Landau levels with magnetic tunnelling in Weyl semimetals

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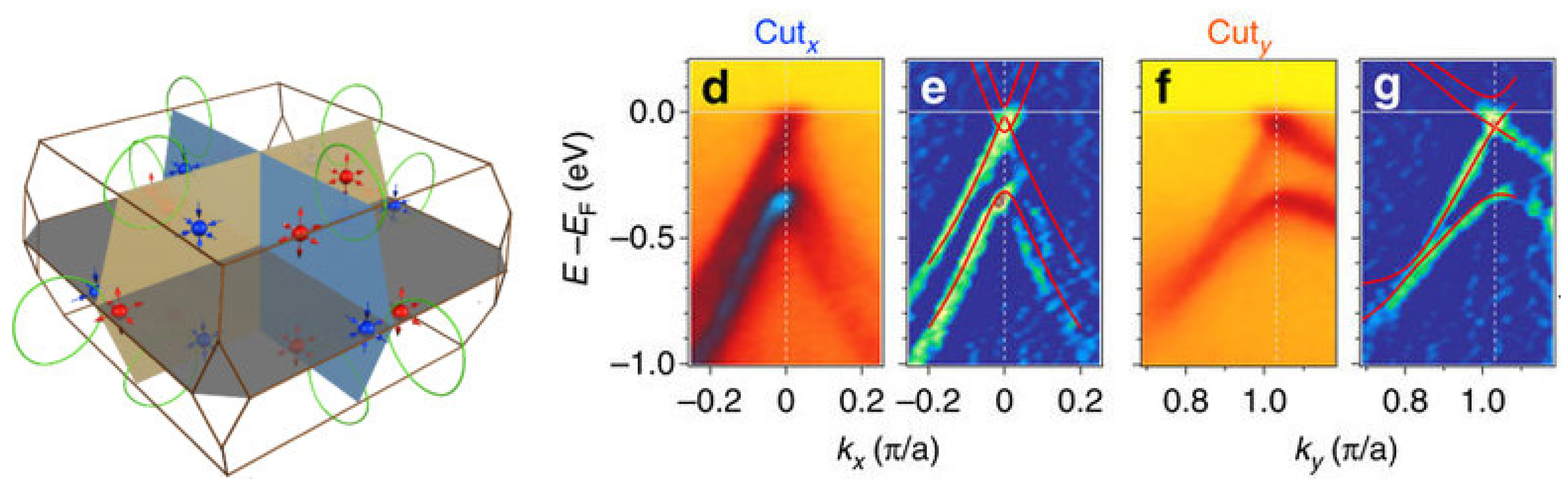
Abstract

We study [1] Landau levels (LLs) of Weyl semimetal (WSM) with two adjacent Weyl nodes. We consider different orientations $\eta = \angle(\mathbf{B}, \mathbf{k}_0)$ of magnetic field $\mathbf{B}$ with respect to $\mathbf{k}_0$, the vector of Weyl nodes splitting. Magnetic field facilitates the tunneling between the nodes giving rise to a gap in the transverse energy of the zeroth LL. We show how the spectrum is rearranged at different η and how this manifests itself in the change of behavior of differential magnetoconductance $dG(B)/dB$ of a ballistic p–n junction. Unlike the single-cone model where Klein tunneling reveals itself in positive $dG(B)/dB$, in the two-cone case $G(B)$ is non-monotonic with maximum at $B_c \propto \Phi_0 k_0^2/\ln(k_0 l_E)$ for large $k_0 l_E$, where $l_E = \sqrt{\hbar v/|e|E}$ with E for built in electric field and Φ_0 for magnetic flux quantum.

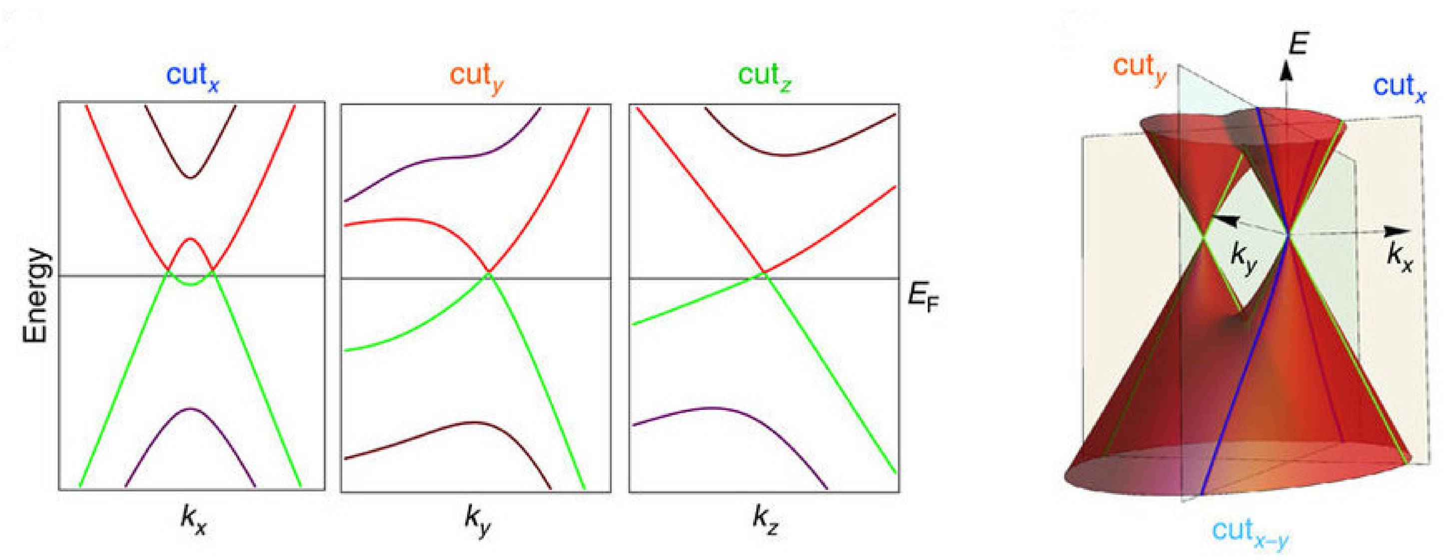
Weyl Semimetals and where to find them

The WSM state was first discovered in TaAs and TaP. First principle calculations [6] confirmed by later ARPES experiments [7] revealed that in both materials all Weyl nodes form a set of closely positioned pairs of opposite chirality in momentum space.



Usually Weyl points are considered separately [2], however, we propose to describe Weyl pair via generic [3] long-wave Hamiltonian (Δ — energy offset from chemical potential).

$$\hat{H} = \Delta + \frac{\hbar^2}{2m}\left(\hat{k}_x^2 - k_0^2\right)\sigma_x + \hbar v\left(\hat{k}_y\sigma_y + \hat{k}_z\sigma_z\right), \tag{1}$$



Landau levels

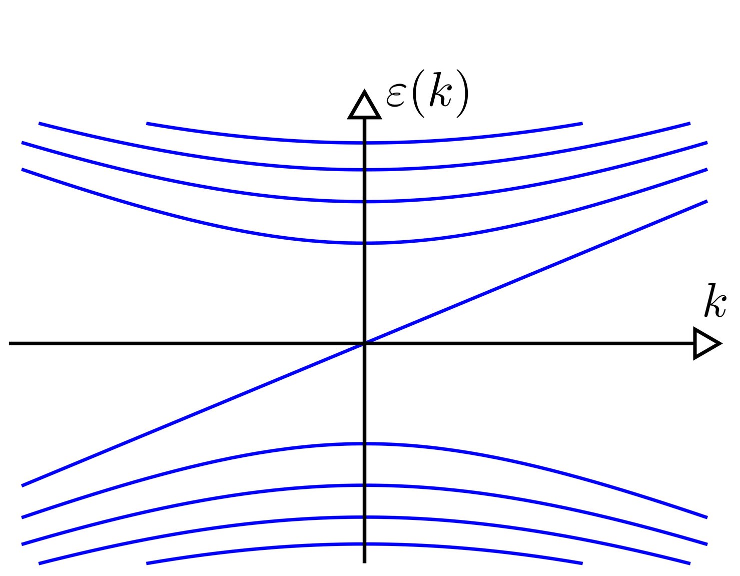
Single Weyl node in magnetic field

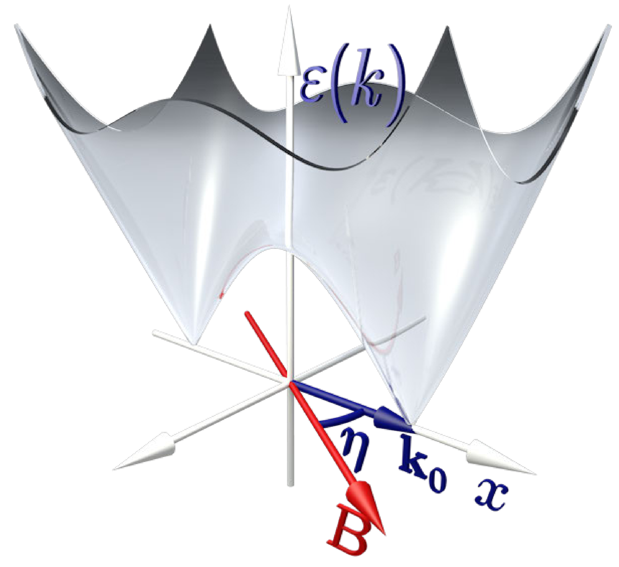
Weyl node's Hamiltonian in magnetic field $\mathbf{B} \parallel Oz$

$$\hat{H} = \hbar v\boldsymbol{\sigma}\cdot\left(\hat{\mathbf{k}} - \frac{e}{\hbar c}\mathbf{A}\right) \propto \begin{pmatrix} k_z & -y-\partial_y \\ -y+\partial_y & k_z \end{pmatrix}, \quad \mathbf{A} = (-By, 0, 0) \tag{2}$$

is solved via the combination of harmonic oscillator functions [2].

$$\chi_{n\neq 0} = \begin{pmatrix} c_n^{(1)}\psi^{osc}_{|n|}(y) \\ c_n^{(2)}\psi^{osc}_{|n|-1}(y) \end{pmatrix} \quad \chi_0 = \begin{pmatrix} \psi_0^{osc}(y) \\ 0 \end{pmatrix} \quad \begin{matrix} \varepsilon_{n\neq 0} = \hbar v\,\mathrm{sgn}(n)\sqrt{2|n|l_B^{-2} + k_z^2} \\ \varepsilon_0 = \hbar v k_z \end{matrix} \tag{3}$$





Weyl pair in magnetic field

For the direction of the magnetic field parallel to the node splitting $\mathbf{B} \parallel Ox$ Hamiltonian can be diagonalized analytically. Let me choose Landau gauge $\mathbf{A} = (0, 0, By)$ and substitute $\psi = \frac{1}{\sqrt{2}}(1 + i\sigma_y)e^{ik_x x + ik_z z}\chi(y)$.

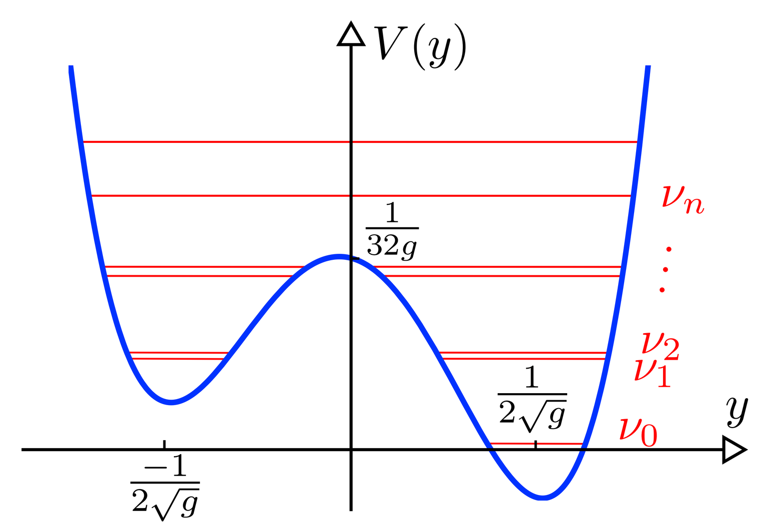
$$\frac{l_B}{\hbar v}\cdot\hat{H} = \frac{\hbar}{2ml_B}\left(k_0^2 - k_x^2\right)\sigma_z + \left(\hat{k}_y\sigma_y + (k_z - y)\sigma_x\right) \propto \begin{pmatrix} \frac{\hbar}{2mv}(k_0^2 - k_x^2) & yl_B^{-2} - \partial_y \\ yl_B^{-2} + \partial_y & \frac{\hbar}{2mv}(k_x^2 - k_0^2) \end{pmatrix}. \tag{4}$$

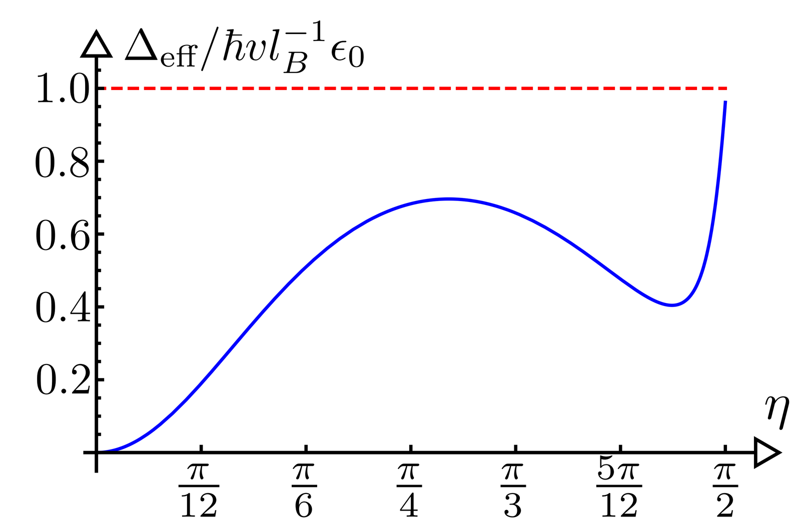
$$\chi_{n\neq 0} = \begin{pmatrix} c_n^{(1)}\psi^{osc}_{|n|-1}(y) \\ c_n^{(2)}\psi^{osc}_{|n|}(y) \end{pmatrix} \quad \chi_0 = \begin{pmatrix} 0 \\ \psi_0^{osc}(y) \end{pmatrix} \quad \begin{matrix} \varepsilon_{n\neq 0} = \hbar v\,\mathrm{sgn}(n)\sqrt{\frac{2|n|}{l_B^2} + \left(\frac{\hbar(k_z^2 - k_0^2)}{2mv}\right)^2} \\ \varepsilon_0 = \frac{\hbar^2}{2m}(k_0^2 - k_x^2). \end{matrix} \tag{5}$$

For the direction perpendicular to the node splitting $\mathbf{B} \parallel Oy$ eigenfuncitons are the solutions of Schrodinger equation in quartic tilted double–well potential.

$$\frac{l_B}{\hbar v}\hat{H} = W(y)\sigma_x + \left(\hat{k}_y\sigma_y + k_z\sigma_z\right) \propto \begin{pmatrix} k_z & W(y) - \partial_y \\ W(y) + \partial_y & k_z \end{pmatrix}, \quad W(y) = \frac{\hbar}{2ml_B}\left(y^2 - k_0^2\right). \tag{6}$$

$$\left[-\partial_y^2 + g\left(y^2 - \frac{1}{4g}\right)^2 \mp 2\sqrt{g}y\right]\chi_n^{1,2} = \frac{\varepsilon^2}{\zeta}\chi_n^{1,2}. \quad \begin{matrix} \zeta \equiv \hbar k_0/mv, \\ g^{-1} \equiv 4\zeta k_0^2 l_B^2 \end{matrix} \tag{7}$$



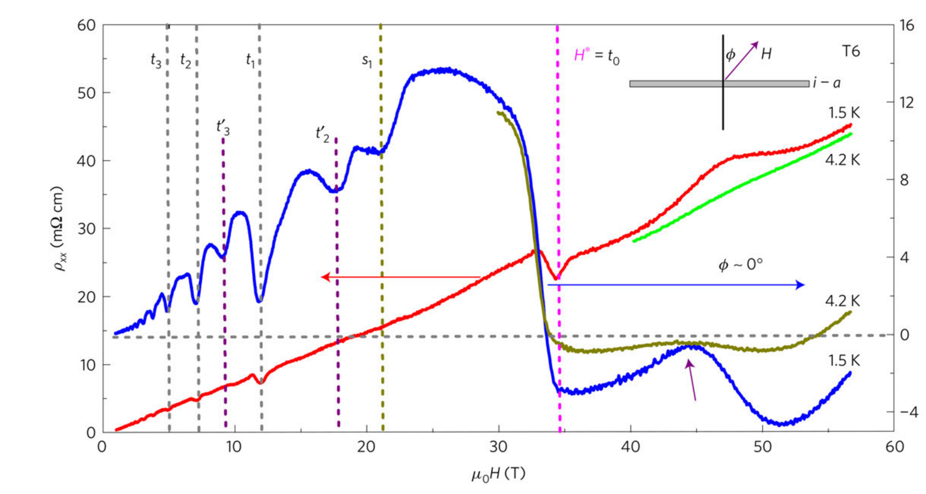


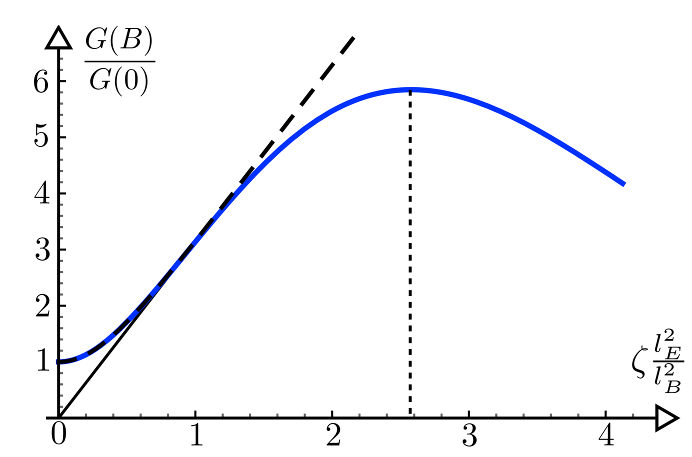
Such quasi–super–symmetric potential has a non–perturbative in magnetic field ground state energy, analytical expression for which is one of the main result of our work.

$$\varepsilon_0 = \frac{(\hbar k_0)^2}{m}\sqrt{\frac{B}{\pi B_0}}\exp\left(-\frac{2B_0}{3B}\right), \quad B_0 = \zeta\frac{\Phi_0 k_0^2}{\pi}, \tag{8}$$

Manifestations of the spectrum gap

The spectrum gap has been in the transport experiment (SdH oscillations) [4] and were independently found numerically [5]. The gap also manifests itself in the conductance of the ballistic p–n junction where instead of linear grow of the conductance with B as single–cone model predicts, $G(B)$ changes its behavior at fields $B_c \approx B_0/\ln(k_0 l_E)$ with magnitude of order 10 T for TaAs, TaP.





Main Results

- Landau levels of realistic WSM pair model are studied. Spectrum descriptions for $\angle(\mathbf{B}, \mathbf{k}) = 0, \frac{\pi}{2}$ are found analytically and numerical dispersion $\varepsilon(k)$ dependencies for arbitrary angles are presented.
- Non–perturbative eigenvalue problem for quartic tilted quasi–super–symmetric potential is solved via enhanced semiclassical method.
- The problems of ballistic magnetoconductance of p–n junction for $\mathbf{E} \parallel \mathbf{B} \perp \mathbf{k}_0$ is solved. Qualitatively new result for $G(B)$ dependence is found.

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