LETTERS

Isotropic quantum scattering and unconventional superconductivity

T. Park[1,2], V. A. Sidorov[1,3], F. Ronning[1], J.-X. Zhu[1], Y. Tokiwa[1], H. Lee[1], E. D. Bauer[1], R. Movshovich[1], J. L. Sarrao[1] & J. D. Thompson[1]

Superconductivity without phonons has been proposed for strongly correlated electron materials that are tuned close to a zero-temperature magnetic instability of itinerant charge carriers[1]. Near this boundary, quantum fluctuations of magnetic degrees of freedom assume the role of phonons in conventional superconductors, creating an attractive interaction that 'glues' electrons into superconducting pairs. Here we show that superconductivity can arise from a very different spectrum of fluctuations associated with a local (or Kondo-breakdown) quantum critical point[2–5] that is revealed in isotropic scattering of charge carriers and a sublinear, temperature-dependent electrical resistivity. At this critical point, accessed by applying pressure to the strongly correlated, local-moment antiferromagnet $CeRhIn_5$, magnetic and charge fluctuations coexist and produce electronic scattering that is maximal at the optimal pressure for superconductivity. This previously unanticipated source of pairing glue[6] opens possibilities for understanding and discovering new unconventional forms of superconductivity.

In conventional superconductors, excitations of a solid's crystal lattice provide an attractive interaction that binds itinerant electrons into pairs with zero net spin and momentum[7]. The resulting state of superconductivity is very sensitive to the presence of paramagnetic impurities, such as cerium: coupling of the paramagnetic spin **S** to the spin **s** of itinerant electrons, in the form $J\mathbf{S}\cdot\mathbf{s}$, where J is the coupling strength, scatters electrons and breaks electron pairs[8]. Consequently, it has been a challenge to explain discoveries of unconventional superconductivity in strongly correlated electron materials with dense arrays of paramagnetic ions, such as cerium-based heavy-fermion compounds[9]. This form of spin–spin coupling is the origin of the Kondo effect, which gives itinerant charge carriers their heavy mass in heavy-fermion systems and, in the process, creates a 'large' Fermi volume that encloses the paramagnetic electrons, for example the 4*f* electrons of cerium[10].

The proximity of superconductivity in heavy fermions, such as the prototype $CeCu_2Si_2$, to a spin instability of their large Fermi surfaces suggests that magnetic fluctuations provide the attractive 'glue' in the same way that lattice fluctuations do in conventional superconductors[1,9]. As a spin-density instability is tuned by a non-thermal parameter, such as pressure, towards a continuous transition at $T = 0$ K, magnetic excitations become quantum mechanically critical, leading to a divergent magnetic susceptibility at the ordering wave vector **Q**, a condition favourable for creating superconducting electron pairs with finite angular momenta[9]. Quantum fluctuations of the spin density also strongly scatter electrons on parts of the Fermi surface connected by the wave vector **Q**, giving an electrical resistivity, ρ, that increases from $T = 0$ K with a power-law dependence $\rho \propto T^{\epsilon}$, where $1 \leq \varepsilon < 3/2$, which is distinct from the characteristic T^2 dependence of a Fermi liquid that emerges as the strongly correlated electron system is tuned away from its quantum critical point[11].

Quantum criticality of a very different kind has been proposed for some heavy-fermion materials whose magnetism derives from the indirect interaction among localized magnetic moments[2–5]. Deep in the magnetically ordered phase, the Kondo effect is absent and the Fermi volume is small, that is, does not include the localized electrons, but as the $T = 0$ boundary between paramagnetic and localized magnetic states is approached, the Fermi volume jumps in size. A consequence of such a quantum phase transition is that the Fermi surface becomes critical at the $T = 0$ magnetic–paramagnetic boundary, which is consistent with the criticality having a spatially local character and creates a spectrum of fluctuations that dominate physical properties, such as resistivity, even at temperatures well above $T = 0$ K (ref. 12). In comparison with a spin-density quantum phase transition that affects only a portion of the Fermi surface and involves only magnetic degrees of freedom, a local type of quantum phase transition is more 'violent', producing fluctuations in spin and charge channels that separately or collectively could promote an attractive interaction between electron pairs. However, the lack of a theoretical basis for superconductivity and the absence of superconductivity in the prime candidates for local criticality, $YbRh_2Si_2$ and $CeCu_{6-x}Au_x$, question the viability of superconductivity mediated by locally critical fluctuations[6]. Using the heavy-fermion antiferromagnet $CeRhIn_5$ as an example, we report evidence that fluctuations from a local form of quantum criticality can provide a new route to unconventional superconductivity.

Figure 1 displays a temperature-pressure map of the local exponent, $\varepsilon \equiv \partial \ln(\rho(T) - \rho(T = 0))/\partial(\ln T)$, of the electrical resistivity of $CeRhIn_5$. Funnel-shaped yellow boundaries in Fig. 1 that emerge near the maximum pressure-induced superconducting transition temperature, T_c, mark a lower crossover temperature from an unusual state with a resistivity, $\rho \propto T^{0.85}$, sublinearly dependent on T (or 'sub-T-linear'). (Representative pressure- and temperature-dependent resistivity curves and their analysis, shown in Supplementary Figs 1 and 2, document the origin of the colour map and phase boundaries.) In the low-pressure limit, the yellow boundary reflects the onset of short-ranged antiferromagnetic spin correlations over a small interval above the Néel temperature, T_N (ref. 13), but signals a change in resistivity to a $T^{3/2}$ dependence before settling into a heavy Fermi liquid state at $T < T_{FL}$ in the high-pressure limit. The upper boundary of this unusual state is determined by $T_{max}/2$, where T_{max} is the temperature at which the resistivity is a maximum. At 2.35 GPa, where there is no magnetic order, this phase with sub-T-linear resistivity extends to progressively lower temperatures as superconductivity is suppressed by an applied magnetic field. At 10 T, which is slightly higher than $H_{c2}(0)$, the field necessary to suppress superconductivity

[1]Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA. [2]Department of Physics, Sungkyunkwan University, Suwon 440-746, South Korea. [3]Vereshchagin Institute of High Pressure Physics, RAS, 142190 Troitsk, Russia.

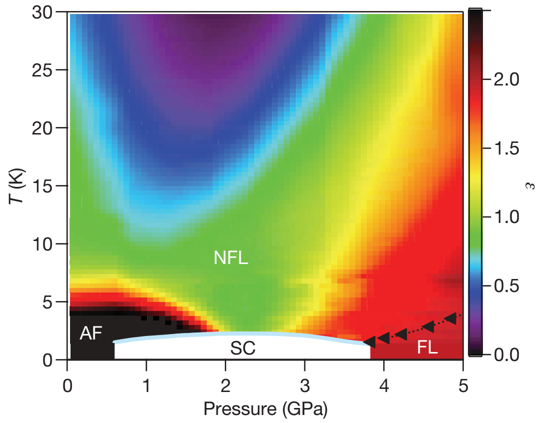

Figure 1 | Temperature–pressure phase diagram of $CeRhIn_5$. Colours represent the local exponent, $\varepsilon \equiv \partial(\ln \Delta\rho)/\partial(\ln T)$, at zero magnetic field, where $\Delta\rho = \rho - \rho(T = 0\,K) = AT^{\varepsilon}$. The resistivity, ρ, was measured along the *c* axis of this tetragonal crystal. The residual resistivity, $\rho(T = 0\,K)$, and temperature coefficient, A, were obtained with least-squares fitting to the power-law form at low temperatures and are shown in Supplementary Fig. 1. Also shown are boundaries of the phase of local-moment antiferromagnetic (AF) order, the superconductivity (SC) phase, and the region of temperature below which the resistivity follows a T^2 temperature dependence characteristic of a Landau Fermi liquid. The cone-shaped region of green denotes a state of sub-*T*-linear resistivity, labelled NFL and discussed in the text, that appears to emanate from the dome of superconductivity, where $T_c = 2.3$ K is a maximum. For comparison, the SC and AF phases are coloured white and black, respectively.

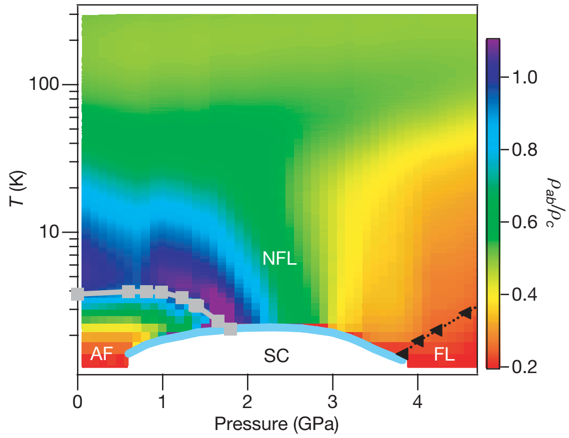

Figure 2 | Temperature–pressure variation of resistivity anisotropy. Apparent structure in the colour map (describing ρ_{ab}/ρ_c) is due to an interpolation of data obtained at pressures slightly different from those used to determine ρ_{ab} and ρ_c. Significantly, the resistivity anisotropy found at high temperatures persists to the lowest temperature in the NFL pressure range where ρ_c (Fig. 1) and ρ_{ab} exhibit a sub-*T*-linear variation. Data representative of those from which this map was constructed are shown in Supplementary Fig. 4. The SC phase is coloured white.

completely, the weakly field-dependent sub-*T*-linearity holds from ~10 K to 250 mK, and crosses over to a T^2 (Fermi liquid) dependence below 150 mK (Supplementary Fig. 3). We emphasize that this sub-*T*-linear behaviour with a single temperature exponent over a broad temperature range is distinct from crossover behaviour that is often observed in heavy-fermion compounds as they are warmed from a low-temperature Fermi liquid behaviour (T^2 dependence) to a resistivity maximum near 100 K: the temperature exponent in the crossover regime varies with temperature; that is, there is no unique power-law behaviour.

Studies of specific heat as a function of pressure have revealed that the Néel transition extends continuously to $T = 0$ at 2.35 GPa in the presence of a magnetic field suppressing superconductivity[14]. This magnetic quantum critical point at 2.35 GPa offers a possible explanation for the strange metallic behaviour found at the point of maximum T_c; however, the sub-*T*-linear resistivity is not anticipated by any theory of spin-density criticality[15]. The nonconformity of $CeRhIn_5$ to the spin-density model indicates that the quantum critical point in $CeRhIn_5$ may differ in nature from a magnetic instability of the Fermi surface. When coupled with quantum oscillation measurements at 2.35 GPa (ref. 16), which show an abrupt change in the Fermi surface, the convergence of multiple energy scales represented by the crossover and phase-transition boundaries in Fig. 1 is consistent with an interpretation as a local form of criticality that involves magnetic as well as fermionic degrees of freedom[2–6], where, now, the yellow boundary at high pressures can be understood as a crossover temperature below which incoherent scattering due to quantum fluctuations starts to yield to coherent scattering within the lattice of Kondo sites.

Strong support for the spatially local nature of this criticality comes from electrical transport measured perpendicular (ρ_{ab}) and parallel to the tetragonal *c* axis (ρ_c) (Fig. 2). At temperatures higher than ~100 K, where charge scattering comes predominantly from randomly oriented cerium 4*f*-electron moments, the ratio $\rho_{ab}/\rho_c \approx 0.5$ is essentially independent of pressure and set primarily by intrinsic crystalline anisotropy. On the other hand, below T_{FL} and at high pressures, transport anisotropy increases by a factor of 2.5, to give $\rho_{ab}/\rho_c \approx 0.2$. We ascribe this increase in anisotropy to characteristics of the large Fermi volume that now includes the 'Kondo-ized' 4*f* electrons of cerium. The related superconductor $CeCoIn_5$, which has a large Fermi volume, has the effective mass anisotropy $m_a^*/m_c^* \approx 0.18$ (ref. 17), where m^* reflects many-body correlation effects that also are present in $CeRhIn_5$ below T_{FL}.

The pronounced anisotropy observed in the Fermi liquid state becomes progressively less obvious with decreasing pressure. In the quantum critical regime, where the resistivity is sub-*T*-linear, the anisotropy ratio is almost temperature independent and is similar to that at room temperature. With the assumption of independent scattering sources, the total scattering rate is $1/\tau = 1/\tau_i + 1/\tau_q$, where τ_i and τ_q are the collision times for scattering by impurities and by excitations, respectively. Potential scattering from impurities is isotropic, leaving crystal anisotropy, which changes very weakly with pressure[18], and scattering from fluctuations associated with the quantum phase transition as sources of resistive anisotropy. The absence of new anisotropy in the quantum critical regime argues against a spin-density quantum critical interpretation because, in this case, the strong scattering from parts of the Fermi surface spanned by **Q** is expected to be highly anisotropic[19], reflecting the Fermi surface topology of the large-volume paramagnetic state. Instead, isotropic scattering induced over the entire Fermi surface at a local or Kondo-breakdown quantum critical point is consistent with our observations. Model calculations, presented in the Supplementary Fig. 5, show that the sublinear temperature dependence of electrical resistivity can arise from isotropic scattering from fluctuations associated with a local quantum critical point. We note that a similar sub-*T*-linear resistivity has been shown to be present in a Kondo-breakdown model[5].

Fluctuations from a local form of quantum criticality may be responsible for the unconventional superconductivity of $CeRhIn_5$. Figure 3 displays a map of the isothermal resistivity, normalized by the resistivity in the normal metallic phase at 5.2 GPa, as a function of pressure. As seen in this figure and in Supplementary Fig. 6, the highest scattering rate and the highest T_c occur simultaneously, which appears to contradict the conventional view that scattering is harmful to unconventional superconductivity[20,21]: superconductivity disappears when the resistivity reaches a comparable value of 20 μΩ cm in disordered $CeCoIn_5$. Unlike chemical substitution, pressure does not induce extra disorder. Instead, the maximum resistivity in the vicinity of the quantum critical point is due to the build-up of quantum fluctuations that amplifies scattering by the small number of impurities in this very

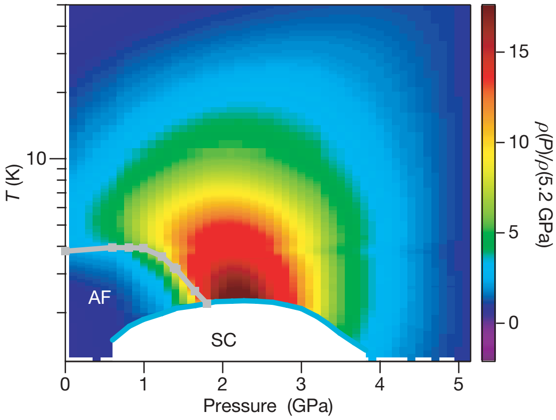

Figure 3 | Pressure-dependent *c*-axis resistivity. The colour map describes the *c*-axis resistivity normalized by its value in the normal metallic state at 5.2 GPa. This resistivity ratio is highest at temperatures and pressures where the resistivity is sub-T-linear (Fig. 1) and resistivity anisotropy (Fig. 2) is the same as at high temperatures. Maximum scattering appears above the maximum T_c of the superconducting dome. Representative isothermal cuts of the resistivity ratio, used to construct the colour map, are shown in Supplementary Fig. 6. The SC phase is coloured white.

pure single crystal of $CeRhIn_5$. The high spectral density of quantum fluctuations, reflected in the maximum of ρ_c (which occurs at 2.3 K), then provides the glue for optimal electron pairing.

In $CeCu_2Si_2$, where two domes of superconductivity emerge with applied pressure, spin-density and valence fluctuations are proposed to mediate electron pairing separately for each dome, with a T_c higher by a factor of four in the dome associated with valence fluctuations[22]. In $CeRhIn_5$, the local nature of quantum criticality implies simultaneous fluctuations in spin and charge channels. Our experiments cannot resolve which channels or channel dominate(s) the pairing interaction in $CeRhIn_5$, but the multi-criticality of $CeRhIn_5$ appears to be key to understanding the sub-T-linear resistivity and the robustness of the superconductivity over a wide pressure range. This work raises the fundamental issues of determining (1) how multiple fluctuating channels interplay with each other to produce superconductivity; (2) the appropriate description of fluctuations that arise from a local or Kondo-breakdown quantum critical point; (3) why there is no superconductivity in comparably pure crystals of $YbRh_2Si_2$; and (4) whether a similar analysis could be applicable to other heavy-fermion superconductors such as $PuCoGa_5$, where composite pairs of local moments and electrons are proposed[23] to condense to form superconductivity. The solutions of these problems will guide the search for new examples of unconventional superconductivity and will be broadly applicable to other strongly correlated superconductors, such as the high-T_c copper oxide superconductors[24], in which two domes of superconductivity or one extensive superconducting dome may naturally arise, as a function of doping, from multiple quantum critical points.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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