, and R. W. Erwin, Phys. Rev. B 62, 14621 (2000); ibid 67, 099903(E) (2003).
26 T. Mito, S. Kawasaki, G. Qing Zheng, Y. Kawasaki, K. Ishida, Y. Kitaoka, D. Aoki, Y. Haga, and Y. Onuki,
Physica B 312–313, 16 (2002).

27 T. Mito, S. Kawasaki, G.-q. Zheng, Y. Kawasaki, K. Ishida, Y. Kitaoka, D. Aoki, Y. Haga, and Y. Onuki, Phys. Rev. B 63, 220507 (2001).

28 T. Mito, S. Kawasaki, Y. Kawasaki, G.-q. Zheng, Y. Kitaoka, D. Aoki, Y. Haga, and Y. Onuki, Phys. Rev. Lett 90, 077004 (2003).

29 W. Bao, S. F. Trevino, J. W. Lynn, P. G. Pagliuso, J. L. Sarrao, J. D. Thompson, and Z. Fisk, App. Phys. A 74, 557 (2002).

30 S. Majumdar, G. Balakrishnan, M. R. Lees, D. McK.Paul and G. J. McIntyre, Phys. Rev. B 66, 212502 (2002).

31 S. Kawasaki, T. Mito, G.-q. Zheng, C. Thessieu, Y. Kawasaki, K. Ishida, Y. Kitaoka, T. Muramatsu, T. C. Kobayashi, D. Aoki, et al., Phys. Rev. B 65, 020504 (2002).

32 H. Shishido, R. Settai, S. Araki, T. Ueda, Y. Inada, T. C. Kobayashi, T. Muramatsu, Y. Haga, and Y. Onuki, Phys. Rev. B 66, 214510 (2002).

33 R. S. Kumar, H. Kohlmonn, B. E. Light, A. L. Cornelius, V. Raghavan, T. W. Darling, and J. L. Sarrao, cond-mat/0209005 (2002).

34 E. G. Moshopoulou, Z. Fisk, J. L. Sarrao, and J. D. Thompson, J. Solid State Chem. 25, 158 (2001).

35 P. G. Pagliuso, C. Petrovic, R. Movshovich, D. Hall, M. F. Hundley, J. L. Sarrao, J. D. Thompson, and Z. Fisk, Phys. Rev. B 64, 100503 (2001).

36 J. D. Thompson, Rev. Sci. Instrum. 55, 231 (1984).

37 W. Bao, G. Aeppli, J. W. Lynn, P. G. Pagliuso, J. L. Sarrao, M. F. Hundley, J. D. Thompson, and Z. Fisk, Phys. Rev. B 65, 100505 (2002).

38 M. J. Cooper, Acta Crystallogr. Sect.A, 624 (1968); M. J. Cooper and R. Nathans, Acta Crystallogr. Sect.A, 619 (1968).

39 J.-M. Mignot, A. Llobet, and Ar. Abanov, Private communication (2002).

40 M. Blume, A. J. Freeman, and R. E. Watson, J. Chem. Phys. 37, 1245 (1962).

41 A. D. Christianson, J. M. Lawrence, P. G. Pagliuso, N. O. Moreno, J. L. Sarrao, J. D. Thompson, P. S. Riseborough, S. Kern, E. A. Goremychkin, and A. H. Lacerda, Phys. Rev. B 66, 193102 (2002).

42 N. J. Curro, J. L. Sarrao, J. D. Thompson, P. G. Pagliuso, S. Kos, Ar. Abanov, and D. Pines, Phys. Rev. Lett. 90, 227202 (2003).

43 G. Knebel, D. Braithwaite, P. C. Canfield, G. Lapertot, and J. Flouquet, High Pressure Res. 22, 167 (2002).