Electrical Control of Weyl Singularity Points Emerged in Multi-terminal Josephson Junctions

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Topological property of materials is a central interest in recent solid-state physics. We investigate the artificial topological state of multi-terminal Josephson junctions (MJJ). MJJ is a structure in which the superconducting terminals are extended to three or more. The Andreev bound states formed in the Josephson junction (JJ) show a 2π periodic dependence on the phase difference φ between the superconductors. MJJ has the N superconducting terminals, so MJJ independently has the multiple phase differences $\varphi_1, \varphi_2, \cdots, \varphi_{N-1}$. Then, the Andreev bound states of the MJJ are 2π periodic in all phases. The energy $E(\varphi_1, \varphi_2, \cdots, \varphi_{N-1})$ of Andreev bound states forms the "band structure", an analogy that becomes apparent when considering $\varphi_1, \varphi_2, \cdots, \varphi_{N-1}$ as crystal momenta. In this artificial energy band, the topologically protected Weyl singularity points emerge in the Andreev bound states [1].

In this study, we introduce a quantum point contact (QPC) structure into the MJJ, modulating the "band structure" created by Andreev bound states to manipulate Weyl singularity points. Weyl singularity points have positive and negative topological charges, and their pair annihilation leads to a topological phase transition. We show that electrical control of the topological phase is possible by using the gate voltage to control the QPC. Moreover, a control of terminals by the QPC increases or decreases the dimensionality of the band energy, giving rise to a novel quantum effect.

First, in the case of four-terminal JJs. This system has three phase differences $\varphi_1, \varphi_2, \varphi_3$. Here, we consider one sample from MJJ. Figure1 shows the dynamics of Weyl points in the 3D space through $\varphi_1, \varphi_2, \varphi_3$ when the transmission is controlled by one-terminal QPC. W1 and W1' (W2 and W2') denote the trajectory of the Weyl points with negative (positive) topological charge. By decreasing the transmission, two pairs of four Weyl points are generated. Then, note that the total topological charge is neutral, hence the Nielsen-Ninomiya theorem is satisfied. Further decreasing the transmission, the Weyl points with different charge move and annihilate. Then, the topological phase transition occurs. Figure1 shows the circular trajectory of Weyl points. For another sample, we find a different type of trajectory. Owing to the difference, we can consider new classification of topology.

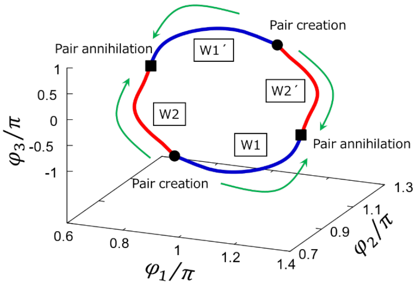

Fig.1. Trajectory of four Weyl points due to the change in transmittance. Each axis represents the superconducting phase difference. Four Weyl points W1, W2, W1', and W2' move with the transmission control. At this time, pair creation and annihilation occur. Weyl points creates two pairs of different topological charges.

Next, we consider five-terminal JJs. We switch continuously from four to five-terminal by controlling the transmittance of the fifth terminal from $T_4 = 0$ to 1. We treat T_4 and the fifth phase difference φ_4 as control parameters and observe the number of Weyl points shown in Fig. 2. We identified three regions where the number of Weyl points is 0, 2 or 4. In Fig.2, by keeping φ_4 at 0 and varying T_4, the number of Weyl points changes from 4 to 0. At this moment, four Weyl points simultaneously cause pair annihilation and creation, similarly to Fig. 1. This indicates the fact that five-terminal JJ is equivalent with four-terminal JJ when φ_4 is zero. However, by keeping φ_4 at nonzero and varying, region of two Weyl singularity points emerges. This state doesn't exist in the four-terminal system. This is due to the effect of the fifth phase difference φ_4 breaking the time-reversal symmetry.

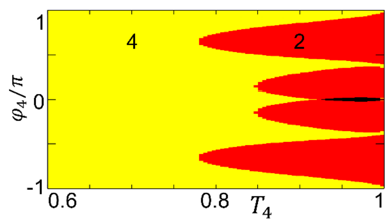

Fig.2. Topological phase daiagram of the number of Weyl points in a five-terminal JJ with changes in superconducting phase difference and transmittance. The horizontal and vertical axis are transmittance and the phase difference of the fifth terminal. In a region of 4, pair annihilation doesn't occur. In a region of 2, when one pair annihilate, the other pair undergoes pair creation. There are no Weyl singularity points in the black region.

References

[1] T. Yokoyama and Yu. V. Nazarov, PRB, 92, 155437 (2015).