

Competition and collaboration between magnetism and superconductivity: Electronic structures of ferromagnetic superconductors UGe₂, URhGe, and UCoGe

Superconductivity is one of the most fascinating platforms for condensed matter physicists. The superconducting state is a significant quantummechanical phenomenon, and it can be observed macroscopically. Furthermore, its fundamental understanding is required subject for its technological applications such as superefficient electrical-transport systems and ultrahigh-speed maglevs. Conventionally, magnetic fields and magnetism have been considered as enemies of superconductivity: for example, a high magnetic field simply suppresses superconducting states in most superconductors. This stereotype has been defied in recent years by the discovery of some rare-earth and actinide compounds that exhibit coexisting magnetic ordering and superconductivity. In particular, the discovery of ferromagnetic superconductors in some uranium-based compounds motivated us to reconsider the relationship between magnetism and superconductivity [1].

In the present study, we have revealed the electronic structures of the uranium-based ferromagnetic superconductors UGe₂, UCoGe, [2] and URhGe [3] by angle-resolved photoelectron spectroscopy (ARPES) by using soft X-rays at beamline **BL23SU**. We found that U 5*f* electrons in these compounds have an essentially itinerant character, and they exhibit both ferromagnetic orderings and superconducting states. These results further infer that the magnetic instability might be a possible glue of superconducting electrons, which are referred to as Cooper pairs. Magnetism and superconductivity are not enemies and help each other in these compounds.

Figure 1 shows the crystal structures of UGe₂, URhGe, and UCoGe. UGe₂ has a body-centered

orthorhombic structure while URhGe and UCoGe have a simple orthorhombic structure. An interesting point is that they have similar zigzag chains of uranium atoms, and these characteristic structures are considered to be the origin of their unique physical properties. Although it is generally believed that the U 5*f* electrons in these compounds have itinerant characters, other scenarios such as a completely localized model or the dualism of U 5*f* states have also been proposed. ARPES is one of the most powerful experimental methods for revealing the electronic structures of solids. In particular ARPES with soft X-ray synchrotron radiation is suitable for studying the bulk electronic structures of U 5*f* states.

Figure 2 summarizes the ARPES spectra and the results of the band structure calculations of UGe₂, URhGe, and UCoGe [2-4]. Their overall band structures and the results of the band calculations in an energy scale of a few electronvolts are shown in Figs. 2(a, b, c). All samples are in paramagnetic phases. Contributions from U 5f states exist in the vicinity of $E_{\rm F}$. They exhibit strong momentum dependences, suggesting that they form itinerant quasi-particle bands in these compounds. In the spectra of URhGe and UCoGe, Rh 4d or Co 3d bands exist on the high-binding-energy side, which have finite hybridizations with U 5f states. There are some good correspondences between the experimental ARPES spectra and the results of the band structure calculation.

Figures 2(d, e, f) show the electronic structures and the results of band structure calculations in the vicinity of $E_{\rm F}$. The spectra have been divided by the Fermi-Dirac function convoluted by the instrumental



Fig. 1. Crystal structures of UGe₂, URhGe, and UCoGe.

energy resolution to show the states at $E_{\rm F}$ more clearly. These electronic structures in the vicinity of $E_{\rm F}$ have a particular importance since they govern their Fermi surfaces, which determine the transport properties of materials. The comparison between ARPES spectra and their simulations based on the band structure calculations exhibits both agreement and disagreement. In particular, the electronic structures just below E_F exhibit very complicated behaviors in both the experiments and calculations, and the agreement is not as good as in the cases of band structures in an energy scale of eV order. Figures 2(g, h, i) show the Fermi surfaces of these compounds obtained by the band structure calculations. They have very complicated three-dimensional shapes. This is due to the low-symmetry nature of their crystal structures, which removes the degeneracies of bands. On the other hand, the experimental band structures in the vicinity of $E_{\rm F}$ exhibit considerable deviation from the calculation. This suggests that the shapes of the Fermi surfaces of these compounds are qualitatively different from the results of calculations, possibly due to the finite electron correlation effect in the complicated band structures of the low-symmetry crystals.

All these results suggest that band structure calculations with all U 5f electrons treated as being itinerant are a good starting point to describe their overall electronic structures, but the topologies of their Fermi surfaces are considerably different from those obtained by calculations. The possible origins of these discrepancies are the very complicated band structures of these compounds due to the low-symmetry nature of their crystal structures and the weak but finite contributions from the electron correlation effect. To account for the contributions from the electron correlation effect, it is essential to include the dynamical nature of U 5f electrons in the lowsymmetry crystals.



Fig. 2. ARPES spectra and the results of band structure calculations of UGe2, URhGe, and UCoGe [2-4].

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References

- [1] D. Aoki and J. Flouquet: J. Phys. Soc. Jpn. 81 (2012) 011003
- [2] S. Fujimori, T. Ohkochi, I. Kawasaki, A. Yasui, Y. Takeda,
- T. Okane, Y. Saitoh, A. Fujimori, H. Yamagami, Y. Haga,
- E. Yamamoto and Y. Ōnuki: Phys. Rev. B 91 (2015) 174503.
- [3] S. Fujimori et al.: Phys. Rev. B 89 (2014) 104518.
- [4] S. Fujimori, Y. Takeda, T. Okane, Y. Saitoh, A. Fujimori, H. Yamagami, Y. Haga, E. Yamamoto and Y. Onuki: J. Phys. Soc. Jpn. 85 (2016) 062001.