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Hybrid Weyl semimetal under crossed electric and magnetic fields: Field tuning of spectrum type

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ABSTRACT

There are two types (WSM-I and WSM-II) of the WSMs. The WSMs of different types have various topological and transport properties. Besides pure WSM-I and WSM-II, there exists a novel type, dubbed "hybrid Weyl semimetal", which contains the Weyl points of both types. In this Letter we consider the hybrid WSM under crossed magnetic and electric fields. The electromagnetic field induces transition between different types of spectrum in Weyl point (WP). Thus, hybrid phase of the WSM can be tunable using the electromagnetic field. Finally, we proposed a new field-induced type of hybrid WSM in which two different regimes of spectrum coexist. In this case, the spectrum near the first WP corresponds to electric regime (no Landau levels) and the spectrum in the second WP with opposite chirality corresponds to magnetic regime (there are Landau levels).

1. Introduction

Investigation of topological materials is a major topics of modern condensed matter physics. Besides of new perspectives for future electronics, such studies provide a unique information about the key phenomena of the quantum field theory. The existence of the three types of particles – Dirac, Weyl and Majorana – is one of the main predictions of the particle physics. These predictions have already been realized in topological materials in a form of quasiparticles. While no candidate Weyl fermions were observed as fundamental particles in experiments on the high-energy particles physics. In addition to well-known effects and particles, the physics of topological matter contains a number of new exotic results. Review of the main results in this area is given in Ref. [1–4].

WSMs are one of the most promising topological materials [2], [4–14]. The minimal Hamiltonian of the WSMs can be formed at the intersection of the Fermi pockets and has the form

$$\hat{\mathcal{H}} = \pm \upsilon_F \sigma \mathbf{p} + \boldsymbol{\omega}^\eta \mathbf{p}. \tag{1}$$

The signs "±" denote the chirality of the Weyl points, $\mathbf{p}$ is the carrier momentum near WPs: $\mathbf{p} = \hbar(\mathbf{k} - \mathbf{k}_+)$ near W_+ and $\mathbf{p} = \hbar(\mathbf{k} - \mathbf{k}_-)$ near W_-, υ_F is the Fermi velocity of carriers, $\boldsymbol{\sigma} = \sigma_x, \sigma_y, \sigma_z$ are the Pauli matrices, $\boldsymbol{\omega}^\eta = (\omega_x^\eta, \omega_y^\eta, \omega_z^\eta)$ is the tilt parameter, $\eta = +1$ for the W_+ and $\eta = -1$ for W_-. If $\upsilon_F^2 > \omega^2$, where $\omega^2 = \omega_x^2 + \omega_y^2 + \omega_z^2$, then this Hamiltonian describes the WSMs-I (WSMs of type-I) with tilted spectrum, and at $\upsilon_F^2 < \omega^2$ this Hamiltonian corresponds to WSMs-II (WSMs of type-II). The Hamiltonian (1) gives the following expression for the energy spectrum: $\varepsilon = \pm \upsilon_F |p| + \boldsymbol{\omega}^\eta \mathbf{p}$. Such WPs are still topologically protected. The WSMs-II have been proposed recently [9–12]. These are fermion systems of a new type with a strong violation of Lorentz invariance. The compounds WTe_2 and $MoTe_2$ are the materials representing the family of WSMs-II. It was shown that WTe_2 contains eight WPs in the Brillouin zone, while $MoTe_2$ is characterized by four WPs. The WSMs of different types have different topological and transport properties. Topological phase transitions between different types of WSMs were discussed in details in Ref. [15]. Besides pure WSMs-I and WSMs-II, there exists a novel type, dubbed "hybrid Weyl semimetal" [16], which contains both types of Weyl points. Such WSMs can be called type-3/2 WSMs. For example, if WP with a positive chirality is type I and the other WP with the opposite chirality is type II then we can write that $\upsilon_F^2 > (\omega^+)^2$ and $\upsilon_F^2 < (\omega^-)^2$ for such hybrid WSMs. Recent studies of transport properties of these hybrid WSMs [17,18] show that in such materials the anomalous Hall transport is realized.

The influence of various external perturbations on the properties of WSMs is a topic of interest from both the fundamental and applied points of view. In particular, Dirac systems exhibit interesting relativistic effects under crossed magnetic and electric

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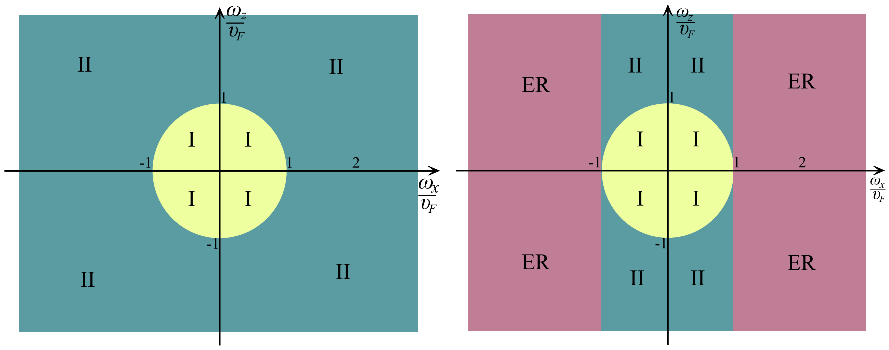

Fig. 1. WSM diagram in $\left(\frac{\omega_x}{\upsilon_F}, \frac{\omega_z}{\upsilon_F}\right)$ plane without (left) and under magnetic field (right). ER denotes the electric regime. Here we put that $\omega_y = 0$.

fields [19–22]. The electric field significantly affects the Landau levels (LLs), and accordingly, quantum oscillations. This is due to the fact that a cyclotron mass depends on the energy in the case of the Dirac spectrum. Recently, Landau quantization and quantum magnetic oscillations in WSMs under crossed fields have been investigated [23–26]. A particularly interesting phenomenon which occur under crossed fields is the collapse of LLs, i.e. the disappearance of LLs, when the electron drift velocity becomes equal to the Fermi velocity. Another interesting phenomenon (see below) is the electromagnetic field-induced transition between different types of WSMs. Thus, an electric field can be used as an additional tool to control the diamagnetism of Dirac systems.

In this letter we consider the effect of crossed electric and magnetic fields on the type of the hybrid WSM spectrum. In the first part we consider the electric field induced transition between different types of Landau spectrum. Here we also show a possibility of the electric field-induced coexistence of type-I and type-II spectra. In the second part, we apply these results to hybrid WSM and discuss some conceptual questions of physics of crossed fields.

2. Changing of Landau spectrum type induced by electric field

As we note above, a spectrum type is defined by the ratio of υ_F^2 and $\left(\omega^\eta\right)^2$. The condition $\upsilon_F^2 = \left(\omega^\eta\right)^2$ corresponds to the phase transition point between WSM-I and WSM-II. This transition can be attributed to the family of Lifshitz-like phase transitions [15]. The DoS has a singularity at this phase transition point. Indeed, in the case of Hamiltonian (1) we can obtain the following expression for DoS (see [12,13])

$$\rho_0 = \frac{1}{(2\pi\hbar)^2} \frac{\upsilon_F}{\left(\upsilon_F^2 - (\omega^\eta)^2\right)^2} \frac{\varepsilon^2}{\hbar} \quad (2)$$

As we can see, point $\upsilon_F^2 = \left(\omega^\eta\right)^2$ is the pole of DoS. The phase diagram in $\left(\frac{\omega_x}{\upsilon_F}, \frac{\omega_z}{\upsilon_F}\right)$ plane is given in Fig. 1(left).

In the presence of the magnetic field we should replace $\mathbf{p} \to \boldsymbol{\pi} = \mathbf{p} + e/c\mathbf{A}$ in the Eq. (1). Using the Landau gauge we obtain the following expression for LLs (details see in [23,24])

$$\varepsilon_n^\eta = sgn(n)\upsilon_F\sqrt{2\gamma_0^3 l_H^{-2}\hbar^2 n + \gamma_0^2 p_z^2} + \omega_z^\eta p_z, \quad n \neq 0, \quad (3)$$

$$\varepsilon_0^\eta = (\eta\upsilon_F\gamma_0 + \omega_z^\eta)p_z, \quad n = 0. \quad (4)$$

In the last equations $\gamma_0 = \sqrt{1 - \frac{\left(\omega_x^\eta\right)^2 + \left(\omega_y^\eta\right)^2}{\upsilon_F^2}}$. Note that the magnetic field doesn't affect the type of spectrum. The difference between two types is defined only by the ratio of υ_F^2 and $\left(\omega^\eta\right)^2$ like in the case of absence of the magnetic field. The phase diagram in the presence of the magnetic field is given in Fig. 1(right).

Let's consider the influence of the electric field on the Landau quantization in WSMs. We consider WSM under magnetic $\mathbf{H} = (0, 0, H)$ and electric $\mathbf{E} = (0, E, 0)$ fields. The solution of Landau quantization problem for the case has the following form

$$\varepsilon_n^\eta = sgn(n)\upsilon_F\sqrt{2\gamma_\eta^3 l_H^{-2}\hbar^2 n + \gamma_\eta^2 p_z^2} + \omega_z^\eta p_z + \upsilon_0 p_x, \quad n \neq 0 \quad (5)$$

$$\varepsilon_0^\eta = (\eta\upsilon_F\gamma_\eta + \omega_z^\eta)p_z + \upsilon_0 p_x, \quad n = 0, \quad (6)$$

where $\gamma_\eta = \sqrt{1 - \frac{(\upsilon_0 - \omega_x^\eta)^2 + \left(\omega_y^\eta\right)^2}{\upsilon_F^2}}$, $\boldsymbol{\upsilon}_0 = c[\mathbf{EH}]/H^2$. One can see that at $\upsilon_F^2\gamma_\eta^2 < \left(\omega_z^\eta\right)^2$ the LLs (5) correspond to WSMs-I. From the other hand, when $\upsilon_F^2\gamma_\eta^2 > \left(\omega_z^\eta\right)^2$ we have LLs of WSMs-II. Thus, condition $\upsilon_F^2\gamma_\eta^2 = \left(\omega_z^\eta\right)^2$ corresponds to the phase transition point between WSM-I and WSM-II. This phase transition occurs at $\upsilon_0 = -\sqrt{\upsilon_F^2 - \left(\omega_y^\eta\right)^2 - \left(\omega_z^\eta\right)^2} + \omega_x^\eta$. The magnetic field along the Z axis quantifies the motion in the XY plane. The motion in the Z direction remains free. Thus, in the presence of the magnetic field, the type of the spectrum is determined by the behavior of the velocity $\upsilon_z^n = \partial\varepsilon_n/\partial p_z$. The electric field changes the velocity along the Z axis. But the electric field along the Y axis changes only the y-th component of the momentum. A natural question arises: why does the electric field along the Y axis affect the velocity υ_z? This is a relativistic effect. This is due to the fact that in the case of the relativistic spectrum the velocity $\upsilon_i = \partial\varepsilon/\partial p_i$ depends on all the components of the momentum. This effect absences in the nonrelativistic system, since in such a case, the i-th velocity component is determined only by the i-th component of the momentum: $\upsilon_i = p_i/m$.

In the presence of crossed electric and magnetic fields the following expression for DoS can be obtained

$$\rho(\varepsilon) = \frac{1}{L_y(2\pi\hbar)^2}\int dp_x \int dp_z \times \sum_{\alpha=\pm}\{\delta(\varepsilon - \varepsilon_0^\pm) + 2\sum_{n=1}^{\infty}\delta(\varepsilon - \varepsilon_n^\pm)\}, \quad (7)$$

where $\alpha = +1$ for electrons and $\alpha = -1$ for holes. In (7), we take into account that zero LL is degenerated twice less than the other levels, i.e. 0th LL is chiral. The integration over p_x is carried out from 0 to p_0. The value p_0 is determined from the degeneracy condition for the LLs: $p_0 = eHL_y/c$. Applying the Poisson summation formula

$$\frac{1}{2} + \sum_{n=1}^{\infty} f(n) = \int_0^\infty f(x)dx + 2Re\sum_{k=1}^{\infty}\int_0^\infty f(x)e^{2\pi ikx}dx \quad (8)$$