Fermionic Critical Fluctuations: Potential Driver of Strange Metallicity and Violation of the Wiedemann–Franz Law in $YbRh_2Si_2$

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Results of combined thermal and electrical transport measurements through the magnetic field-induced quantum critical point (QCP) in the heavy-fermion compound $YbRh_2Si_2$ were revisited to explore the relationship between the strange-metal behavior observed in electrical and electronic thermal resistivities and the violation of the Wiedemann–Franz (WF) law in the zero-temperature limit. A new type of inelastic scattering center for the charge and heat carriers was detected, attributed to small-to-large Fermi surface fluctuations operating near the Kondo-destroying QCP. These fermionic quantum critical fluctuations are considered the primary driver of the strange-metal behavior and the violation of the WF law.

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1. Mott-Type Quantum Critical Point (QCP). Quantum criticality in strongly correlated electron systems remains an exciting research field in condensed matter physics. Much insight into this topic has been gained regarding antiferromagnetic (AF) heavy-fermion compounds.[1,2] The conventional *itinerant* spin-density-wave instability at zero temperature, explored by theorists many years ago,[3–5] was studied in detail for the heavy-fermion metal $CeCu_2Si_2$.[6] While here the charge carriers (propagating Kondo singlets) remain intact at the AF instability, they apparently break apart at the AF QCP investigated in the heavy-fermion metals $CeCu_{5.9}Au_{0.1}$[7,8] and $CeRhIn_5$.[9–11] As the Kondo-breakdown instability in the latter two compounds involves a $4f$-electron localization/delocalization mechanism, it is frequently labeled a "partial Mott" or "Mott-type" quantum phase transition. This type of unconventional *local* QCP[12,13] gives rise to "strange metallicity" which is of high interest in contemporary research on strongly correlated materials[14–18] and has been discussed in connection with astrophysics.[19] Strange-metal behavior is characterized by a logarithmic divergence of the Sommerfeld coefficient of the electronic specific heat and a linear temperature dependence of the electrical resistivity, represented as $\Delta\rho(T) = [\rho(T) - \rho_0] = aT$ (ρ_0: residual resistivity).[2,20,21] A Kondo-destroying QCP has also been established for the canonical heavy-fermion metal $YbRh_2Si_2$ under magnetic field tuning at a very low critical field [$B_N = 0.06$ T ($\perp$ c-axis)], where the AF order smoothly disappears,[2,22] as shown in Fig. 1.[23] At $B = B_N$, the crossover temperature $T_{FL}(B)$ also vanishes, below which heavy Fermi-liquid (FL) behavior emerges on the paramagnetic side of the phase diagram. In addition, another line, $T^*(B)$, starts at $B = B_N$ with an almost infinite slope, indicating the crossover from a small Fermi surface at low fields to a larger one at elevated fields.[2,22] This crossover continuously broadens with increasing field, as indicated in Fig. 1.

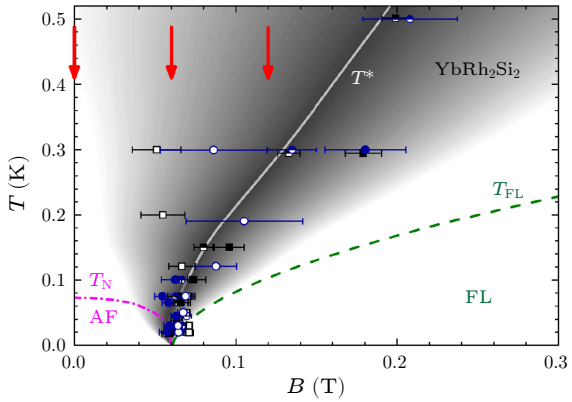

Fig. 1. Temperature (T)–magnetic field (B) phase diagram for $YbRh_2Si_2$, displaying a Kondo-breakdown QCP at $T = 0$ and $B_N = 0.06$ T, where the following coincide: (i) the phase-transition line $T_N(B)$ of the antiferromagnetically ordered phase at low fields, (ii) the crossover line $T_{FL}(B)$ to the low-T heavy Fermi-liquid (FL) phase at elevated fields, and (iii) $T^*(B)$, indicating a Mott-type crossover from small-to-large Fermi surface. $T^*(B)$ was determined from the midpoints of thermally broadened jumps in the isothermal field dependences of magneto-transport results. The corresponding crossover widths are indicated by the horizontal bars. The grayscale visualizes the slope of the isothermal magnetoresistance as a function of field. Red arrows indicate $B = 0$, B_N, and $2B_N$, respectively. Reproduced from Schuberth *et al.*[23]

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2. Strange-Metal Behavior in Thermal and Electrical Transport: Violation of the Wiedemann–Franz (WF) Law. Low-temperature electrical and thermal resistivities, $\rho(T)$ and $w(T) = \mathrm{L}_0 T/\kappa(T)$, of $YbRh_2Si_2$ were determined in the field range 0–1 T.[24] Here, $\kappa(T)$ represents the measured thermal conductivity, and $\mathrm{L}_0 = (\pi k_\mathrm{B})^2/3e^2$ is Sommerfeld's constant. As shown in Fig. 2,[25] at elevated temperatures ($T > 0.1$ K), the thermal resistivity is larger than its electrical counterpart, with both displaying linear-in-T behavior in a certain T-window. At very low fields, an additional magnon-derived contribution $\kappa_\mathrm{m}(T)$ appears in the thermal conductivity below $T \approx 0.1$ K. $\kappa_\mathrm{m}(T)$ is observed even at the critical field $B_\mathrm{N} = 0.06$ T, where it originates in short-lived magnon ("paramagnon") excitations. A small contribution from $\kappa_\mathrm{m}(T)$ appears to exist even up to $B = 0.1$ T. For $B \geq 0.2$ T, $\Delta w(T) = [w(T) - w_0] = A'T^2$ at sufficiently low temperatures, while for both $B = 0$ and 0.02 T, the electrical resistivity $\rho(T)$ shows a kink at and a FL-type quadratic temperature dependence [$\Delta\rho(T) = AT^2$] below the Néel temperature T_N. At $B_\mathrm{N} = 0.06$ T, ρ is linear in T down to 0.01 K, the lowest accessible temperature.[22] Recently, $\Delta\rho(T) = [\rho(T) - \rho_0] = aT$ has been observed at temperatures as low as 0.001 K.[26] This suggests that, exactly at the critical field B_N, $YbRh_2Si_2$ is a strange metal down to $T = 0$. At $B \geq 0.08$ T, the low-T electrical resistivity displays a strong T^2-dependence,[24,25] which proves the existence of a heavy Fermi liquid.

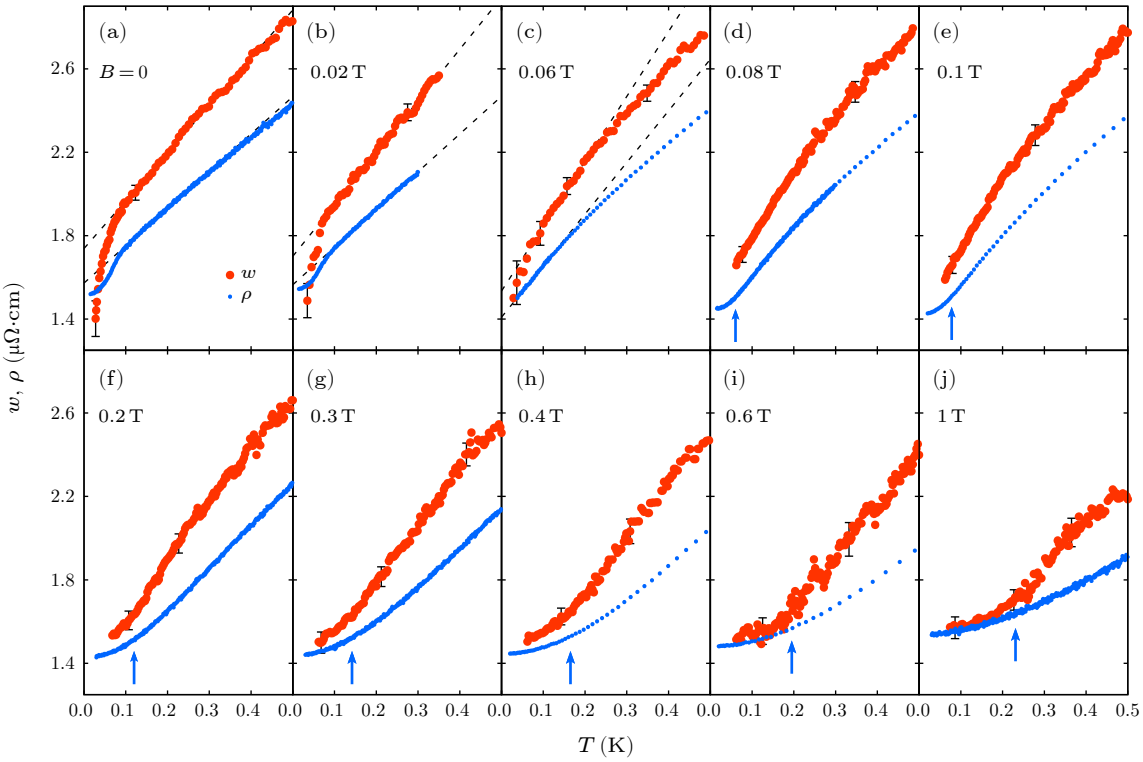

Fig. 2. Combined electrical and thermal transport through the quantum critical field $B_\mathrm{N} = 0.06$ T ($\perp$ c-axis) in single-crystalline $YbRh_2Si_2$. The electrical and thermal resistivities $\rho(T)$ and $w(T) = \mathrm{L}_0 T/\kappa(T)$ are displayed, in the same units, as a function of temperature for $T \leq 0.5$ K at $B = 0$, $B = B_\mathrm{N}$ and varying magnetic fields below and above B_N. Here, $\kappa(T)$ is the measured thermal conductivity and $\mathrm{L}_0 = (1/3)(\pi k_\mathrm{B}/e)^2$ is Sommerfeld's constant. At $B = B_\mathrm{N}$, strange-metal behavior is observed only for $T < 0.3$ K in $w(T)$ and < 0.2 K in $\rho(T)$, indicating the high quality of this single crystal.[2] In contrast, for a slightly germanium-substituted single crystal with ten times larger residual resistivity, strange-metal behavior was registered over three decades in T up to 10 K.[22] Reproduced from Steglich *et al.*[25]

Using the Lorenz number $L(T) = \rho(T)\kappa(T)/T$, the Lorenz ratio is defined by $L(T)/\mathrm{L}_0 = \rho(T)/w(T)$. This ratio was determined for $YbRh_2Si_2$ by Pourret *et al.*[27] in an extended T-window for $B = 0$ and various applied fields at and above the critical field that here amounts to $B_\mathrm{N} \approx 0.07$ T (Fig. 3). Below $T \approx 0.1$ K, the results for $B = 0$ and $B = B_\mathrm{N}$ display a pronounced upturn, a remnant of which being recognized at $B = 0.11$ and 0.17 T. This is proportional to the bosonic conductivity $\kappa_\mathrm{m}(T)$, which vanishes at $T = 0$. Therefore, the extra contribution to $L(T)/\mathrm{L}_0$ must reach a maximum before disappearing at $T = 0$. In the heavy FL phase at $B = 0$ and for all field values $B < B_\mathrm{N}$, the low-T electrical and *electronic* thermal resistivities $\rho(T)$ and $w_\mathrm{el}(T)$, respectively, follow a T^2-dependence. Here, the WF law, which holds only for purely elastic scattering processes, must be valid in the zero-temperature limit. This implies that $\rho_0 = w_0$ and $L(0) = \mathrm{L}_0$. The same is true for all field values $B > B_\mathrm{N}$. However, at $B = B_\mathrm{N}$, the Lorenz ratio amounts to $L(0)/\mathrm{L}_0 \approx 0.9$ at $T = 0$, where

$\kappa_m(T) = 0$. At this critical field, $\Delta\rho(T) = aT$ and, most likely, $\Delta w_{el}(T) = a'T$ display strange-metal behavior at the lowest accessible temperatures. Both are of disparate size in that (i) the slope a' is larger than its counterpart a and (ii) the residual electronic thermal resistivity $w_{el,0}$ exceeds the residual electrical resistivity ρ_0 by approximately 10%. This clearly indicates that the WF law is violated exactly at the Kondo-destroying QCP. A similar observation was reported for YbAgGe.[28] For a detailed discussion of the contrasting claims by other groups concerning $YbRh_2Si_2$, see Ref. [23].

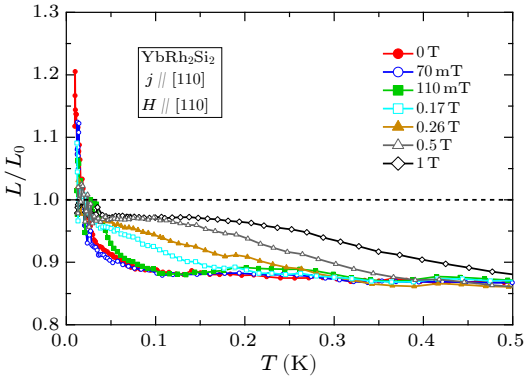

Fig. 3. Lorenz ratio $L(T)/L_0 = \rho(T)/w(T)$ for a $YbRh_2Si_2$ single crystal (with QCP at $T = 0$ and $B_N \approx 0.07$ T) for $B = 0$, $B = B_N$, and varying fields $B > B_N$ in an extended T window of 0.08 K $\leq T \leq$ 0.5 K. Reproduced with permission from Pourret *et al.*[27] The Physical Society of Japan Copyright (2014).

The apparent violation of the WF law in $YbRh_2Si_2$ was demonstrated by measuring the temperature dependence of the low-T electrical resistivity for two different currents ($j = 2.4$ and 5.0 μA) both near and far from the critical field $B_N = 0.059$ T,[25] specifically at $B = 0.05$ and 0.06 T as well as $B = 0$, 0.1, and 0.2 T (Fig. 4). In the vicinity of B_N, at $B = 0.05$ and 0.06 T, the large current of 5.0 μA causes the sample to be heated up at sufficiently low temperatures (red arrows), resulting in an enhanced $\rho(T)$ that follows an FL-type quadratic T-dependence. Under the low current of 2.4 μA, the resistivity is smaller, exhibiting a linear T-dependence down to the lowest accessible temperature. In addition, no heating is observed apart from B_N, neither at $B = 0$ nor at $B = 0.1$ and 0.2 T. A possible explanation for this heating effect involves the strong reduction of the low-T electronic thermal conductivity $\kappa_{el}(T)$ in the vicinity of $B = B_N$ which overcompensates, under the large current (like under an increasing field, *cf.* Figs. 2d and 2e), a substantially weakened (para)magnon contribution $\kappa_m(T)$. As a result, the Joule heat produced by the large current will be prevented from being efficiently dissipated. Figure 4 also shows a jump of the residual resistivity ρ_0 at or close to $B = B_N$, illustrating an abrupt increase in the charge-carrier density with increasing field, as expected at the Kondo-destroying QCP.[12,13,25]

To further investigate the apparent strange metallic ground state of $YbRh_2Si_2$ and the simultaneous violation

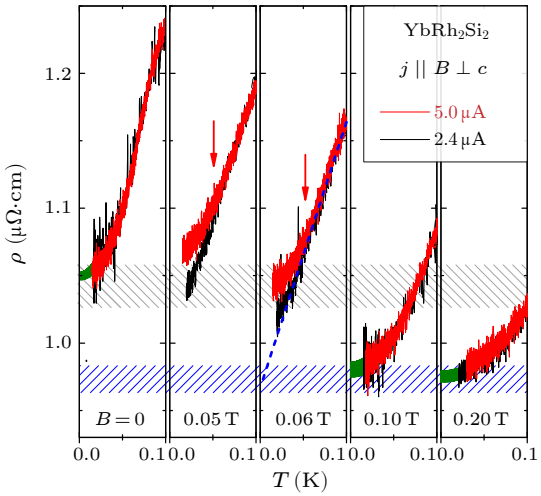

Fig. 4. ρ vs T at varying magnetic fields (B) for a $YbRh_2Si_2$ single crystal ($B_N = 0.059$ T). Black (small current j): no heating. At $B = 0$, 0.1, and 0.2 T, $\rho(T)$ shows a T^2-dependence at low temperatures. For $B = 0.05$ T ($\leq B_N$) and 0.06 T ($\geq B_N$), $\rho(T)$ is linear in T to the lowest accessible temperature. The residual resistivity ρ_0 at $B = 0$ as well as 0.05 T (grey shading) is substantially higher than that at $B > B_N$ (blue shading). Extrapolations to $T = 0$ at/far away from B_N are shown in blue/green. The abrupt change in ρ_0 indicates a reduced carrier density at low fields. Red (large j): for both $B = 0.05$ T and 0.06 T, $\Delta\rho(T)$ deviates from the linear-in-T dependence (red arrows) and becomes proportional to T^2 at low temperatures. The observed heating on the approach of the QCP under large current conditions is owing to additional inelastic scatterings discussed in the text. Reproduced from Steglich *et al.*[25]

of the WF law at its QCP, the isothermal field tuning of $L(B)/L_0$ has been explored at temperatures $T \geq 0.1$ K—within a temperature range where, owing to the absence of any (para)magnon excitations, the thermal transport is purely electronic.[24] The results presented in Fig. 5 were obtained from the temperature traces shown in Fig. 2. The Lorenz ratio is found to be smaller than one across the entire (T, B) range displayed in Fig. 5. This indicates dominating inelastic scattering processes, notably electron–electron and electron–spin fluctuation scatterings, both of which disappear in the zero-temperature limit because of phase-space arguments in the former and the bosonic origin in the latter case. Interestingly, a pronounced minimum is observed in $L(B)/L_0$, which, at sufficiently low T, occurs right at the crossover field $B^*(T)$ (*cf.* vertical arrows) and has the same width as the small-to-large Fermi surface crossover (*cf.* horizontal bars), as inferred from Fig. 1. In an isothermal experiment that allows for the continuous registration of $L(B)/L_0$ up to $B = 12$ T, this minimum was clearly resolved at $B \approx 0.5$ T for a temperature as high as $T = 0.49$ K.[29] In accordance with the initial, nearly infinite slope of the $T^*(B)$ crossover line at low T (Fig. 1), the position B^* of the $L(B)/L_0$ minimum at $T = 0.1$ K, the lowest temperature used in this study, is close to the critical field $B_N = 0.06$ T. Here, its depth already amounts to ≈ 0.9 (Fig. 5). Therefore, it is reason-

able to assume that upon cooling, the *electronic* Lorenz ratio $L_{\rm el}(B)/{\rm L}_0$ will display a continuously narrowing dip of depth ≈ 0.9. At zero temperature, this will take the form of a delta function at $B^* = B_{\rm N}$.[24]

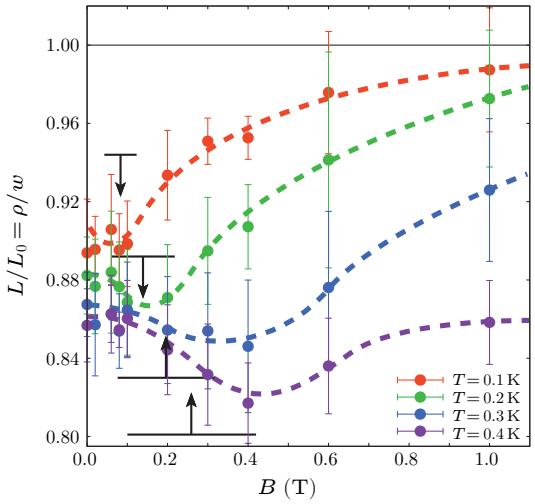

Fig. 5. Isothermal field dependences of the Lorenz ratio $L(B)/{\rm L}_0$ in $YbRh_2Si_2$ single crystals at different temperatures in the paramagnetic regime ($0.1\,{\rm K} \leq T \leq 0.4\,{\rm K}$), where the thermal transport is purely electronic because of the absence of (para)magnon excitations. The data were taken from the temperature traces shown in Fig. 2. A minimum is found near the Mott-type small-to-large Fermi surface crossover field $B^*(T)$ (vertical arrows), as displayed in Fig. 1, and it has a width similar to that of this crossover (horizontal bars). This indicates an additional inelastic scattering process attributed to *fermionic* quantum critical fluctuations (see text). In the zero-temperature limit, this minimum in the *electronic* Lorenz ratio is extrapolated to be a sharp drop exactly at the critical field $B_{\rm N} = 0.06\,{\rm T}$, where $L(B_{\rm N})/{\rm L}_0 \approx 0.9$, indicating a violation of the WF law. Reproduced from Pfau *et al.*[24]

3. Quantum Critical Small-to-Large Fermi Surface Fluctuations: Prime Candidate for Driving Strange Metallicity and Violation of the WF Law. How to interpret the afore-reached conclusions? First, at finite temperatures, the broadened minimum observed in the isothermal field dependence of the Lorenz ratio indicates a new inelastic scattering process intimately related to the small-to-large Fermi surface crossover at the Kondo-breakdown QCP. Second, the small-to-large Fermi surface fluctuations represent quantum critical fluctuations of a *fermionic* nature, which differ from their bosonic counterparts that involve spin fluctuations. Unlike the latter, these fermionic excitations persist at $T = 0$, where the small and large Fermi surfaces coexist; for, upon cooling, their quasiparticle weights smoothly disappear at the Kondo-destroying QCP.[24] We conclude that these fermionic small-to-large Fermi surface fluctuations serve as the primary scattering centers for the charge and heat carriers, i.e., the low-energy excitations of the two Fermi surfaces. They are, therefore, considered the prime candidate responsible for the strange metallicity and violation of the WF law in $YbRh_2Si_2$. Future theoretical work is needed to characterize the microscopic nature of this novel type of quantum critical fluctuation.

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