μSR study of CeRhIn₅ under applied pressure

R H Heffner¹,², T Goko³,⁴, D Andreica⁵, K Ohishi⁷, W Higemoto², T U Ito², A Amato⁶, J Spehling⁸, H -H Klauss⁸, E D Bauer¹, J D Thompson¹ and Y J Uemura¹

¹ Los Alamos National Laboratory, Los Alamos, NM, 87545 USA
² ASRC, Japan Atomic Energy Agency, Tokai-mura, Ibaraki 319-1195, Japan
³ Dept. of Physics, Columbia University, New York, NY 10027 USA
⁴ TRIUMF, Vancouver, British Columbia, V6T 2A3 Canada
⁵ Faculty of Physics, Babes-Boyai University, 400084 Cluj-Napoca, Romania
⁶ Laboratory for Muon Spectroscopy, PSI, CH-5232 Villigen PSI, Switzerland
⁷ Advanced Meson Science Laboratory, Riken, Wako, 351-0198 Japan
⁸ Institut für Festkörperphysik, TU Dresden, D-01069 Dresden, Germany

E-mail: muonphysics@hotmail.com

Abstract. At ambient pressure CeRhIn₅ is an incommensurate antiferromagnet with Néel temperature Tₙ = 3.8 K. The application of pressure reduces Tₙ and yields (1) a state in which AFM coexists with superconductivity, and then (2) a superconducting state in the absence of AFM. We report transverse-field muon spin relaxation (μSR) measurements at pressures 2.07 and 2.26 GPa in the pure superconducting state of single-crystalline CeRhIn₅, which has a tetragonal structure. μSR is sensitive to the local field distribution produced by the vortex lattice in a mixed superconducting state, allowing a measurement of the magnetic field penetration depth λ(T). We measured λₘ(T) for applied field along the c-axis as a function of temperature T, and find λₘ(0) = 372(5) nm and 338(6) nm for P = 2.07 GPa and 2.26 GPa, respectively. The temperature dependence of the superfluid density ρₛ(T) ∝ λ⁻²(T) was found to be ρₛ(T) ∝ Tⁿ, with n = 1.9(2).

1. Introduction

CeRhIn₅ is an example of a system exhibiting competing broken symmetry ground states near a quantum critical point (QCP) [1]. At ambient-pressure CeRhIn₅ is an incommensurate, local-moment (μ = 0.8 μᵦ) antiferromagnet with Néel temperature Tₙ = 3.8 K [2]. As pressure is applied Tₙ increases slightly and then decreases, extrapolating towards zero in the region 2.3-2.4 GPa. For P ≈ 0.8 – 1.8 GPa, bulk superconductivity coexists with magnetic order, and for P > 1.8 GPa superconductivity is found in the apparent absence of magnetic order. CeRhIn₅ is thus an example of a quantum-critical system where the magnetic order parameter is driven to zero by applied pressure and where magnetism and superconductivity interact.

Several important magnetic and superconducting properties of this system have been determined. At ambient pressure the magnetic order has been found to be an incommensurate helix along the c-axis with moments in the a-b plane and propagation vector \( \mathbf{k} = (0.5, 0.5, \delta=0.298) \), with \( \delta \) changing as pressure exceeds about 1 GPa [2]. Nuclear quadrupole resonance (NQR) experiments [3] exhibit an additional commensurate phase above 1.7 GPa, though this has not been verified by neutron
scattering [2]. An unconventional superconducting order parameter (having a symmetry lower than that of the tetragonal lattice) has been found from NQR [4] and field-oriented specific heat [5] measurements.

Muon spin relaxation ($\mu$SR) experiments can yield important additional information. Beams of polarized positive muons can be produced with sufficient momentum to penetrate high pressure cells enabling muon experiments on materials under applied pressure. The $\mu^+$ occupies one or more interstitial lattice sites and serves as a probe of the local magnetic field, allowing measurements of the magnetic and superconducting properties of materials. The volume fraction of ordered magnetic states can also be easily determined.

In a type II superconductor such as CeRhIn$_5$ the applied magnetic field penetrates in discreet, quantized vortices. The field in the sample falls off between the vortices with a characteristic length $\lambda$, the magnetic field penetration depth. This yields an inhomogeneous internal field distribution which is sensed as a relaxation of the muon’s spin polarization in a $\mu$SR experiment [6]. The penetration depth is related to the superfluid density $\rho_s$ by the relation $\lambda^{-2} \propto \rho_s/m^*$, where $m^*$ is the effective mass of the paired electrons. Here we report $\mu$SR studies of the penetration depth $\lambda(T)$ in a single crystal of CeRhIn$_5$ under small applied magnetic field $H = 0.05$ T at pressures $P = 2.07$ and $2.26$ GPa.

2. Experimental Procedures

2.1 High pressure cell and CeRhIn$_5$ sample

The high-pressure experiments were performed on the GPD spectrometer at the Paul Scherer Institute (PSI) in Villigen, Switzerland, using backward-decay positive muons. In addition, some measurements were taken at the GPS spectrometer at PSI to obtain spectra below $T_N$ in a nearly background free environment to establish the form of the fitting functions for the data taken in the pressure cell.

A pressure cell made from MP35N alloy was used, with about a 5 mm diameter cylindrical sample space for pressures $P < 2.5$ GPa. The cell was thermally anchored to a helium-3 cryostat, allowing measurements between about $T = 0.25 – 300$ K. The pressure medium inside the cell was Daphne oil. The applied pressure was measured in-situ at low temperatures by ac susceptibility using the pressure dependence of the superconducting transition temperature of a small piece of In wire located near the sample inside the pressure cell [7]. The pressure determinations were performed at temperatures close to those of the $\mu$SR measurements themselves.

The sample was a cylindrically-shaped CeRhIn$_5$ single crystal about 5 mm in diameter and about 17 mm long with its b-axis along the cylinder axis. The incoming muon beam momentum (and, hence, spin polarization $S_\mu$) was aligned in the horizontal plane perpendicular to the sample b-axis (the vertical direction of the GPD spectrometer). The applied field $H$ could therefore be rotated in the a-c plane of the sample by rotating the cell through an angle $\theta$ about its vertical axis. In this way $H$ could be oriented along the c-axis of the sample, as described below.

2.2 Transverse field $\mu$SR signals

In a static magnetic field $|B|$ oriented transversely to the muon spin ($\mathbf{B} \perp S_\mu$, denoted TF below) the muon relaxation function is given by $G(t)\cos(2\pi\nu t + \phi)$, where $2\pi\nu = \gamma_\mu|B|$ and the muon’s gyromagnetic ratio $\gamma_\mu = 2\pi \times 135.54$ MHz/T. The function $G(t)$ describes the relaxation of the spin polarization, in our case by an inhomogeneous field distribution [6]. Figure 1a shows the Fourier transformed $\mu$SR signals for data taken with an empty cell in $H = 0.05$ T. Good fits to the muon relaxation function for these data were obtained with a stretched exponential function $G_s(t) = A_s \exp(-(\lambda_s t)^\beta)$.

Inside the sample, and above the superconducting transition temperature $T_c$, the muons predominantly experience randomly-oriented, quasi-static nuclear dipole fields. Below $T_c$ muons stop randomly with respect to the flux-line-lattice (FFL), and the resultant inhomogeneous field distribution
causes a dephasing of the ensemble of muon spins which can be reasonably approximated by a Gaussian relaxation function (figure 1b below). (More complicated expressions which take into account the asymmetric field distribution produced by the FLL [9] are not justified in this experiment due to the large background produced by the pressure cell.) Hence, the transverse muon relaxation function $G(t)$ was fit by a sum of two terms corresponding to muons stopping in the sample and the cell, respectively:

$$G(t) = A_1 \exp(-\sigma^2 t^2/2) \cos (2\pi \nu t + \phi) + A_c \exp(-\lambda_c t) \cos (2\pi \nu_c t + \phi),$$  \hspace{1cm} (1)

with fixed values $A_1 = 0.25$ and $A_c = 0.75$. The values for $A_1$ and $A_c$ were determined by fits to the amplitudes of the oscillating signal below $T_N$ in zero applied field (ZF). Under these conditions the ZF relaxation from the empty cell was found to be well described by $G(t) = A_1 \exp(-\lambda_0 t) G_{KT}(t) + A_2$, where $G_{KT}(t)$ is the well-known Kubo-Toyabe relaxation function [10] and $\lambda_0$ is a fit parameter. Thus, because the cell produced no oscillation signal, the fraction of muons stopping in the sample could be determined by the relative amplitude of the oscillating signal in ZF below $T_N$. Note that the sample filling factor of $\approx 25\%$ measured in this way agrees well with a geometrical calculation of the area subtended by the sample in the beam.

2.3 Sample alignment

The measured value of $\lambda$ depends on the orientation of the applied magnetic field with respect to the crystalline axes in a non-cubic material. When the field is oriented along the tetragonal c-axis, superconducting screening currents flow in the a-b plane and one measures $\lambda_{ab}$. In CeRhIn$_5$, the internal fields $B$ below $T_N$ lie predominantly along the c-axis for the measured $\mu^+$ interstitial sites [8]. Therefore, the sample could be aligned so that $S_{\mu}$ was perpendicular to the c-axis by maximizing the amplitudes of the muons’ precession signals as a function of the angle $\theta$ in zero applied field. In this way, the applied field could be oriented along the sample’s c-axis.

**Figure 1a.** Fourier transformed frequency spectra for cell alone in $H = 0.05$ T. The curves (color on line) range from 3.00 K to 0.23 K (top to bottom).

**Figure 1b.** Fourier transformed frequency spectra for sample plus cell in $H = 0.05$ T. The curves (color on line) range from 3.00 K to 0.23 K (top to bottom).
3. Determination of $\lambda_{ab}(T)$

The TF data were fit to equation (1) with the cell parameters $\lambda_c$ and $\beta$ held fixed at their values determined from the cell-only data. All data were taken in a field-cooled manner to establish an equilibrium field distribution in the superconducting state. Figure 2 shows the temperature dependence of the parameters $\sigma(T)$ and $\nu(T)$ in 0.05 T transverse field taken at $P = 2.07$ and 2.26 GPa. At these pressures the sample is in the pure superconducting state. Several features are evident. Above $T_c \approx 2.2$ K $\sigma(T)$ is roughly independent of temperature and pressure, corresponding to relaxation in the paramagnetic state of CeRhIn$_5$. Below $T_c \approx 2.2$ K $\sigma(T)$ increases in value due to the inhomogeneous field distribution produced by the FLL, and $\nu_1(T)$ decreases in value due to the Meissner screening by the supercurrents.

To obtain the signal $\sigma_v(T)$ from the FLL one unfolds the Gaussian widths according to $
abla^2 = \sigma^2 - \sigma_b^2$, where $\sigma_b$ is the average temperature-independent background rate above $T_c$. These unfolded data are shown in figure 3, using $\sigma_b = 0.271 \mu s^{-1}$ for $P = 2.07$ GPa and $\sigma_b = 0.269 \mu s^{-1}$ for $P = 2.26$ GPa. Also shown in figure 3 is a fit to an empirical formula for the superfluid density $\rho_s(T)$ appropriate for unconventional superconductors [11]:

$$\rho_s(0) - \rho_s(T) \propto T^n.$$  

Here we note that $\sigma_v \propto \rho_s/m^*$, and we assume that the effective mass $m^*$ is independent of temperature. We obtain $\sigma_v(0) = 0.91(3) \mu s^{-1}$ and $n = 1.83(27)$ for $P = 2.07$ GPa and $\sigma_v(0) = 0.75(2) \mu s^{-1}$ and $n = 1.94(27)$ for 2.26 GPa. $T_c$ was fixed in the fits at 2.2 K.

To estimate $\lambda_{ab}(0)$ from $\sigma_v(0)$ we use a well-known relation [12] valid for $H \ll H_{c2}$ and given in equation (3). $H_{c2}(0)$ is greater than 10 T for the pressures of interest [13].
\[ \sigma_r^2/\mu^2 = <\Delta B^2> = 0.00371 \phi_0^2/\lambda_{ab}^4, \]  

(3)

where \(<\Delta B^2>\) is the mean square field distribution caused by the FLL and \(\phi_0 = hc/2e = 2.07 \times 10^{-15}\) Tm\(^2\) is the magnetic flux quantum. This yields \(\lambda_{ab}(0) = 372(5)\) nm and 338(6) nm for \(P = 2.07\) GPa and 2.26 GPa, respectively. The errors are statistical. Note that no mean-free-path corrections have yet been made to these values.

4. Conclusions

We have measured the TF-\(\mu\)SR relaxation rate at \(P = 2.07\) GPa and 2.26 GPa in the pure superconducting state of CeRhIn\(_5\) and extracted the temperature dependence and magnitude of the magnetic field penetration depth (or, alternatively, the superfluid density). We find that the density \(\rho_s(0)\) is slightly higher at the higher pressure, which may result from the increased conduction electron itinerancy with pressure in this system. The temperature dependence of \(\rho_s(T)\) at the two pressures is essentially the same, and can be parameterized by equation (2) with \(<n> \cong 1.9(2)\). We note that a simple (BCS) two-fluid model of superconductivity gives \(n = 4\). Thus, our results show a power-law temperature dependence, indicating nodes in the superconducting order parameter, and a significantly weaker temperature dependence than for a BCS superconductor, both consistent with an unconventional order parameter. Finally, we estimate the Ginsburg-Landau coherence length \(\xi_{GL}\) from the upper critical field as \(\xi_{GL}^2 = \phi_0/2\pi H_{c2}(0)\), yielding \(\xi_{GL} < 5.6\) nm for \(H_{c2}(0) > 10\) T [13]. This yields \(\kappa = \lambda_{ab}/\xi > 63\), taking the average of the measured values of \(\lambda_{ab}\) quoted above. This value can be compared to CeCoIn\(_5\) (\(\kappa \cong 69\)) and CeIrIn\(_5\) (\(\kappa \cong 26\)), both ambient-pressure superconductors.

References

[1] Park T, Ronning F, Yuan H Q, Salamon M B, Movshovich R, Sarrao J L and Thompson J D 2006 Nature 440 65; Knebel G, Aoki D, Braithwaite D, Salce B and Flouquet J 2006 Phys. Rev. B 74, 020501(R)
[2] Aso N, Kiwamu I, Yoshizawa H, Fujiwara T, Uwatoko Y, Chen Gen-Fu, Sato N K and Miyake K 2009 J. Phys. Soc. Jpn. 78 073703 and references therein
[3] Yashima M, Mukuda2009 Phys. Rev. B 79 214528
[4] Kohori Y, Yamato Y, Imamoto Y and Kohara T 2000 Eur. Phys. J. B 18 1601
[5] Park T, Bauer E D and Thompson J D 2008 Phys Rev. Lett. 101 177002; Park T and Thompson J D 2009 New J. Phys. 11 055062

Figure 3a. Temperature dependence of \(\sigma_r(T)\) at \(P = 2.07\) GPa with fit (solid curve) to equation (2). \(\sigma_r(0) = 0.75(2)\) \(\mu s^{-1}\), \(n = 1.94(27)\). \(T_c\) fixed at 2.2 K.

Figure 3b. Temperature dependence of \(\sigma_r(T)\) at \(P = 2.26\) GPa with fit (solid curve) to equation (2). \(\sigma_r(0) = 0.91(3)\) \(\mu s^{-1}\), \(n = 1.83(27)\). \(T_c\) fixed at 2.2 K.
[6] Schenck A 1985 *Muon Spin Rotation Spectroscopy: Principles and Applications to Solid State Physics* (Hilger, Bristol)

[7] Eiling A and Schilling J S 1981 *J. Phys. F: Metal Phys.* **11** 623

[8] Schenck A, Andreica D, Gygax F N, Aoki D and Onuki Y 2002 *Phys. Rev.* B **66** 144404

[9] Sonier J E, Brewer J and Kiefl R F 2000 *Rev. Mod. Phys.* **72** 769

[10] Kubo R and Toyabe T 1967 in *Magnetic Resonance and Relaxation* (ed. R. Blinc, North Holland, Amsterdam) 810

[11] Sigrist M 2005 *Lectures on the Physics of Highly Correlated System IX: Ninth Training Course* (ed. Avella A and Mancini F) American Institute of Physics 0-7354-0279-5/05 p. 165

[12] Brandt E H 1988 *Phys. Rev.* B **37** 2349

[13] Ida Y, Settai R, Ota Y, Honda F and Onuki Y 2008 *J. Phys. Soc. Jpn.* **77** 084708; Knebel G, Aoki D, Brison J-P and Flouquet J 2008 *J. Phys. Soc. Jpn.* **77** 114704

**Acknowledgements**

DA acknowledges partial financial support from the Romanian CNCSIS project 444/2009.