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Magnetic-field-driven quantum critical behavior in graphite and bismuth

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Abstract

We study magnetotransport properties of graphite and rhombohedral bismuth samples and found that in both materials applied magnetic field induces the metal–insulator- (MIT) and reentrant insulator–metal-type (IMT) transformations. The corresponding transition boundaries plotted on the magnetic field–temperature ($B-T$) plane nearly coincide for these semimetals and can be best described by power laws $T \sim (B-B_c)^{\kappa}$, where B_c is a critical field at $T=0$ and $\kappa = 0.45 \pm 0.05$. We show that insulator–metal–insulator (I–M–I) transformations take place in the Landau level quantization regime and illustrate how the IMT in quasi-3D graphite transforms into a cascade of I–M–I transitions, related to the quantum Hall effect in quasi-2D graphite samples. We discuss the possible coupling of superconducting and excitonic correlations with the observed phenomena, as well as signatures of quantum phase transitions associated with the M–I and I–M transformations.

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Nowadays, semimetals with a small carrier concentration and a small effective mass regained a broad scientific interest. In particular, recent experiments revealed the occurrence of the quantum Hall effect (QHE) as well as of Dirac fermions in both multi- [1–6] and single-layer [7,8] graphite (graphene) samples.

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From a wider perspective, graphite and other semimetals such as bismuth (Bi) are most suitable objects to study the behavior of the electronic matter in strong magnetic field. The magnetic field $B \geqslant B_{QL}$ applied to a bulk conductor pulls carriers into the lowest Landau level (LLL) which reduces their effective dimensionality from 3D to 1D and enhances fermion pairing instabilities towards an excitonic insulator [9], superconductor [10], spin- and charge-density wave (SDW and CDW) states [11,12], or Luttinger liquid state [13]. A magnetic-field-induced unconventional Fermi liquid which differs from both the Luttinger- and Landau-type has also been proposed [14].

Graphite and bismuth possess low densities of electrons (e) and holes (h); $N_e \sim N_h \sim 10^{17}\ \mathrm{cm}^{-3}$ in Bi [15], and $N_e \sim N_h \sim 10^{17} \cdots 10^{18}\ \mathrm{cm}^{-3}$ in graphite [16] with very small effective masses; $m^* \sim 10^{-3}$–$10^{-2} m_0$ [15,16], m_0 being the free electron mass. For light carriers, the quantum limit, for instance in graphite, can be reached at $B \geqslant \mu_0 H \sim 0.1$ T, and $B \equiv B_{QL} \approx 7$ T pulls all carriers into LLL [16]. The magnetic-field-driven CDW-like state has been observed in magnetoresistance measurements [17,18] for single crystalline graphite at $B \geqslant 20$ T, i.e. in the ultra-quantum limit. Indications for an excitonic phase in the quantum limit have been found in acoustic measurements of bismuth [19].

Recently, both magnetic-field-driven metal–insulator and reentrant insulator–metal transformations (MIT and IMT) have been measured in these semimetals at much lower fields ($\sim 0.1 \cdots 1$ T) by various groups [1,20,21]. The obtained results have been analyzed in terms of excitonic and superconducting instabilities [1] or using classical multi-band models [20,21]. Actually, observations of both QHE and Dirac-like spectrum in graphite [1–8] provide strong arguments against a classical treatment of the magnetotransport in this material.

On the other hand, it is expected [22–24] that electron–electron interaction and/or applied magnetic field induce the excitonic gap in graphite. Thus, the magnetic-field-driven metal–excitonic insulator transition in graphite is seen as the condensed-matter realization of the magnetic catalysis (MC) phenomenon known in relativistic theories of (2+1)-dimensional Dirac fermions [25].

The very small effective mass of carriers in bismuth ($\sim 0.001 m_0$ [15]) implies that these may be considered as Dirac-like fermions in 3+1 dimensions. Because of the effective dimensional reduction in the quantized field, MC phenomenon is expected to occur in 3+1 dimensions as well [26]. Hence, the underlying physics in bismuth and graphite may not be so different. The reduced dimensionality of bismuth (3D → 2D) due to surface effects [27,28] suggests even more close analogy between these materials.

If the Landau level quantization and the related quantum phenomena dominate the metal–insulator and insulator–metal transformations, one expects a quite similar or even universal (magneto)transport properties of bismuth and graphite in spite of their quite different electronic band structures. Hence, a comparative study of these materials can be a "smoking gun" proof of one or another approach.

Here, we present the results of magnetoresistance and Hall effect measurements performed on rhombohedral Bi and graphite. The results demonstrate the occurrence of magnetic-field-driven MIT and reentrant insulator–metal transitions in both materials. The corresponding transition boundaries plotted on the magnetic field–temperature ($B - T$) plane nearly coincide and can be best described by dependencies $T \sim (B - B_c)^{\kappa}$ with $\kappa = 0.45 \pm 0.05$. Such power laws usually appear in the scaling theory of quantum phase transitions (QPT) [29]. In our case, this would imply the existence of two zero-temperature critical fields $B_c^{IMT} > B_c^{MIT}$. On the other hand, it is also found that the two-parameter