Edge states at the boundary of hexagonal and Lieb lattices in a quantizing magnetic field

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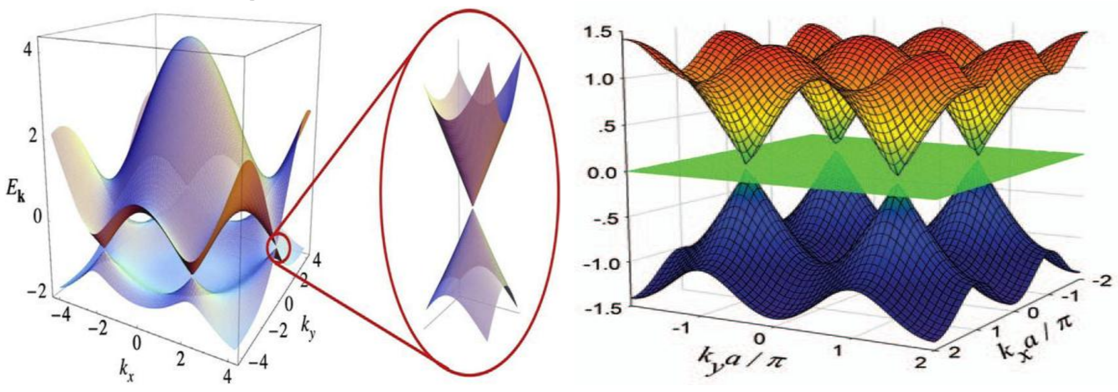
A boundary of two media with different topological order can be characterized by series of properties, the existence of which is protected. In the present work, the properties of such a boundary of two conductors are studied in a quantizing magnetic field: with charge carriers of the Dirac type and so-called spin-1 fermions, which are realized in graphene-like and Lieb lattices [1] respectively. Both lattices are characterized by the presence of a cone in the electron energy spectrum, the Klein paradox, but differ in Berry phase, which is equal to π in the graphene-like lattice, and trivial in the Lieb lattice. Which also attracts attention due to the presence of the flat band (Fig.1).



a. b.

Fig.1 *The electron energy spectrum of grapheme-like (a) and Lieb lattices.*

Problem formulation.

Let us consider the contact between the Lieb lattice and a graphene-like lattice, as shown in Fig. 2. within the standard nearest neighbor approximation for the electronic energy spectrum

$$E = \sum_{i,j} t_{i,j}\bar{\phi}_i\phi_j, \qquad (1)$$

where $t_{i,j} = t_L$ for Lieb lattice, $t_{i,j} = t_G$ for the graphene-like lattice, and $t_{i,j} = t_M$ between atoms of two types, the summation is carried out over all pairs of neighboring atoms, ϕ_i -- amplitude of the probability of finding an electron near a site i. The energy of edge states is considered positive and small enough so that deviations from the linearity of the energy spectrum can be neglected,

$$0 < E << t_{G,L,M}\ . \qquad (2)$$

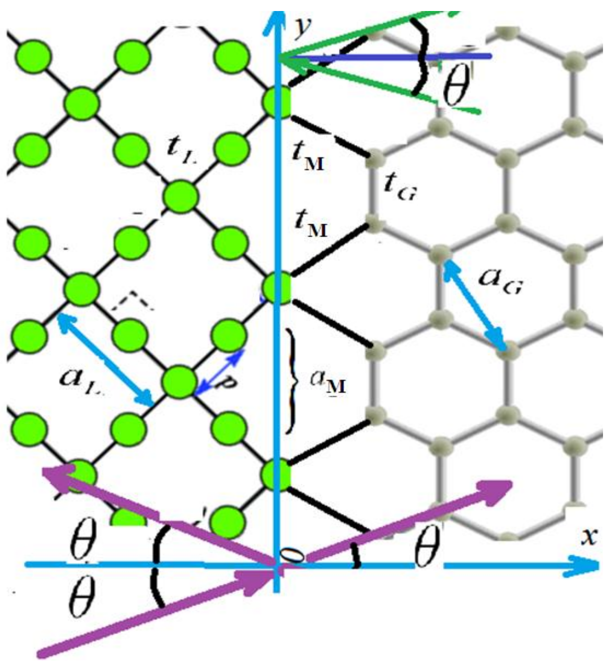
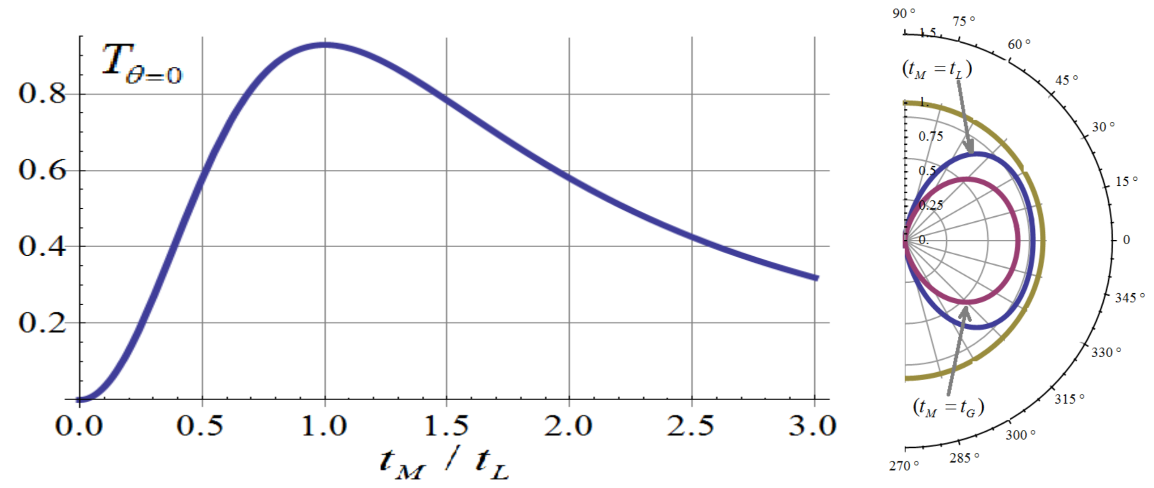


Fig.1 *The boundary of two lattices and some of their parameters.*

Results:

A transmission coefficient is calculated. Spin-nonconserving Klein tunneling cannot occur (Fig.3), in contrast to the model proposed in [2].



a. b.

Fig.3. *Dependence of the transmission coefficient on the overlap integral at normal incidence (a) and its angular dependence (b).*

It is shown that edge states arise that join the properties of conductors to the trivial and nontrivial Berry phase. The energy of edge states is calculated numerically.

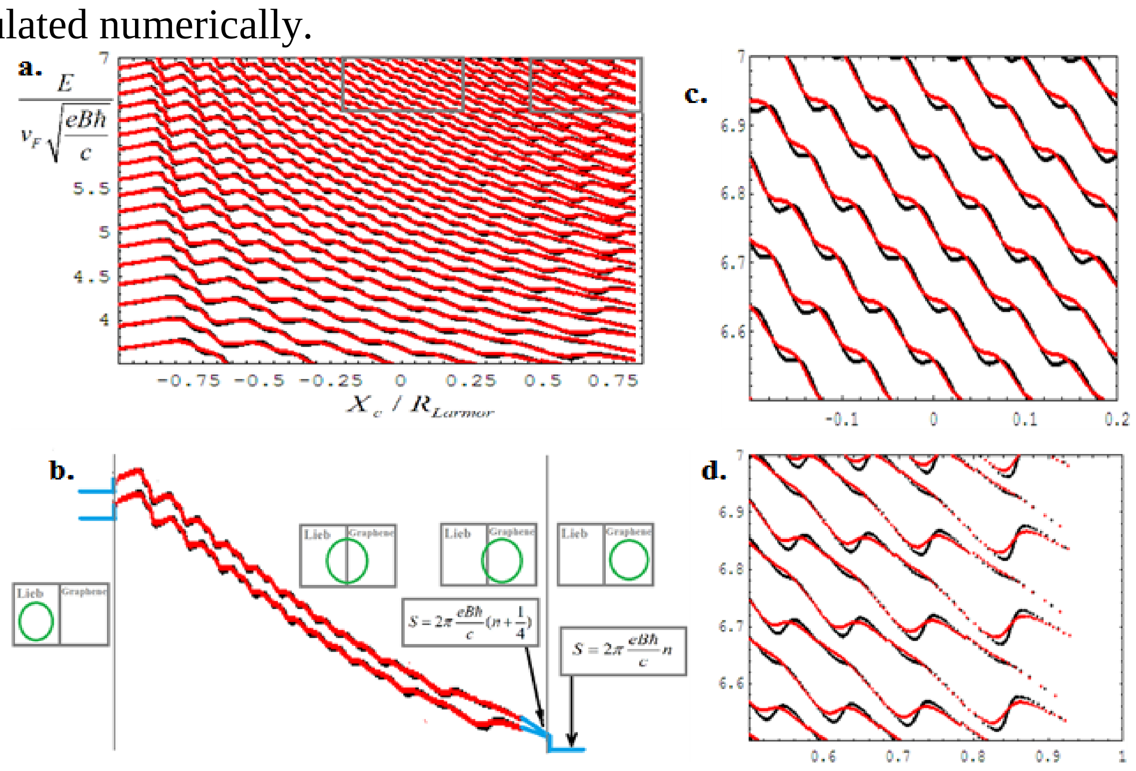


Fig.4. *The energy of the edge state as a function of the coordinate of its center (a) and the qualitative behavior of the dependence (b). Increased fragments (c,d).*

An analogue of the area quantization rule is obtained:

$$\tilde{S}_L = 2\pi n - \frac{\pi}{2} + 2Arg\left(\sqrt{3}\,(sin\theta + sin\tilde{S}_G) + cos\tilde{S}_G\, cos\theta + \frac{2i}{\sqrt{3}}\frac{t_L t_G}{t_M^2} cos\tilde{S}_G\, cos^2\theta\right), \qquad (3)$$

where where S_G and S_L are areas of segments of the edge state in the graphene-like lattice and the Lieb lattice respectively, $\tilde{S}_{L,G} = \frac{c}{|e|B\hbar} S_{p^2}^{L,G}$.

Asymptotic behavior of energy levels contains information about the influence of the Berry phase on edge states. It is thus easy to see that the increase in $S_{p^2}^G$ leads to an additional phase shift equal to the effect of the Berry phase, while for $S_{p^2}^L$ such there is none (Fig.5), illustrating the absence of a Berry phase in the Lieb lattice.

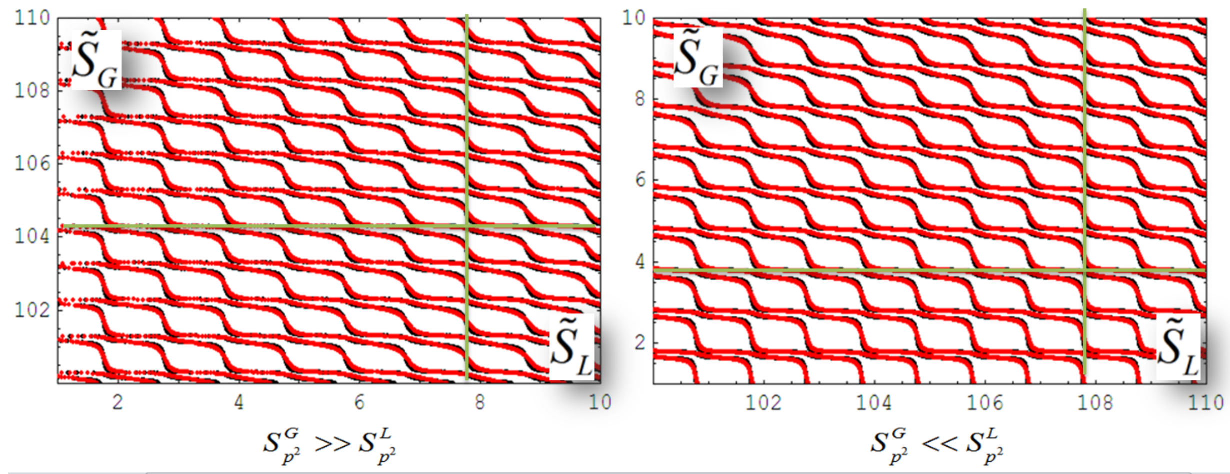


Fig.5. *Edge states for* $t_M = t_L$ *(red),* $t_M = t_G$ *(black) and asymptotics (green).*

Edge states lead to the appearance of a characteristic series of root singularities in the density of states $\nu(E)$, which are shown in the Fig.6.

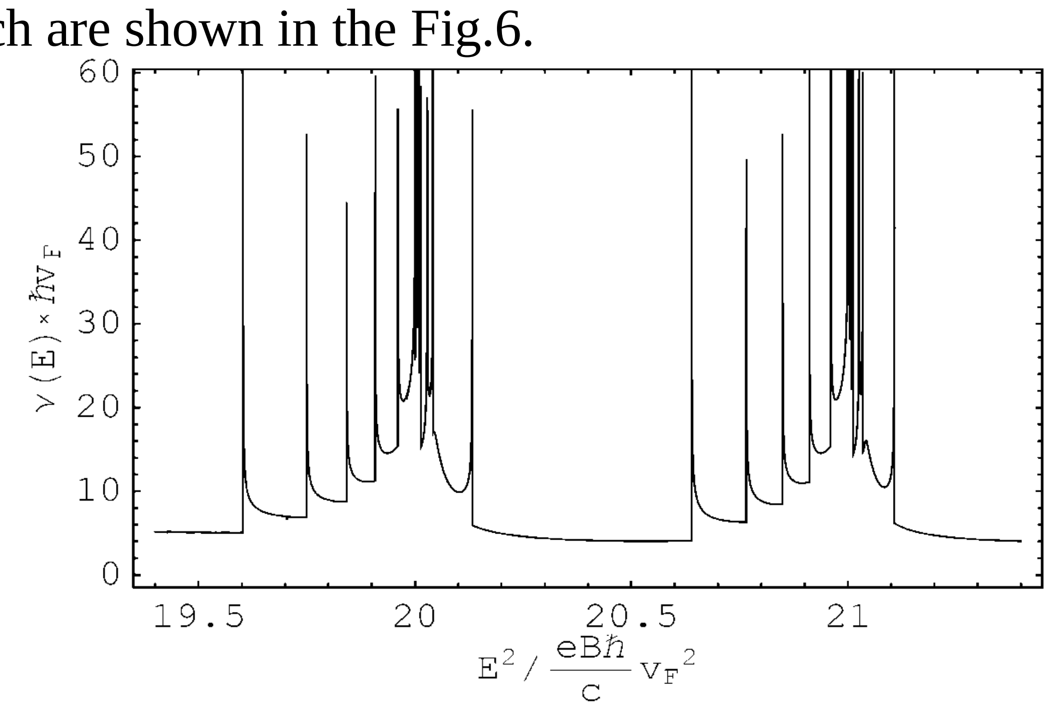


Fig.3. *Density of states.*

[1] Elliott H. Lieb, Phys. Rev. Lett. 62, 10, 1201 (1989). https://doi.org/10.1103/PhysRevLett.62.1927.5

[2] Luyang Wang and Dao-Xin Yao, Phys. Rev. B 98, 161403 (2018). https://doi.org/10.1103/PhysRevB.98.161403