Pis'ma v ZhETF, vol. 110, iss. 4, pp. 266 – 267

Fermion condensation, T-linear resistivity and Planckian limit

V. R. Shaginyan[+*1)], *M. Ya. Amusia*[×°], *A. Z. Msezane*[*], *V. A. Stephanovich*[▽], *G. S. Japaridze*[*], *S. A. Artamonov*[+]

[+]*Petersburg Nuclear Physics Institute of NRC "Kurchatov Institute", 188300 Gatchina, Russia*

[*]*Clark Atlanta University, Atlanta, GA 30314, USA*

[×]*Racah Institute of Physics, Hebrew University, Jerusalem 91904, Israel*

[°]*Ioffe Physical Technical Institute, Russian Academy of Sciences, 194021 St. Petersburg, Russia*

[▽]*Institute of Physics, Opole University, Oleska 48, 45-052 Opole, Poland*

Submitted 26 June 2019
Resubmitted 14 July 2019
Accepted 14 July 2019

DOI: 10.1134/S0370274X19160100

Exotic experimentally observable properties of different classes of strongly correlated Fermi systems are still remain largely unexplained due to the lack of universal underlying physical mechanism. It is customary to attribute these properties to so-called non-Fermi-liquid (NFL) behavior. Latter behavior is widely observed in heavy-fermion (HF) metals, graphene, and high-T_c superconductors (HTSC). Experimental data collected on many of these systems show that at $T = 0$ a portion of their excitation spectrum becomes dispersionless, giving rise to so-called flat bands, see, e.g., [1–4]. The presence of flat band indicates that the system is close to the topological fermion-condensation quantum phase transition (FCQPT) [1, 2, 4], leading to flat bands ($\varepsilon(\mathbf{k}) = \mu$, where $\varepsilon(\mathbf{k})$ is quasiparticle energy and μ is a chemical potential) formation. Recent challenging experimental findings of linear temperature T dependence of the resistivity $\rho(T) \propto T$ collected on HTSC, graphene, HF and conventional metals, have revealed that the scattering rate $1/\tau$ of charge carriers reaches the so-called universal Planckian limit $1/(T\tau) = k_B/\hbar$ (k_B and $\hbar = h/2\pi$ are the Boltzmann and Plank constants, respectively) [5–8]. Note that above Planckian limit, used to explain the universal scattering rate in the so-called Planckian metals [5–8], can occur accidentally since its experimental manifestations in other (than Planckian) metals may be equally well explained by more conventional physical mechanisms like those related to phonon contribution [3].

Within the framework of the fermion condensation (FC) theory, we show that the quasi-classical physics is still applicable to describe the universal scattering rate $1/\tau$, experimentally observed in strongly correlated metals at their quantum critical region. This is because flat bands, responsible for quantum criticality, generate transverse zero-sound mode, reminiscent of the phonon mode in solids, with the Debye temperature T_D [3]. At $T \geq T_D$ the mechanism of the linear temperature dependence of the resistivity is the same both in conventional metals and strongly correlated ones, and is represented by electron-phonon scattering. Therefore, it is electron-phonon scattering at $T \geq T_D$, which yields the near material-independence of the lifetime τ. It is expressed as $1/(\tau T) \sim k_B/\hbar$. The observed scattering rate is well explained by the emergence of flat bands formed by the topological FQCPT, rather than by the so called Planckian limit at which the assumed Planckian scattering rate takes place. At low temperatures, the observed resistivity in HTSC and HF metals obeys linear law (so-called linear T-resistivity)

$$\rho(T) = \rho_0 + AT. \tag{1}$$

Here ρ_0 is the residual resistivity and A is a T-independent coefficient. On the other hand, at room temperature the T-linear resistivity is exhibited by conventional metals such as Al, Ag or Cu. In case of a simple metal with a single Fermi surface pocket the resistivity reads $e^2 n\rho = p_F/(\tau v_F)$, where e is the electronic charge, τ is the lifetime, n is the carrier concentration, and p_F and v_F are the Fermi momentum and velocity respectively. Representing the lifetime τ (inverse scattering rate) of quasiparticles in the form

$$\frac{\hbar}{\tau} \simeq a_1 + \frac{k_B T}{a_2}, \tag{2}$$

we obtain [3]

$$a_2 \frac{e^2 n\hbar}{p_F k_B} \frac{\partial \rho}{\partial T} = \frac{1}{v_F}, \tag{3}$$

[1)]e-mail: vrshag@thd.pnpi.spb.ru

where a_1 and a_2 are T-independent parameters. A challenging point for a theory is that experimental data confirm Eq. (3) for both strongly correlated metals (HF metals and HTSC) and ordinary ones, provided that these demonstrate the linear T-dependence of their resistivity [5], see Fig. 1.

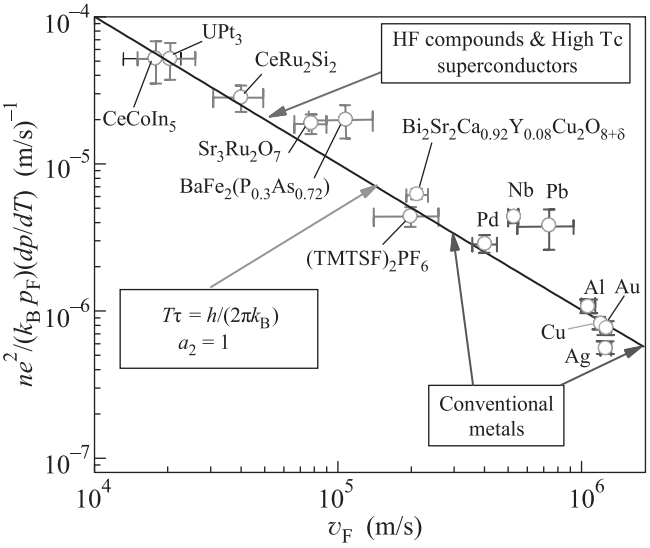

Fig. 1. (Color online) Scattering rates per kelvin of different strongly correlated metals like HF ones, HTSC, organic and conventional metals [5]. All these metals exhibit $\rho(T) \propto T$ and demonstrate two orders of magnitude variations in their Fermi velocities v_F. The parameter $a_2 \simeq 1$ gives the best fit shown by the solid line, and corresponds to the scattering rate $\tau T = h/(2\pi k_B)$, with $h = 2\pi\hbar$, see Eqs. (3) and (4). The region occupied by the conventional metals is highlighted by two (blue) arrows. The single (green) arrow shows the region of strongly correlated metals, including organic ones. Note, that at low temperatures $T \ll T_D$, the scattering rate per kelvin of a conventional metal is orders of magnitude lower, and does not correspond to the Planckian limit

The coefficient a_2 is always close to unity, $0.7 \leq a_2 \leq 2.7$, notwithstanding huge distinction in the absolute value of ρ, T and Fermi velocities v_F, varying by two orders of magnitude [5]. As a result, it follows from Eq. (2) that the T-linear scattering rate is of universal form, $1/(\tau T) \sim k_B/\hbar$.

As it is seen from Fig. 1, this scaling relation spans two orders of magnitude in v_F, attesting to the robustness of the observed empirical law [5]. This behavior is explained within the framework of the FC theory, since for both conventional metals and strongly correlated ones the scattering rate is defined by phonons [3, 9]. In case of conventional metals at $T > T_D$ it is well known that phonons make the main contribution to the linear dependence of the resistivity. On the other hand, it has been shown that the quasi-classical physics describes the T-linear dependence of the resistivity of strongly correlated metals at $T > T_D$, since flat bands, forming the quantum criticality, generate transverse zero-sound mode with the Debye temperature T_D located within the quantum criticality area [3, 9]. Therefore, the T-linear dependence is formed by electron-phonon scattering in both ordinary metals and strongly correlated ones. As a result, it is electron-phonon scattering that leads to the near material-independence of the lifetime τ that is expressed as

$$\tau T \sim \frac{\hbar}{k_B}. \tag{4}$$

We stress, that the Planckian limit may occur accidentally: it is highly improbable that it would be realized in conventional metals, which, obviously, cannot be recognized as Planckian ones with quantum criticality at high or low temperatures. The fact, that we observe the same universal behavior of the scattering rate in microscopically different strongly correlated compounds like HTSC, HF and conventional metals, suggests that some general theory is needed to explain the above body of materials and their behavior in the uniform manner. We may conclude that the FC theory is a suitable candidate.

We thank V. A. Khodel for stimulating discussions.

This work was partly supported by U.S. DOE (United States Department of Energy), Division of Chemical Sciences, Office of Basic Energy Sciences, Office of Energy Research.

Full text of the paper is published in JETP Letters journal. DOI: 10.1134/S002136401916001X

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