Discovery of New Chiral Fermions in CoSi

The search for new fermions in condensed matter is currently a hot topic in materials science. Topological semimetals with chiral crystal structure were predicted to host new types of massless fermions distinct from well-known Dirac and Weyl fermions, whereas such exotic fermions are yet to be clarified. Using angle-resolved photoemission spectroscopy (ARPES), we demonstrated that cobalt silicide CoSi hosts two types of exotic fermions, a spin-1 fermion and a double Weyl fermion. We also revealed unusual Fermi-arc surface states connecting the Fermi surfaces associated with these fermions. Our result provides the first experimental evidence for the chiral topological fermions beyond Dirac and Weyl fermions, and paves the way toward realizing exotic electronic properties associated with exotic nodal fermions.

The discovery of Dirac fermions in graphene has accelerated investigations on the physical properties of Dirac-fermion systems and the utilization of Dirac fermions in advanced electronic devices. The Dirac fermion is regarded to be highly useful, for example, in high-speed devices, due to its inherently high mobility. The recent discovery of another type of massless fermion, called the Weyl fermion, increased the categories of nodal fermions and triggered further investigations on unusual magneto-transport properties. Such discoveries naturally pose an essential question as to whether or not more exotic nodal fermions beyond the so-far discovered Dirac and Weyl fermions can be realized. It has been recently proposed by theory that new types of fermions can exist in crystals with specific symmetries and space groups [1–5]. This is exemplified by the prediction of a *spin-1 fermion* containing Dirac-type energy dispersion and a flat energy band, as well as a *double Weyl fermion* which is composed of two Dirac-cone-like energy dispersions [Fig. 1(A)] [6]. Intriguingly, while Dirac and Weyl fermions could manifest themselves in elementary-particle physics and can exist in vacuum, these new types of massless fermions in condensed-matter systems have no counterparts in elementary particles. Moreover, such fermions likely have topological properties (such as robustness against impurities) and could be useful for advanced applications beyond the framework of so-far realized Dirac and Weyl fermions. It is thus highly desirable to experimentally verify the existence of such new types of nodal fermions.

We have fabricated a high-quality single crystal of cubic CoSi with chiral crystal structure [Fig. 1(B)] which was predicted to host unconventional nodal fermions [6], and have accurately determined its electronic structure using high-resolution angle-resolved photoemission spectroscopy (ARPES) [7]. By utilizing bulk-sensitive soft-X-ray (SX) photons as well as surface-sensitive vacuum ultraviolet (VUV) photons, we have succeeded for the first time in directly observing the three-dimensional (3D) band structure of the bulk as well as the 2D band structure of the surface. As a result, we revealed two kinds of nodal fermions. The first one is seen around the Γ point of the bulk Brillouin zone and shows an energy dispersion characterized by an X-shaped band and a flat band which intersect exactly at the Γ point [Fig. 1(C)]. This strongly supports the existence of a spin-1 fermion in CoSi. The second one is seen at the R point of the bulk Brillouin zone showing a couple of Dirac-cone-like energy dispersions that intersect exactly at the R point [Fig. 1(D)], supporting the existence of a double Weyl fermion. Intriguingly, experimental band dispersions were found to show good agreement with the calculated band structure obtained by first-principles band calculations for bulk CoSi, as indicated by red curves in Figs. 1(C) and 1(D). We also found that there exist no other bulk Fermi surfaces, suggesting that low-energy excitations in CoSi are solely dictated by the energy bands related to these fermions, providing an excellent opportunity to realize unconventional transport properties.

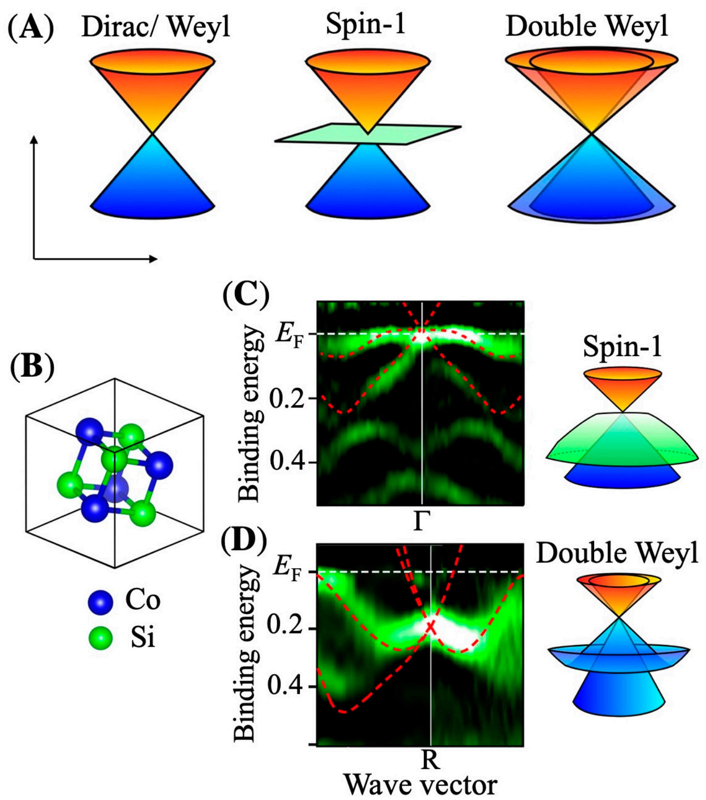

Figure 1: (A) Schematic band dispersion of Dirac/Weyl, spin-1, and double Weyl fermions. (B) Crystal structure of CoSi. (C), (D) Experimental band dispersions (second derivative of ARPES intensity) together with the calculated band dispersions (red curve) around the Γ and R points of the bulk Brillouin zone, measured at hν = 170 eV and 136.4–181.2 eV, respectively [7].

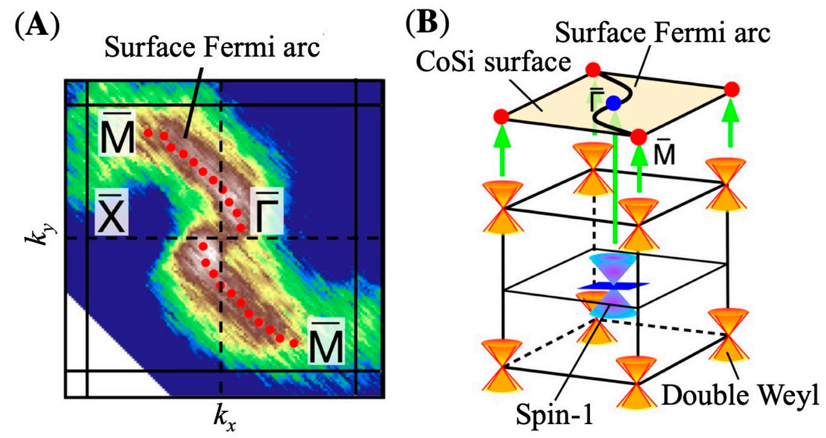

Figure 2: (A) Fermi-surface mapping of CoSi with VUV photons (hν = 67 eV) supporting the existence of Fermi-arc surface states [7]. (B) Schematic showing the relationship between the bulk nodal-fermion features and the Fermi-arc surface states.

To search for the possible existence of surface states associated with these fermions, we performed ARPES measurements with VUV photons. As shown in Fig. 2(A), the ARPES intensity is apparently elongated toward two of four adjacent $\bar{M}$ points in the surface Brillouin zone, producing a two-fold-symmetric "Z"-shaped intensity pattern. This feature is commonly observed at other photon energies (not shown), suggestive of its surface origin, and is likely attributed to the predicted Fermi-arc surface states [6], since the calculated surface states exhibit the two-fold-symmetric Fermi contour and connect with the bulk Fermi surfaces at the $\bar{\Gamma}$ and $\bar{M}$ points [Fig. 2(B)], consistent with the present ARPES results.

Based on the observation of both bulk nodal-fermion features and the Fermi-arc surface states, the present ARPES study on CoSi firmly establishes the existence of new fermions in a solid which have no counterparts in elementary particles. The result also lays a foundation for studying unconventional physical properties related to the chiral fermions, and paves the way toward the possible application of exotic nodal fermions in advanced electronics.

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