The discovery of superconductivity in heavy fermion (HF) compounds has stimulated the studies of this class of materials [1]. Recently, a “high-\(T_C\)” superconductivity of \(T_C = 18\) K was discovered in PuCoGa\(_5\) [2], indicating that there remains an unexplored class of exotic superconductors in HF compounds. In these compounds, the superconductivity coexists or competes with magnetic ordering, and this is the most characteristic feature of HF superconductors. It has been proposed that these properties originated from the dual character of \(f\) electrons, i.e., their localized and delocalized characters [3]. However, their detailed electronic structures have not been studied yet, and the nature of \(f\) electrons as well as the mechanism of the superconductivity originating from such electrons are not well understood. To reveal the electronic structures of HF superconductors, we have performed angle resolved photoemission spectroscopy (ARPES) experiments for typical HF superconductors, namely. UPd\(_2\)Al\(_3\) and CeIrIn\(_5\). UPd\(_2\)Al\(_3\) shows an antiferromagnetic transition at \(T_N = 14\) K, and undergoes a transition into the superconducting state at \(T_C = 2\) K. CeIrIn\(_5\) is a HF superconductor with \(T_C = 0.4\) K. Although it does not show the magnetic ordering, CeRh\(_{1-x}\)Ir\(_x\)In\(_5\) exhibits both superconductivity and antiferromagnetic (AF) ordering in \(0.3 < x < 0.6\) [4], suggesting that the ground state of CeIrIn\(_5\) is very close to the magnetic ordering state. The Fermi surfaces of both compounds, at low temperatures were investigated by dHvA experiments, and they were well explained by the band structure calculations [5,6]. Therefore, it is considered that \(f\)-electrons have strong itinerant character in these compounds. Photoemission experiments were mainly performed at SPring-8 beamline BL23SU. \(4d-4f\) resonant ARPES experiment for CeIrIn\(_5\) was performed at Hiroshima Synchrotron Radiation Research Center (HiSOR) BL-1.

Figure 1 shows the \(f\)-derived angle-integrated photoemission (AIPES) spectra of UPd\(_2\)Al\(_3\) and CeIrIn\(_5\). The \(U\) 5f spectrum of UPd\(_2\)Al\(_3\) was obtained by subtracting the photoemission spectra measured at \(h\nu = 400\) eV and \(h\nu = 800\) eV, and the Ce 4f spectrum of CeIrIn\(_5\) was obtained using 3d-4f resonant photoemission (\(h\nu = 881.2\) eV). Both spectra have two pronounced components as indicated by the triangles in the figure. One is located around \(E_F\), and the other is located on the deeper binding energy side. The relative intensities and the positions of this broad satellite differ markedly between UPd\(_2\)Al\(_3\) and CeIrIn\(_5\). These satellites originate from the electron correlation effects, which cannot be taken into account by band structure calculations. The Ce 4f spectrum of CeIrIn\(_5\) is essentially understood within the framework of the single impurity model, suggesting that Ce 4f electrons in this compound are dominated by the localized character. On the other hand, the U 5f spectrum of UPd\(_2\)Al\(_3\) is dominated by the strong quasi-particle peak located near \(E_F\), and the intensity of the correlated feature is much weaker than that of CeIrIn5.

Figure 2 shows ARPES spectra of UPd\(_2\)Al\(_3\) measured for A-H-L direction at \(h\nu = 465\) eV and ARPES spectra of CeIrIn\(_5\) measured for \(\Gamma\)-X direction at \(h\nu = 122\) eV. For both directions of Brillouin zone, Fermi surfaces with large contribution from \(f\) states are expected in band structure calculations. In these spectra, the contribution from \(U\) 5f states or Ce 4f states is dominant. For UPd\(_2\)Al\(_3\), some dispersive bands were clearly observed in the ARPES spectra, suggesting that the \(U\) 5f states have strong itinerant character. On the other hand, the ARPES spectra of CeIrIn\(_5\) have the double peak structure arising from the spin-orbit interaction. In contrast to the case of
UPd$_2$Al$_3$, their momentum dependence is very small, suggesting that the 4f electrons are dominated by the localized character. A detailed analysis of ARPES spectra suggests that the peak near $E_F$ has a small energy dispersion of ~30 meV [7], and that this might be the origin of the observed itinerant nature of Ce 4f states in this compound. Therefore, we have observed the very different natures of f electrons in UPd$_2$Al$_3$ and CeIrIn$_5$. For UPd$_2$Al$_3$, although a correlated feature exists, the itinerant nature dominates the spectra. Meanwhile, for CeIrIn$_5$, the localized nature dominates the spectra, and the contribution from itinerant states is very small. The present results bring us a step closer to understanding the dual natures of f electrons in HF superconductors [8].

![ARPES spectra](image)

**Fig. 2.** (a) ARPES spectra of UPd$_2$Al$_3$ measured at $h\nu = 465$ eV and (b) ARPES spectra of CeIrIn$_5$ measured at $h\nu = 122$ eV.

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References