Magnetism and superconductivity in CeRh$_{1-x}$Ir$_x$In$_5$ heavy fermion materials.

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We report zero-field $\mu$SR studies of cerium based heavy-fermion materials CeRh$_{1-x}$Ir$_x$In$_5$. In the superconducting $x=0.75$ and $1$ compositions muon spin relaxation functions were found to be temperature independent across $T_c$; no evidence for the presence of electronic magnetic moments was observed. The $x=0.5$ material is antiferromagnetic below $T_N=3.75$ K and superconducting below $T_c=0.8$ K. $\mu$SR spectra show the gradual onset of damped coherent oscillations characteristic of magnetic order below $T_N$. At 1.65 K the total oscillating amplitude accounts for at least 85% of the sample volume. No change in precession frequency or amplitude is detected on cooling below $T_c$, indicating the microscopic coexistence of magnetism and superconductivity in this material.

A tetragonal HoCoGa$_5$ crystal structure is common to all the CeMIn$_5$ materials, which may be viewed as alternating layers of CeIn$_3$ and MIn$_2$. Varying fractions of Ir, Rh or Co on the M site results in a rich phase diagram exhibiting antiferromagnetic and superconducting properties. It has been noted [1] that the superconducting transition temperature $T_c$ increases monotonically with $c/a$, suggesting that the superconductivity is most robust when the layers of CeIn$_3$ are more isolated. It is not clear whether this reflects a shift toward optimal hybridization, or greater 2D character in a possible magnetic pairing interaction. CeCoIn$_5$ has the highest $T_c=2.3$ K of the known heavy fermion superconductors [2]. Specific heat and thermal conductivity measurements on CeCoIn$_5$ and CeRhIn$_5$ found power-law temperature dependencies, indicating the presence of lines of nodes in their superconducting gaps [3]. These results led to speculation that 2D (or at least anisotropic) AFM fluctuations play an important role in magnetically-mediated heavy-fermion superconductivity within the CeMIn$_5$ family. Recent theoretical work has also found that quasi-2D magnetic fluctuations result in superconductivity at higher temperatures than 3D fluctuations in metals which are nearly antiferromagnetic [4]. However, neutron scattering experiments on CeRhIn$_5$ found AFM fluctuations along the $c$-axis, with a weaker interaction than between Ce moments in-plane, but concluded that magnetic correlations are nonetheless 3D in nature [5]. We have performed $\mu$SR experiments on several superconducting compositions of CeRh$_{1-x}$Ir$_x$In$_5$, with the objective of elucidating the magnetic and superconducting properties of these materials.

The phase diagram of CeRh$_{1-x}$Ir$_x$In$_5$ shows a range of magnetic and superconducting properties which may be tuned with composition or pressure [6]. CeRhIn$_5$ is known from neutron scattering experiments to have an incommensurate antiferromagnetic order below $T_N=3.8$ K, in which the moments lie in the $a-b$ plane but spiral $107^\circ$ per unit cell along the $c$-axis [7]. Superconductivity is present for compositions $0.3 < x < 1$, and there is evidence from macroscopic susceptibility and resistivity measurements that AFM order and superconductivity coexist for $0.3 < x < 0.6$ [1]. A local probe like $\mu$SR can address whether the magnetism and superconductivity coexist on a microscopic scale.

Zero-field time-differential $\mu$SR spectra were taken on superconducting samples of CeIrIn$_5$ ($T_c=0.4$ K) and CeRh$_{0.25}$Ir$_{0.75}$In$_5$ ($T_c=0.7$ K) with the dilution refrigerator at the TRIUMF M15 channel. Zero magnetic field (ZF) conditions were prepared by quenching the superconducting solenoid in the dilution refrigerator. Residual fields on the order of 1 G were then zeroed to less than 20 mG with external trim coils and a field-zeroing method described elsewhere in these proceedings [8]. Samples were oriented with their $c$ axes nominally parallel to the muon momentum and spin.

A background signal originating from muons stopping in cryostat parts near the sample position was characterized with the entire area of the silver sample stage covered by a GaAs wafer, which produces no decay asymmetry in ZF. In both CeIrIn$_5$ and CeRh$_{0.25}$Ir$_{0.75}$In$_5$ the experimental decay asymmetry followed a slow, static Gaussian Kubo-Toyabe form with temperature-independent relaxation rates $\Delta$ across their superconducting transitions, shown in Fig. 1. Average values of $\Delta$ in CeIrIn$_5$ and CeRh$_{0.25}$Ir$_{0.75}$In$_5$ were found to be $0.239(4)$ and $0.276(2)$ $\mu$s$^{-1}$ respectively. There is thus no evidence of an increased relaxation rate or coherent precession signal which might result from the onset of electronic (spin or orbital) moments at $T_c$. These results are similar to...
those recently published by Higemoto et al. [9] who also found no observable electronic magnetic moment in the superconducting state in CeIrIn$_5$. Our results differ in that we obtained excellent fits of the polarization to a static Kubo-Toyabe relaxation function.

Zero-field experiments were performed on two samples of CeRh$_{0.5}$Ir$_{0.5}$In$_5$ at the LTF ($T \leq 1.15$ K) and GPS ($T \geq 1.65$ K) channels at PSI, Switzerland. Auxiliary experiments found no indications of inhomogeneity in these samples; sharp transitions were found in bulk resistivity and AC susceptibility. $\mu$SR spectra (Fig. 2a) show rapidly-damped, coherent oscillations developing below $T_N=3.75$ K. This component of the signal is clearly not of a Kubo-Toyabe form since the minimum in corrected asymmetry is negative. From $T_N$ down to 2 K the static Gaussian Kubo-Toyabe (G-KT) component diminishes in amplitude, while the oscillating and longitudinal components grow. Above $T=2$ K the experimental asymmetry was fitted to the sum of two oscillating signals, plus the slow G-KT and a longitudinal signal due to that component of the muon spin parallel to the local magnetic field. The total asymmetry remained constant. The G-KT signal vanishes at temperatures of 1.65 K and below. For spectra taken in the dilution refrigerator, a non-relaxing silver background component was also present. Figure 2b shows examples of two spectra at 0.1 and 1.15 K.

Two oscillating components were observed in the first $\mu$s of the CeRh$_{0.5}$Ir$_{0.5}$In$_5$ spectra taken at temperatures below 2.75 K. Total asymmetry of the oscillating components saturated by $T=2$ K. Rapid damping made it impossible to obtain reliable fits to the higher frequency and its relaxation rate, however. The muon site(s) in these materials remain to be determined. Nevertheless, transverse field data in CeIrIn$_5$ from $T=2$–300 K [10] show that the muon stops in two magnetically inequivalent sites. This is consistent with the two observed oscillating signals in CeRh$_{0.5}$Ir$_{0.5}$In$_5$. High relaxation rates may be the result of a broad field distribution at the muon sites which would result from incommensurate magnetic order similar to that in CeRhIn$_5$.

The smaller frequency in CeRh$_{0.5}$Ir$_{0.5}$In$_5$ ($\nu_1(T)$ in Fig. 3) is nearly temperature-independent below 1.15 K, with no obvious discontinuity at $T_c$. The oscillating asymmetry in spectra taken with the muon spin rotated (to 50° from the c-axis) amounted to 85% of the full asymmetry so at least 85% of the sample volume is magnetic. Spectra were essentially indistinguishable between $T=1.15$ K and 0.050 K, but these spectra have smaller oscillating amplitudes and larger longitudinal amplitudes due to the orientation of the muon spin with respect to the local field. We have therefore normalized the total oscillating fraction measured in spectra for $T \leq 1.15$ K to those measured with rotated spin at $T \geq 1.65$ K. This corrected oscillating fraction is also shown in Fig. 3. Note that no change occurred in the asymmetry or frequency on crossing the superconducting transition - i.e., magnetic order persists unchanged into the superconducting state. Susceptibility measurements reveal a diamagnetic signal at $T_c$ that is at least 85% of that expected for full shielding. We, therefore, conclude that superconductivity and AFM order must coexist microscopically in the majority of the sample volume.

In summary, we find no evidence for electronic magnetic moments coincident with the onset of superconductivity in CeIrIn$_5$ or CeIr$_{0.75}$Rh$_{0.25}$In$_5$. Furthermore, the antiferromagnetism in CeIr$_{0.5}$Rh$_{0.5}$In$_5$ coexists microscopically with superconductivity below $T_c$.

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FIGURE CAPTIONS

Fig.1 ZF static Gaussian Kubo-Toyabe widths in CeIrIn$_5$ (squares) and CeRh$_{0.25}$Ir$_{0.75}$In$_5$ (circles) are temperature independent across superconducting transition.
temperatures $T_c$.

Fig.2. (a) Corrected Up-Down asymmetries in CeRh$_{0.5}$Ir$_{0.5}$In$_5$ at several temperatures, showing the gradual evolution of the spin relaxation function from a static Gaussian Kubo-Toyabe to oscillating and longitudinal components. The muon spins in these spectra were rotated to approximately 50° from the $c$ axis. (b) Low temperature Back-Forward asymmetries at $T$=0.1 and 1.15 K with muon spins oriented along the $c$ axis. Low temperature spectra taken in the dilution refrigerator are virtually identical.

Fig.3. The temperature dependence of the frequency $\nu_1$ (circles) and total oscillating amplitude (triangles) in two samples of CeRh$_{0.5}$Ir$_{0.5}$In$_5$. No change in the relaxation function is seen on crossing into the superconducting state at $T_c$=0.8 K. Filled symbols correspond to sample 1.
\( T_c \) MHz 

\( V_1 \), MHz 

Total Oscillating Fraction 

Temperature, K