H71.00197 Field-controlled transport of Dirac particles with elliptical dispersion

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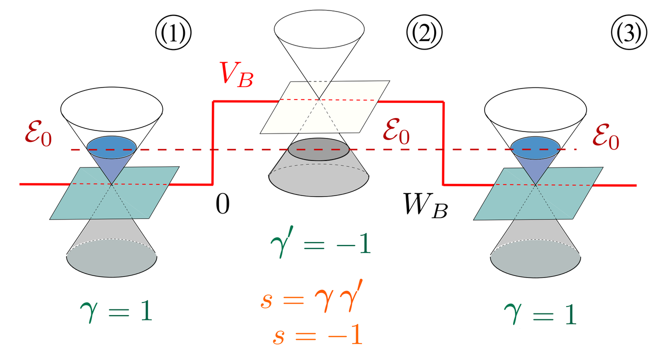
ABSTRACT

- investigate tunneling and transport properties of Dirac electrons dressed by a linearly-polarized, off-resonance, high-frequency dressing field
- employ Floquet-Magnus perturbation theory to obtain the energy dispersion relation and dressed electron wave functions
- illustrate how features of the anomalous Klein paradox, *i.e.*, a complete, asymmetrical electron transmission, which is independent on the barrier height or width, is modified by the anisotropic energy dispersion caused by the applied dressing field
- investigate the current strength and its dependence on the asymmetry introduced by Klein tunneling in graphene and dice lattice sheets
- predict a decrease in transmission current when the Klein transmission peak is located at a larger angle
- expect larger transmission current in the dice lattice than in graphene due to a much broader Klein tunneling peak in the former system
- anticipate useful transport properties for the design of electronic and optical devices and electronic lenses in ballistic-electron optics

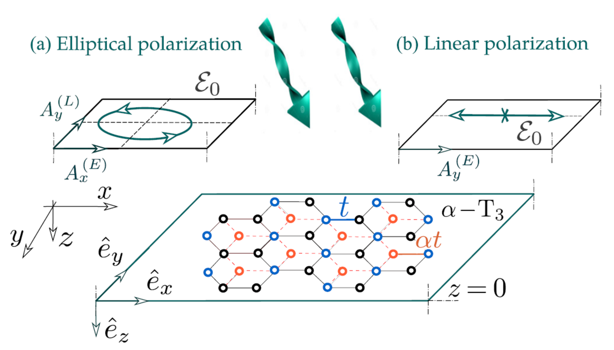
ELECTRON TUNNELING THROUGH A SQUARE POTENTIAL BARRIER

- an incident electron with kinetic energy $\mathcal{E}_0$ tunnels through a rectangular potential barrier
- barrier height V_B is chosen such that $0 < \mathcal{E}_0 < V_B$
- electron-hole-electron transitions occur between the two barrier edges $x = 0$ and $x = W_B$
- $\gamma = +1$ (or -1) refers to the Fermi energy located within the upper (lower) Dirac cone
- the unit of energy for $\mathcal{E}_0$ and V_B is the Fermi energy $E_F^{(0)}$
- the unit of length for W_B is $1/k_F^{(0)}$
- $k_F^{(0)} = \sqrt{\pi n_0}$ is the Fermi wave number
- $E_F^{(0)} = \hbar v_F k_F^{(0)}$ with v_F the Fermi velocity and n_0 the areal doping density



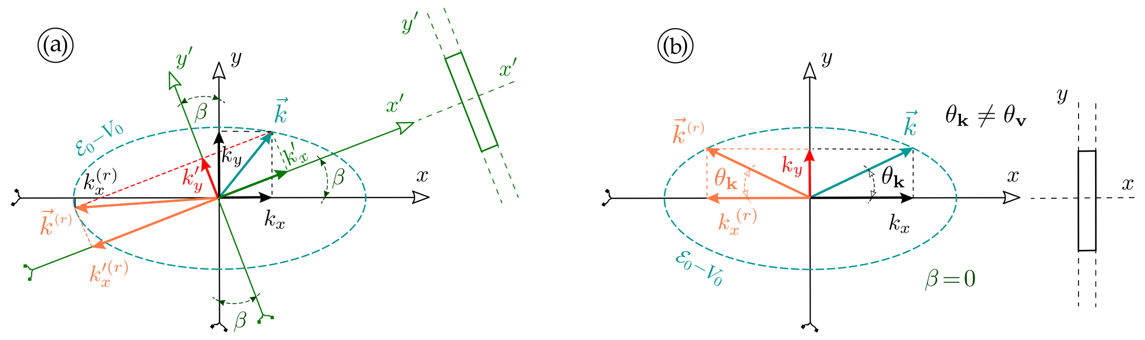
Rectangular potential barrier, $V(x) = V_B\,\Theta(x)\Theta(W_B - x)$, with $\Theta(x)$ the Heaviside unit step function.

PHOTON-DRESSED ELECTRONIC STATES



α-$\mathcal{T}_3$ lattice in the xy-plane irradiated with (a) elliptically and (b) linearly polarized off-resonance optical dressing fields. $\mathcal{E}_0$ is the amplitude of the incident light's electric field component.

- components of the wave vector $\boldsymbol{k}$ and anisotropic energy dispersion of an α-$\mathcal{T}_3$ lattice under linearly polarized irradiation
- frame $\{x, y\}$ is associated with the long-axis $\hat{\boldsymbol{x}}$ of elliptical energy dispersion
- frame $\{x', y'\}$ is associated with the normal-direction $\hat{\boldsymbol{x}}'$ to the potential barrier
- frames connected by an in-plane rotation angle β
- wave vector components $k_{x'}$ and $k_{y'}$ are given in the $\{x', y'\}$ frame since they are related to the direction of incoming electrons
- spinor angle $\theta_{\mathbf{s}}$ and group velocity angle $\theta_{\mathbf{v}}$ is defined in the $\{x, y\}$ frame, corresponding to the two axes of elliptical energy dispersion
- $\boldsymbol{v}_G$ and $\boldsymbol{k}$ are generally not aligned ($\theta_{\mathbf{k}} \neq \theta_{\mathbf{v}}$) and the panels (a), (b) correspond to $\beta \neq 0$ and $\beta = 0$



TRANSMISSION COEFFICIENT AND TUNNELING CONDUCTIVITY

- an approximate expression for the electron transmission through a high potential barrier $V_B \gg \mathcal{E}_0$ is

$$T_0\left(\mathcal{E}_0, \theta_{\mathbf{k}}^{(1)} \mid \beta = 0\right) \approx \frac{\cos^2 \theta_{\mathbf{k}}^{(1)}}{1 - \cos^2\left(k_x^{(2)} W_B\right)\, \sin^2 \theta_{\mathbf{k}}^{(1)}}$$

- Klein paradox with complete transmission and zero reflection is always present for head-on collisions, when $\theta_{\mathbf{k}}^{(1)} = 0$
- other resonances of unimpeded tunneling exist, corresponding to $k_x^{(2)} W_B = \pi \times$ integer
- secondary peak locations depend on the barrier width W_B and the longitudinal wave number $k_x^{(2)}$ within the barrier region
- the longitudinal wave number is determined by a relation connecting the kinetic energy $\mathcal{E}_0$ of incoming particles and the barrier height V_B
- the tunneling conductivity is

$$\sigma\left(\mathcal{E}_0, \theta_{\mathbf{k}}^{(1)} \mid \beta\right) = \frac{k_F W_B}{\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\theta_{\mathbf{v}} T_0\left(\mathcal{E}_0, \theta_{\mathbf{k}}^{(1)} \mid \theta_{\mathbf{v}}, \beta\right) \cos\left(\theta_{\mathbf{v}}\right)$$

DICE LATTICE WAVE FUNCTIONS IN THE SQUARE BARRIER REGION

- **Region 1**

$$\Psi_\gamma^{(1)}(\lambda_0, \boldsymbol{k}) = \frac{1}{4} \exp\left(ik_{x'}^{(1)} x'\right) \exp\left(ik_{y'}\, y'\right) \begin{bmatrix} e^{-i\theta_{\mathbf{s}}^{(1)}} \\ \sqrt{2}\,\gamma \\ e^{i\theta_{\mathbf{s}}^{(1)}} \end{bmatrix} + \frac{r}{4} \exp\left(ik_{x'}^{(1,r)} x'\right) \exp\left(ik_{y'}\, y'\right) \begin{bmatrix} e^{-i\theta_{\mathbf{s}}^{(1,r)}} \\ \sqrt{2}\,\gamma \\ e^{i\theta_{\mathbf{s}}^{(1,r)}} \end{bmatrix},$$

where $\gamma = +1$ for electrons and -1 for holes and $\theta_{\mathbf{s}}(\boldsymbol{k} \mid \lambda_0)$ is the spinor angle

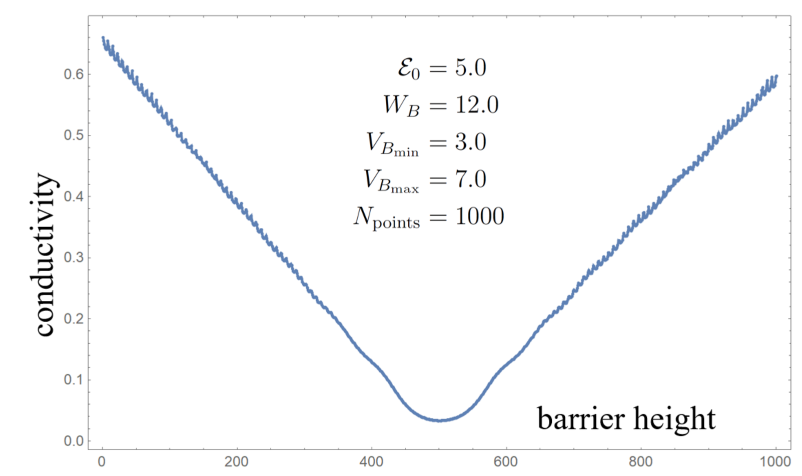
- **Region 2**

$$\Psi_{\gamma'}^{(2)}(\lambda_0, \boldsymbol{k}) = \frac{a}{4} \exp\left(ik_{x'}^{(2)} x'\right) \exp\left(ik_{y'} y'\right) \begin{bmatrix} e^{-i\theta_{\mathbf{s}}^{(2)}} \\ \sqrt{2}\,\gamma' \\ e^{i\theta_{\mathbf{s}}^{(2)}} \end{bmatrix} + \frac{b}{4} \exp\left(ik_{x'}^{(2,r)} x'\right) \exp\left(ik_{y'} y'\right) \begin{bmatrix} e^{-i\theta_{\mathbf{s}}^{(2,r)}} \\ \sqrt{2}\,\gamma' \\ e^{i\theta_{\mathbf{s}}^{(2,r)}} \end{bmatrix},$$

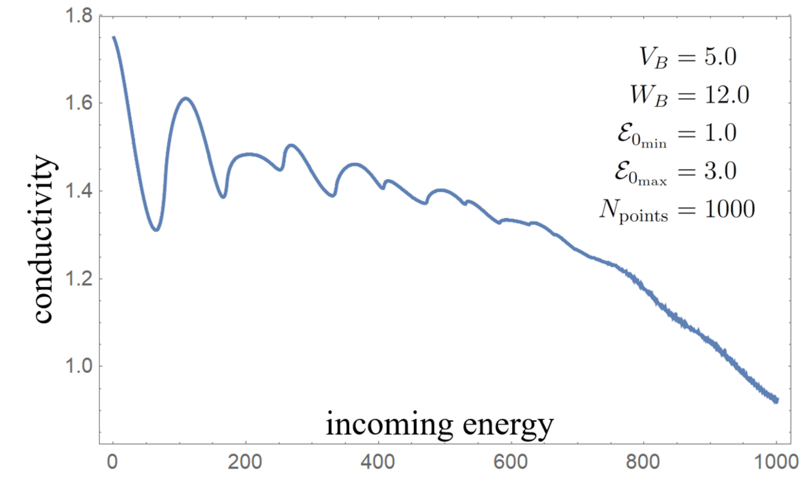
- **Region 3**

$$\Psi_\gamma^{(3)}(\lambda_0, \boldsymbol{k}) = \frac{t}{4} \exp\left(ik_{x'}^{(1)} x'\right) \exp\left(ik_{y'} y'\right) \begin{bmatrix} e^{-i\theta_{\mathbf{s}}^{(1)}} \\ \sqrt{2}\,\gamma \\ e^{i\theta_{\mathbf{s}}^{(1)}} \end{bmatrix}.$$

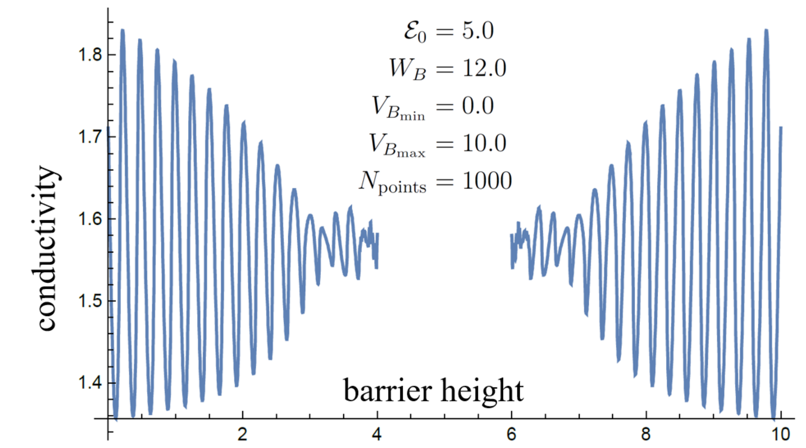
CURRENT VS. BARRIER HEIGHT AND CURRENT VS. INCOMING ENERGY



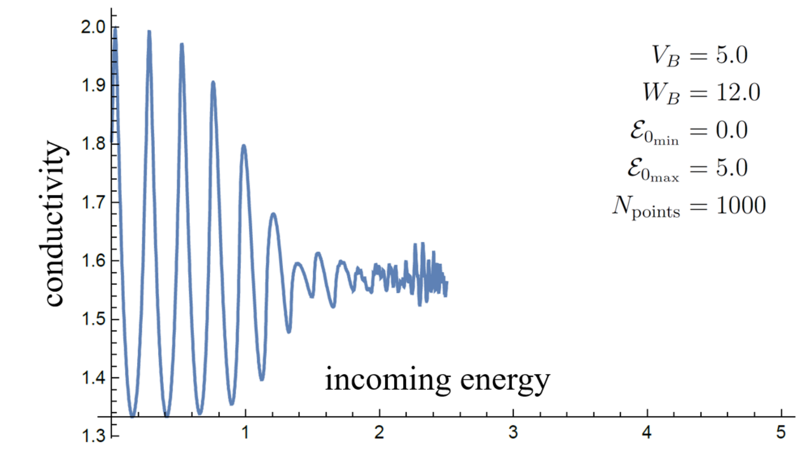
analytical result



analytical result



numerical result



numerical result

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