Prediction of spin polarized Fermi arcs in quasiparticle interference in CeBi

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Abstract
We predict that CeBi in the ferromagnetic state is a Weyl semimetal. Our calculations within density functional theory show the existence of two pairs of Weyl nodes on the momentum path (0,0,kz) at 15meV above and 100meV below the Fermi level. Two corresponding Fermi arcs are obtained on surfaces of mirror-symmetric (010)-oriented slabs at E=15meV and both arcs are interrupted into three segments due to hybridization with a set of trivial surface bands. By studying the spin texture of surface states, we find the two Fermi arcs are strongly spin polarized but in opposite directions, which can be detected by spin-polarized ARPES measurements. Our theoretical study of quasiparticle interference (QPI) for a nonmagnetic impurity at the Bi site also reveals several features related to the Fermi arcs. Specifically, we predict that the spin polarization of the Fermi arcs leads to a bifurcation-shaped feature only in the spin-dependent QPI spectrum, serving as a fingerprint of the Weyl nodes.

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We predict that CeBi in the ferromagnetic state is a Weyl semimetal. Our calculations within density functional theory show the existence of two pairs of Weyl nodes on the momentum path \((0, 0, k_z)\) at 15 meV above and 100 meV below the Fermi level. Two corresponding Fermi arcs are obtained on surfaces of mirror-symmetric (010)-oriented slabs at \(E = 15\) meV and both arcs are interrupted into three segments due to hybridization with a set of trivial surface bands. By studying the spin texture of surface states, we find the two Fermi arcs are strongly spin polarized but in opposite directions, which can be detected by spin-polarized ARPES measurements. Our theoretical study of quasiparticle interference (QPI) for a nonmagnetic impurity at the Bi site also reveals several features related to the Fermi arcs. Specifically, we predict that the spin polarization of the Fermi arcs leads to a bifurcation-shaped feature only in the spin-dependent QPI spectrum, serving as a fingerprint of the Weyl nodes.

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I. INTRODUCTION

Despite being predicted more than 90 years ago as an elegant special solution of the relativistic wave equation, Weyl fermions have never been observed in nature. However, just as the sun was setting on the Weyl fermion, they were observed as a quasiparticle in the electronic structure of TaAs, thereby pushing Weyl physics back to the vanguard and invigorating the search for other exotic relativistic particles within solids. Weyl fermions appear in condensed matter systems when a single Dirac cone is split into two by the breaking of either time-reversal [1–6] or inversion symmetry [7–13]. This process generates a pair of conelike features with opposite chirality defined by their Berry curvature [14]. As a direct consequence, anomalous surface states appear connecting Weyl nodes of opposite topological charge, providing an experimentally accessible fingerprint of the underlying nontrivial band topology [4,15–21].

Recently, magnetic Weyl semimetals have been gaining interest for providing a new platform to study the interplay between chirality, magnetism, correlation, and topological order, thus opening up new routes to novel quantum states, spin polarized but in opposite directions, which can be detected by spin-polarized ARPES measurements. Our theoretical study of quasiparticle interference (QPI) for a nonmagnetic impurity at the Bi site also reveals several features related to the Fermi arcs. Specifically, we predict that the spin polarization of the Fermi arcs leads to a bifurcation-shaped feature only in the spin-dependent QPI spectrum, serving as a fingerprint of the Weyl nodes.

This allows simpler band structures thereby facilitating clearer comparisons with theoretical predictions, and more robust applications in spintronics [28–30] and quantum computation [31–34]. Another advantage is the magnetic field tunability which provides us a strong tool for controlling the band structure and related electromagnetic functionality.

To date very few magnetic Weyl materials have been synthesized, demonstrating an urgent and important need for more theoretical material predictions and robust growth protocols. Only very recently have Co₃Sn₂S₂ and Co₂MnGa been reported as possible magnetic Weyl semimetals with six Weyl nodes and nodal lines, respectively [4–6]. This is far from enough to explore the wide range of possible exotic states. Interestingly, recent experimental reports of a pronounced negative magnetoresistance and observed band inversion in cerium monopnictides [35–37] and the geometrically frustrated Shastry-Sutherland lattice GdB₄ [38] could provide clues to a possible new material family harboring Weyl physics.

In this paper, we argue that CeBi in the ferromagnetic (FM) state is a magnetic Weyl semimetal using first-principles LDA + \(U\) calculations, and we predict robust quasiparticle interference (QPI) signatures of spin polarized Fermi arcs directly accessible by spin resolved scanning tunneling spectroscopy (STS). By aligning the Ce magnetic moments along the\(c\) axis, we find two pairs of Weyl nodes on the zone diagonal along the \(k_z\) axis at 15 meV above and 100 meV below the Fermi level. Then by examining a (010)-oriented slab which is mirror symmetric, two Fermi arcs of opposite spin polarization are observed on both the top and bottom of surfaces, stretching across the Brillouin zone. These Fermi...
arcs then hybridize with a set of trivial surface states producing a spin vortex encircling the $\vec{M}$ point in the Brillouin zone. Finally, by considering a weak potential scatterer at the Bi site on the surface, we predict several features directly related to the scattering among the Fermi arcs in the QPI spectra. Specifically, there is a bifurcation-shaped feature originating from the scattering between the two symmetric outer segments of the spin-up Fermi arc. We propose this feature as a direct indicator of the Weyl nodes for future experiments. Moreover, due to the isolation of the Weyl nodes near the Fermi level, we find CeBi to be a robust platform for theoretical and experimental analysis of Weyl physics with minimal interference from trivial bulk states.

II. METHOD

First-principles band structure calculations were carried out within density functional theory framework using the generalized-gradient approximation (GGA) as implemented in the all-electron code Wien2K [39], which is based on the augmented-plane-wave + local-orbitals (APW + lo) basis set. Spin-orbit coupling was included in the self-consistency cycles. Furthermore, the Hubbard Coulomb interaction on Ce-$4f$ electrons was incorporated to ensure a fully localized Ce-$4f$ state, which also gives a total magnetic moment of $2\mu_B$/Ce consistent with earlier studies on cerium monopnicides [35,40,41]. Although these compounds exhibit several field-induced magnetic phases, a ferromagneticlike state can be stabilized using state-of-the-art cryogenic STM in 3D vector magnetic fields above 4 T [35,41,42]. The topological analysis was performed by employing a real-space tight-binding model Hamiltonian, which was obtained by using the wien2wannier interface [43]. Bi-6p and Ce-5d states were included in generating Wannier functions. It is worth mentioning that the DFT + $U$ method for a nonmagnetic phase will still leave the $f$ electron pinned around the Fermi level, which is completely different from the spin-polarized case [44]. Therefore, the DFT + $U$ approach is not appropriate to describe strongly correlated materials in a paramagnetic state, for which one needs to resort to more powerful methods like DFT + DMFT [45].

To identify the presence of a pair of Weyl nodes in a given band structure, we must check if the band crossings are topologically trivial or nontrivial. That is, we must calculate the Berry curvature vector $\Omega_{n,\alpha\beta}(\mathbf{k})$ as implemented in the WannierTools package [46-48], for a given band $n$ and momenta $\mathbf{k}$ as

$$\Omega_{n,\alpha\beta}(\mathbf{k}) = -2\text{Im} \sum_{m \neq n} \frac{v_{nm,\alpha}(\mathbf{k})v_{mn,\beta}(\mathbf{k})}{[\epsilon_{mn} - \epsilon_{nk}]^2},$$

where $\epsilon_{nk}$ is the eigenvalue of Hamiltonian $H$ for band $n$ and momenta $\mathbf{k}$ and the matrix elements of the Cartesian velocity operators $\hat{v}_\alpha = (i/\hbar)[\hat{H}, \hat{r}_\alpha]$ are given by

$$v_{nm,\alpha}(\mathbf{k}) = \langle \phi_{nk} | \frac{\partial \hat{H}(\mathbf{k})}{\partial \hat{r}_\alpha} | \phi_{mn} \rangle.$$  

Finally the Berry curvature vector is given by

$$\Omega_{n,\gamma}(\mathbf{k}) = \epsilon_{\alpha\beta\gamma} \Omega_{n,\alpha\beta}(\mathbf{k}),$$

where $\epsilon_{\alpha\beta\gamma}$ is the Levi-Civita tensor.

The surface electronic structure was calculated using both the direct diagonalization and the iterative Greens function method [49,50]. The QPI spectra was obtained within the $T$-matrix approximation as given by

$$\text{QPI}(\mathbf{q}, \omega) = i(2\pi)^{-1} \int d^2k (2\pi)^{-2} [B(\mathbf{q}, \omega) - B^*(-\mathbf{q}, \omega)],$$

where $B(\mathbf{q}, \omega) = \text{Tr}[G(\mathbf{k} + \mathbf{q}, \omega)T(\omega)G(\mathbf{k}, \omega)]$ with $\mathbf{q}$ and $\omega$ the scattered wave vector and quasiparticle energy, respectively. $G$ is the spin-dependent matrix surface Greens function composed of 6 Bi-6p and 10 Ce-5d orbitals, and $T$ is the scattering $T$ matrix containing all multiple scattering effects off a single-site impurity. Since the infinite sum of multiple scattering terms form a geometric series, the $T$ matrix can be compactly written as $T(\omega) = [I - V_{\text{imp}}(2\pi)^{-2} \int d^2k G(\mathbf{k}, \omega)]^{-1} V_{\text{imp}}$, where $V_{\text{imp}}$ is the impurity potential. Here we considered a Born approximation of the impurity scattering such that $T = V_{\text{imp}}$ and further chose $V_{\text{imp}}$ to be a constant diagonal matrix with nonzero elements only for $p$ ($d$) orbitals for a Bi (Ce) impurity site. Our general methodology for QPI prediction in CeBi is justified by the good agreement between calculated and experimental STS data on the (001)-oriented slab, shown in detail in the Supplemental Material (SM) [50].

III. BAND STRUCTURE AND WEYL NODES

Figure 1 (left panel) shows the crystal structure of CeBi in the FM phase along with its corresponding face-centered-cubic (FCC) Brillouin zone, where various high symmetry lines are marked. The middle panel presents the electronic band dispersions evaluated over the full set of high symmetry points. The energy bands near the Fermi level are mainly of Bi-6p and Ce-5d character. Moreover, the moment-carrying
localized Ce-4f states, which provide an effective Zeeman exchange field, are seen as a flat band at 3 eV binding energies. We choose $U = 7.9$ eV and $J = 0.69$ eV in our ab initio calculations to make the Ce-4f energy level consistent with the corresponding state in CeSb as reported by photoemission spectroscopy [51]. Moreover, the nontrivial topological nature of low-energy states in CeBi are not sensitive to the value of $U$ once Ce-4f electrons are quite localized in the ferromagnetic phase.

The most important feature of the band structure is the pair of Weyl nodes that appears along $\Gamma-Z$ at the Fermi level. These two Weyl nodes are formed by the crossing of Bi-6p and Ce-5d $t_{2g}$ orbital character bands that have been spin split by the internal Zeeman exchange field [Fig. 1 (right panel)]. The Weyl nodes $w_1$ and $w_2$ are located at $(0, 0, 0.22\frac{\pi}{a})$ and $(0, 0, 0.28\frac{\pi}{a})$ in the Brillouin zone and at 15 meV above and 100 meV below the Fermi level, respectively. Here $a$ is the lattice constant of the cubic conventional cell and hereafter we will choose $4\pi/a = 1$. Due to mirror symmetry in the $xy$ plane, a duplicate pair of Weyl nodes are found along the $-k_z$ axis, named $\bar{w}_1$ and $\bar{w}_2$. The locations of these four Weyl nodes are marked in the Brillouin zone [Fig. 1 (left panel)] by the teal (orange) dots, where the teal (orange) color indicates a Weyl node as a source (sink) of Berry curvature. Importantly, since the Weyl nodes in CeBi are isolated near the Fermi level, the experimental signatures and theoretical analysis will be less obstructed as compared to Co$_3$Sn$_2$S$_2$ and Co$_2$MnGa.

Figure 2(a) shows $w_1$ and $w_2$ near the Fermi level along the $-Z-\Gamma-Z$ cut in the Brillouin zone. The band that passes through the Weyl nodes is marked in red. Figure 2(b) shows the corresponding Berry curvature vector field in the $xz$ plane of the first Brillouin zone for the red band in Fig. 2(a). Two clear divergences in the vector field are seen along $\pm Z-\Gamma$ at the Weyl nodes, with one node as a source (teal) and the other a sink (orange) of topological charge. This confirms the topologically nontrivial nature of these Weyl band crossings. Furthermore, we identified 16 additional pairs of Weyl node existing above the Fermi energy, each marked in Fig. 2(a) by an orange or teal circle denoting its topological charge.

IV. SURFACE SPECTRAL FUNCTIONS

Due to the presence of Weyl nodes near the Fermi level we expect the emergence of a pair of Fermi arcs connecting nodes of opposite topological charge when CeBi is cleaved along a given crystal plane exposing a surface. However, the situation is more subtle in magnetic Weyl materials. Since the internal magnetic moments on the Ce atoms point in the $c$-axis...
FIG. 5. (a) QPI spectra for a (010)-oriented surface of FM CeBi with the dominant scattering vectors indicated. (b) Surface spectral function with the trivial $pz$ states removed with various characteristic scattering transitions marked. (c) QPI spectra corresponding to the surface spectral function in (b). (d) Surface spectral function with Fermi arcs and spin vortex removed, with dominant scattering vectors indicated. (e) QPI spectra corresponding to the surface spectral function in (d). (f) QPI spectra of the spin-up channel and (g) spin-down channel for the Fermi arcs (highlighted in the red frame) have the corresponding bulk bands in Fig. 3(b). This indicates that the Fermi arcs are the nontrivial topology induced edge states. The massless energy bands corresponding to Fermi arcs are shown in the Supplemental Material [50].

Figure 4(a) shows the surface spectral function $A_{\text{surf}}(\mathbf{k}, \omega)$ for an effective 64-layer (010)-oriented slab in the surface reciprocal space, centered at the $\bar{M}$ point, for a constant-energy cut of $\omega = \omega_1$. Two clear Fermi arcs are seen connecting projections of the Weyl nodes $\bar{w}_1$ to $\bar{w}_2$ and $\bar{w}_2$ to $\bar{w}_1$, labeled as arc I and arc II, respectively. By breaking down the spectral function into its orbital components, we find the Fermi arcs to be mainly composed of Bi $px$ and $py$ and Ce $t_2g$ orbitals. The dominant Bi $px$ and weaker Bi $pz$ contribution, along with their spin dependence, is given in Fig. 4(b).

Interestingly, as the two Fermi arcs traverse across the Brillouin zone they are intersected by and hybridize with two majority $pz$ character trivial bands extending along the $k_x$ direction [Fig. 4(a)]. The avoided crossing between these two sets of bands yields a nearly continuous outer cross shaped Fermi surface and a rectangular pocket surrounding $\bar{M}$. Moreover, additional trivial surface states are observed around the $\bar{M}$/Gamma1 point, but they do not interact with the arcs.

Figure 4(c) shows $\langle\sigma_3(k, \omega)\rangle = -\frac{1}{4}\text{ImTr}[\sigma_3G(k, \omega)]$ in the first Brillouin zone for a constant-energy cut of $\omega = \omega_1$, where red (blue) indicates the strength of the positive (negative) $\sigma_3$ projection of the surface spectral function. Here we find arc I and arc II to be oppositely spin polarized, which is also reflected in Fig. 4(b). This is the consequence of the spin-momentum locking effect around the $\bar{M}$ point which originates from the strong spin-orbital coupling in CeBi. Moreover, the strength of polarization is generically greater for arc I compared to arc II, due to the FM order along the $c$ axis.

Figures 4(d) and 4(e) show the full spin texture of the Fermi arcs in the (010)-oriented slab. We note several important features: (i) Arc I is strongly polarized along $+z$, whereas arc II is strongly polarized along $-z$. (ii) Due to inversion symmetry, the spin polarization for a given $(k_z, k_x)$ on the bottom
surface is equivalent to the spin polarization on the top surface at \((-k_z, -k_x)\). (iii) The Fermi surface pocket surrounding \(M\) forms a spin vortex in the momentum space, owing to strong spin-orbit coupling. (iv) The spin-polarization vector lies completely in the \((k_z, k_x)\) plane, where \(s_y\) is strictly zero. The absence of any out-of-plane spin polarization \(S_y\) is guaranteed by the combined symmetry of time-reversal symmetry \(T\) and twofold rotational symmetry along the \(y\) axis \(C_2\), even though \(T\) or \(C_2\) itself is broken. This symmetry is satisfied for the Hamiltonian of the \((010)\) slab with \(C_{2y}T H(k_z, k_x)T^{-1}C_{2y}^{-1} = H(k_z, k_x)\). Since \(T\) flips all spin components and reverses all crystal momenta, and \(C_{2y}\) only flips \(S_z, S_z\) and reverses \(k_z, k_z\), the combined transformation \(C_{2y}T\) maps \((k_z, k_x)\) to itself and reverses \(S_y\). Because \((C_{2y}T)^2 = 1\), there is no Kramers degeneracy, implying \(C_{2y}T(k_z, k_x)\) and \(|k_z, k_x\rangle\) can only differ by a phase, forbidding different \(S_y\). Therefore, the expectation value of \(S_y\) must be strictly zero throughout the Brillouin zone.

V. QUASIPARTICLE INTERFERENCE

A. Bi-site impurity

At first we present our theoretical study on the \((010)\)-oriented surface QPI derived from scattering between these surface states due to an isotropic nonmagnetic impurity at the Bi site. Figure 5(a) shows the QPI spectra in the first Brillouin zone for a constant energy cut of \(\omega = \omega_1\). Firstly, we notice that almost all \(\mathbf{q} = 0\) scattering is suppressed by destructive interference between the various multiorbital scattering channels. This phenomena is not present in the simple joint density of state description since the phase of wave functions is neglected. But because QPI(0, \(\omega \propto \int d^2k \text{ImTr}[G(\mathbf{k}, \omega)T(\mathbf{k}, \omega)G(\mathbf{k}, \omega)], the off diagonal components of the matrix Green’s function contribute to the QPI signal. Moreover, the sign of the imaginary part of the product is highly sensitive to the relative sign between real and imaginary parts of the Green function and \(\mathbf{k}\) in the Brillouin zone. Therefore, even after integrating over the full zone the results may be quite small. A similar cancellation takes place for scattering at finite \(\mathbf{q}\), which leads to a quite broad and smooth QPI spectrum despite sharp features in the spectral function.

In Fig. 5(a) the five main features in the QPI pattern, corresponding to strong scattering between the surface states, are labeled with \(Q_1\) through \(Q_5\) and are highlighted by red dash circles and rectangles. In order to pinpoint the origin of these strong features, we isolate various sections of the surface spectral function by masking out the Green function in other sections and amplify their effect on the QPI spectra. If we only consider the scattering between the Fermi arcs, spin vortex, and bands surrounding \(\bar{\Gamma}\) [Fig. 5(b)] we find the \(Q_1\), \(Q_2\), and \(Q_3\) features persist in the QPI [Fig. 5(c)]. Therefore, we find the momentum transfer \(Q_1\) to connect the outer segment of the Fermi arc to the pocket surrounding \(M\). \(Q_2\) scatters electrons from the outer segments of Fermi arcs to the trivial bands around \(\bar{\Gamma}\). Because the Fermi arc is curved, a curved bridgelike dispersion is seen in the \(Q_2\) rectangle. \(Q_3\) transfers momentum between the Fermi pocket to the trivial bands around \(\bar{\Gamma}\). If we now consider the spectral function in the region away from the Fermi arcs and spin vortex [Fig. 5(d)], we find the remaining Fermi sheets clearly produce the remaining features \(Q_4\) and \(Q_5\) [Fig. 5(e)]. \(Q_4\) comes from the internal scattering of the bands around \(\bar{\Gamma}\), whereas the \(Q_5\) scattering vector connects \(p_{23}\) dominant states to those surrounding \(\bar{\Gamma}\).

Since the surface spectral function exhibits a strong spin texture, it is reasonable to expect a highly spin dependent QPI. Figures 5(f) and 5(g) show the up- and down-spin projection of the QPI spectra. These two patterns are quite similar except for scattering momenta related to \(Q_1\). Since \(Q_1\) connects Fermi arcs of the same \(\pm z\) spin polarization, the intensity in the spin-up QPI channel is stronger than that in the spin-down channel. This stark difference in the spin-up and spin-down QPI maps provides a direct experimentally accessible prediction of the underlying spin-polarized Fermi arcs.

Thus far, we have covered all the strong scattering transitions in the QPI map. However, the scattering between the two outer Fermi arcs appears to be missing. There should be features in the QPI spectra corresponding to this scattering channel. Indeed, upon close inspection, a red flat tail can be seen at \((q_z, q_x) = (\pm 0.25, 0)\) in Figs. 5(a), 5(c), and 5(f) corresponding to this ‘missing’ scattering pathway. Figure 6(a) shows a zoomed in section of the QPI map given in Fig. 5(a) displaying a dispersing bifurcating feature. The trunk, which is the tail mentioned above, extends from \(q_z = 0.23\) to about \(q_z = 0.26\), and bifurcates into two branches. The intensity of the two branches decreases with increasing \(q_z\), but the branch between \(q_z = 0.26\) to \(q_z = 0.33\) is still clearly seen. This bifurcation shaped feature originates from electrons scattered between the shoulderlike portion (denoted by \(Q’\)) and the slope (marked by \(Q’’\)) of the Fermi arc, as shown in Fig. 6(b). The enhanced scattering along \(q_z = 0\) originates from pure shoulder-shoulder \(Q’\) scattering spanning between the mirrored sections of the Fermi arcs. For \(q_z > 0.26\), \(Q’’\)
momentum transfers becomes dominant, tracing out the curvature of the Fermi arc. The intensity of the QPI decreases increased $Q''$ due to the reduction in the nesting between the shoulder and the curving Fermi arc, therefore, generating the two bifurcating branches in the QPI spectrum.

Figure 7 shows the energy dependence of the Fermi arc I and the bifurcation feature. From panels (a)–(c), we see that as energy increases from $-50$ meV to 50 meV, the Fermi arc becomes more curved due to the energetic distance from the Weyl node [50]. This manifests in QPI as a growing angle of the bifurcation branches as shown in Figs. 7(d)–7(f).

B. Ce-site impurity

Now we replace the Bi impurity with a Ce impurity and mark the difference in the surface spectral function and QPI. Here, the $d$ orbitals play the key role in the Ce impurity induced scattering. We find two noteworthy scattering vectors labeled $Q_1$ and $Q_2$ shown in Fig. 8. $Q_1$ connects the Fermi arcs with trivial bands around $\Gamma_1$. Additionally, because the Ce magnetic moments are along the positive $z$ direction, the spectral function for spin-up $d$ orbitals is more intense than the spin-down $d$ orbitals. As a result, the $Q_1$ spikelike feature in the total and spin-up QPI spectrum is shown in Figs. 8(e) and 8(f), whereas this feature is not clear in Fig. 8(g). The momentum transfer $Q_2$, which is similar to $Q_4$ in the case of Bi impurity, comes from the internal scattering of the bands around the $\Gamma$ point. This scattering channel is strong for both spin-up and spin-down channels, which makes it a strong feature in all QPI maps. The features displayed for a Ce impurity are not as rich as those found for a Bi-site scatter because the existence of a dense set of Ce-5$d$ bands surrounding the $\Gamma$ point at the Fermi level that generate a significant trivial band scattering background, thus, washing out most features related to Fermi arc scattering in the QPI.

VI. QPI FOR HIGHER ENERGY WEYL NODE

In the previous sections, we have studied the surface states and QPI spectra originating from near the Fermi level of a (010)-oriented slab. Here, we study the surface projected spectral function and QPI map of the (010)-oriented slab for a pair of Weyl nodes above the Fermi level at 0.915 eV, as indicated by the red dashed line in Fig. 9(a). We chose this specific pair of Weyl nodes since they are quite isolated from other intruding bands, which tend to complicate the observation of the Fermi arcs. This Weyl node and the one just below it are both sources of Berry flux as indicated in Fig. 2(a). The surface spectral function at this energy is shown by Fig. 9(b), where two clear winglike features are found near $\Gamma_1$ along the $k_x$ axis. Zooming in on these features [Fig. 9(c)], it is easy to see that they are Fermi arcs which connect the Weyl nodes. Figure 9(d) shows the $\sigma_3$ projection of the spectral function.
In the first Brillouin zone, where the red (blue) intensity indicates the strength of the spin-up (spin-down) polarization. Figure 9(e) shows a closeup showing a clear spin texture of the Fermi arc. Similar to our earlier discussion, the scattering between the Fermi arcs with different spin textures can lead to interesting features in the total and spin resolved QPI spectra, as shown in Figs. 9(f), 9(g), and 9(h). Because the spin-up Fermi arcs are curved and the spin-down arcs are relatively flat, the QPI map yields curved and flat features in the spin-up and spin-down QPI spectra, respectively, as indicated by the black arrows. The total QPI also displays a similar curved feature as shown in Fig. 9(f).

VII. CONCLUSION

In summary, we have found theoretically that CeBi is a magnetic Weyl semimetal with two pairs of Weyl nodes close to the Fermi level. The induced two Fermi arcs have opposite spin polarization directions on each surface of a mirror symmetric slab. A nonmagnetic impurity at the Bi site can lead to the Fermi level. The induced two Fermi arcs have opposite magnetic Weyl semimetal with two pairs of Weyl nodes close.

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