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Asymmetric tunneling conductance and the non-Fermi liquid behavior of strongly correlated Fermi systems

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The scanning tunneling microscopy and the point contact spectroscopy based on Andreev reflection [1, 2] are sensitive to quasiparticle occupation numbers, and are ideal techniques to study the effects of particle-hole symmetry violation, making the differential tunneling conductivity and dynamic conductance to be asymmetric function with respect to the applied voltage V. The asymmetric part of the conductivity $\sigma_{\rm asym}(V) \equiv I'(V) - I'(-V)$ $(I' \equiv dI/dV)$ can be observed when strongly correlated Fermi system is either in its normal or superconducting (SC) state [3–7]. This asymmetry does not occur in conventional metals, for in the Landau Fermi liquid (LFL) theory the particle-hole symmetry is conserved and both the differential tunneling conductivity and dynamic conductance are symmetric functions of V [2, 8, 9]. The theory of fermion condensation (FC) taking place at the topological fermion condensation quantum phase transition (FCQPT) 8, 10–12] allows one to explain the non-Fermi liquid (NFL) behavior of many strongly correlated Fermi systems. It has been predicted within the framework of FC theory, that the differential tunneling conductivity becomes noticeably asymmetric in heavy fermion (HF) metals. The reason for that is that their electronic system is located near FCQPT, forming flat bands and violating both the particle-hole and the time-reversal symmetry [3, 6–9]. As a result, the asymmetric part $\sigma_{\rm asym}$ becomes finite. The application of magnetic field destroys the NFL behavior, and restores the above symmetries, nullifying $\sigma_{\rm asym}$. This nullification can be extracted from recent experimental observations [13–15] and has been predicted theoretically in [3, 6, 7]. The experimental observation of flat band and SC state at low temperatures T in graphene [13] attract a strong attention to the band flattening, for it can lead to the bulk room-T superconductivity in graphite [16]. Both the band flattening and the emergence of SC state are in accordance with recent experimental and theoretical observations suggesting that the flattening indeed raises T_c, and can be accompanied by asymmetrical conductivity that can induce the time-reversal symmetry breaking [16–21]. Obviously, $\sigma_{\rm asym}$ becomes finite as particle-hole symmetry is violated and we obtain the expression for $\sigma_{\rm asym}(V)$ when the system is in its normal state [3, 6–9]

$$\sigma_{\rm asym}(V) \simeq c\left(\frac{V}{2T}\right)\frac{p_f - p_i}{p_F} \simeq c\frac{V}{2T}\frac{S_0}{x}. \qquad (1)$$

In Equation (1), $x = p_F^3/(3\pi^2)$ is a density of the heavy electron liquid, $(p_f - p_i)$ is the region occupied by FC, c is a constant of the order of unity. We note that S_0, characterizing the normal state, can be estimated measuring the asymmetric part of tunneling conductance in the superconducting state. In order to observe the finite asymmetry of the conductivity, the measurements have to be carried out when the corresponding HF metal demonstrates the NFL behavior with particle-hole asymmetry. Latter asymmetry is typical for HF metals located near FCQPT. Thus, we conclude that the emergence of $\sigma_{\rm asym}(V)$ is the typical feature of the NFL behavior. It has been predicted within the framework of the FC theory that $\sigma_{\rm asym}(V)$ becomes finite in the archetypical HF metal $YbRh_2Si_2$, and disappears if the metal is moved to the LFL state by magnetic field [3, 7]. The asymmetric conductivity [14] and its suppression [15] have been observed in $YbRh_2Si_2$ as it is reported in Fig. 1. In that case magnetic field B is applied parallel to the magnetically hard c axis and the suppression takes place at $B \geq 7$ T. The asymmetric part of the differential resistance $\sigma_{asym}(k\Omega) = dV/dI(I) - dV/dI(-I)$, extracted from measurements on graphene [13], diminishes at el-

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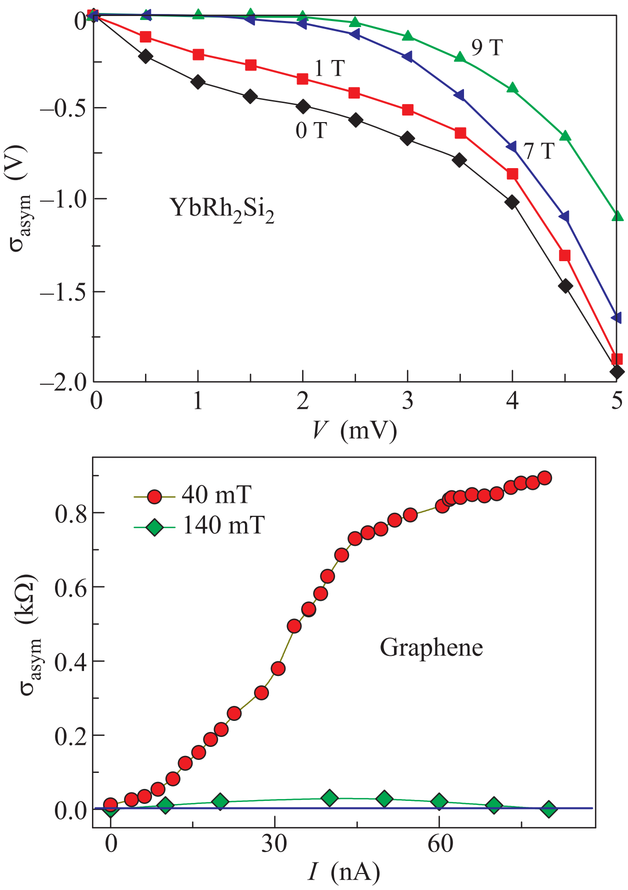

Fig. 1. (Color online) The asymmetric part $\sigma_{\text{asym}}(V)$ at different applied magnetic fields, shown in the legends. Upper panel: $\sigma_{\text{asym}}(V)$ is extracted from the experimental data collected on the HF metal $YbRh_2Si_2$ [15]. At $B \geq 7\,\text{T}$ $\sigma_{\text{asym}}(V)$ vanishes at $V \leq 2\,\text{mV} \sim 9\,\text{T}$. Lower panel: The asymmetric part of the differential resistance $\sigma_{\text{asym}}(k\Omega) = dV/dI(I) - dV/dI(-I)$ is extracted from experimental data on graphene [13]. The asymmetry emerges at $B \leq 80\,\text{mT}$ and vanishes at $B \simeq 140\,\text{mT}$

evated magnetic field, and vanishes at $B \simeq 140$ mT, as it is seen from Fig. 1, lower panel. This observation is of great importance, for the graphene has a perfect flat band, making the particle-hole asymmetry generated by FC be obviously exhibited [13]. It is also clearly seen from Fig. 1, lower panel, that under the application of tiny magnetic field $B \simeq 140$ mT the asymmetric part $\sigma_{asym}(k\Omega)$ of the differential resistance vanishes, for the system transits to the LFL state. Thus, the asymmetric part σ_{asym} of the tunneling conductivity/resistivity arises due to the FC phenomenon in the corresponding substance. This asymmetry is obviously a NFL property. To the best of our knowledge, the FC theory is the only one capable to explain the above experimental puzzles. Namely, in accordance with the prediction [3, 6, 7], σ_{asym} vanishes under the application of magnetic field as a material transits to the LFL state and the particle-hole symmetry restores. Therefore, FCQPT is intrinsic to strongly correlated substances and can be viewed as the universal cause of their non-Fermi liquid behavior.

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