Two-Dimensional Electronic States Localized on the Clean Surface of the Topological Kondo Insulator YbB_{12}

The unconventional two-dimensional electronic state localized on the atomically-flat clean surface of an ytterbium dodecaboride (YbB_{12}) single crystal was discovered by using synchrotron-radiation angle-resolved photoelectron spectroscopy. The surface electronic state of YbB_{12} was revealed to be protected by the synergetic effect between the topology and strong electron correlation (Kondo effect) of the three-dimensional (bulk) bands of YbB_{12}. These results warrant further research on the combination between topological surface states and strong electron correlation.

Different from the inside of a crystal (bulk), where atoms align according to the perfect three-dimensional periodicity, various unique phenomena occur on the surface of a crystal. Among them, the surface electronic states strongly related to the bulk atomic/electronic structures are an interesting field as the crossover region between three-dimensional bulk and two-dimensional surface. Among such physical phenomena, a Topological Surface State (TSS) [1], whose properties are determined by the symmetry of the electronic state in the bulk, has attracted much attention in the last decade. The TSS shows a metallic band structure hosting the two-dimensional conduction path on the crystal surface without being affected by fine atomic structures or by contaminations on the crystalline surface. The spin orientation of the TSS varies depending on the flow of electrons even if the bulk has no magnetism. These features of TSS are attractive for industrial applications such as next-generation spintronic devices. On the other hand, from a scientific point of view, electronic correlation effects on the TSS in particular have been discussed in recent years.

Strong electron-correlation effects cause various phenomena such as high-temperature superconductivity and giant magnetoresistance in bulk electronic structures. Various new physical phenomena due to the combination of these phenomena and the TSS are theoretically predicted [2]. However, it is difficult to experimentally fabricate the TSS which is closely involved in strong electron correlation effects. One particular insulator, samarium hexaboride (SmB_6), which is called the Topological Kondo Insulator (TKI) and transitions from metal to semiconductor via the Kondo effect at low temperatures, was reported [3]. However, since some researchers interpreted the surface electronic state of SmB_6 differently [4], it is still unclear whether or not SmB_6 is really a TKI or if there exists a TSS that would appear through electronic correlation.

In this work, we have discovered a new TSS on a clean surface of ytterbium dodecaboride (YbB_{12}) by synchrotron-radiation angle-resolved photoelectron spectroscopy (ARPES). YbB_{12} is known as another typical material that undergoes the metal to semiconductor transition via the Kondo effect as SmB_6, but its surface electronic structure had been unclear since an experimental technique for obtaining a clean surface of YbB_{12} had not been established. We succeeded in obtaining an atomically-flat clean surface of YbB_{12} in an ultra-high vacuum chamber [5] and revealed that the surface state showed continuous dispersion across the Fermi level, indicating its metallic nature, as well as clear hybridization and reconstruction as expected from the Kondo effect of the bulk electronic structure [6].

Figure 1 shows the wide-valence band spectra for the YbB_{12}(001) surface cleaned *in-situ* by flashing the sample up to 1650 K for ~10 s. The upper (lower) spectrum is obtained with the surface- (bulk-) sensitive condition taken at the photon energy of 80 eV (500 eV). The Yb^{2+}-4*f* peaks (0, 1.5 eV) and Yb^{3+}-4*f* multiplet peaks appeared in the same way in both the bulk and surface region, indicating that a clean surface without any contamination was prepared successfully: the broad hump at 1–4 eV in the surface spectrum is from B-2*sp* bands which are not visible in the 500-eV excitation spectrum of the bulk-sensitive condition because of the low cross section of the B-2*sp* bands at the excitation photon energy.

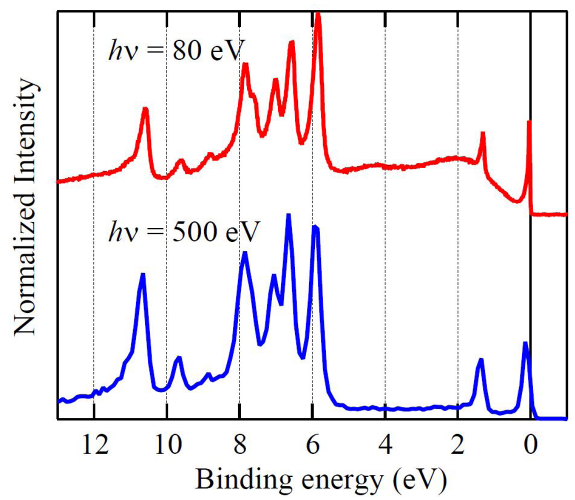

Figure 1: Wide valence-band spectra of the clean surface of YbB_{12}(001) taken at the excitation photon energies of 80 eV (surface sensitive) and 500 eV (bulk sensitive) at the temperature of 20 K.

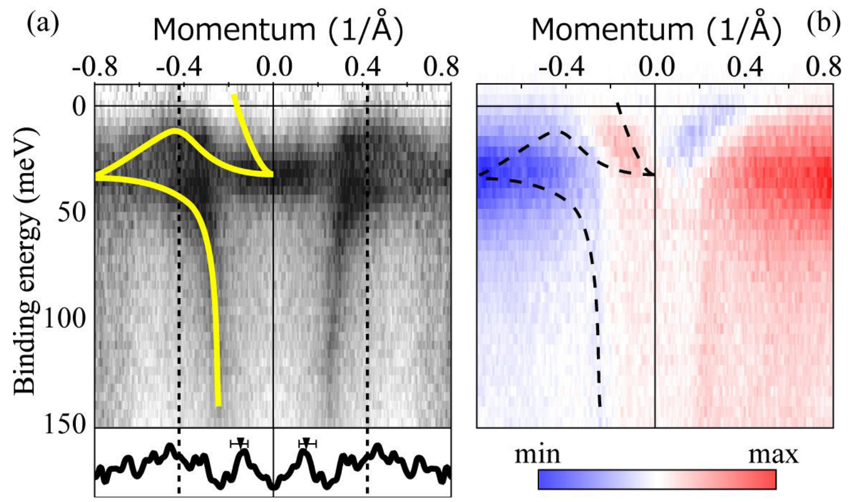

Figure 2: (a) ARPES image of YbB_{12}(001). The dark area shows high electron intensity. Yellow lines are guides to the eye for surface-state dispersions. The lower inset is the momentum distribution curve at the Fermi level. **(b)** Orbital polarization structure obtained by circular dichroism of ARPES. The red/blue area represents the polarization along the opposite direction to each other. Dashed lines are surface-state dispersions in **(a)**.

Figure 2 is an ARPES image showing the surface electronic structure at the temperature of 20 K. As indicated by the yellow guide in **Fig. 2a**, the surface states clearly disperse across the Fermi level, indicating its metallic nature. The metallic nature is not the three-dimensional bulk bands of YbB_{12} since it shows a metal-to-semiconductor transition with decreasing temperature and thus the bulk bands are absent around the Fermi level. **Figure 2b** is the circular dichroism of ARPES indicating the helical orbital polarization of the metallic surface state. Such orbital polarization is closely related to the spin polarization. These results strongly suggest that the metallic surface state on YbB_{12}(001) is the topological surface state. Moreover, since the TSS disperses across the bulk Kondo gap, this topological state is driven by the Kondo effect.

REFERENCES

[1] M. Z. Hasan and C. L. Kane, *Rev. Mod. Phys.* **82**, 3045 (2010).
[2] M. Dzero, K. Sun, V. Galitski and P. Coleman, *Phys. Rev. Lett.* **103**, 106408 (2010).
[3] H. Miyazaki, T. Hajiri, T. Ito, S. Kunii and S. Kimura, *Phys. Rev. B* **86**, 075105 (2012).
[4] P. Hlawenka, K. Siemensmeyer, E. Weschke, A. Varykhalov, J. Sánchez-Barriga, N. Y. Shitsevalova, A. V. Dukhnenko, V. B. Filipov, S. Gabáni, K. Flachbart, O. Rader and E. D. L. Rienks, arXiv: 1502.01542 (2015).
[5] K. Hagiwara, Y. Takeno, Y Ohtsubo, R. Yukawa, M. Kobayashi, K. Horiba, H. Kumigashira, J. Rault, P. L. Fèvre, F. Bertran, A. Taleb-Ibrahimi, F. Iga and S. Kimura, *J. Phys.: Conference Series* **807**, 012003 (2017).
[6] K. Hagiwara, Y. Ohtsubo, M. Matsunami, S. Ideta, K. Tanaka, H. Miyazaki, J. E. Rault, P. L. Fèvre, F. Bertran, A. Taleb-Ibrahimi, R. Yukawa, M. Kobayashi, K. Horiba, H. Kumigashira, K. Sumida, T. Okuda, F. Iga and S. Kimura, *Nature Commun.* **7**, 12690 (2016).

BEAMLINE

BL-2A

Y. Ohtsubo[1], K. Hagiwara[1], J. E. Rault[2], P. Le Fèvre[2], F. Bertran[2], A. Taleb-Ibrahimi[2], R. Yukawa[3], M. Kobayashi[3], K. Horiba[3], H. Kumigashira[3], F. Iga[4] and S. Kimura[1] ([1]Osaka Univ., [2]Synchrotron SOLEIL, [3]KEK-IMSS-PF, [4]Ibaraki Univ.)