Realization of a Monoatomic Layer Heavy Fermion

Heavy fermion (HF), which originates from the hybridization between localized *f*-electrons and conductive carriers via the Kondo effect, is a host of exotic physical phenomena among strongly correlated electron systems. Dimensionality in HFs is also essential for the quantum criticality between the localized and itinerant characters. However, the realization of the perfect two-dimensional (2D) HF materials is still a challenging topic. Here, we report the 2D HF in the monoatomic-layer Kondo lattice $YbCu_2$ fabricated on a Cu(111) substrate observed with synchrotron-based photoemission spectroscopies. Our study provides a new aspect as an ideal 2D HF material for understanding the Kondo effect at low dimensions.

Heavy fermion (HF) systems in rare-earth (RE) intermetallic compounds originating from hybridization between localized 4*f*-electrons and conduction electrons (*c*-*f* hybridization) are extensively studied in the field of strongly correlated electron systems [1]. Depending on the hybridization strength at low temperatures, the physical properties change from itinerant HF due to the Kondo effect to a magnetic ordering with localized *f*-electrons due to the Ruderman–Kittel–Kasuya–Yosida interaction. The competition between the duality of the *f*-electrons makes a magnetic quantum critical point (QCP), resulting in the emergence of fertile quantum phenomena such as non-Fermi liquid behavior and non-BCS HF superconductivity [2].

The dimensionality in the system characterizes the fundamental physical property. The combination of the HF state and low dimensionality modifies the ground state to the vicinity of the QCP because the order parameter of HF systems is much more sensitive to dimensionality [3]. However, the details have remained unclear due to the lack of promising materials to investigate the low-dimensional HF. In this study, we report the two-dimensional (2D) HF electronic structure of a novel Yb-based monoatomic layer material $YbCu_2$ on a Cu(111) substrate by synchrotron-based angle-resolved photoemission spectroscopy (ARPES) and core-level photoemission spectroscopy.

The fabricated surface atomic structure of $YbCu_2$ on Cu(111) is shown in Figs. 1(a, b). The Yb atoms surrounded by Cu atoms are arranged in a triangular lattice. Figure 1(c) shows the ARPES image around the Γ point at 15 K. There are two significant bands: one is the flat band (S1) close to the Fermi level (E_F), and the other is the highly dispersive band (S2) with the top at the Γ point. By comparing with the DFT calculation, the flat and dispersive bands mainly originate from the Yb^{2+} $4f_{7/2}$ and the mixing of the Yb 5*d* and Cu *sp* and *d* orbitals, respectively [4]. The conduction band splits into S1 and S2 branches, indicating the *c*-*f* hybridization formation. To evaluate the *c*-*f* hybridization parameters, the dispersion bands were fitted with the periodic Anderson model (PAM) [5]. The Fermi velocity (v_F) and Fermi wavenumber (k_F) of the bare unhybridized conduction band were evaluated as 4.77 eV Å and 0.004 $Å^{-1}$, respectively. From these values, the effective mass of bare conduction band m_b becomes 5.65×10^{-33} kg. On the other hand, by the PAM fitting of the ARPES band dispersion near E_F at 15 K, v_F and k_F of the *c*-*f* hybridization band are 0.58 eV Å and 0.055 $Å^{-1}$, respectively, and the effective mass m^* of the HF band is 6.56×10^{-31} kg. By comparing the experimentally obtained heavy conduction band at 15 K and the simulated bare conduction band, a mass enhancement factor (m^*/m_b) is about 120 at 15 K, suggesting the appearance of heavy quasiparticles at low temperatures.

To determine the dimensionality of the *c*-*f* hybridization bands, the photon-energy dependence of ARPES was measured, as shown in Fig. 1(d). The S1 and S2 bands are almost straight at different photon energies, indicating no out-of-plane dispersion. These experimental results strongly suggest that the *c*-*f* hybridization bands have the 2D HF character, i.e., the fabricated monoatomic layer $YbCu_2$ is 2D HF.

The HF character strongly relates to the mixed valence of the Yb ions. To clarify the valency of the Yb ions, the Yb 3*d* core-level spectrum was measured at 15 K, as shown in Fig. 2. The photoelectron peaks at the binding energies of 1528 and 1538 eV originate from the Yb^{2+} and Yb^{3+} 3*d* final states, respectively. From the intensity ratio between the Yb^{2+} and Yb^{3+} peaks after subtracting the background, the mean valence of Yb ions was evaluated as 2.41±0.01, indicating mixed valence character.

Our spectroscopic data provide direct evidence of the appearance of a purely 2D HF state with the mixed valence in a monolayer material. $YbCu_2$ is the minimal material to realize a low-dimensional HF, which is the host of the novel electron-correlation-driven phenomena such as atomic-layer unconventional superconductivity.

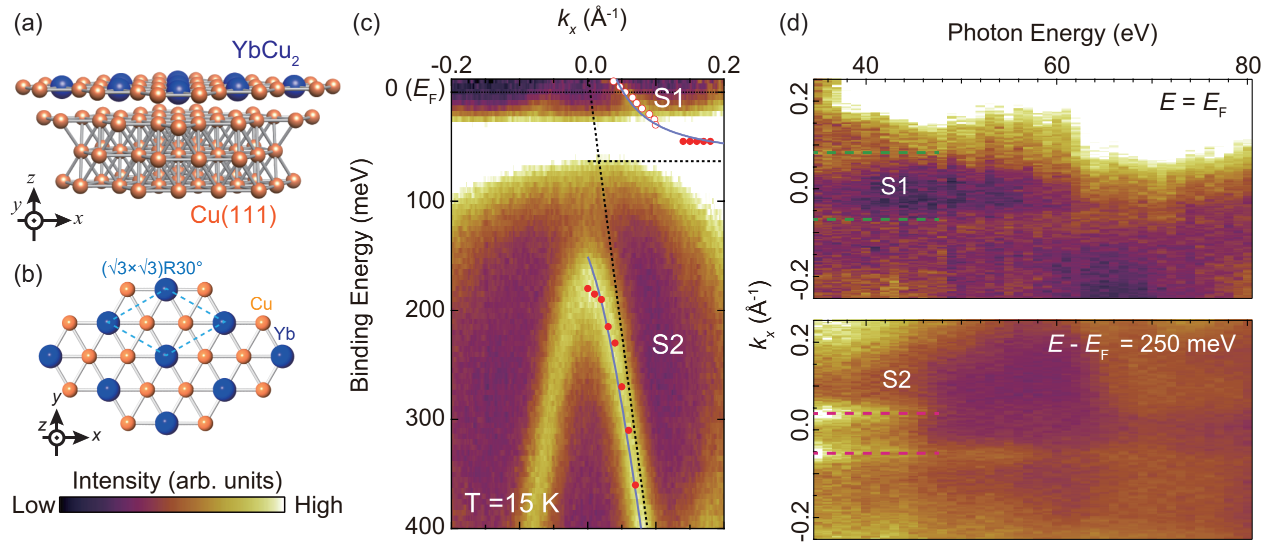

Figure 1: (a) A surface atomic structure of $YbCu_2$/Cu(111). **(b)** Top view of monoatomic-layer $YbCu_2$. The dashed line indicates the unit cell of $YbCu_2$. **(c)** ARPES image near the Γ point taken with circularly polarized 35-eV photons at 15 K. ARPES intensities are divided by the Fermi–Dirac distribution function convolved with the instrumental resolution. The open and filled circles indicate the peak positions from energy distribution curves (EDCs) and momentum distribution curves (MDCs), respectively. The solid and dotted lines indicate the simulated band dispersions by the periodic Anderson model for the hybridization energies of 120 and 0 meV, respectively. **(d)** Photon-energy dependence of MDCs at the normal emission at binding energies of 0 meV (upper panel) and 250 meV (lower panel) with the energy windows of ±10 meV. Dashed lines indicate the guide of the MDC peak position by eye.

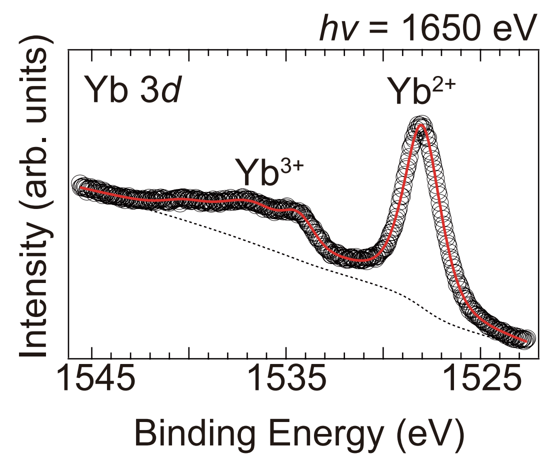

Figure 2: Yb 3*d* core-level spectrum of $YbCu_2$/Cu(111) taken with 1650-eV photons at the temperature of 15 K. Black circles and red line represent the raw data and fitted curve, respectively. The dotted line indicates the Shirley-type background.

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