



# Dependence of temperature-dependent electrical resistivity of SrIrO<sub>3</sub> on hydrostatic pressure to 9.1 kbar



N. Foroozani <sup>a</sup>, J. Lim <sup>a</sup>, L. Li <sup>b</sup>, G. Cao <sup>b</sup>, J.S. Schilling <sup>a,\*</sup>

<sup>a</sup> Department of Physics, Washington University, St. Louis, MO 63130, USA

<sup>b</sup> Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506, USA

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## ABSTRACT

Non-Fermi-liquid behavior and close proximity to a quantum critical point in the 5d transition metal iridate SrIrO<sub>3</sub> at ambient pressure motivate our search for possible anomalous behavior in its transport properties under pressure. The electrical resistivity in the *ab*-plane of a single crystal of SrIrO<sub>3</sub> has been measured over the temperature range 1.35–285 K at both ambient and 9.1 kbar hydrostatic pressure. The resistivity decreases slightly over the entire temperature range, but no superconducting transition or changes in the non-Fermi-liquid behavior are observed under pressure. It is estimated that significantly higher pressures are likely required before sizable changes in the properties of SrIrO<sub>3</sub> will occur.

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The 4d and 5d transition metal oxides are the subject of considerable current interest [1]. The ruthenates MRuO<sub>3</sub> (M = Ba, Sr, Ca) are metallic, both BaRuO<sub>3</sub> and SrRuO<sub>3</sub> exhibiting itinerant ferromagnetic behavior [2,3]. CaRuO<sub>3</sub> does not order magnetically. This could be because its smaller unit cell volume leads to greater overlap of the 4d-orbitals of Ru nearest-neighbors, resulting in greater bandwidth and a decreased electronic density of states at the Fermi energy. Conventional wisdom would then dictate that the corresponding iridates MIrO<sub>3</sub> (M = Ba, Sr, Ca), with their more extended 5d (Ir) wavefunctions, would also be metallic and perhaps no longer magnetic. In contrast, only SrIrO<sub>3</sub> is metallic whereas the neighboring iridates CaIrO<sub>3</sub> and BaIrO<sub>3</sub> with their smaller and larger unit cells, respectively, are insulators. These marked differences are believed to arise from the strongly enhanced spin-orbit coupling for the heavy iridium cation [1,4,5]. In addition, in both the ruthenates [2] and iridates [4], rigid tilts, rotations, and deformation of the RuO<sub>6</sub> or IrO<sub>6</sub> octahedra likely play an important role.

The strong spin-orbit coupling in the iridates leads to many other unconventional electronic, magnetic, and lattice properties that have only recently begun to be explored. Whereas in transition metal systems orbital moments are in general quenched by the crystalline electric field, in insulating BaIrO<sub>3</sub> Ir's 5d orbital moment has been found to be 50% larger than its spin moment and, even more surprisingly, the magnetic state is not itinerant but rather local in character [6]. If 25% of Ba is replaced by Sr in BaIrO<sub>3</sub>, the magnetic order disappears accompanied by an

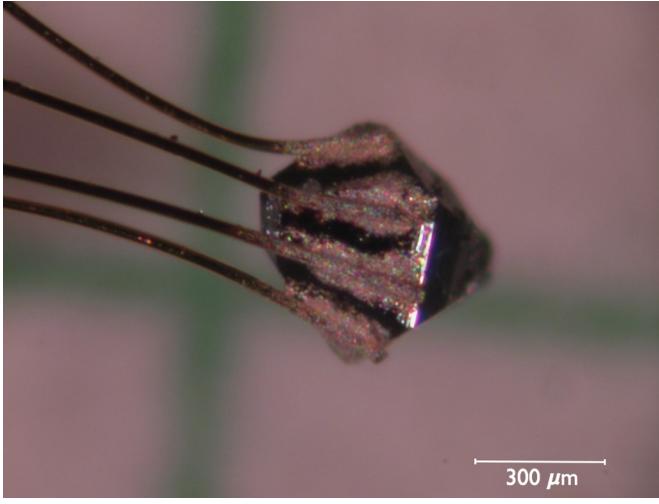
insulator-to-metal transition [4]. That this is not solely a result of the decrease in unit cell volume is seen from the fact that subjecting BaIrO<sub>3</sub> to pressures above 40 kbar does suppress the magnetic order without, however, inducing metalization [7].

The strong spin-orbit coupling is likely to also lead to anomalous properties in SrIrO<sub>3</sub>, a paramagnetic metal at ambient pressure. Although its electronic specific heat coefficient  $\gamma = 1.5 \text{ mJ/mole K}^2$  is not enhanced, an anomaly in the specific heat does appear below 5 K and non-Fermi-liquid behavior is evident below 120 K in its transport properties [5]. In addition, the proximity of SrIrO<sub>3</sub> to ferromagnetism and a possible quantum critical point is indicated by the fact that the application of only 0.23 T magnetic field suffices to induce a ferromagnetic transition below 2 K that extrapolates to 0 K at only 0.23 T. It would be interesting to study the effect of hydrostatic pressure on this compound to establish whether its proximity to a quantum critical point leads to strong changes in the non-Fermi-liquid behavior and/or the emergence of superconductivity. Under sufficient pressure to shrink the unit cell volume of SrIrO<sub>3</sub> close to that of CaIrO<sub>3</sub>, it is conceivable that the antiferromagnetic insulating state of CaIrO<sub>3</sub> might be induced. Longo et al. [8] have shown that at 40 kbar and 1000 °C a structural transition from distorted hexagonal to orthorhombic occurs; since the transition pressure is even much higher at lower temperatures, it is well beyond the range of the present experiments to 9.1 kbar.

The electrical resistivity of SrIrO<sub>3</sub> was measured as a function of both temperature (1.3–285 K) and hydrostatic pressure to 9.1 kbar using a He-gas compressor system. No superconducting transition was observed. In addition, the temperature-dependent electrical resistivity decreased only slightly under pressure with no observable change in the non-Fermi-liquid behavior. Apparently, much

\* Corresponding author. Tel.: +1 314 935 6239.

E-mail address: [jss@wuphys.wustl.edu](mailto:jss@wuphys.wustl.edu) (J.S. Schilling).



**Fig. 1.** Single crystal of  $\text{SrIrO}_3$  contacted in  $ab$ -plane by four  $20 \mu\text{m}$  gold wires.

higher pressures must be applied to cause significant changes in this compound.

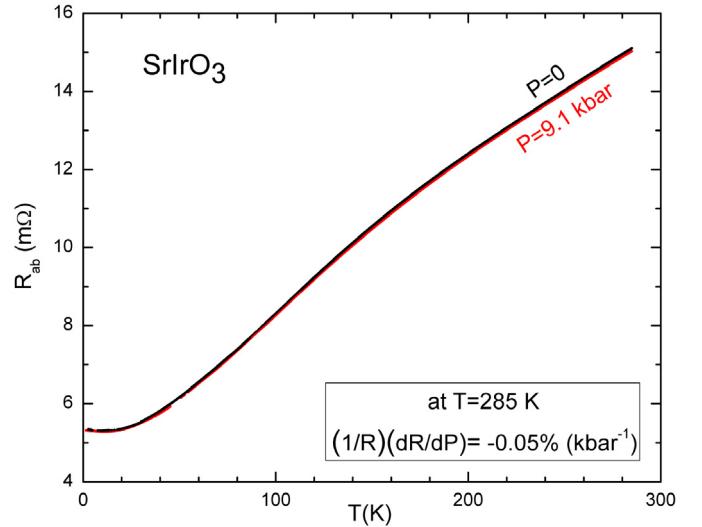
The single crystals studied were synthesized using a self-flux technique described elsewhere [5]. The structure of  $\text{SrIrO}_3$  was determined using a Nonius Kappa CCD X-ray diffractometer with sample temperature controlled using a nitrogen stream. Chemical compositions of the single crystals were determined using energy dispersive X-ray analysis (EDX) (Hitachi/Oxford 3000).

Four-point ac electrical resistivity measurements were carried out in the  $ab$ -plane of a small  $\text{SrIrO}_3$  crystal (see Fig. 1). Gold wires ( $20 \mu\text{m}$  diameter) were contacted to the sample with silver paint. An excitation current of  $2 \text{ mA}$  (rms) at  $15 \text{ Hz}$  was applied and the small voltage detected by a Stanford Research SR830 digital lock-in amplifier with a SR554 transformer preamplifier. Temperatures as low as  $1.35 \text{ K}$  could be reached using a Roots pump to reduce the vapor pressure over the liquid He in the sample tube of a Janis SuperVariTemp cryostat.

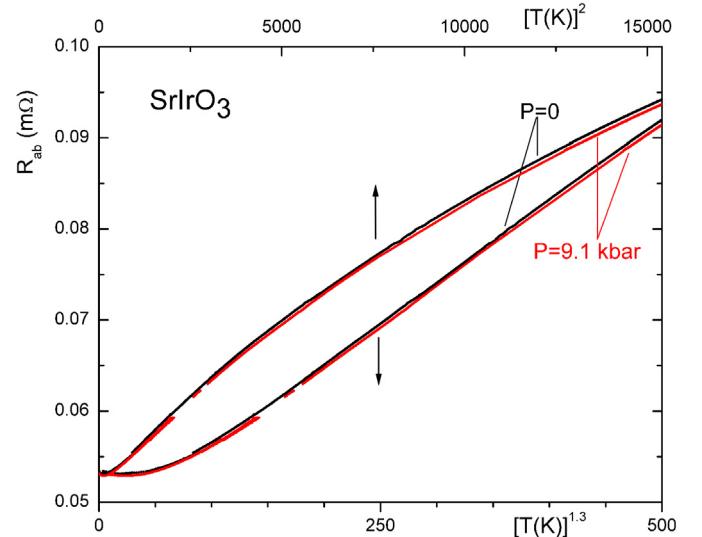
To generate pressures to  $9.1 \text{ kbar}$ , the sample was placed in the  $7 \text{ mm}$  diameter bore of a CuBe high-pressure cell from Unipress connected to a three-stage Harwood compressor system. He gas from the compressor is fed into the pressure cell via a  $3/0.3 \text{ mm}$  diameter CuBe capillary tube. A sizable “dead volume” at ambient temperature reduces the decrease of He-gas pressure on cooling from ambient to low temperatures. In this experiment the applied pressure of  $9.1 \text{ kbar}$  at ambient temperature decreased to  $7.9 \text{ kbar}$  at  $4 \text{ K}$ . Further details of the He-gas system are given elsewhere [9].

In Fig. 2 the temperature dependence of the electrical resistance for  $\text{SrIrO}_3$  in the  $ab$ -plane,  $R_{ab}(T)$ , is shown from  $1.35 \text{ K}$  to  $285 \text{ K}$  for  $0$  and  $9.1 \text{ kbar}$  pressure. The resistance decreases slightly with pressure over the entire temperature range at the rate  $R^{-1}(dR/dP) = -0.05\% \text{ kbar}^{-1}$  at  $285 \text{ K}$  and  $-0.02\% \text{ kbar}^{-1}$  at  $50 \text{ K}$ .

The resistance  $R$  is related to the resistivity  $\rho$  by  $R = \rho(L/A)$ , where  $A$  is the cross-section area of the sample perpendicular to the current flow and  $L$  is the separation between the two voltage contacts. Were the sample structure cubic, the compressibility would be isotropic and the ratio  $L/A$  would necessarily increase with pressure since  $A$  would decrease twice as fast as  $L$ , thus leading to  $dR/dP > 0$  ( $\rho$  is assumed constant). The crystal structure of  $\text{SrIrO}_3$ , however, is not cubic but rather a monoclinic distortion of the hexagonal  $\text{BaTiO}_3$  structure [8]. Since the more highly compressible  $c$  lattice parameter is included in the area  $A$ ,  $L/A$  for  $\text{SrIrO}_3$  would likely increase with pressure more rapidly than for a cubic crystal. The measured decrease of the resistance  $R(T)$  with pressure thus cannot originate from the factor  $L/A$  but rather



**Fig. 2.** Electrical resistance of  $\text{SrIrO}_3$  in  $ab$ -plane versus temperature at ambient (black lines) and  $9.1 \text{ kbar}$  pressure (red lines). Data at  $9.1 \text{ kbar}$  between  $88 \text{ K}$  and  $104 \text{ K}$  are interpolated. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)



**Fig. 3.** Electrical resistance of  $\text{SrIrO}_3$  in  $ab$ -plane plotted versus both  $T^{1.3}$  (lower scale) and  $T^2$  (upper scale) for temperatures up to  $120 \text{ K}$  revealing non-Fermi-liquid behavior. Data at ambient pressure (black lines); data at  $9.1 \text{ kbar}$  (red lines). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

must be due to a decrease in the resistivity  $\rho(T)$  itself with pressure. Since the direction-dependent compressibility of  $\text{SrIrO}_3$  has yet to be determined, we are only able to reliably calculate the sign of  $d\rho/dP$ , but not its magnitude. However, to the extent that the directional compressibilities of  $\text{SrIrO}_3$  are the same as for  $\text{BaIrO}_3$  [7], the rate of change of  $L/A$  with pressure would be approximately  $+0.03\% \text{ kbar}^{-1}$  which leads to the estimate at  $285 \text{ K}$  of  $\rho^{-1}(d\rho/dP) = -0.08\% \text{ kbar}^{-1}$ . For comparison, the resistivity of Cu metal, whose bulk modulus is almost identical to that of  $\text{SrIrO}_3$ , exhibits at ambient temperature a pressure derivative  $\rho^{-1}(d\rho/dP) = -0.2\% \text{ kbar}^{-1}$  [10], about twice that for  $\text{SrIrO}_3$ ; for Cu the decrease in the resistivity with pressure is primarily due to the shift of the phonon modes to higher frequencies (lattice stiffening).

Cao et al. [5] have given evidence for non-Fermi-liquid behavior in  $\text{SrIrO}_3$  from the temperature dependence of the electrical resistance below  $120 \text{ K}$  where  $R$  is found to deviate strongly from

a  $R \propto T^2$  power law, showing instead  $R \propto T^{1.5}$ . In Fig. 3  $R(T)$  is plotted against both  $T^2$  and  $T^{1.3}$  over the same temperature range 0 to 120 K. In the present experiment the  $R \propto T^{1.3}$  dependence fits the resistivity data better than  $R \propto T^2$  or even  $R \propto T^{1.5}$ ; the  $R \propto T^{1.3}$  dependence is seen to not change with pressure.

A crude estimate of the magnitude of the pressure necessary to cause significant changes in the properties of SrIrO<sub>3</sub> would be to ask what pressure  $P_c$  would be required to reduce the unit cell volume of SrIrO<sub>3</sub> (246.5 Å<sup>3</sup> [11]) to that of CaIrO<sub>3</sub> (226.3 Å<sup>3</sup> [12]). For want of high-pressure X-ray studies on these two compounds, we use the bulk modulus of BaIrO<sub>3</sub>, namely 1460 kbar [6], to arrive at the estimate of  $P_c \approx 120$  kbar, a pressure 15× higher than that used in the present experiments. It would be interesting to repeat the present experiments to pressures of at least 150 kbar to see whether under such pressures SrIrO<sub>3</sub> becomes an antiferromagnetic insulator. One should be aware, however, that the unit cell volume is only one of several factors determining the properties of the iridates. Rigid tilts, rotations, and deformation of the IrO<sub>6</sub> octahedra likely also play an important role [4].

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