Synthetic Metals 210 (2015) 9–18

Contents lists available at ScienceDirect

Synthetic Metals

journal homepage: www.elsevier.com/locate/synmet

Spontaneous chiral symmetry breaking in bilayer graphene

Fan Zhang

Department of Physics, University of Texas at Dallas, Richardson, TX 75080, USA

ARTICLE INFO

Article history:
Received 9 February 2015
Received in revised form 18 July 2015
Accepted 20 July 2015
Available online 19 August 2015

Keywords:
Bilayer graphene
Rhombohedral stacking
Electron–electron interaction
Spontaneous symmetry breaking
Topological state
Hall conductivity

ABSTRACT

Bilayer graphene and its thicker cousins with Rhombohedral stacking have attracted considerable attention because of their susceptibility to a variety of broken chiral symmetry states. Due to large density-of-states and quantized Berry phases near their gapless band touching points, each spin-valley flavor spontaneously transfers charge between layers to yield opening of energy gaps in quasiparticle spectra and spreading of momentum-space Berry curvatures. In this article we review the development of theories that predicted such chiral symmetry breaking and classified the possible topological many-body ground states, and the observations in recent experiments that are in reasonable agreement with these theories.

1. Introduction to chiral graphene

Success in exfoliating monolayer and few-layer graphene sheets from bulk graphite, combined with progress in their epitaxial growth, has opened up a rich new topic in two-dimensional electron systems (2DES) [1]. Graphene 2DES are remarkable for several different reasons. The fact that they are truly two dimensional on an atomic length scale elevates 2DES physics from the low-temperature world to the room-temperature world. Furthermore, they are accurately described by very simple models over very wide energy ranges and yet have electronic properties that can be qualitatively altered simply by stacking them in different arrangements, and by adjusting external gate voltages or magnetic fields. Lastly but not the least, it is relatively easy to access graphene samples and to purify them, which practically promotes the experimental examinations of fascinating theories on graphene 2DES.

The basic building block of all graphene 2DES is the isolated monolayer, which is described by a massless Dirac $\boldsymbol{k}\cdot\boldsymbol{p}$ Hamiltonian over a wide energy range [1]. Special for graphene, the Dirac model is massless, with two Weyl points [2] of opposite chiralities located at valley K and K', i.e., the two inequivalent Brillouin zone corners. The massless Dirac model has linear dispersions and chiral quasiparticles, and in the graphene case the chirality refers to the alignment between the direction of $\boldsymbol{k}\cdot\boldsymbol{p}$ momentum and the direction of pseudospin associated with the A/B sublattice degree-of-freedom of graphene's honeycomb lattice. Intriguingly, the two Weyl points at valley K and K' are protected by the translational symmetry, a chiral symmetry, and a Berry phase $\pm\pi$. We will elaborate more on these two features below.

When N honeycomb graphene layers are stacked, electronic properties are strongly modified in a way that is controlled by the specific stacking arrangement [1]. It turns out that among all the stacking possibilities, only the Rhombohedral (ABC or chiral) arrangement [3–5] inherits and extends the most interesting features of monolayer graphene, as we now explain [5]. (i) There are two low energy sublattice sites, as the other sublattice site energies are repelled from the Fermi level by the interlayer hopping γ_1 and thus irrelevant at low energies, as shown in Fig. 1. This suggests that a two-band model provides a useful tool to describe the long-wavelength physics. (ii) The low-energy sublattice sites are localized in the outermost layers, at A_1 and B_N, and can be separated energetically by an electric field perpendicular to the film. (iii) Hopping between low-energy sites via high-energy states is an N-step process which leads to $\pm p^N$ dispersions in conduction and valence bands, and sublattice pseudospin chirality N (or Berry phase $N\pi$). (iv) The low-energy bands are increasingly flat for larger N, at least when weak remote hopping processes are neglected, and the opportunity for interesting interaction and disorder physics is therefore stronger. Consequently, in the simplified chiral model, the density-of-states $\nu(E)\sim E^{(2-N)/N}$ diverges as E approaches zero for $N>2$ whereas it remains finite for $N=2$ and vanishes for $N=1$ (these properties also have some relevance to more general stacking arrangements since the low-energy Hamiltonian of a multilayer with any type of stacking can always be chiral-decomposed [3] to a

E-mail address: zhang@utdallas.edu

http://dx.doi.org/10.1016/j.synthmet.2015.07.028
0379-6779/

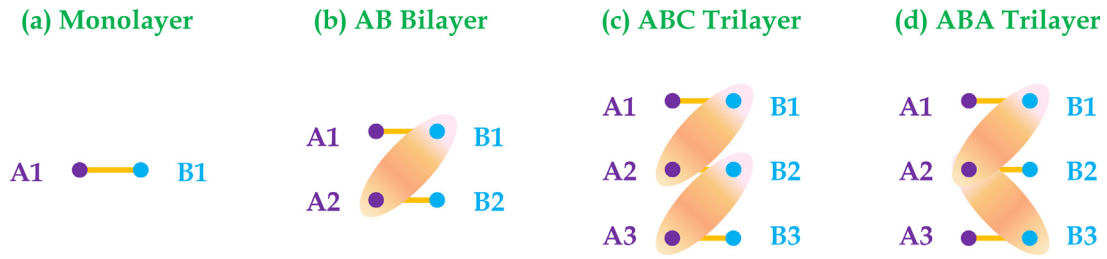

Fig. 1. Schematic electronic unit-cell structures of few-layer graphene. (a)–(c) Rhombohedral (ABC) stacked graphene layers. The sublattices coupled by the strongest interlayer bonds characterized by the vertical γ_1 hopping parameter are indicated by shading and have little weight in the low-energy effective states. Both the monolayer and the bilayer can be viewed as either Rhombohedral (ABC) or Bernal (AB) stacked graphene. (d) Bernal (ABA) stacked trilayer graphene for comparison. Figures adapted from Ref. [6]. The corresponding real-space stacking structures can be found in Ref. [1].

direct sum of ABC-stacked layers. Monolayer and bilayer graphene can be viewed as ABC-stacked few-layers with $N=1$ and $N=2$, respectively).

We refer the family of ABC-stacked N-layer graphene collectively as the chiral 2DES. It follows the properties (i)–(iv) that the electronic properties of N-layer chiral 2DES can be well described by $\mathbf{k}\cdot\mathbf{p}$ band Hamiltonians [4,5]

$$H_N = \frac{(v_0 p)^N}{(-\gamma_1)^{N-1}}[\cos(N\phi_{\boldsymbol{p}})\sigma_x + \sin(N\phi_{\boldsymbol{p}})\sigma_y]. \quad (1)$$

We have used the notation $\cos\phi_{\boldsymbol{p}} = \tau_z p_x/p$ and $\sin\phi_{\boldsymbol{p}} = p_y/p$ where $\tau_z = \pm 1$ labels K and K' valleys. The Pauli matrices $\boldsymbol{\sigma}$ act on a pseudospin degree-of-freedom, i.e., the two low-energy sublattices A_1 and B_N. We choose the positive and negative eigenstates of σ_z to denote B_N (bottom layer) and A_1 (top layer), respectively. The Pauli matrices $\boldsymbol{s}$ will be reserved to denote the electron spin. $v_0 \sim 10^6$ m/s is the Fermi velocity in graphene, and $\gamma_1 \sim 0.4$ eV is the nearest neighbor interlayer hopping energy. Neutral chiral 2DES with $N>1$ has been proved to be fertile ground for new many-body physics [5–7]. Because of the large density-of-states and the $N\pi$ Berry phases near low energy band-contact points, such 2DES at zero external fields are susceptible to chiral symmetry breaking, leading to a family of gapped spontaneous quantum Hall states distinguished by valley and spin dependent quantized Hall conductivities [7]. In these states, each spin-valley flavor spontaneously transfers charge between layers [7–10]. Particularly in high mobility suspended bilayers [11], reproducible experimental observations [12–19] are in reasonable agreement with original theoretical predictions [7–10], both of which will be reviewed in this article.

2. Semimetals with protected Fermi points

Notably, the Fermi surface consists of two band touching points at K and K' for charge neutral chiral 2DES, which are indeed protected. As implied by Eq. (1), the layer pseudospin rotates N times faster than the momentum orientation angle. This amounts to acquiring a Berry phase $N\pi$ when a quasiparticle circles one of the band-contact points once [4,5]. The Berry phases are opposite for electron and hole bands, and for K and K' valleys. The quantization of Berry phase, instead of being accidental, is directly dictated by the following chiral (sublattice) symmetry [20,21]

$$\{H_N, \sigma_z\} = 0. \quad (2)$$

This chiral symmetry requires that at any momentum $\boldsymbol{p}$ a state with energy E must have a partner state with energy $-E$. The gapless band-contact nature of the spectra of Hamiltonians (1) is protected by the chiral symmetry, since any loop enclosing one band touching point has a nontrivial Berry phase $\pm N\pi$ (a topological winding number N) and is thus not contractible. One can always redefine the zero energy at each $\boldsymbol{p}$ to respect the chiral symmetry if a $h(\boldsymbol{p})\sigma_0$ term is introduced to Eq. (1). In this case, at each $\boldsymbol{p}$ the eigenstates do not alter and the Berry connection remains the same. The chiral symmetry is also robust to any perturbation proportional to $\sigma_{x,y}$. A notable example is the trigonal warping effect [4,5,22,23], in which the additional $\sigma_{x,y}$ terms, instead of gapping a spectrum, only split a band-contact point with Berry phase $N\pi$ into Weyl points with Berry phase $\pm\pi$ each and $N\pi$ in total [23].

However, the chiral symmetry is broken and the energy spectrum acquires a gap ($2m$ at $\boldsymbol{p}=0$) in the presence of a $m\sigma_z$ term [23]. In this case, at each $\boldsymbol{p}$ the eigenstates becomes pseudospin polarized and the two monopoles at $\boldsymbol{p}=0$ spread out near the two valley centers, producing substantial momentum-space Berry curvatures. Of course, even in the presence of the chiral symmetry, the band-contact points can be gapped out, if gauge symmetry or translational symmetry are broken. As two examples, a superconducting gap may open when a chiral 2DES is in proximity to a BCS superconductor substrate or electrode [24,25]; the K and K' valleys may couple to each other and become gapped in pair annihilation by Kekulé pattern of bond distortions [26,27]. Nevertheless, our focus will be the chiral symmetry breaking and spontaneous gap (mass) generation [7] that is driven by electron-electron interactions [8–10].

3. Spontaneous symmetry breaking

Because of the large density-of-states and the $N\pi$ Berry phases near low-energy band touching points, chiral 2DES with $N>1$ at zero external fields are strongly susceptible to broken symmetry states [7,28–31]. It is of interesting to determine whether the layer pseudospin orientations in model (1) will be driven out-of-plane or acquire an in-plane distortion in the presence of electron-electron interactions [8,32–35]. This amounts to asking for each spin-valley flavor whether the chiral symmetry or the rotational symmetry will be spontaneously broken. In this section we review perturbative renormalization group (PRG) analysis [9,28,29,32,36–46], in which lattice effects are completely ignored and the long-range of the Coulomb interaction is not treated explicitly. The continuum approach is strongly motivated by the low-density of strongly correlated electrons. The use of short-range interactions is crudely justified [44] by appealing to screening considerations, and arguing that the momentum-independent interaction parameters represent an average over the relevant portion of momentum space. Note that the length scale, related to the higher energy cutoff $\sim\gamma_1 = 400$ meV, is more than 10 times of the graphene lattice constant a. We therefore emphasize [44] that unlike the Hubbard model where the short-range interactions are the on-site repulsions, the short-range interactions approximation below correctly takes into account the long-range character of Coulomb interactions implicitly. In our view models in which interactions are cut off at atomic length scales [38,43], although technically interesting, are unlikely to be relevant to few-layer graphene.