Dirac cones, from graphene to cold atoms

Gilles Montambaux*[1]

[1]Laboratoire de Physique des Solides (LPS) – CNRS : UMR8502, Université Paris XI - Paris Sud – Bat.
510 91405 Orsay cedex, France

Abstract

Gilles Montambaux
Laboratoire de Physique des Solides, CNRS UMR 8502, Université Paris-Sud, F-91405 Orsay, France

gilles.montambaux@u-psud.fr

The so many fascinating properties of graphene, like the massless propagation of the electrons, are the subject of an intense research activity. On the other hand there is a growing interest for the study of "artificial graphenes", that is totally different and new systems which bear exciting similarities with graphene, among them: lattices of ultracold atoms, photonic lattices or "molecular graphene". The advantage of these artificial structures is that they serve as new playgrounds for measuring and testing physical phenomena which may not be reachable in graphene. In particular the possibility of controlling the position of the pair of Dirac points (or Dirac cones) existing in the electronic spectrum of graphene.

These cones, which describe the band structure in the vicinity of the two connected energy bands, are characterized by a topological "charge", that is essentially the Berry phase. The cones can be moved in reciprocal space by appropriate modification of external parameters (pressure, twist, sliding, stress, etc.). They can be manipulated, created or suppressed under the condition that the total topological charge be conserved. The merging between two Dirac cones is thus a topological transition that may be described by two distinct universality classes, according to whether the two cones have opposite or like topological charges [1,2]. At the merging between two Dirac cones of opposite charges, the spectrum is quite surprising: the electrons stay massless along one direction like in graphene, but they become massive in the opposite direction. This hybrid (also called semi-Dirac) regime cannot be reached experimentally in a graphene sheet, since it is impossible to deform it sufficiently without tearing it apart.

Recently, an experimental team in Źurich realized an ultracold gas of atoms moving in a potential landscape designed by laser fields to realize a kind of 'artificial graphene' [3]. Atoms now play the role of electrons and laser fields that of the crystalline lattice. This artificial graphene can be manipulated and deformed at will. Using this trick, the experimentalists managed to reach the required limit to observe the merging transition. By accelerating the atoms and measuring their evolution from low to high energy states (i.e. from the valence band to the conduction band), it is possible to follow the scenario of the merging transition.

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*Speaker

We have given a complete explanation of these experiments thanks to a model developed in our group [4]. We were able to compute the probability for an atom to get transferred from one band to the other as a function of the direction of acceleration. Thus we could confirm the proposed merging scenario [1,2]. More recently we have studied particularly the situation where atoms are accelerated along the axis of the two Dirac cones and experience two Landau-Zener transitions in a row. In this case, we expect the possibility of quantum interferences in momentum space leading to the yet to be observed St’uckelberg oscillations [4].

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