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Quantum limit in a quasi-one-dimensional conductor in a high tilted magnetic field

A. G. Lebed[1)]

Department of Physics, University of Arizona, AZ 85721, Tucson, USA

L.D. Landau Institute for Theoretical Physics RAS, 117334 Moscow, Russia

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Fermi-liquid theory has been successful in explanations of very unusual magnetic properties in quasi-one-dimensional (Q1D) conductors [1]. The first historically discovered such properties, the so-called Field-Induced Spin-Density-Waves and related 3D quantum Hall effect in Q1D conductors $(\mathrm{TMTSF})_2X$ ($X = \mathrm{ClO}_4$, PF_6, NO_3, etc.) [2, 3], were explained [1, 4–10] by studying peculiarities of semiclassical electron motion along open Q1D sheets of the Fermi surface and electron-hole interactions under such conditions. New concept, 3D $\rightarrow$ 2D dimensional crossover, was introduced [4] in the framework of Fermi-liquid approach. Extensions of this concept to different 3D $\rightarrow$ 1D $\rightarrow$ 2D crossovers in a tilted magnetic field allowed to explain such phenomena as the so-called Lebed's magic angles (LMA) and Lee–Naughton–Lebed's oscillations (see, for example, Ref. [11] and references therein). It is important that all the above mentioned physical phenomena happen in low enough magnetic fields, where the "sizes" of electron trajectories are less than inter-chain and inter-plane distances. Despite the above-described success, non-Fermi-liquid properties have been also studied both theoretically [12–15] and experimentally. For instance, there exist experimental claims that Fermi liquid cannot explain adequately the LMA phenomena in the Nernst [16–20] and Hall [21] effects.

An important step in studying magnetic properties of layered Q1D compounds was made in Ref. [21], where it was suggested that some other types of 3D $\rightarrow$ 2D crossovers – quantum dimensional crossovers – can occur in such compounds in high magnetic fields. It was shown [22] that, at high magnetic fields, the typical "sizes" of electron trajectories can become less than inter-layered distances in layered Q1D conductors, which results in the appearance of such unusual phenomenon as the Reentrant Superconductivity [22–24]. Different types of quantum 3D $\rightarrow$ 2D and 3D $\rightarrow$ 1D dimensional crossovers have been recently studied theoretically [25–28]. In particular, in Ref. [27], it was shown that, when strong magnetic field was applied far enough from the main crystallographic axes of a Q1D conductor, we have almost 1D electron spectrum and can expect non-Fermi-liquid behavior, whereas, for the magnetic field directions close to the main crystallographic axis, we have 2D electron spectrum and, thus, Fermi-liquid properties have to restore. On this basis, in Ref. [27], Fermi-liquid – non-Fermi-liquid angular crossovers were suggested to occur in a Q1D conductor in a high magnetic field and the critical magnetic field was estimated as $H \simeq 25\,\mathrm{T}$ in layered Q1D conductor $(\mathrm{Per})_2\mathrm{Pt}(\mathrm{mnt})_2$.

We pay attention that all previous considerations of the quantum dimensional crossovers [22–28] are based on quasi-classical version of the so-called Peierls substitution method [4, 1]. The goal of our paper is to solve a fully quantum mechanical problem for a Q1D geometry of electron spectrum in a perpendicular magnetic field. We show that at high magnetic fields electron wave functions indeed localize on the 1D conducting chains, unless the magnetic field is directed along one of the main crystallographic axes. If a magnetic field is directed along one of the axes, it is shown that electron wave functions are localized only on 2D planes. This property of electron wave functions confirms the hypothesis of Ref. [27] about possible angular Fermi-liquid – non-Fermi-liquid crossovers (or phase transitions).

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[1)]e-mail: lebed@email.arizona.edu

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