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Flat band and Planckian metal

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We discuss the recent extension of the Sachdev-Ye-Kitaev (SYK) microscopic model¹, which demonstrates the characteristic features of the Khodel-Shaginyan fermion condensate² – the existence of the finite region of momenta, where the energy of electrons is exactly zero (the flat band). The microscopic derivation of the flat band in this interacting model supports the original idea of Khodel and Shaginyan based on the phenomenological approach. It also suggests that it is the flat band, which is responsible for the linear dependence of resistivity on temperature in "strange metals".

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Recently, in the paper "Theory of the Planck metal", Patel and Sachdev considered a model of interacting fermions which describes a Planckian metal at low temperatures, in order to explain the linear temperature dependence of their resistivity.¹ We show here that the proposed scenario actually describes the formation of the Khodel-Shaginyan fermion condensate² (the flat band). This supports the idea that the flat band is responsible for the linear dependence of resistivity on temperature in "strange metals".

There are different potential sources of the formation of the electronic flat band with zero energy, see e.g. Ref.³. In particular it can be formed due to electron-electron interaction. The flat band formed by interaction has been first discussed by Khodel and Shaginyan (KS) in 1990², who used the phenomenological Landau theory of Fermi liquid, see also⁴⁻⁷ and Fig. 1. This dispersionless energy spectrum has a singular density of states. As a result the superconducting gap and transition temperature are proportional to the coupling constant instead of the exponential suppression in conventional metals with Fermi surfaces. For nuclear systems the linear dependence of the superconducting gap on the coupling constant has been found by Belyaev⁸. In a more rigorous manner the flat band induced by interaction has been obtained in Refs.^{9,10}. Experimentally the merging of levels at the Fermi surface due to interaction has been reported in Refs.^{11,12}

In twisted bilayer graphene there is indication that interaction leads to the further flattening of the spectrum^{13,14} in addition to the geometrical/topological flattening caused by the magic angle twist^{15,16}.

In recent paper by Patel and Sachdev¹ the lattice extension of the Sachdev-Ye-Kitaev (SYK) model has been used to study the problem of the "bad metal" with the universal linear dependence of resistivity on temperature¹⁷⁻²⁰. However, it appears that signatures of the KS flat band in Figure 1 (*right panel*) are very similar to those in Figs. 2a and 3a from Patel and Sachdev (PS)¹. Indeed, Fig. 2a from the PS paper shows the occupancy $n(\mathbf{p})$, which exhibits the same behavior as $n(\mathbf{p})$ in Fig. 1 (*right panel*), with the finite region where $0 < n(\mathbf{p}) < 1$.

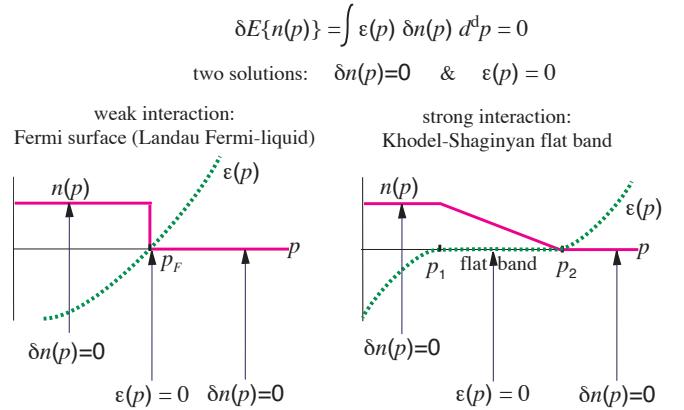


FIG. 1: Consequences of Landau theory of Fermi liquid. Variation of the energy functional over the occupancy $n(\mathbf{p})$ gives two possible solutions: $\epsilon(\mathbf{p}) = 0$ and $\delta n(\mathbf{p}) = 0$ ($n(\mathbf{p}) = 0$ or $n(\mathbf{p}) = 1$). *left*: The Landau Fermi liquid, where the solution $\epsilon(\mathbf{p}) = 0$ takes place on Fermi surface. Outside of Fermi surface one has either $n(\mathbf{p}) = 0$ or $n(\mathbf{p}) = 1$. *right*: Khodel-Shaginyan flat band, where the solution $\epsilon(\mathbf{p}) = 0$ takes place in the finite region of momentum space. In this region $0 < n(\mathbf{p}) < 1$.

According to Khodel-Shaginyan, in this region the quasi-particle energy should be zero. And this is clearly seen from the electron spectral density shown in Fig. 3a of the PS paper. So one may conclude that the extended SYK model provides another possible realization of the KS flat band.

That is why the extended SYK model can be used for studying different properties of the materials which experience formation of the KS flat band, including possibly the "bad metal" behavior. In this model, the universal linear dependence of resistivity on temperature has been obtained¹ in the regime, where the signatures of the flat band are transparent. From that one may conclude that the phenomenon of Planck metal or bad metal is the consequence of the Khodel-Shaginyan flat band emerging in this model. The idea that the flat band may serve as the origin of the "strange metal" behavior has been suggested

earlier, see e.g. Ref.²¹, and recent papers^{22,23}.

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