Artificial graphenes

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 (Fig.1). 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 Zürich 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 to follow the scenario of the merging transition (Fig.2).

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 Stückelberg oscillations [4].

Fascinating properties of graphene can also be simulated with a novel setup where cm-size cylindrical plastic dots replace carbon atoms and microwaves replace the electrons (Fig.3). The recipe is simple: take a few hundred dots sandwiched between two metal plates and arrange them in a honeycomb lattice like the carbon atoms in graphene. Then let a radio wave propagate through this artificial crystal. This new setup realizes a microwave analog simulator of the quantum propagation of electrons in graphene.

The experimental setup permits a perfect control of the lattice. The distance between the dots fixes the intensity of the electromagnetic coupling. The configuration of the edges, well-known to play an important role in graphene but difficult to control, is quite easy to modify here. The density of electromagnetic modes of this "microwaves graphene" presents the expected conic structure in the vicinity of a « Dirac point ». It is possible to measure, for each mode, the spatial repartition of the microwave field. In the isotropic configuration, there are no edges states along armchair edges, as expected. When a strain is applied along a crystallographic axis, the density of modes changes near the Dirac points, and beyond a critical frequency, a gap appears in the density of modes. The strain also induces novel exotic edge states whose localization along the edges increases with the strain (Fig.4), as predicted [6]. The future studies will address the structure of the edge states for more complex deformations. Moreover with an inhomogeneous strain, it is possible to simulate effects similar to those of artificial gauge fields.

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References

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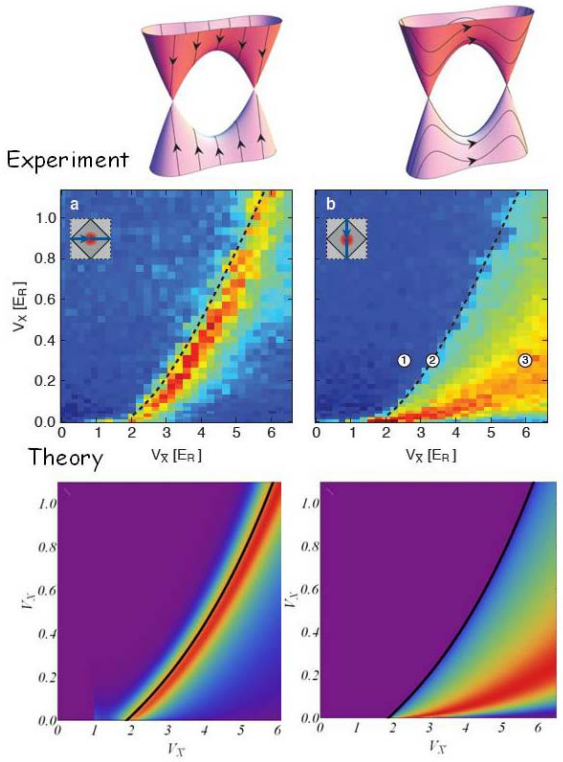
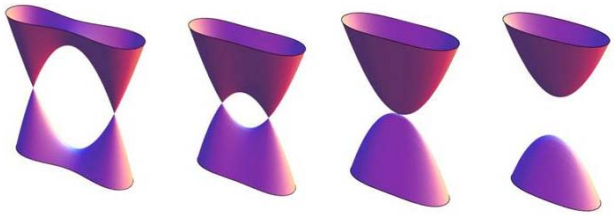
Figures

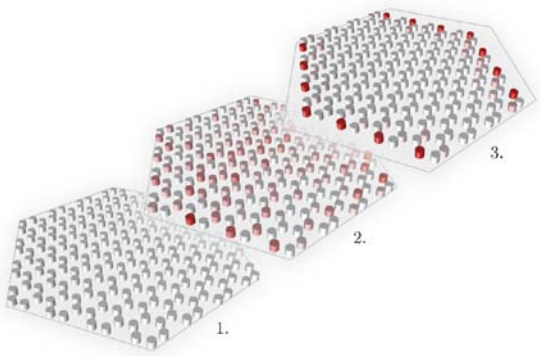
(2) Fraction of atoms transferred in the upper band as a function of the optical lattice parameters (max is red) for atoms accelerated along the direction perpendicular (left) or parallel (right) to the axis relating the two cones. The experimental results of [3] are shown in the upper figure and the results of our theory [4] for the merging of Dirac points are plotted in the lower figures.





(1) The scenario for the merging of a pair of Dirac points is universal [1,2]

(3) Lattice of dielectric dots.



(4) *New states appear along the armchair edges when the honeycomb lattice is compressed.*