A Magnetic Weyl Fermion State in Non-Collinear Antiferromagnet Mn_3Sn

Weyl fermions have been recently observed as gapless topological excitations in a number of inversion-breaking semimetals. However, their realization in spontaneously time-reversal-symmetry-breaking phases so far has evaded experimental detection. We present here an angle-resolved photoemission study of a noncollinear antiferromagnet Mn_3Sn that exhibits a large anomalous Hall effect even at room temperature, and reveal a magnetic Weyl fermion state in the quasiparticle electronic structures by a detailed comparison with our density functional theory calculation and transport measurements. This discovery lays the foundation for a new field of science and technology involving the magnetic Weyl excitations of the novel magnet, "*Weyl magnet.*"

When either inversion-symmetry or time-reversal-symmetry (TRS) is broken in solid states, two nondegenerate energy bands can touch at pairs of isolated points in the momentum (k) space, giving rise to Weyl quasiparticles. The touching points, the so-called Weyl points, act as the monopoles of Berry curvature [1], leading to exotic bulk properties represented by a large anomalous Hall effect (AHE).

In the past three years, Weyl fermion states have been experimentally observed as gapless topological excitation in a number of inversion-breaking semimetals by angle-resolved photoemission spectroscopy (ARPES) [2]. However, their realization in spontaneously TRS-breaking phases, the so-called magnetic Weyl fermion, has remained hypothetical even though they have been theoretically predicted since the early stage of research [3].

In this work, by using synchrotron radiation ARPES, we observed the magnetic Weyl fermion state in a noncollinear antiferromagnet, Mn_3Sn. This compound is formed by a stacking of kagome lattice and the geometrical frustration leads to a 120° structure of Mn moments, whose symmetry allows a very small spin canting and thus vanishingly small magnetization [Fig. 1(a)]. Remarkably, this is the first antiferromagnet (AFM) that exhibits a surprisingly large AHE below the Néel temperature of 430 K [4]. Such a large AHE in an AFM indicates a novel mechanism that induces a large Berry curvature [5, 6].

According to our density functional theory calculation, the TRS-breaking in Mn_3Sn lifts the spin degeneracy and leads to band crossing at many *k* points, resulting in various pairs of Weyl nodes. Among them, the most relevant for macroscopic measurements are found in the $k_z = 0$ plane [Fig. 1(b)]. As an important consequence of the magnetic symmetry, the electronic structure becomes orthorhombic. For the K–M–K line [arrows in Fig. 1(b)], the electron–hole band crossing generates the Weyl nodes. Therefore, the presence of the electron and hole bands around the M point is key for realizing magnetic Weyl fermions in Mn_3Sn.

To search for these quasiparticle structures in three dimensions, we use synchrotron radiation ARPES. By changing $h\nu$, we observe clear k_z dispersion along the H–K–H line with the quasiparticle peak developed near the Fermi level (E_F) around K in Fig. 1(d). This clarifies that the incident $h\nu$ of 103 eV selectively detects the bulk band dispersion at $k_z = 0$, where the Weyl nodes should exist near E_F. Moreover, the contour of photoelectron intensity clarifies the location of the Fermi surfaces (FSs) on the k_x–k_y plane [Fig. 1(c)]. The experiment clearly captures the main elliptical-shaped contours centered at the M points, which have the same topology as the theoretical FSs (solid circle). This agreement is significant as it is this electron band that creates the Weyl points at its intersection with the other hole band.

Figure 1(e) shows ARPES images along the K–M–K high symmetry line obtained before (left) and after (right) dividing the intensities by the Fermi–Dirac distribution function to detect thermally populated bands above E_F. We observe intensity anomalies particularly in the momentum distribution curve [Fig. 1(f)], arising from the crossings between the electron and hole bands. Comparing with theory, we note that the peak (red bar) at $k_x \approx 0.3$ Å^{-1} (–0.3 Å^{-1}) between K and M points most likely comes from the dispersion in the immediate vicinity of the Weyl point W^+_1 (W^-_2) [Fig. 1(b)]. The peak (red bar) at $k_x \approx 0.5$ Å^{-1} (–0.5 Å^{-1}) between the K and Γ_{2nd} points corresponds to a large electron band, which crosses with another band and forms a Weyl point W^-_1 (W^+_2) of different chirality. The single peak at $k_x \approx 0.1$ Å^{-1} [blue bar in Fig. 1(f)] is shifted from $k_x = 0$ by the intensity gradient and would arise from the flat hole band at ~14 meV above E_F. These results appear to be consistent with the theoretically predicted FSs and quasiparticle band structures.

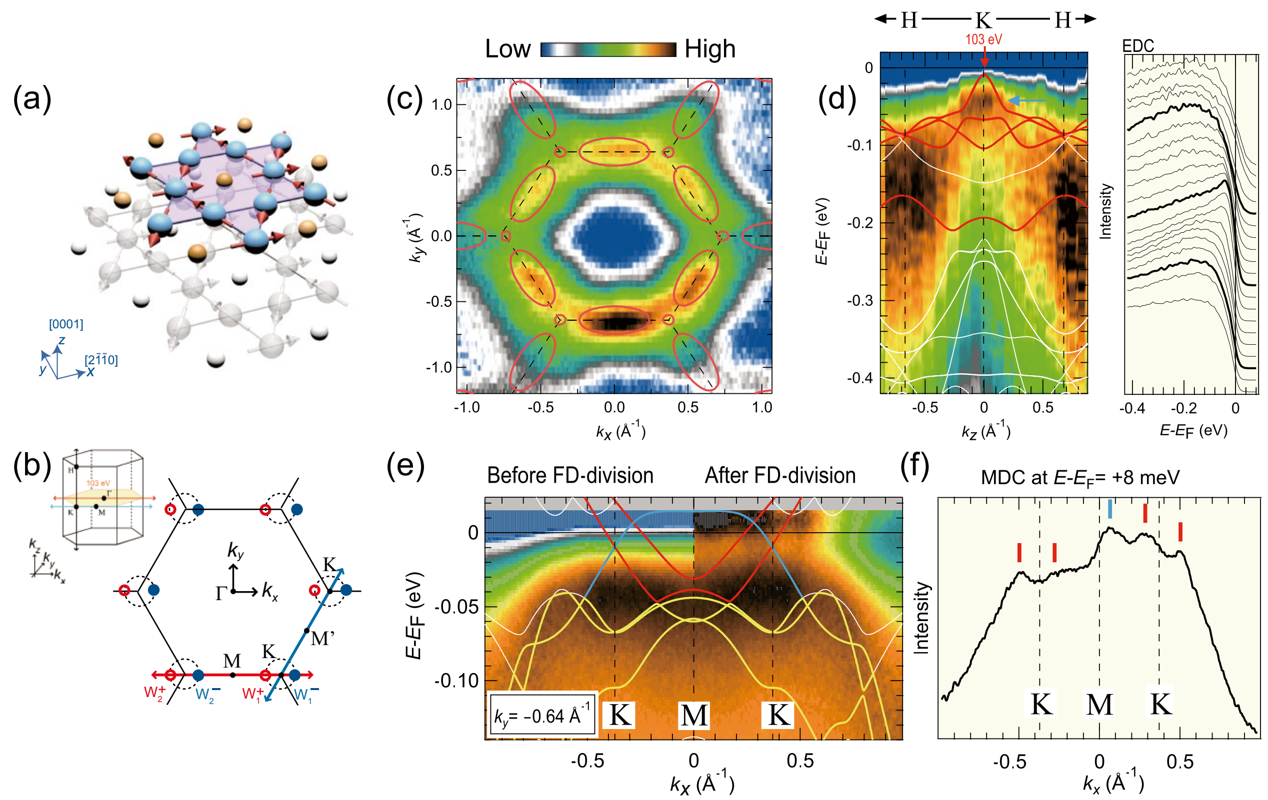

Figure 1: (a) Magnetic texture in the kagome lattice. Arrows indicate Mn moments which have the local easy axis parallel to the in-plane direction along the x axis. (b) Distribution of the Weyl points in the bands on the k_x–k_y plane at $k_z = 0$ near E_F for the magnetic texture shown in (a), and Brillouin zone, showing the momentum sheet at $k_z = 0$. (c) ARPES intensity at E_F in the k_x–k_y plane using an energy $h\nu = 103$ eV and the calculated Fermi surface (purple curves). (d) Left: k_z dispersion along the H–K–H high-symmetry line [black arrows in (b)], and Right: corresponding energy distribution curves (EDC). The ARPES maps are compared to the band calculations with strong band renormalization by a factor of five (solid lines). (e) ARPES E-k_x cuts and the theoretical band structures along the K–M–K high symmetry line. (f) Corresponding momentum distribution curve (MDC) at E–$E_F \approx 8$ meV.

Moreover, these results of the spectroscopic measurement of the Weyl points are consistent with our transport measurements that show topological transport properties such as AHE and chiral anomaly [7]. These facts constitute evidence for magnetic Weyl fermions realized in Mn_3Sn. Our experimental observations thus mark the start of basic research on magnetic Weyl fermions in the novel magnet, "*Weyl magnet,*" which may well lead to novel electronic and spintronic technology for future applications.

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