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What can we learn from nonequilibrium response of a strange metal?[1)]

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The recent paper by Liyang Chen et al. [1] reports on the measurements of shot noise in heavy fermion strange metal $YbRh_2Si_2$ patterned into the nanowire shape. The authors argue that the observed shot noise suppression cannot be attributed to electron-phonon energy relaxation in a standard Fermi liquid model, suggesting a failure of the quasiparticle concept. In the present manuscript we argue that this conclusion is debatable and electron-phonon relaxation plays important role in the experiment.

Figura 1a shows the sketch of the devices studied, made from a 60 nm thick $YbRh_2Si_2$ film, with nanowire-shaped constrictions of lengths L and widths w, connected to source and drain pads. The pads are covered with 200 nm of gold, which has approximately 10 times higher conductivity than $YbRh_2Si_2$ at low temperatures. We assume that the current is redistributed between $YbRh_2Si_2$ and gold layers, like it is illustrated in the bottom of Fig. 1a. The region where current redistribution occurs is determined by the current transfer length, λ, which depends on the interface conductance per unit area, $\sigma_{\rm int}$, reflecting the quality of the $YbRh_2Si_2$/Au interface. The authors provide data for three short devices with $L \lesssim 1\,\mu$m and one long device with $L = 28\,\mu$m with widths range from 140 nm to 300 nm. We argue that the contribution to the measured resistance and noise may come not only from the nanowires themselves but also from a significant part of the pads and λ may lay in the range of hundreds of micrometers.

We first discuss and analyze the experimental data for the long device. Due to length of constriction, the effect of the interface can likely be neglected. We find that the electron-phonon scattering length in $YbRh_2Si_2$ is approximately $1\,\mu$m at 3 K and decreases with increasing temperature. This implies that, in the presence of a bias current I, the electron system in the long constriction can be described by a position-independent electronic temperature $T_e(I)$, except for short regions near the pads. We obtain $T_e(I)$ dependence by extracting $R = V/I$ from the differential resistance at $T_0 = 3$, 5, and 7 K and using the fact that the temperature dependence of the normalized resistance of the devices is the same as that for the unpatterned film. The curves $T_e(I)$ we calculated allow one to estimate the electron-phonon coupling, which describes the power flow from the electron to the phonon subsystem in a steady state via $P_{e-ph} = P_J = \mathcal{V}\Sigma_{e-ph}(T_e^n - T_{ph}^n)$, where P_J is the released Joule heat power, $\mathcal{V}$ is the system volume, T_{ph} is the phononic temperature and the exponent n typically varies in the range $n \approx 3{-}5$. The devices are patterned on crystalline germanium substrates ensuring $T_{ph} = T_0$. We found that $n = 4.7$ fits the data perfectly with $\Sigma_{e-ph} = 9.6 \times 10^8\,\mathrm{W/K^{4.7}m^3}$ ($w = 300$ nm). From here, we extract the T-dependence of the electron-phonon scattering length using $l_{e-ph} = L\left[\mathcal{L}/nT^{n-2}\mathcal{V}\Sigma_{e-ph}R(T)\right]^{1/2}$, where $\mathcal{L}$ is the Lorenz number. The result is shown in Fig. 1d and in the given temperature range can be reasonably approximated as $l_{e-ph} \propto T^{-1.7}$ (dashed line). Importantly, $l_{e-ph}(3\,\mathrm{K}) \approx 1.4\,\mu$m ensuring the possibility to introduce position-independent electronic temperature $T_e(I)$ which will be further used in noise treatment.

Before discussing nonequilibrium noise, we note some general details of the noise measurements. In the setup used in [1], see Fig. 1b for the schematic circuit, the voltage noise before amplification is determined by two contributions, $S_V(I) = \left[\frac{4k_{\rm B}T_e(I)}{R_{\rm diff}(I)} + S_{\rm amp}\right] R_{\rm diff}^2(I)$, where $R_{\rm diff} = dV/dI$ is the differential resistance of the device, the first term comes from the current noise of the device itself, the second term is defined by the parasitic input noise of the amplifiers $S_{\rm amp}$, and $S_V(0)$ is the voltage noise in equilibrium. So, along with deter-

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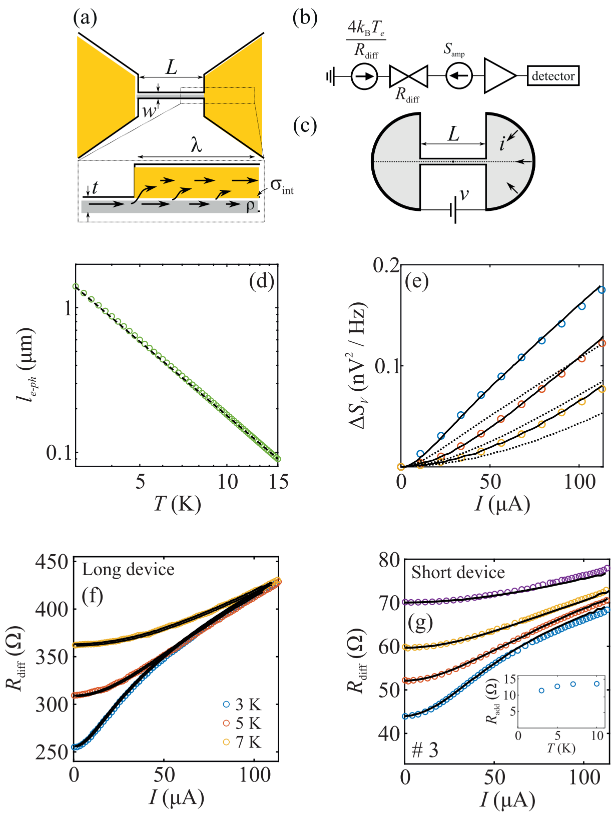

Fig. 1. (Color online) (a) – Schematic representation of a device. $YbRh_2Si_2$ 60 nm film (gray) is patterned into a constriction with length L and width w connecting two pads covered with 200 nm of gold (yellow). Interface between $YbRh_2Si_2$ and gold is characterized by conductivity $\sigma_{\rm int}$, current transfer length λ. (b) – Equivalent circuit of noise measurement setup. (c) – Geometry used in numerical modelling to calculate the total current through the constriction in response to the applied bias voltage. (d) – Electron-phonon scattering length as a function of temperature. Dashed line is $l_{e-ph} \propto T^{-1.7}$. (e) – Excess voltage noise spectral density of the device, as a function of bias current. Symbols represent the data from the experiment [1]. The dotted and dashed lines correspond to with $S_{\rm amp} = 0$ and $S_{\rm amp} = 5 \cdot 10^{-25}\,{\rm A^2/Hz}$, respectively. Numerical simulation of nonequilibrium response for both: (f) – long and (g) – short (device # 3) constrictions. Symbols in panels reproduce the experimental results of [1] for differential resistance as a function of bias current. Solid lines are obtained with numerical simulation

mining the gain it is also important to get the magnitude of amplifier noise. Typically, using homemade voltage amplifier at 4.2 K, its input current noise is on the order of $10^{-27}\,{\rm A^2/Hz}$. The authors of [1] use room-temperature commercial preamplifiers LI-75 and SR-560 in which one can expect $S_{\rm amp} \gtrsim 10^{-25}\,{\rm A^2/Hz}$. We note that this current noise can not be extracted from the setup calibration [1], because it was performed by detecting the room temperature thermal noise of resistors which is $1.6 \cdot 10^{-22}\,{\rm A^2/Hz}$ for a typical used $100\,\Omega$ and by far exceeds the expected value of $S_{\rm amp}$. At the same time, the current noise of a strange metal long device at 5 K and with a resistance of approximately $300\,\Omega$ is $9 \cdot 10^{-25}\,{\rm A^2/Hz}$ which is comparable to the expected value of $S_{\rm amp}$. By solid lines in Fig. 1e we show the best fits to the experimental data (symbols) of [1] obtained with $S_{\rm amp} = 5 \cdot 10^{-25}\,{\rm A^2/Hz}$ which perfectly falls in the above order of magnitude expectation.

Numerical simulations are performed in the geometry of Fig. 1c. Here, the radius of pads equals $20\,\mu$m and the current redistribution on the lateral scale of these pads is neglected. The electrodes are indicated by thick black lines. This geometry is close to the geometry of the patterned film nearby the constriction in real devices and the scale of $20\,\mu$m is large enough to capture the nonlinearity of differential resistance. Fig. 1f, g demonstrates comparison of experimental data for both long and short devices with simulations using $\Sigma_{e-ph} = 6.1 \cdot 10^8\,{\rm W/K^5m^3}$, $n = 5$ and $\rho(T) = 10.8 + 1.67\,T\,[\mu\Omega \cdot {\rm cm}]$. Note that the difference between thus obtained Σ_{e-ph} and the value extracted from Fig. 1c is due to the slightly different n. The fit is perfect for the long device, however the fit for the short device is obtained with $R_{\rm diff} = dv/di + R_{\rm add}(T)$, where $R_{\rm add}(T)$ is chosen as current-independent quantity to fit the linear-response resistance for all four temperatures of interest (see inset).

Our findings make the statement on the failure of quasiparticle concept in $YbRh_2Si_2$ arguable and provide information essential for further transport experiments. We thank Liyang Chen and Douglas Natelson for valuable comments on the device fabrication details.

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