Coulomb Drag and Heat Transfer in Strange Metals

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(Received 5 May 2023; accepted 11 August 2023; published 30 August 2023)

We address Coulomb drag and near-field heat transfer in a double-layer system of incoherent metals. Each layer is modeled by an array of tunnel-coupled SYK dots with random interlayer interactions. Depending on the strength of intradot interactions and interdot tunneling, this model captures the crossover from the Fermi liquid to a strange metal phase. The absence of quasiparticles in the strange metal leads to temperature-independent drag resistivity, which is in strong contrast with the quadratic temperature dependence in the Fermi liquid regime. We show that all the parameters can be independently measured in near-field heat transfer experiments, performed in Fermi liquid and strange metal regimes.

DOI: 10.1103/PhysRevLett.131.096501

The electronic double layers—spatially separated and interactively coupled conducting circuits—provide a versatile array of low-dimensional quantum systems designed to directly probe electronic correlations via nonlocal transport measurements such as Coulomb drag [1]. Such double layers can be formed out of 0D quantum dots and point contacts [2–4], 1D nanowires [5–8], and topological edge states [9], and bilayers of 2DEG [10–12] or graphene [13–15]. These devices enable the exploration of various electron transport regimes and the identification of correlated electronic phases from the distinct temperature dependence of the drag resistance.

In the Fermi liquid (FL) regime the drag resistance is expected to scale quadratically with the temperature at the lowest temperatures. This result follows from the simple argument of the phase space available for the quasiparticle scattering that can be accurately established in the microscopic kinetic theory [16–18]. The interplay of screening and diffusion leads to the enhancement of drag resistance in the disordered systems [19–21]. At intermediate temperatures, dragging is dominated by the collective modes and resistance peaks at the energies of plasmons in 2D bilayers. The further fall-off of drag resistance at higher temperatures can be described by hydrodynamic effects and is governed by the electron liquid viscosity in clean systems [22,23]. All these features are well understood and rigorously described within the framework of the Fermi liquid theory.

There are known examples of essentially non-Fermi liquid behavior in systems where the quasiparticle concept breaks down. For instance, in Luttinger liquids kinematics of 1D collisions of electrons with linear spectrum dictates that drag is dominated by the interwire backscattering [24,25]. This translates into the signature power-law temperature dependence of drag resistance with the power exponent dependent on the strength of electron interaction. At the lowest temperatures, however, the transresistivity diverges, due to the formation of locked charge density waves. The enhancement of resistance occurs also in 2D layers provided that interactions are sufficiently strong and the electron system is on one of the possible microemulsion phases at the onset of Wigner crystallization [26]. Another notable example is the regime of drag between fractional quantum Hall liquids, where the transresistance is determined by the scattering and Coulomb screening effects of composite fermions [27–30]. Ultimately, the strong coupling limit may lead to pairing and interlayer (indirect excitonic) superfluidity [31,32] that can be detected in the Coulomb drag counterflow setup.

In recent years much of the attention in the context of electronic transport is devoted to understanding the strange metal (SM) behavior in strongly correlated materials with and without quasiparticles, revealing the microscopic origin of the Planckian dissipation [33–38]. This broad interest facilitates the development of the corresponding transport theory for strange metal bilayers that may provide additional insights into the intricate physical properties of these systems. For that purpose, we use the paradigmatic Sachdev-Ye-Kitaev (SYK) model [39–41], which describes a strongly interacting quantum many-body system without quasiparticle excitations that is maximally chaotic, nearly conformally invariant, and exactly solvable in the limit of a large number of interacting particles. We derive analytical results for the drag resistance and near-field thermal conductance in bilayers of SYK arrays. Our analysis leads us to drastically different conclusions concerning the temperature dependence of the drag resistance in the SM phase as compared to the FL, and different from the earlier study based on the hydrodynamiclike holographic model of the strange metal [42].

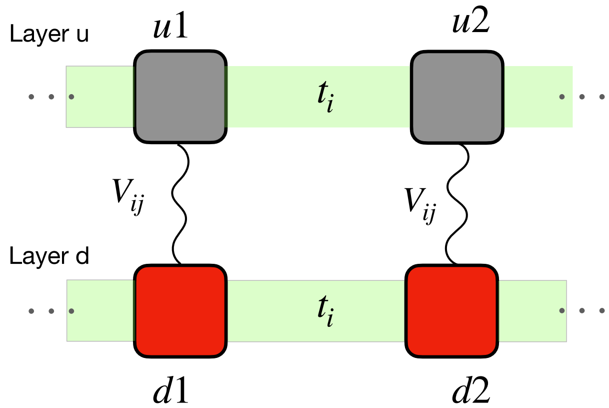

FIG. 1. Schematic representation of the SYK double layer setup. The four depicted dots is the minimal set needed to evaluate the drag transconductance.

To reveal the main qualitative features of the Coulomb drag in incoherent metals, we consider a theoretical model, which consists of two layers, dubbed by u and d, coupled by interactions. Each layer consists of an array of SYK dots, coupled by direct particle tunneling, see Fig. 1. The Hamiltonian of the adopted model reads

$$H = \sum_{\nu=u,d} \sum_{r} H^{\nu r}_{\mathrm{SYK}} + \sum_{\nu=u,d} H^{\nu}_{t} + V_{\mathrm{int}}. \tag{1}$$

Here the first term describes the set of isolated SYK dots

$$H^{\nu r}_{\mathrm{SYK}} = \sum_{ij,kl}^{N} J^{\nu r}_{ij,kl} c^{+}_{\nu ri} c^{+}_{\nu rj} c_{\nu rk} c_{\nu rl}, \tag{2}$$

where $J^{\nu r}_{ij,kl}$ are random couplings drawn from the Gaussian distribution with zero mean and the variances $\overline{|J^{\nu r}_{ij,kl}|^2} = (2J^2/N^3)$. The interactions in different dots are statistically independent of each other. The second term in Eq. (1) describes the interdot tunneling of electrons in each layer

$$H^{\nu}_{t} = \sum_{\langle r,r' \rangle} \sum_{i}^{N} t^{\nu}_{i} (c^{+}_{\nu ri} c_{\nu r'i} + \mathrm{H.c.}), \tag{3}$$

where t^{ν}_{i} denotes random tunneling amplitudes derived from the Gaussian distribution with zero mean and the variance $\overline{|t^{\nu}_{i}|^2} = t_0^2$, and the sum $\langle r, r' \rangle$ runs over the nearest neighbors. The tunneling couplings in different layers are statistically independent. We associate the site index i, j, k, l within the SYK dot with a quantum number characterizing some quantum mechanical state (orbital), which is conserved by the tunneling. The last term in Eq. (1) describes interlayer interactions. Being guided by the random interactions within the SYK dot, we adopt the random interdot interaction between the on-site charge densities

$$V_{\mathrm{int}} = \sum_{i,j}^{N} V_{ij} \sum_{r} c^{+}_{uri} c_{uri} c^{+}_{drj} c_{drj}. \tag{4}$$

The random interaction constants V_{ij} have zero mean and are characterized by the variance $\langle V_{ij}^2 \rangle = (V^2/N)$.

Each isolated SYK dot provides a model of an incoherent metal that completely lacks electron or hole quasiparticles [39,40]. However, a weak electron hopping within an array of SYK dots changes the low-energy spectrum, restoring coherent quasiparticles. This, in turn, induces a crossover between the high-temperature incoherent SYK metal and low-temperature FL metal at a temperature of $T_0 \sim t_0^2/J$, which is determined by the electron escape rate from the SYK-grain [35,41,43–46]. The model adopted here exhibits the same crossover. As we will show, the crossover between the SYK and FL regimes results in a qualitative change in the Coulomb drag resistance.

Because of the intrinsic incoherence in an SYK dot, the temperature dependence of the transconductance is a local feature of two neighboring dots in each layer, which we assign with the numbers $r = 1$, $r' = 2$, as shown in Fig. 1. The global resistance is given by electric circuitry rules of connecting such local elements in a larger circuit. Thus, though the total drag resistance does depend on the geometry and the dimensionality of the array, its temperature dependence is independent of those (contrary to the coherent metal case [20,24]).

The drag conductance is calculated according to the Kubo formula approach developed in Refs. [20,21]. The basic diagram describing the drag response between the layers u and d is shown in Fig. 2(a). Solid lines in Fig. 2 denote the one-particle Green's functions of the SYK model. Since Coulomb drag is possible only if the particle-hole symmetry is violated, we assume that the SYK grains in both layers are away from half-filling. The charge asymmetry is parametrized by the parameters, introduced for SYK model in

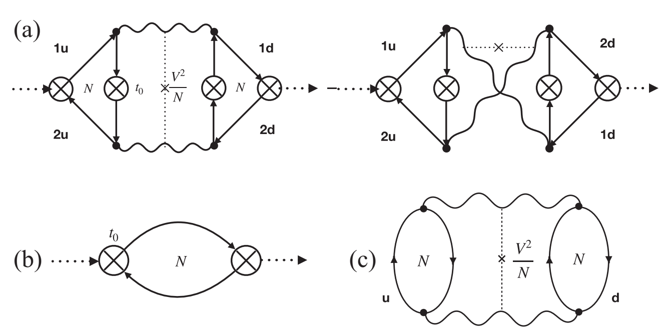

FIG. 2. (a) Diagrams for the drag transconductance. Full lines represent interacting SYK Green's functions, wavy lines—interlayer interactions, and crossed circles—intralayer tunneling. (b) Diagram for the interdot conductance within a single layer. (c) Diagram describing the heat current between the SYK dots in the up (u) and down (d) layers. Factors of N are indicated explicitly.

Ref. [47], $\mathcal{E}_{u,d} \propto -d\mu_{u,d}/dT$, that are proportional to the temperature derivative of the corresponding chemical potentials. Detailed calculations outlined in the Supplemental Material [48] result in the following expression for the drag conductance in the strange metal (SM) regime

$$\sigma_{\mathrm{Drag}}^{\mathrm{SM}} \approx 58.6N \frac{V^2}{J^2} \frac{T_0^2}{T^2} \mathcal{E}_u \mathcal{E}_d. \tag{5}$$

The drag conductance diminishes with temperature as T^{-2}. At the same time, the dc conductance within the layer behaves as $1/T$, [43], $\sigma^{\mathrm{SM}} \approx 0.886N(e^2/h)(T_0/T)$ (for details see Supplemental Material [48]). As a result the drag trans-resistance between the two strange metals is *temperature independent*:

$$\rho_{\mathrm{Drag}}^{\mathrm{SM}} = \frac{\sigma_{\mathrm{Drag}}^{\mathrm{SM}}}{(\sigma^{\mathrm{SM}})^2} \approx \frac{C^{\mathrm{SM}}}{N} \frac{h}{e^2} \frac{V^2}{J^2} \mathcal{E}_u \mathcal{E}_d, \tag{6}$$

where the numerical factor is estimated as $C^{\mathrm{SM}} \approx 74.7$, and the SM regime is realized for $T > T_0$. Furthermore, we find that in this regime drag resistance remains independent of the tunneling strength t_0. This universality leads us to conclude that the validity of Eq. (6) extends beyond the specific microscopic model used in this Letter. Besides the evident proportionality to the charge asymmetries in both layers, the only physical parameter governing the drag conductance is the ratio of the inter- and intralayer interactions, V/J. Remarkably, this parameter can be independently determined through the measurement of the near-field heat transport [49–52], as we demonstrate below.

The temperature-independent drag resistance of the strange metal stands in stark contrast to the drag resistance in the Fermi liquid, which is proportional to T^2. In the Fermi liquid regime at $T < T_0 < t_0$, tunneling is the most relevant term in the Hamiltonian. It smears the low-energy SYK singularity in the single-particle density of states, substituting it with a semicircular energy band with a width of $4t_0$ (at larger energy, $2t_0 < \epsilon < J$, the SYK-like tails remain). Assuming that the two chemical potentials fall within this central band, $|\mu_{u,d}| < 2t_0$, the calculations of the drag conductance that are outlined in the Supplemental Material [48] result in

$$\sigma_{\mathrm{Drag}}^{\mathrm{FL}} \propto N \frac{V^2}{J^2} \frac{T^2}{T_0^2} \mathcal{E}_u \mathcal{E}_d. \tag{7}$$

Meanwhile, the intralayer conductance in the FL regime is independent of temperature, $\sigma^{\mathrm{FL}} = (e^2/\pi h)N$. Therefore, the resulting drag resistance is given by

$$\rho_{\mathrm{Drag}}^{\mathrm{FL}} \approx \frac{C^{\mathrm{FL}}}{N} \frac{h}{e^2} \frac{V^2}{J^2} \frac{T^2}{T_0^2} \mathcal{E}_u \mathcal{E}_d, \tag{8}$$

where $C^{\mathrm{FL}} \approx 429.2$ (for a detailed derivation of these results, see the Supplemental Material [48]).

We conclude that the overall temperature dependence of the drag resistance rises as $\sim T^2$ at low temperatures in the Fermi liquid regime and saturates to a temperature independent value at high temperatures in the SM regime. The drag resistances given by Eqs. (6), (8) become comparable in the range of temperature $T \sim T_0 = t_0^2/J$ that marks the crossover between the Fermi-liquid and SM regimes. Since the numerical coefficient by the drag resistance in the Fermi liquid regime Eq. (8) is larger than the one in the SM regime Eq. (6), the estimation of the drag resistance in the two regimes at $T = T_0$ gives $\rho_{\mathrm{Drag}}^{\mathrm{FL}}(T_0) > \rho_{\mathrm{Drag}}^{\mathrm{SM}}$, which suggests that the overall temperature dependence may exhibit a maximum at temperatures about T_0.

One may derive a phenomenological expression for the overall temperature dependence of the drag resistance based on the following physical picture. The energy spectrum in the tunnel-coupled SYK dots can be roughly separated into two regions. The states within the energy window of the order of the tunneling escape rate $T_0 = t_0^2/J$ form a quasi-Fermi liquid, contributing to the drag resistance according to Eq. (8). On the other hand, the energy states beyond the energy window of T_0 form the strange metal, leading to the drag resistance as given by Eq. (6). Both parts of the spectrum constitute the two liquids, contributing in parallel to the overall resistance. Since the high-energy states' population necessitates their thermal activation, the two liquids' contributions should be weighted by their corresponding thermal activation probabilities, resulting in the following expression for the inverse resistance:

$$\frac{1}{\rho_{\mathrm{Drag}}} = \frac{1 - e^{-T_0/T}}{\rho_{\mathrm{Drag}}^{\mathrm{FL}}} + \frac{e^{-T_0/T}}{\rho_{\mathrm{Drag}}^{\mathrm{SM}}}. \tag{9}$$

Qualitative temperature dependence of the drag resistance is shown in Fig. 3. It is important to note that the drag

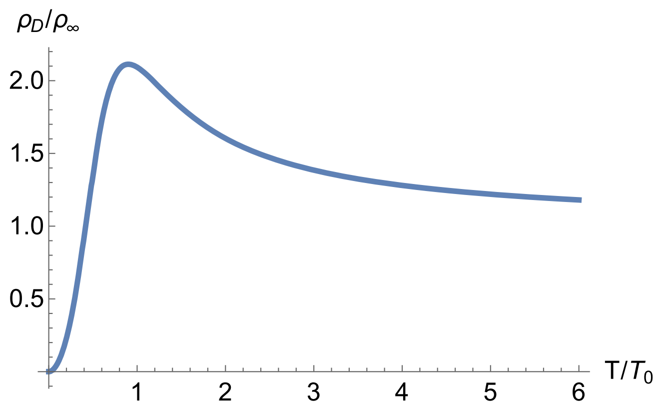

FIG. 3. Temperature dependence of the drag resistance (in units of the drag resistance at high temperature ρ_∞): the T^2 increase of resistance in the low temperature FL regime changes to saturation in the high temperature SM regime.

resistance calculation in the crossover regime necessitates exact form of the one-particle Green's functions of the tunnel-coupled SYK grains at the crossover temperature, which is currently unavailable to the best of our knowledge. Therefore, the question of whether the overall temperature dependence of the drag resistance exhibits a maximum remains open.

Consider now the near-field heat transfer conductance in the model described by Eqs. (1)–(4). In the lowest order of interaction, the near-field heat transfer flux J_h is given by the diagram shown in Fig. 2(c), leading to the following result for the heat conductance in the SM regime:

$$\varkappa^{\mathrm{SM}} = \frac{J_h}{\Delta T} = 0.015N\frac{V^2}{J^2}T, \tag{10}$$

where $T = (T_u + T_d)/2$, $\Delta T = T_u - T_d$, and we assume a small temperature difference $\Delta T \ll T$. Equation (10) shows that the near-field heat conductance $\varkappa^{\mathrm{SM}} = J_h/\Delta T$ is a linear function of temperature. The slope of the temperature dependence of the heat conductance is then directly related to the ratio V^2/J^2 characterizing the interaction strength in the SM regime. Therefore, one can relate the drag resistance and the heat conductance as follows

$$\rho^{\mathrm{SM}}_{\mathrm{Drag}} = \frac{A^{\mathrm{SM}}}{N^2}\frac{h}{e^2}\mathcal{E}_u\mathcal{E}_d\frac{d\varkappa^{\mathrm{SM}}}{dT}, \tag{11}$$

where the constant $A^{\mathrm{SM}} \approx 4980$. Equation (11) provides a universal relation between the results of two different experiments in the incoherent metal.

Remarkably, the same functional relation (11) between the drag resistance and the heat conductance holds in the Fermi liquid regime with a somewhat different numerical coefficient $A^{\mathrm{FL}} \approx 180$. Indeed, the corresponding heat conductance is known to be [48–51]

$$\varkappa^{\mathrm{FL}} = 0.8N\frac{V^2T^3}{t_0^4} = 0.8N\frac{V^2}{J^2}\frac{T^3}{T_0^2}. \tag{12}$$

Along with Eq. (8) this leads to Eq. (11) with the aforementioned A^{FL}.

In summary, we studied the nonlocal electrical and thermal transport in the interactively coupled double layers of two strange metals. Each layer is modeled by the Hamiltonian of tunnel-coupled SYK quantum dots. This model is known to capture the physics of strange metal phases in the proper regime of parameters. If the temperature is smaller than the characteristic scale set by intergrain tunneling and intragrain interaction, we recover the FL regime with the quadratic temperature dependence of drag resistivity [Eq. (8)]. In the temperature range above that scale, we find transresistance approaching the limiting value, Eq. (6), from above. The latter fact reflects the interplay of Planckian intralayer dissipation and interaction-mediated interlayer dragging. Results obtained for our microscopic model differ from the recent study of the drag between two strange metal layers using the Einstein-Maxwell-dilaton model from holography, which claims $\rho_{\mathrm{Drag}} \propto T^4$ [42]. Finally, we calculated near-field interlayer thermal conductance. The established relationship, Eq. (11), between drag resistance and the near-field heat conductance that is free of parameters of the considered model suggests the universality of this result.

We thank A. Patel for the communication regarding Ref. [35]. This work was supported by the National Science Foundation Grant No. DMR-2203411 and H. I. Romnes Faculty Fellowship provided by the University of Wisconsin-Madison Office of the Vice Chancellor for Research and Graduate Education with funding from the Wisconsin Alumni Research Foundation (A. L.). This work was partially supported by the Simons Foundation Targeted Grant for the Fine Theoretical Physics Institute. A. K. was supported by the NSF Grant No. DMR-2037654. A. C. thanks the Fine Theoretical Physics Institute at the University of Minnesota for hospitality.

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