Universality of non-equilibrium fluctuations in strongly correlated quantum liquids

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Interacting quantum many-body systems constitute a fascinating research field because they form quantum liquids with remarkable properties and universal behaviour¹. In fermionic systems, such quantum liquids are realized in helium-3 liquid, heavy fermion systems¹, neutron stars and cold gases². Their properties in the linear-response regime have been successfully described by the theory of Fermi liquids¹. The idea is that they behave as an ensemble of non-interacting 'quasi-particles'. However, non-equilibrium properties have still to be established and remain a key issue of many-body physics. Here, we show a precise experimental demonstration of Landau Fermi liquid theory extended to the non-equilibrium regime in a zero-dimensional system. Combining transport and ultra-sensitive current noise measurements, we have unambiguously identified the SU(2) (ref. 3) and SU(4) (refs 4–8) symmetries of a quantum liquid in a carbon nanotube tuned in the universal Kondo regime. Whereas the free quasi-particle picture is found valid around equilibrium⁹, an enhancement of the current fluctuations is detected out of equilibrium and perfectly explained by an effective charge induced by the residual interaction between quasi-particles^{8,10–17}. Moreover, an as-yet-unknown scaling law for the effective charge is discovered, suggesting a new non-equilibrium universality. Our method paves a new way to explore the exotic nature of quantum liquids out of equilibrium through their fluctuations in a wide variety of physical systems¹⁸.

The Kondo effect¹⁹ is a typical example of a quantum many-body effect, where a localized spin is screened by the surrounding conduction electrons at low temperature to form a unique correlated ground state. The Kondo state is described well by the Fermi liquid theory at equilibrium^{1,9}, which makes it an ideal testbed to go beyond equilibrium. To unveil the universal behaviour of non-equilibrium Fermi liquid¹¹, we have used the current fluctuations or shot noise in a Kondo-correlated nanotube quantum dot¹⁸.

When electrons are transmitted through this system, the scattering induces the shot noise, which sensitively reflects the nature of the quasi-particles²⁰, as shown in the upper panel of Fig. 1a. A remarkable prediction of the non-equilibrium Fermi liquid theory is that the residual interaction between quasi-particles creates an additional scattering of two quasi-particles which enhances the noise (see the lower panel of Fig. 1a)^{10,12–15}. This two-particle scattering is characterized by an effective charge e^* larger than e (electron charge). This value, closely related to the Wilson ratio, is universal for the Fermi liquid in the Kondo regime as it depends only

on the symmetry group of the system^{13–15}. Although some aspects of Kondo-associated noise have been reported^{8,16,17}, a rigorous, self-consistent treatment in a regime where universal results apply is at the core of the present work. Actually, by investigating the same nanotube quantum dot in the spin degenerate SU(2) Kondo regime and in the spin-orbit degenerate SU(4) regime, the noise is proved to contain distinct signatures of these two symmetries, confirming theoretical developments of Fermi liquid theory out of equilibrium.

In our experiment, we measured the conductance and current noise through a carbon nanotube quantum dot grown by chemical vapour deposition²¹. Iron catalyst was deposited on an oxidized undoped silicon wafer and exposed to 10 mbar of acetylene for 9 s at 900 °C. The nanotube was connected with a Pd(6 nm)/Al(70 nm) bilayer deposited by e-gun evaporation. The distance between the contacts is 400 nm and a side gate electrode is deposited to tune the potential of the quantum dot (see Fig. 1b). A magnetic field of 0.08 T is applied to suppress superconductivity of the contacts. To measure accurately the shot noise, our sample is connected to a resonant (2.58 MHz) LC circuit thermalized at the mixing chamber of the dilution fridge. The signal across this resonator is amplified with an in-house-built cryogenic low-noise amplifier²² thermalized on the 1 K pot and again at room temperature. The power spectral density of the noise is obtained by fast Fourier transformation of the time-domain signal acquired by a digitizer (National Instruments PCI-5922). The current noise of the sample is extracted from the fit of the shape of the resonance in the frequency domain.

Figure 2a presents the image plot of the differential conductance of the sample (G) at temperature $T = 16$ mK as a function of source-drain voltage (V_{sd}) and gate voltage (V_g). This stability diagram shows the fourfold-degenerated Coulomb diamonds specific to carbon nanotubes. The spectrum consists of successive four-electron shells. We denote by $N = 0, 1, 2, 3$ the number of electrons in the last shell. Remarkably, the SU(2) and SU(4) Kondo ridges⁶ emerge as horizontal bright regions (high conductance) at $V_{sd} = 0$.

For the moment, we concentrate on the SU(2) region. A cut of the conductance at $V_{sd} = 0$ is represented in the upper panel of Fig. 2b. Two Kondo ridges appear as plateaux where G is maximum for the fillings $N = 1$ (ridge A) and $N = 3$ (ridge B), whereas G decreases to almost zero for even N . In addition, the ridge B is flat and the unitary limit is achieved: the conductance reaches the quantum of conductance $G_Q = 2e^2/h$, which is a signature of the perfect Kondo effect in a dot with symmetric coupling to the leads. The Kondo temperature (T_K) is 1.6 ± 0.05 K in the centre of this ridge (see Supplementary Information).

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Figure 1 | Illustration of the interaction effect in the quantum liquid and design of the sample. a, Scheme of a quantum dot coupled to two leads. If a single spin is confined on the dot and the coupling with the leads is strong enough, the Kondo effect occurs. The full black line represents the extension of the Kondo state where electrons form a strongly correlated Fermi liquid. Our work consists in a collision experiment. We inject electrons through this state and observe through the current fluctuations which quasi-particles are backscattered. (Top) At low energy, this liquid can be understood as an ensemble of non-interacting quasi-particles. During a collision, only single quasi-particles are excited and backscattered by an incoming electron. (Bottom) At higher energy the incoming electron can excite two quasi-particles of the Fermi liquid through the residual interaction between quasi-particles (orange wavy line). The scattered current consists then of single or double quasi-particle shots which increase the current fluctuations. The effective charge e^* is a measure of the probability for these two processes. The Wilson ratio R quantifies the strength of the interaction between two quasi-particles. **b**, Sample and experimental set-up. SEM image of a carbon nanotube connected to metallic leads on a silicon wafer. It is connected to the current and noise measurement set-up through a resonant circuit fixed on the mixing chamber of the dilution fridge. The gate voltage V_g tunes the number of electrons (N) in the dot and the coupling between dot and leads.

The current noise S_i and G are plotted in Fig. 2c,d for $N=2$ and $N=3$, respectively, as a function of the source–drain current I_{sd} . Outside the Kondo ridge ($N=2$) S_i is linear with $|I_{sd}|$, whereas on the ridge the shot noise is flat around $I_{sd}=0$ and enhanced at high current when the energy of incoming electrons approaches a fraction of T_K . At high voltage ($eV_{sd} \gg k_B T_K$), a linear behaviour is recovered, with $S_i = 2e|I_{sd}|$. To analyse the low-energy properties, we have extracted the Fano factor (F), which is defined as $S_i = 2eF|I_{sd}|$, from a linear fit at low current. F varies from approximately zero on the Kondo ridge to $F=1$ outside, as shown in the bottom panel of Fig. 2b. Indeed, at very low energy, as the free quasi-particle picture of the Fermi liquid theory teaches us, the conductance and the noise for a multichannel conductor can be written as a function of transmission T_i for each channel $i=1,2,3 \dots$ (ref. 20):

$$G = G_Q \sum T_i \quad \text{and} \quad F = \frac{G_Q}{G} \sum T_i(1 - T_i) \quad (1)$$

For the SU(2) symmetry, transport occurs through one single channel, yielding $G = G_Q T_1$ and $F = 1 - T_1$. On the Kondo ridge,

the conductance is $G = G_Q$, yielding $T_1 = 1$ and $F = 1 - T_1 = 0$. This is a direct signature of the Kondo resonance which allows a perfect transmission and thus no partition of quasi-particles near equilibrium. In the Coulomb blockade regime, for even N , the transport is blocked ($T_1 \ll 1$), yielding $F \approx 1$, indicating that transport occurs through tunnelling events resulting in conventional Poissonian noise.

At higher voltages ($0 < eV_{sd} \leq k_B T_K/2$) we concentrate only on the nonlinear terms for current and noise by subtracting the linear part. We defined $S_K = S_i - 2eF|I_{sd}|$ and the backscattered current $I_K = G(0)V_{sd} - I_{sd}$ (refs 10,13). These quantities are related through the effective charge^{10,12,13,23} e^* :

$$S_K = 2e^*|I_K| \quad (2)$$

This effective charge does not imply an exotic charge, as in the quantum Hall regime, but is related to the probability that one particle or two particles are backscattered in the Fermi liquid (see Supplementary). Figure 3a,b shows the evolution of the conductance on ridge B as a function of magnetic field B and the corresponding noise S_K as a function of I_K , respectively. The temperature dependence is analysed in detail in the Supplementary Information. The effective charge is directly given by the slope at low current I_K ($eV_{sd} < k_B T_K$), yielding for the lowest field and temperature $e^*/e = 1.7 \pm 0.1$. This result is in good agreement with theory^{10,12}, which predicts $e^*/e = 5/3 \approx 1.67$, corresponding to equal probabilities for one- or two-particle scattering. Figure 3c represents the evolution of e^* with magnetic field and temperature. On this graph e^* is represented as a function of the reduced scales T/T_K for temperature or $g\mu_B B/2k_B T_K$ for the field, where $g=2$ is the Landé factor and μ_B the Bohr magneton (see Supplementary Information). All the data points seem to fall on the same curve, suggesting that e^* obeys a logarithmic scaling law which has not yet been predicted.

The Wilson ratio R has been extracted from the formula^{12,15}

$$\frac{e^*}{e} = \frac{1 + 9(n-1)(R-1)^2}{1 + 5(n-1)(R-1)^2} \quad (3)$$

where n characterizes the symmetry group SU(n) of the Kondo state. This number R is directly related to the ratio U/Γ , with U the charging energy of the quantum dot and Γ the coupling to the electrodes. It reflects the strength of the interaction in the Fermi liquid and is the only parameter to characterize the system, going from $R=1$ in the non-interacting case ($U=0$) to $R=2$ in the strong SU(2) Kondo limit ($U \rightarrow \infty$) (see Fig. 3d). Our value for e^* yields $R = 1.95 \pm 0.1$, ensuring strong interactions and thus a universal regime.

For consistency, R was independently extracted by fitting the evolution of conductance with B , V_{sd} and T at low excitation (see Supplementary Information) without any assumption on T_K . This result, $R = 1.95 \pm 0.1$, agrees perfectly with the value extracted from e^* . Finally, from the dependence of T_K with gate voltage, we have independently extracted the values $U = 6 \pm 0.5$ meV and $\Gamma = 1.8 \pm 0.2$ meV. This consistency is illustrated in Fig. 3d, where the two independent values for R and U/Γ cross on the theoretical curve.

The effect of asymmetric lead–dot coupling was tested on the ridge A, where $G = 0.85 G_Q$. Asymmetry is defined by the factor δ such that $G(0) = (1 - \delta)G_Q$. We have measured an effective charge $e^*/e = 1.2 \pm 0.08$, in good agreement with ref. 14, which predicts $e^*/e = 5/3 - (8/3)\delta = 1.26$.

Now, what can we learn from the SU(4) symmetry emerging on the right-hand side of Fig. 2a? A zoom is plotted in the upper panel of Fig. 4a and a cross-section is shown in the middle panel. Because spin and orbital degrees of freedom are degenerated, two channels contribute to transport, and Kondo resonance emerges at every filling factor, $N=1, 2$ and 3 electrons^{4–7}. At odd filling, the channels

Figure 2 | Stability diagram and shot noise for the SU(2) Kondo effect at $T = 16$ mK. **a**, Two-dimensional plot of the conductance as a function of V_{sd} and V_g . Kondo ridges appear as bright horizontal lines for $V_{sd} = 0$. In the SU(2) region two ridges show up for $N=1$ and $N=3$ electrons. For SU(4) the Kondo ridge exists for $N=1, 2$ and 3 electrons. Note that the conductance scale is $2e^2/h$ for SU(2) whereas it is $2 \times 2e^2/h$ for SU(4). An in-plane magnetic field of 0.08 T is applied to suppress superconductivity in the contacts. **b**, Upper panel: Cross-sections of the conductance of the SU(2) Kondo region at zero bias as a function of V_g for different temperatures. Two Kondo ridges A and B are clearly visible. Lower panel: Fano factor extracted from the linear part of the current noise in the regime $eV_{sd} \ll k_B T_K$ ($I_{sd} \leq 5$ nA) using the definition $S_I = 2eF|I_{sd}|$. Error bars take into account the uncertainty of the linear fit performed on slightly different current ranges in the limit $eV_{sd} \ll k_B T_K$. **c**, Conductance (black line) and noise (red dots) as a function of I_{sd} for the blocked region ($N=2$). The noise is linear with $|I_{sd}|$, with a slope around $2e$. Outside the Kondo ridge, owing to the very small transmission, the quantum dot is close to the tunnelling regime characterized by a full Poissonian noise with $F=1$. **d**, Conductance (black line) and noise (red dots) as a function of I_{sd} on the Kondo ridge ($N=3$). The slope of S_I around $I_{sd} = 0$ is almost zero owing to the perfect transmission ($F=0.06$).

are half transmitted ($T_1 = T_2 = 0.5$), yielding the same conductance G_Q as in the SU(2) symmetry. However, for $N=2$, current is transmitted through two perfect channels ($T_1 = T_2 = 1$), increasing

the conductance to $G = 2 G_Q$. In this region the conductance hardly depends on temperature up to 800 mK, reflecting a large T_K , as expected for the SU(4) symmetry²⁴. This is confirmed by the full

Figure 3 | Evolution of Kondo correlations with magnetic field and temperature. **a**, Evolution of the differential conductance from 0.075 T to 0.975 T in steps of 0.075 T. **b**, Kondo excess current noise S_K as a function of backscattering current I_K (see text for definition) for the same fields. The effective charge e^* is extracted from the slope $S_K/2eI_K$ at low current. The dashed red line shows result of the linear fit, yielding $e^*/e = 1.7 \pm 0.1$. The curves are shifted for clarity. **c**, Effective charge as a function of T/T_K and $g\mu_B B/2k_B T_K$ in a semi-log plot. Both can be described by the same line, which is a signature of a scaling law for $e^*(T, B)$ and suggests a logarithmic behaviour. Error bars take into account the uncertainty of the linear fit of S_K as a function of I_K performed on slightly different current ranges in the limit $eV_{sd} \ll k_B T_K$. **d**, Wilson ratio as a function of U/Γ calculated with the formula from ref. 15. For SU(2), vertical error bars represent the value for R extracted from e^* and from the scaling analysis of the conductance shown in the Supplementary Information. Horizontal error bar represents the value for U/Γ extracted independently from the fit of Kondo temperature shown in the Supplementary Information. The crossing on the theoretical curve shows the agreement of our measurement with the extension of Fermi liquid theory out of equilibrium. For SU(4), the value of R is extracted from e^* . The yellow part of the graph represents the region of universality: all the properties depend on a single parameter T_K for a given symmetry group¹¹.

width of the curve $G(V_{sd})$, which gives $T_K \approx 11$ K for $N=2$ and $T_K \approx 17$ K for $N=1$ or 3.

The first result to emphasize is that the linear part of the current noise is qualitatively different from SU(2) and is a powerful experimental tool to distinguish the two symmetries^{14,18}. The upper part of Fig. 4b represents the conductance at $N=3$ for SU(2) and SU(4) as a function of the rescaled voltage $eV_{sd}/k_B T_K$. The two curves are barely distinguishable. However, the current noise shown on the lower part of Fig. 4b is qualitatively different as it is almost zero for the SU(2) symmetry, whereas it is linear with $|I_{sd}|$ for SU(4). The linear noise is one order of magnitude stronger for SU(4) than for SU(2). Indeed, the Fano factor for two channels such that $T_1 = T_2 = 0.5$ is $F=0.5$ for the SU(4) symmetry, whereas for SU(2) a single channel with $T_1 = 1$ yields $F=0$. The complete evolution of F is summarized in the lower part of Fig. 4a. It changes from $F \approx 1$ outside the Kondo ridge to $F=0.5$ for $N=1$ and 3, reaching $F=0.07$ for $N=2$. This confirms that in the $N=2$ SU(4) case, transport takes place through two almost perfect channels ($T_1 = T_2 = 1$) without partition, yielding $F \approx 0$.

Finally we discuss e^* and R for the SU(4) symmetry at half filling ($N=2$). S_K and I_K have been computed by using the same procedure as explained for SU(2). The result, shown in Fig. 4c, gives $e^*/e = 1.45 \pm 0.1$ and $R = 1.35 \pm 0.1$ from (equation (3)). The decreasing value for R and e^* reflects the increasing number of degenerated states. When degeneracy increases, electrons

correlations become weaker and the non-interacting value is recovered for SU(n) when $n \rightarrow \infty$. The values for e^* and R are in good agreement with refs 14,15 (also see Fig. 3d), which predict $e^* = 1.5$ and $R = 4/3$, confirming that non-equilibrium Fermi liquid theory can be extended to more exotic classes of Fermi liquids.

Our experimental results emphasize three important points for the theory of Fermi liquids. First, in the linear regime they can be described as free quasi-particles, as the spirit of the theory teaches us. This allows one to clearly distinguish the different symmetry classes of Fermi liquids through shot noise measurements, whereas it is hardly possible from the conductance. Second, by probing the nonlinear noise, we have shown that out of equilibrium the residual interaction between quasi-particles shows up and creates a peculiar two-particle scattering, which bears the signature of the correlated nature of quantum liquids. Finally, the newly discovered out-of-equilibrium scaling law should trigger theoretical developments to deepen our understanding of universal behaviours in these liquids.

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References

1. Mahan, G. D. *Many-Particle Physics* (Plenum Press, 1990).
2. Bloch, I., Dalibard, J. & Nascimbène, S. Quantum simulations with ultracold quantum gases. *Nature Phys.* **8**, 267–276 (2012).

Figure 4 | The SU(4) Kondo state and comparison with the SU(2) symmetry. **a**, Top: Two-dimensional plot of the conductance as a function of V_{sd} and V_g in the SU(4) state. Middle: cross-section of the conductance as a function of the gate voltage at $V_{sd} = 0$ measured at different temperatures. G reaches $1.8 \times 2e^2/h$ for the filling $N=2$. Bottom: Extracted Fano factor. Error bars come from the linear fit of S_I as a function of I_{sd} in the limit $eV_{sd} \ll k_B T_K$. As expected it varies from $F \approx 0$ for $N=2$ to $F=0.5$ for $N=1$, and finally $F=1$ in the tunnelling regime (outside the Kondo ridge). **b**, Comparison of the conductance (top) and the noise (bottom) for the SU(2) Kondo state and SU(4) at filling $N=3$. In both cases the conductance is the same and the two states are not distinguishable. At low voltage, the noise S_I is qualitatively strongly different. For SU(2) the slope (Fano factor) is close to 0, as the transmission is almost perfect ($T_1=T_2=1$), whereas the linear part is very important in the SU(4) state, as transport occurs through two half transmitting channels ($T_1=T_2=0.5$), yielding $F=0.5$. For clarity, as asymmetry with respect to V_{sd} appears in the SU(4) state at large voltage, we compare only the symmetrized part of the conductance and the noise for SU(4). We used the definition: $G^{sym}(V_{sd}) = (G(V_{sd}) + G(-V_{sd}))/2$ and $S_I^{sym}(V_{sd}) = (S_I(V_{sd}) + S_I(-V_{sd}))/2$. **c**, Kondo excess noise for the SU(4) symmetry at filling $N=2$. A linear fit at low current using formula (2) gives $e^*/e = 1.45 \pm 0.1$, yielding $R = 1.35 \pm 0.1$.

- van der Wiel, W. G. *et al.* The Kondo effect in the unitary limit. *Science* **289**, 2105–2108 (2000).
- Jarillo-Herrero, P., Kong, J., Zant, H. S. J. V. D. & Dekker, C. Orbital Kondo effect in carbon nanotubes. *Nature* **434**, 484–488 (2005).
- Makarovski, A., Zhukov, A., Liu, J. & Finkelstein, G. SU(2) and SU(4) Kondo effects in carbon nanotube quantum dots. *Phys. Rev. B* **75**, 241407 (2007).
- Cleuziou, J. P., NGuyen, N. G., Florens, S. & Wernsdorfer, W. Interplay of the Kondo effect and strong spin–orbit coupling in multihole ultraclean carbon nanotubes. *Phys. Rev. Lett.* **111**, 136803 (2013).
- Schmid, D. R. *et al.* Broken SU(4) symmetry in a Kondo-correlated carbon nanotube. *Phys. Rev. B* **91**, 155435 (2015).
- Delattre, T. *et al.* Noisy Kondo impurities. *Nature Phys.* **5**, 208–212 (2009).
- Nozières, P. A “Fermi-Liquid” description of the Kondo problem at low temperatures. *J. Low Temp. Phys.* **17**, 31–42 (1974).
- Sela, E., Oreg, Y., von Oppen, F. & Koch, J. Fractional shot noise in the Kondo regime. *Phys. Rev. Lett.* **97**, 086601 (2006).
- Oguri, A. Fermi liquid theory for the nonequilibrium Kondo effect at low bias voltages. *J. Phys. Soc. Jpn* **74**, 110–117 (2005).

12. Gogolin, A. & Komnik, A. Full counting statistics for the Kondo dot in the unitary limit. *Phys. Rev. Lett.* **97**, 016602 (2006).
13. Mora, C., Leyronas, X. & Regnault, N. Current noise through a Kondo quantum dot in a SU(N) Fermi liquid state. *Phys. Rev. Lett.* **100**, 036604 (2008).
14. Mora, C., Vitushinsky, P., Leyronas, X., Clerk, A. & Le Hur, K. Theory of nonequilibrium transport in the SU(N) Kondo regime. *Phys. Rev. B* **80**, 155322 (2009).
15. Sakano, R., Fujii, T. & Oguri, A. Kondo crossover in shot noise of a single quantum dot with orbital degeneracy. *Phys. Rev. B* **83**, 075440 (2011).
16. Zarchin, O., Zaffalon, M., Heiblum, M., Mahalu, D. & Umansky, V. Two-electron bunching in transport through a quantum dot induced by Kondo correlations. *Phys. Rev. B* **77**, 241303 (2008).
17. Yamauchi, Y. *et al.* Evolution of the Kondo effect in a quantum dot probed by shot noise. *Phys. Rev. Lett.* **106**, 176601 (2011).
18. Egger, R. What the noise is all about. *Nature Phys.* **5**, 175–176 (2009).
19. Kondo, J. Resistance minimum in dilute magnetic alloys. *Prog. Theor. Phys.* **32**, 37–49 (1964).
20. Blanter, Y. M. & Büttiker, M. Shot noise in mesoscopic conductors. *Phys. Rep.* **336**, 1–166 (2000).
21. Kasumov, Y. *et al.* CVD growth of carbon nanotubes at very low pressure of acetylene. *Appl. Phys. A* **88**, 687–691 (2007).
22. Arakawa, T., Nishihara, Y., Maeda, M., Norimoto, S. & Kobayashi, K. Cryogenic amplifier for shot noise measurement at 20 mK. *Appl. Phys. Lett.* **103**, 172104 (2013).
23. Sakano, R., Oguri, A., Kato, T. & Tarucha, S. Full counting statistics for SU(N) impurity Anderson model. *Phys. Rev. B* **83**, 241301 (2011).
24. Galpin, M. R., Logan, D. E. & Krishnamurthy, H. R. Quantum phase transition in capacitively coupled double quantum dots. *Phys. Rev. Lett.* **94**, 186406 (2005).

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Author contributions

All the authors contributed to the analysis of the data and commented on the manuscript. M.F., R. Delagrè, R.W. and R. Deblock designed the sample. M.F., T.A., T.H. and R.F. performed the noise experiments and analysed the data. M.F. and K.K. planned and supervised the research.

Additional information

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Competing financial interests

The authors declare no competing financial interests.