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To cite this article: Kenta K Tanaka et al 2017 J. Phys.: Conf. Ser. 871 012024

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Spin-polarized local density of states around vortex in helical $p$-wave superconductors

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Abstract. Based on the quasi-classical Eilenberger theory, we investigate the magnetic field dependence of order-parameters and spin-polarized local density of states (LDOS) in the vortex lattice state of helical $p$-wave superconductors. The spin-polarized LDOS is induced by the vorticity coupling to the chirality of up-spin pair or down-spin pair, even when Knight shift does not change. We clarify the instability of the helical $p$-wave state at high field, and that the spin-polarized LDOS shows the unique behaviors of the helical $p$-wave state.

1. Introduction

The ruthenate superconductor Sr$_2$RuO$_4$ being a candidate for the spin-triplet chiral $p$-wave superconductor [1, 2] has attracted great interest in condensed matter physics, since topological quantum states such as a Majorana state are expected. However, the detail structure of $d$-vector in Sr$_2$RuO$_4$ remains unclear in spite of various studies both experimentally and theoretically. Thus, the helical $p$-wave state also has been studied as another scenario [3, 4, 5, 6]. In addition, according to the theoretical study employing the multi-orbital model of Sr$_2$RuO$_4$ [7], the condensation energy of chiral and helical $p$-wave states are very close. Therefore, it is important that we investigate an behavior of physical quantity depending on the $d$-vector symmetry to distinguish between the chiral and helical states in Sr$_2$RuO$_4$ or other candidate superconductors.

In the bulk state of chiral superconductor, the superconducting state with broken time-reversal symmetry is realized because of finite angular momentum of Cooper pair ($L_z \neq 0$). The chirality of Cooper pair in the chiral $p$-wave superconductor, i.e., $L_z = \pm 1$ can be distinguished via coherence effect in the vortex state. From the theoretical studies for the impurity effects on the local density of states (LDOS) and the local NMR relaxation rate [8, 9, 10, 11, 12], the chirality dependence of physical quantities is appeared by the vorticity coupling to the chirality, depending on whether the chirality is parallel ($L_z = +1$) or anti-parallel ($L_z = -1$) to the vorticity ($W = +1$) [13, 14]. On the other hand, the bulk state of helical $p$-wave superconductor is time-reversal-invariant. This is because the chirality $L_z = \pm 1$ are quenched with the degeneracy between up-spin and down-spin pairs. The order-parameter of up-spin (down-spin) pair $\Delta_{\uparrow\uparrow} (\Delta_{\downarrow\downarrow})$ has chirality $L_z = -1 (+1)$ so that $L_z + S_z = 0$ [3]. $S_z = +1(-1)$ is quantum number of spin state in up-spin (down-spin) pair. Therefore, in the vortex state of helical $p$-wave superconductor, spin components of LDOS are expected to show an unique behaviors, reflecting the vorticity coupling to the chirality of $\Delta_{\uparrow\uparrow} (L_z = -1)$ or $\Delta_{\downarrow\downarrow} (L_z = +1)$.
The site- and energy-dependence of LDOS in the vortex state can be detected by the scanning tunneling microscopy and spectroscopy (STM/STS) measurements in the various superconductors [15, 16]. Recently, the STM/STS measurement in the vortex state of topological insulator-superconductor Bi$_2$Te$_3$/NbSe$_2$ heterostructure has also performed [17], and theoretical analyses for the measurement have supported the existence of Majonara state at the inside of the vortex core [18, 19]. The spin-polarized Majonara state in the vortex state of heterostructure has been also examined by using the spin-polarized STM/STS method [20], which can selectively observe the spin-dependent conductance. In addition, the spin-polarized Majonara state in the vortex state of Cu$_4$Bi$_2$S$_3$ has been studied by solving the Bogoliubov-de Gennes equation [21].

In this work, we study the magnetic field $H$ dependence of the helical $p$-wave superconductor, and focus on the order-parameters and spin-polarized LDOS in the vortex lattice state. We especially calculate the site $r$- and $H$-dependences of the spin-polarized LDOS, and also the energy $E$ spectra in order to clarify the unique behavior of the helical state. We expect that these calculation results help to investigate the vortex state of helical $p$-wave superconductor and the Majorana state by using the spin-polarized STM/STS method.

This paper is organized as follows. After the introduction, we explain formulation of the Eilenberger equation in the vortex lattice state and the spin-resolved LDOS in section 2. In section 3, we study the $H$-dependence of order-parameter. In section 4, we show the $H$-dependence of spin-resolved and spin-polarized LDOS. The $E$-dependence of LDOS are presented in section 5. The last section is devoted to the summary.

2. Formulation of Eilenberger equation

We calculate the spatial structure of the vortex lattice state by the quasi-classical Eilenberger theory, which is valid for $k_F \xi \gg 1$ ($k_F$ is the Fermi wave number and $\xi$ is the coherence length). For various superconductors including Sr$_2$RuO$_4$, the quasi-classical condition is well satisfied [1, 2].

For simplicity, we assume the helical $p$-wave pairing on the cylindrical Fermi surface, $k = (k_x, k_y) = k_F (\cos \theta_k, \sin \theta_k)$, and the Fermi velocity $v_F = v_{F0} k_F$. In the following, the hat $\hat{v}$ indicates the $2 \times 2$ matrix in spin space and the check $\check{v}$ indicates the $4 \times 4$ matrix in particle-hole and spin spaces.

We obtain quasi-classical Green’s functions $\check{g}(i\omega_n, r, k)$ in the vortex lattice state by solving the Riccati equation derived from Eilenberger equation [22, 23]

$$-i v \cdot \nabla \check{g}(i\omega_n, r, k) = \frac{1}{2} \left[ (i\omega_n - v \cdot A) \check{\sigma}_z - \Delta(r, k), \check{g}(i\omega_n, r, k) \right]$$

in the clean limit, where $v = v_F / v_{F0}$, $r$ is the center-of-mass coordinate of the Cooper pair, $\check{\sigma}_z$ is the Pauli matrix, and $\omega_n$ is Matsubara frequency. The quasi-classical Green’s function and order parameter are defined by

$$\check{g}(i\omega_n, r, k) = -i\pi \left[ \begin{array}{cc} \check{g}(i\omega_n, r, k) & i\check{f}(i\omega_n, r, k) \\ -i\check{f}(i\omega_n, r, k) & -\check{g}(i\omega_n, r, k) \end{array} \right]$$

and

$$\Delta(r, k) = \left[ \begin{array}{cc} 0 & \hat{\Delta}(r, k) \\ -\hat{\Delta}^\dagger(r, k) & 0 \end{array} \right]$$

where $\check{g}^2 = -\pi^2 \mathbf{l}$. The matrix elements of $\check{g}$ and $\Delta$ are defined by $g_{\sigma \sigma'}(i\omega_n, r, k) = \{g_0(i\omega_n, r, k)\hat{1} + \sum_{\mu=x,y,z} g_{\mu}(i\omega_n, r, k) \check{\sigma}_\mu\}_{\sigma \sigma'}$ and $\Delta_{\sigma \sigma'}(r, k) = \left[ \sum_{\mu=x,y,z} (d_{\mu}(r, k) \check{\sigma}_\mu) \right]_{\sigma \sigma'}$ where $\sigma, \sigma' = \uparrow (\text{up-spin})$ or $\downarrow (\text{down-spin})$, and $d_{\mu}$ is $\mu$-component of $d$-vector. On the other hand, when we consider the order-parameter $\Delta_{+,-,\sigma}(r)$ and pairing function $\phi_{p\pm}(k) = k_x \mp ik_y$ for $p_{\pm}$-state, the matrix elements of order-parameter are also defined by

$$\Delta_{\sigma \sigma'}(r, k) = \Delta_{+,\sigma'}(r) \phi_{p+}(k) + \Delta_{-,\sigma'}(r) \phi_{p-}(k).$$
We assume the condition $\Delta_{\uparrow\downarrow} = \Delta_{\downarrow\downarrow} = 0$. Length, temperature, and magnetic field are measured in unit of $\xi_0$, $T_c$, and $B_0$, respectively. Here, $\xi_0 = \hbar v_0 / 2\pi k_B T_c$, $B_0 = \phi_0 / 2\pi \xi_0^2$, with the flux quantum $\phi_0$. $T_c$ is superconducting transition temperature at zero field. The energy $E$, pair potential $\Delta$ and $\omega_n$ are normalized by $\pi k_B T_c$. In the following, we set $\hbar = k_B = 1$. In this work, all calculations are set at $T = 0.5 T_c$.

As magnetic fields are applied to the $\hat{z}$ direction, the vector potential is set by $A(r) = \frac{1}{2} H \times r + a(r)$ in the symmetric gauge, where $H = (0, 0, H)$ is a average flux density, and $a(r)$ is related to the internal magnetic field $B(r) = (0, 0, B(r)) = H + \nabla \times a(r)$. We set the square vortex lattice as the unit cell [1].

In order to obtain the spatial structure of the quasi-classical Green’s functions and the order-parameter $\Delta(r)$ selfconsistently, we calculate $\hat{\Delta}(r)$ by the gap equation

$$
\hat{\Delta}(r) = g N_0 T \sum_{|\omega_n| \leq \omega_{\text{cut}}} \langle \phi_{p\pm}^*(k) \hat{f}(i\omega_n, r, k) \rangle_k,
$$

where $(g N_0)^{-1} = \ln T + 2 T \sum_{0 < \omega_n \leq \omega_{\text{cut}}} \frac{1}{\omega_n}, \langle \ldots \rangle_k$ indicates Fermi surface average, and we set $\omega_{\text{cut}} = 20 k_B T_c$. In equation (5), $\hat{\Delta}(r)$ is parallel to vorticity as $L$ superconductor at $H = 0$. As shown in figure 1(a), we present the quantum $\hat{\Delta}(r)$ selfconsistently, where $\langle f_n \rangle$ and $\langle \phi_{p\pm}^*(k) \hat{f}(i\omega_n, r, k) \rangle_k$ with the Ginzburg-Landau parameter $\kappa = B_0 / \pi k_B T_c \sqrt{8 \pi N_0}$ for the selfconsistent calculation of the vector potential. In this work, we set $\kappa = 2.7$ appropriate to Sr$_2$RuO$_4$ as a candidate superconductor for the chiral or helical state. Equations (1)-(5) for $\omega_n$ are calculated selfconsistently until the order-parameter converges. From this calculation, we obtain the results of $A(r)$, $\Delta(r)$ and the quasi-classical Green’s functions in the vortex lattice state.

$d$-vector in the helical $p$-wave superconductors is defined by $d(d) = k_x \hat{x} + k_y \hat{y} = \phi_{p+}(k) d_+ + \phi_{p-}(k) d_-$ at zero field $H = 0$, with $d_{\pm}(k) = \frac{1}{2} (1, \pm i, 0)$. Thus, when we iterate calculations of equations (1)-(5), as an initial value we set to be $d(r, k) = \frac{1}{2} (1, \pm i, 0)$. The spin-resolved LDOS $N_{\sigma}(E, r)$ is given by

$$
N_{\sigma}(E, r) = \langle \text{Re} \{ \langle g(E + i\eta, r, k) \rangle_{\sigma} \} \rangle_k.
$$

We define the LDOS $N(E, r) = N_{\uparrow}(E, r) + N_{\downarrow}(E, r)$, and spin polarized LDOS $M(E, r) = N_{\uparrow}(E, r) - N_{\downarrow}(E, r)$.

3. $H$-dependence of order-parameter

As shown in figure 1(a), we present the $H$-dependence of spatial average of the order-parameter amplitude, $|\langle \Delta_{\pm,\pm}^\uparrow(r) \rangle_r|$, given by equation (4). In the vortex state of helical $p$-wave superconductor at $H < 0.35 H_{c2}$, up-spin pair is described by $\Delta_{\uparrow\uparrow}^+(r, k) = \Delta_{-\downarrow\downarrow}^+(r, k) \phi_{p+}(k) + \Delta_{+\downarrow\downarrow}^+(r, k) \phi_{p-}(k)$ with small induced component $\Delta_{-\uparrow\downarrow}^+(r, k)$. The small component $\Delta_{-\uparrow\downarrow}^+(r, k)$ is induced around the vortex core, as shown in figure 1(b). The main component $\Delta_{-\uparrow\downarrow}^+(r, k)$ has chirality $L_z = -1$, anti-parallel to vorticity $W = +1$ as $L_z + W = 0$. From the previous theoretical studies for the chiral $p$-wave superconductor [13, 14], the anti-parallel vortex state ($L_z + W = 0$) is stable compared to the parallel vortex state ($L_z + W = +2$). Therefore, the $H$-dependence of $|\langle \Delta_{-\uparrow\downarrow}^+ \rangle_r|$ and $|\langle \Delta_{-\uparrow\downarrow}^\uparrow \rangle_r|$ survive until $H_{c2}$. On the other hand, down-spin pair is described by $\Delta_{\downarrow\uparrow}^-(r, k) = \Delta_{-\uparrow\downarrow}^+(r, k) \phi_{p+}(k) + \Delta_{-\uparrow\downarrow}^+(r, k) \phi_{p-}(k)$ with small induced $\Delta_{-\uparrow\downarrow}^+(r, k)$. In figure 1(a), $\Delta_{\downarrow\uparrow}^-(r, k)$ is rapidly suppressed with increasing $H$, since the chirality $L_z = +1$ of main $\Delta_{-\uparrow\downarrow}^+(r, k)$ is parallel to vorticity as $L_z + W = +2$. Besides, the $r$-dependence of order-parameter at low $H$, main components $\Delta_{-\downarrow\uparrow}^\downarrow$ and $\Delta_{-\downarrow\uparrow}^\uparrow$ show almost same behavior, and the induced component $\Delta_{-\downarrow\uparrow}^+(r, k)$ is very small amplitude at every position, as shown in figure 1(b).
In addition, we find that the helical $p$-wave state is unstable at higher $H$. At $H \sim 0.35 H_{c2}$, our calculation result shows the change of chirality $L_z = +1 \rightarrow -1$ in $\Delta_{\downarrow\uparrow}(r,k)$, and that $\Delta_{\downarrow\downarrow}(r,k)$ becomes main part of $\Delta_{\downarrow\downarrow}(r,k)$. At $H > 0.35 H_{c2}$, $\langle |\Delta_{\downarrow\downarrow}| \rangle_r (\langle |\Delta_{\downarrow\downarrow}| \rangle_r)$ becomes equal to $\langle |\Delta_{\uparrow\uparrow}| \rangle_r (\langle |\Delta_{\uparrow\uparrow}| \rangle_r)$ for main (small) components, so that the order-parameter is chiral form. Here, it remains $d_1 H$. Therefore, the transition at $H \sim 0.35 H_{c2}$ is helical-chiral transition. Note that this critical magnetic field value can shift if there are other contributions to stabilization of helical or chiral state such as spin-orbit coupling [4].

![Figure 1](image_url)

(a) $H$-dependence of the spatial average of the order-parameter amplitudes $\langle|\Delta_{\downarrow\downarrow}|\rangle_r$, $\langle|\Delta_{\downarrow\downarrow}|\rangle_r$, $\langle|\Delta_{\downarrow\downarrow}|\rangle_r$, and $\langle|\Delta_{\downarrow\downarrow}|\rangle_r$ defined by equation (4) in the helical $p$-wave state ($H < 0.35 H_{c2}$) and chiral $p$-wave state ($H > 0.35 H_{c2}$). (b) $r$-dependence of the order-parameter amplitudes $|\Delta_{\downarrow\downarrow}|$, $|\Delta_{\downarrow\downarrow}|$, $|\Delta_{\downarrow\downarrow}|$, and $|\Delta_{\downarrow\downarrow}|$ from the vortex center along the next-nearest-neighbor (NNN) direction at $H/H_{c2}=0.02$. $a_x$ is NNN intervortex distance.

4. $H$-dependence of spin-resolved and spin-polarized LDOS

In figure 2, we present the $H$-dependence of zero-energy $M(E=0,r)$ and $N_\sigma(E=0, r)$ at some positions on a line between NNN vortices at $H < 0.7 H_{c2}$. At the far-site of the vortex center such as $r/a_x = 0.5$ which is midpoint of between NNN vortices and $r/a_x = 0.2$, $N_\sigma(E=0, H > N_\sigma(E=0, H)$ and monotonically increase as a function of $H$. Thus, $M(E=0, r)$ has a finite value and monotonically increase as a function of $H$, and jumps to zero at the helical-chiral transition. On the other hand, at the vortex core region in figures 2(c) and 2(d), $M(E=0, r)$ at $H < 0.35 H_{c2}$ show a convex curve with large amplitude, where the first order transition is not obvious. In particular, at the vortex center in figure 2(e), $H$-dependence of $M(E=0, H)$ shows the monotonic decreasing behavior with sign change. However, the sign change of $M(E=0, H)$ vanishes at the $r/a_x = 0.025$, as shown in figure 2(d). These unique behaviors of the helical state are expected to be observed by spin-polarized STM measurement.

Moreover, we study the $H$-dependence of the zero-energy DOS $\langle N(E=0, r) \rangle_r$ and spin-polarized DOS $\langle M(E=0, r) \rangle_r$ with spin-resolved DOS $\langle N_\sigma(E=0, r) \rangle_r$. As shown in figure 2(f), the $H$-dependence of $\langle N_\uparrow(E=0, r) \rangle_r$ and $\langle M(E=0, r) \rangle_r$ show a similar behavior to the figures 2(a) and 2(b). In particular, the $\langle M(E=0, r) \rangle_r$ jumps to zero at the helical-chiral transition. At $H > 0.35 H_{c2}$ as the vortex state of chiral $p$-wave superconductor, where $\Delta_{\downarrow\downarrow} = \Delta_{\uparrow\uparrow}$. $M$ vanishes. We expect that the jump behavior is observed by the low temperature specific heat measurement. The jump of specific heat is large (small) when the helical-chiral transition occurs at high (small) $H$.

In addition, since the zero energy states localized inside the vortex core in the chiral and helical superconductors correspond to Majorana zero energy mode, figure 2(f) shows that the spin-polarized Majorana state is induced in the helical $p$-wave superconductors. This is another type
of spin-polarized Majorana state than that supposed in the vortex state of Bi$_2$Te$_3$/NbSe$_2$ [19] or Cu$_x$Bi$_2$Si$_3$ [21].

5. $E$-dependences of spin-polarized LDOS

We study the $E$-dependence of $N_\sigma(E, r)$ and $M(E, r)$ at the same positions on a line between NNN vortices, in order to study the LDOS spectrum of spin-polarized STS measurement. As shown in upper panel of figures 3(a)-(c), $N_\uparrow(E=\pm0.5, r)$ are larger than $N_\downarrow(E=\pm0.5, r)$, and the $N_\uparrow$ peaks of the gap edge ($E=\pm0.5$) outside vortices can survive until the vortex center. Thus, $M(E, r)$ at all positions are negative at $E=0$, as shown in lower panel of figures 3(a)-(c). Moreover, we focus on the low- or zero-energy peaks of $N_\sigma$ at the vortex core region, coming from the vortex bound state. As shown in figures 3(b) and 3(c), the height of low-energy peaks in $N_\uparrow$ are smaller than $N_\downarrow$. Thus, $M(E, r = 0)$ is positive around $E = 0$, and $M(E, r)$ at all positions show the sign change as a function of $E$. Note that, these weights cancel each other because of the condition of total spin polarization $\int_0^E M(E, r) dE = 0$. This condition indicates that the Knight shift does not work in the helical $p$-wave state, where $d \parallel \mathbf{H}$. In order to detect the spin-polarized LDOS in the helical state, we have to perform $E$-resolved measurement such as a spin-polarized STM/STS method.

As shown in figures 4(a)-(c), we also investigate the higher field $H \approx 0.29 H_c$ cases. In figure 4(a) at outside of the vortex core $r/a_x = 0.5$, amplitude of low-energy $M(E, r)$ has larger than low field $H \approx 0.02 H_c$ case, since low-energy $N_\sigma(E, r)$ are induced and spin-polarization is reinforced by the magnetic field. Besides, in upper panel of figure 3(a), $E$-dependence of $N_\sigma(E, r)$ almost correspond to the zero magnetic state. In figure 4(b) around the vortex core, we can see some sign change behavior of $M(E, r)$ since the $E$-dependence of $N_\sigma(E, r)$ continuously change at all $E$ range. The $E$-dependence of $M(E, r)$ at the vortex center is notably different from the
low field $H \approx 0.02 H_{c2}$ case in lower panel of figure 3(c). In figure 4(c), the height of zero-energy peak of $N_j$ becomes larger than $N_\uparrow$, resulted in negative $M(E = 0, r = 0)$. To compensate negative value at $E = 0$ and at the gap edge, $M(E, r = 0)$ becomes positive for in-gap states for $0 < |E| < 0.5$.

Figure 3. (a), (b), and (c) $E$-dependence of spin-resolved LDOS $N_j$, $N_\uparrow$ (upper panels), and spin-polarized LDOS $M$ (lower panels) at $H/H_{c2} \approx 0.02$ at $r/a_x = 0.5, 0.1, 0.0$ from the vortex center along the NNN direction, respectively. we use $\eta = 0.03$.

Figure 4. (a), (b), and (c) $E$-dependence of spin-resolved LDOS $N_j$, $N_\uparrow$ (upper panels), and spin-polarized LDOS $M$ (lower panels) at $H/H_{c2} \approx 0.29$ at $r/a_x = 0.5, 0.1, 0.0$ from the vortex center along the NNN direction, respectively. we use $\eta = 0.03$.

6. Summary
We studied the $H$-dependence of helical $p$-wave superconductors, and calculated the order-parameters $\Delta_{\pm,\sigma \sigma'}(r)$ and spin-polarized LDOS $M(E, r)$ by solving the quasi-classical Eilenberger equation in the vortex lattice state. From the calculation results of $H$-dependence of order-parameter, the helical $p$-wave state is unstable at high fields and changes to the chiral $p$-wave state. In addition, we revealed that the spin-polarized LDOS $M(E, r)$ is induced by the vorticity coupling to the chirality, while the Knight shift does not change. In order to identify the helical $p$-wave state at low fields, we especially investigated the $H$-dependence of zero-energy $M(E = 0, r)$ related to Majorana state, and found that $M(E = 0, r)$ shows various behavior as a function $H$ according to its position. In fact, $H$-dependence of $M(E = 0, r)$ shows monotonically increasing behavior with small value at the far-site of the vortex center, convex curve around the vortex core, and monotonically decreasing behavior with sign change at the vortex center. Moreover, we presented the $E$-dependence of $N_j(E, r)$, $N_\uparrow(E, r)$ and $M(E, r)$ at the same positions at low and high fields. The $E$-dependences of $M(E, r)$ at some positions show the unique sign change behavior. These calculation results of spin-polarized LDOS are expected to be examined and be used for detecting the spin-polarized Majorana state by the spin-polarized STM/STS measurement.

Acknowledgments
This work was supported by JSPS KAKENHI Grant Number JP16J05824.
References

[1] Mackenzie A P and Maeno Y 2003 Rev. Mod. Phys. 75 657
[2] Maeno Y, Kittaka S, Nomura T, Yonezawa S and Ishida K 2012 J. Phys. Soc. Jpn. 81 011009
[3] Rice T M and Sigrist M 1995 J. Phys.: Condens. Matter 7 L643
[4] Takamatsu S and Yanase Y 2013 J. Phys. Soc. Jpn. 82 063706
[5] Scaffidi T, Romers J C and Simon S H 2014 Phys. Rev. B 89 220510(R)
[6] Zhang J, Lörscher C, Gu Q and Klemm R A 2014 J. Phys.: Condens. Matter 26 252201
[7] Tsuchiizu M, Yamakawa Y, Onari S, Ohno Y and Kontani H 2015 Phys. Rev. B 91 155103
[8] Kato Y and Hayashi N 2003 Physica C 388 519
[9] Tanuma Y, Hayashi N, Tanaka Y and Golubov A A 2009 Phys. Rev. Lett. 102 117003
[10] Kurosawa N, Hayashi N and Kato Y 2015 J. Phys. Soc. Jpn. 84 114710
[11] Hayashi N and Kato Y 2003 Physica C 388 513
[12] Tanaka K, Ichioaka M and Onari S 2016 Phys. Rev. B 93 094507
[13] Ichioaka M and Machida K 2002 Phys. Rev. B 65 224517
[14] Heeb R and Agterberg D F 1999 Phys. Rev. B 59 7076
[15] Hess H F, Robinson R B, Dynes R C, Valles J M, Jr. and Waszczak J V 1989 Phys. Rev. Lett. 62 214
[16] Fischer O, Kugler M, Maggio-Aprile I, Berthod C and Renner C 2007 Rev. Mod. Phys. 79 353
[17] Xu J -P, Wang M -X, Liu Z L, Ge J -F, Yang X, Liu C, Xu Z A, Guan D, Gao C L, Qian D, Liu Y, Wang Q -H, Zhang F -C and Jia J -F 2015 Phys. Rev. B 91 144504
[18] Li Z -Z, Zhang F -C and Wang Q -H 2014 Sci. Rep. 4, 6363
[19] Kawakami T and Hu X 2015 Phys. Rev. Lett. 115 177001
[20] Sun H -H, Zhang K -W, Hu L -H, Li C, Wang G -Y, Ma H -Y, Xu Z -A, Gao C -L, Guan D -D, Li Y -Y, Liu C, Qian D, Zhou Y, Fu L, Li S -C, Zhang F -C and Jia J -F 2016 Phys. Rev. Lett. 116 257003
[21] Nagai Y, Nakamura H and Machida M 2014 J. Phys. Soc. Jpn. 83 064703
[22] Eilenberger G 1968 Z. Phys. 214 195
[23] Tsutsumi Y, Kawakami T, Shiozaki K, Sato M and Machida K 2015 Phys. Rev. B 91 144504