Behavior near pressure induced quantum criticality in Sr$_3$Ru$_2$O$_7$

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Abstract. The pressure dependence of the ac susceptibility is reported for the itinerant metamagnet Sr$_3$Ru$_2$O$_7$ for the field applied in the ab-plane. At the critical pressure $P_c$ for suppression of the first order jump in magnetization, the susceptibility shows a non-Fermi-liquid, quasi-linear temperature dependence down to the lowest temperature. For pressure $P > P_c$, the temperature dependence reveals a pressure-dependent cross-over, which we interpret as a recovery of Fermi liquid ground state.

1. Introduction
Quantum criticality is produced when the characteristic temperature of a second order phase transition is suppressed to zero by tuning non-thermal parameters such as magnetic field, chemical doping, or pressure. The critical fluctuations associated with a quantum critical point (QCP) can affect the physical properties of the system over a significant portion of the phase diagram. For example, metallic correlated electron systems show non-Fermi liquid behavior in the quantum critical region. A new kind of QCP was recently found in the material Sr$_3$Ru$_2$O$_7$ [1]. This kind of QCP is associated with a first order metamagnetic phase transition, in which no symmetry is broken. Metamagnetism is a phenomenon characterized by a rapid rise in magnetization in a narrow magnetic field range. Quantum criticality is obtained by suppressing the critical temperature $T^*$ of this first order transition to zero, and this critical point is called a “quantum critical end point” (QCEP) to distinguish it from the original definition of QCP associated with a second order transition.

Previous studies in Sr$_3$Ru$_2$O$_7$ have been done with the magnetic-field-angle tuning of metamagnetism. Defining $\theta = 0^\circ$ as the magnetic field parallel to the ab-plane, the metamagnetic critical temperature $T^*$ falls with increasing $\theta$ and a QCEP occurs at about $\theta = 80^\circ$ in a highly pure single crystal [2]. However, in “ultra pure” samples (having residual resistivity...
\(\rho_0 < 0.5\mu\Omega\text{cm}\) compared to the “high purity” sample with \(\rho_0 \sim 2.4\mu\Omega\text{cm}\), no QCEP is observed. Instead, \(T^*\) initially falls as the magnetic field is turned away from the \(ab\)-plane, having a minimum at \(\theta \sim 60^\circ\), and then rises with another nearby first order jump at slightly higher field. A novel nematic phase is enclosed by these two first order transitions [3, 4, 5].

With the assumption that field-angle suppresses the metamagnetism through angle-dependent magnetostriction, pressure should play a role analogous to field angle tuning [2]. The pressure dependence of the metamagnetic critical endpoint temperature \(T^*\) for a field applied in the \(ab\)-plane has been discussed in our recent paper [6]. It is found that \(T^*\) falls monotonically to zero as pressure increases, producing a QCEP at \(P_c \sim 13.6 \pm 0.2\) kbar. Features are observed near the QCEP — the slope of \(T^*\) versus pressure changes at \(\sim 12.8\) kbar, and weak subsidiary maxima appear on either side of the main susceptibility peak at pressures near \(P_c\). However, in that paper, we did not discuss the temperature dependence of the susceptibility for \(P > P_c\). It is expected that at \(P_c\), the system will show non-Fermi-liquid behavior (for example \(\chi(T) = \chi(0) + aT^\alpha\), where \(\alpha \neq 0\)). For \(P > P_c\), Fermi-liquid behavior (\(\chi(T) = \text{const.}\)) should be recovered below a pressure-dependent cross-over temperature [7]. This region could not be explored in field-angle tuning, because the QCEP is just reached at the highest possible angles.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{The real part of the ac susceptibility for 14.2 kbar, 15.7 kbar, 16.7 kbar, and 18.2 kbar. Note that the scales on both the vertical and horizontal axes are different for the four graphs.}
\end{figure}

2. Experiment

A BeCu clamp cell was employed to obtain hydrostatic pressure, with Daphne oil 7373 as the transmitting medium to keep the pressure highly homogeneous. The working pressure was calibrated from the the known temperature dependence of the superconducting transition of tin. The ac susceptibility measurement was done with a set of three detecting coils, containing a central coil connected anti-parallel to two end coils. This configuration reduces the background
pick-up from the pressure cell. The drive frequency was set to 14 Hz, to reduce finite frequency effects [8]. The sample has ultra pure quality with residual resistivity less than 0.5μΩcm.

The dc field was set in the ab-plane, with a slow sweep rate of 0.02 T/min. In this investigation, we are only interested in the relative variation of the ac susceptibility due to the metamagnetic transition ($\Delta \chi$). Therefore arbitrary units, a.u., are used in all the figures. However the relative amplitude of the peaks at different pressures can be compared directly, as the same modulation amplitude and frequency, and the same electronics, were used throughout. A slowly varying background signal including the paramagnetic susceptibility of Sr$_2$Ru$_2$O$_7$ has been subtracted.

3. Results
Here we focus on the $P > P_c$ data. The real part of the ac susceptibility $\Delta \chi'$ exhibits a pronounced peak across the metamagnetic transitions. The peak was followed up to 18 kbar and it shifts to higher field roughly linearly with pressure. The height of the peak decreases with increasing pressure. The results for pressure at 14.2 kbar, 15.7 kbar, 16.7 kbar, and 18.2 kbar are shown in Figure 1.

![Figure 2](image_url). The magnitude of $\Delta \chi'$ peaks, $\Delta \chi'_m$, as a function of temperature for pressures higher than $P_c$. The dashed lines are guides to the eye for the change of the slope.

Figure 2 plots the temperature dependence of the maximum in $\Delta \chi'$. The data points at 14.2 kbar, which is near $P_c$, follow a roughly linear trend all the way to the lowest reachable temperature in our measurement. This is suggestive of a non-Fermi liquid behavior, with strong power-law dependence on temperature. Above the critical point, the data points have a slope change, which is most apparent in the 15.7 kbar data, but weakly visible, with larger error bars, at higher pressures too. The magnitude of the peak in $\Delta \chi'$ initially increases quasi-linearly as temperature falls, then it rises more slowly. The deviation of the quasi-linear trend may reflect the change of the underlying physics from a non-Fermi-liquid behavior to a Fermi-liquid behavior.

The $(T, P)$ phase diagram is given in Figure 3. The blue curve shows the metamagnetic critical endpoint temperatures $T^*$ [6]. The red circles present the temperature at which the maximum in $\Delta \chi'$ has a slope change at pressures higher than $P_c$. The insert shows the pressure dependence of the metamagnetic field. For pressure above the critical pressure, $H_M(70 \text{ mK})$ is used for $H_M(T^*)$, with 70 mK the lowest stable temperature of our measurement. The slope
Figure 3. (color online) The phase diagram inferred from susceptibility measurements. The blue dots consists the measured critical end points $T^*$ [6]. The red circles represent the change in slope in the peak-height vs. temperature curves shown in Figure 2. The dashed lines are guides to the eye.

is unchanged through the QCEP. The $(T, P)$ phase diagram shows a fan-like shape, which is predicted by Hertz’s theory of quantum critical phenomena [7].

4. Summary
In Sr$_3$Ru$_2$O$_7$, it has been previously established that a QCEP can be produced by hydrostatic pressure at $P_c = 13.6 \pm 0.2$ kbar for $H \parallel ab$. In this work, we have used ac susceptibility measurements to show the behavior above the critical pressure $P_c$. The magnitude of the $\Delta \chi'$ peaks increases as temperature falls, with a marked change of slope at a cross-over temperature that tends to zero at the QCEP. We obtained a fan-like phase diagram near the QCEP.

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