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Observation of cyclotron anti-resonance in topological insulator Bi$_2$Te$_3$

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We report on the experimental observation of a cyclotron anti-resonance in a canonical 3D topological insulator Bi$_2$Te$_3$. Magneto-reflectance response of single crystal Bi$_2$Te$_3$ was studied in 18 Tesla magnetic field, and compared to other topological insulators studied before, the main spectral feature is inverted. We refer to it as an anti-resonance. In order to describe this unconventional behaviour we propose the idea of an imaginary cyclotron resonance frequency, which on the other hand indicates that the form of the Lorentz force that magnetic field exerts on charge carriers takes an unconventional form.

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For decades cyclotron resonance has been an important experimental tool in plasma$^{1-3}$ and condensed matter physics$^{4,5}$. In condensed matter physics for example, cyclotron resonance has been used for probing charge dynamics, in particular in semiconductors. Valuable information about band structure, carrier scattering rate, effective mass, etc. can be obtained from these measurements. In recent years, with the advent of materials with Dirac electrons like graphene and topological insulators, cyclotron resonance measurements have been extensively used for probing their electronic structure. Cyclotron resonance has been observed and characterized in single and multiple layer graphene$^{6,7}$, thin films of Bi$_2$Se$_3$,$^8$, bulk Bi$_2$Se$_3$,$^9$, elemental bismuth$^{10-11}$, Bi$_{1-x}$Sb$_x$$^{12,13}$, Bi$_{1-x}$As$_x$$^{14}$, (Bi$_{1-x}$Sb$_x$)$_2$Te$_3$$^{15}$, nano-flakes of Bi$_2$Te$_3$$^{16}$, etc.

In this work we used magneto-optical spectroscopy to study topological insulator Bi$_2$Te$_3$. Magneto-optical activity was detected in reflection spectra, but surprisingly in Bi$_2$Te$_3$ we observed cyclotron anti-resonance, where the spectral feature is inverted, i.e. it is a mirror image of the resonance observed in other systems. For comparison we also measured another canonical topological insulator from the same family Sb$_2$Te$_3$, and we observed a conventional resonance. Based on our data analysis we suggest that the anti-resonance in Bi$_2$Te$_3$ is due to an unconventional form of the Lorentz force that external magnetic exerts on the charge carriers.

Single crystals of Bi$_2$Te$_3$ and Sb$_2$Te$_3$ were grown at Brookhaven National Laboratory$^{17,18}$ and characterized with X-ray diffraction using a Rigaku Miniflex X-ray machine. The analysis showed that samples were single phase, and with lattice parameters consistent with the previously published values$^{19}$. Samples had a thickness of several millimeters, and naturally flat surfaces with a typical size of about 3 mm. Before every spectroscopic measurement the samples were mechanically cleaved in order to expose a fresh surface.

Far-infrared and mid-infrared magneto-reflectance ratios R(\(\omega\),B)/R(\(\omega\), 0 T) were collected at the National High Magnetic Field Laboratory using superconducting 18 T magnet. Reflectance ratios provide the most direct evidence for magneto-optical activity, as they do not require any data analysis or manipulation. All measurements were performed at 5 K, with unpolarized light and with the electric field vector parallel to the quintuple layers of Bi$_2$Te$_3$ and Sb$_2$Te$_3$, i.e. in Faraday geometry.

Figure 1 shows the infrared reflectance ratios R(\(\omega\), B)/R(\(\omega\), 0 T) of Bi$_2$Te$_3$ and Sb$_2$Te$_3$ in magnetic fields up to 18 T. In Bi$_2$Te$_3$ we observed magnetic field induced changes in reflectance (Fig. 1(a)), exceeding 20 % in 18 T, in the region around 800 cm$^{-1}$ (100 meV). This is precisely the region where the plasma minimum was observed in the zero-field reflectance$^{20}$. In Fig. 1(b) we display the ratios for Sb$_2$Te$_3$ and they also show field induced changes with the maximum change of about 10 % around 1,300 cm$^{-1}$ (160 meV), which is the location of plasma minimum in zero field reflectance$^{20}$. In Sb$_2$Te$_3$ conventional cyclotron resonance is observed, similar to other systems, such as graphene, Bi$_2$Se$_3$, bismuth, Bi$_{1-x}$Sb$_x$, etc. The resonance in these systems manifest as a characteristic dip-peak structure in reflectance ratios. Contrary to all of them, in Bi$_2$Te$_3$ we observe the exactly opposite: a peak-dip structure, and we refer to it as an anti-resonance$^{21}$.

In other to explore the origins of observed cyclotron anti-resonance we employ Drude model modified for the presence of magnetic field$^{22}$. In spite of its simplicity, this model has been very successful in describing magneto-optical data in a variety of condensed matter systems, most notably topological insulators$^{8,9,13,23}$. In the semi-
electrons-like and negative for hole-like carriers. Using frequency, and is conventionally taken as positive for \( \omega \) tric constant.

\[ \omega = \frac{eB}{m} \]

where \( \omega \) where the expression on the right is the Lorentz force, \( \vec{F} \) right circularly polarized light \( \tilde{E} \) solve classical approximation, the dynamics of charge carriers (with effective mass \( m \)) in a solid is governed by:\(^{24}\)

\[ m \frac{d\vec{v}}{dt} + m\gamma \vec{v} = -e\tilde{E} - ev \times \vec{B}_0 \]

which, compared with Eq. 2, effectively has an imaginary cyclotron resonance frequency \( \omega_c \). We note however, that the physical meaning of \( \omega_c \) is different from \( \omega_c \) (from Eq. 2) and the two should not be directly compared. We also point out that Eq. 4 satisfies the causality relations \( \tilde{\varepsilon}_\pm(-\omega) = \tilde{\varepsilon}_\pm(\omega) \).

Using this model (Eq. 4) we were able to obtain satisfactory fits for Bi\(_2\)Te\(_3\). The results of the fits are shown with black lines in Fig. 2, for several magnetic field values. As can be seen, the fits can capture all the essential features of the data, in particular the peak-dip structure of Bi\(_2\)Te\(_3\). We find this to be significant, as the conventional model (Eq. 2) cannot fit the data for any values of fitting parameters. It should also be noted that, even though the model Eq. 4 captures the most important feature of the data, it does not reproduce the data around

\[ \tilde{F} = -e \frac{1}{\gamma} \frac{d\vec{v}}{dt} \times \vec{B}_0. \]

Other, more complicated modifications to the Lorentz force are also possible. Making the same assumptions as before\(^{24}\), and solving in the semi-classical approximation as before (Eq. 1), one obtains for the complex dielectric function:

\[ \tilde{\varepsilon}_\pm(\omega) = \varepsilon_\infty \pm \frac{\omega_p^2}{-\omega^2 - i\gamma \omega} \frac{1}{1 - i\omega_c^2 \omega/\gamma} \]

where \( \omega_p \) is the oscillator strength of the resonance mode and \( \gamma \) is its width. \( \varepsilon_\infty \) is the high-frequency dielectric constant. \( \omega_c = eB_0/m \) is the cyclotron resonance frequency, and is conventionally taken as positive for electron-like and negative for hole-like carriers. Using

This model we could obtain good fits of reflectance ratios of Sb\(_2\)Te\(_3\). In Sb\(_2\)Te\(_3\) (and Bi\(_2\)Te\(_3\)) charge carriers are believed to be hole-like\(^{20}\), so \( \omega_c \) is taken as negative. The best fits are shown in Fig. 2(b) with black lines. We notice that the model is capable of capturing all the important features of Sb\(_2\)Te\(_3\) data, in particular, the dip-peak structure characteristic of cyclotron resonance seen in other systems, such as Bi\(_2\)Se\(_3\).4

On the other hand, we have not been able to obtain satisfactory fits of reflectance ratios of Bi\(_2\)Te\(_3\) for any values of model parameters. In particular, the model cannot reproduce the peak-dip structure characteristic of Bi\(_2\)Te\(_3\) data. To circumvent this problem we propose the idea that in Bi\(_2\)Te\(_3\) cyclotron resonance frequency acquires imaginary (or more generally complex) values. Imaginary cyclotron resonance frequency is necessary in order to introduce an additional phase shift in the dielectric function (Eq. 2). The idea was inspired by the recently proposed theory to explain quantum fluctuating superconductivity.\(^{27}\) The authors used a complex cyclotron frequency, and referred to it as the super-cyclotron resonance.

Cyclotron resonance is a direct consequence of applied magnetic field (Eq. 1) and therefore in order to obtain imaginary cyclotron frequency, one must modify the expression for the Lorentz force that magnetic field exerts on charge carriers. We propose that in the case of Bi\(_2\)Te\(_3\) the magnetic part of the Lorentz force should be modified to:

\[ \tilde{F} = -e \frac{1}{\gamma} \frac{d\vec{v}}{dt} \times \vec{B}_0. \]

FIG. 1: (Color online). (a) Reflection ratios of Bi\(_2\)Te\(_3\) at several magnetic field values. The feature around 800 cm\(^{-1}\) is identified as cyclotron anti-resonance, because it is a mirror image of the feature observed in Sb\(_2\)Te\(_3\) (bottom panel). (b) Reflection ratios of Sb\(_2\)Te\(_3\) at several magnetic field values. The feature around 1,300 cm\(^{-1}\) is identified as the usual cyclotron resonance. Note different axes scales between the two panels.

Other, more complicated modifications to the Lorentz force are also possible. Making the same assumptions as before\(^{24}\), and solving in the semi-classical approximation as before (Eq. 1), one obtains for the complex dielectric function:

\[ \tilde{\varepsilon}_\pm(\omega) = \varepsilon_\infty \pm \frac{\omega_p^2}{-\omega^2 - i\gamma \omega + i\omega_c^2 \omega/\gamma} \]

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where \( \omega_p \) is the oscillator strength of the resonance mode and \( \gamma \) is its width. \( \varepsilon_\infty \) is the high-frequency dielectric constant. \( \omega_c = eB_0/m \) is the cyclotron resonance frequency, and is conventionally taken as positive for electron-like and negative for hole-like carriers. Using
900 cm$^{-1}$. This secondary, much weaker structure might be due to Landau level transitions, and additional terms might be needed in Eq. 4 to account for it.

In order to get a better insight into carrier dynamics, we explored other optical functions of both Bi$_2$Te$_3$ and Sb$_2$Te$_3$. From the best fits of reflectance obtained with Eqs. 2 and 4 we generated optical conductivities for left and right circular polarizations of light $\sigma_{\pm}(\omega) = \omega(\varepsilon_{\pm}(\omega) - 1)/(4\pi i)$. Fig. 3 displays the real part of circular conductivity for both Bi$_2$Te$_3$ (top panels) and Sb$_2$Te$_3$ (bottom panels). For Sb$_2$Te$_3$ in zero field both $\sigma_-(\omega)$ and $\sigma_+(\omega)$ are Drude modes. As the field increases, $\sigma_+(\omega)$ is gradually suppressed, whereas in $\sigma_-(\omega)$ the peak gradually shifts to finite frequencies and at 18 T it is at 24 cm$^{-1}$.

On the other hand, the peak in $\sigma_-(\omega)$ is shifted to finite frequencies, and is gradually suppressed, but appears to maintain its width. At 18 T, the peak is at approximately 45 cm$^{-1}$. This behaviour is typical of topological insulators, and has been seen before, for example in Bi$_2$Se$_3$.$^{7,8}$.

Surprisingly, the behaviour of both $\sigma_-(\omega)$ and $\sigma_+(\omega)$ (Fig. 3(a) and (b) respectively) in Bi$_2$Te$_3$ is similar to Sb$_2$Te$_3$, Bi$_2$Se$_3$ and other topological insulators. Even though the model used to fit the data was different, all the features in the $\sigma_{\pm}(\omega)$ spectra are qualitatively similar. In zero field both $\sigma_+(\omega)$ and $\sigma_-(\omega)$ are Drude modes. As the field increases, $\sigma_+(\omega)$ is suppressed, whereas in $\sigma_-(\omega)$ the peak gradually shifts to finite frequencies and at 18 T it is at 24 cm$^{-1}$.

In Fig. 4 we plot the parameters of the best fits from Eqs. 2 and 4. Fig. 4(a) and (b) display the cyclotron resonance frequencies $\omega_c$ and $\omega_r$ for Bi$_2$Te$_3$ and Sb$_2$Te$_3$ respectively. In both compounds we observe linear field dependence which extrapolates to zero in zero field, characteristic of charge carriers with parabolic band dispersion. Linear fits (shown with dashed lines) yield $\hbar \omega_c/B = 0.025$ meV/T and 0.27 meV/T for Bi$_2$Te$_3$ and Sb$_2$Te$_3$ respectively. In the case of Sb$_2$Te$_3$ we can estimate the cyclotron effective mass $m/m_e = 0.42$. This value is in general agreement with earlier reports from quantum oscillations measurements.$^{25,26}$

In summary, magneto-optical study of Bi$_2$Te$_3$ and Sb$_2$Te$_3$ has reveal a cyclotron resonance in the spectra of Sb$_2$Te$_3$, and an anti-resonance in Bi$_2$Te$_3$. To explain the behaviour of Bi$_2$Te$_3$ we introduced the idea of an alternative Lorentz force, which resulted in an imaginary cyclotron frequency. Physical interpretation of this unconventional behaviour requires deeper theoretical analysis of how light couples to charge carriers in Bi$_2$Te$_3$.

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A cyclotron resonance was observed in a recent magneto-transmission study of Bi$\text{_{2}}$Te$\text{_{3}}$ nano-flakes 16.


FIG. 3: (Color online). (a) and (b) Optical conductivities for left and right circularly polarized light $\sigma_{\uparrow}(\omega)$ (right panel) and $\sigma_{\downarrow}(\omega)$ (left panel) for Bi$_2$Te$_3$ at different magnetic fields, generated from the best fits of reflection ratios (Fig. 2). (c) and (d) Optical conductivities $\sigma_{\uparrow}(\omega)$ and $\sigma_{\downarrow}(\omega)$ for Sb$_2$Te$_3$. The same color coding is used in all four panels.

FIG. 4: (Color online). (a) Magnetic field dependence of cyclotron frequency $\omega_c^\prime$ in Bi$_2$Te$_3$. Dashed line is a linear fit of the data. (b) Cyclotron resonance frequency $\omega_c$ of Sb$_2$Te$_3$. Dashed line is a linear fit, from which the cyclotron effective mass of 0.42 $m_e$ was extracted.