Ultrahigh-Resolution Laser Photoemission Study of URu_2Si_2 across the Hidden-Order Transition

Rikiya Yoshida[*,a], Yoshiaki Nakamura[a], Masaki Fukui[a], Yoshinori Haga[b], Etsuji Yamamoto[b], Yoshichika Ōnuki[b,c], Mario Okawa[d], Shik Shin[d], Masaaki Hirai[a], Yuji Muraoka[a], Takayoshi Yokoya[a]

[a]*The Graduate School of Natural Science and Technology, Okayama Univeresity, Okayama, 700-8530, Japan*
[b]*Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195 , Japan*
[c]*Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan*
[d]*Institute for Solid State Physics, The University of Tokyo, Kashiwa, Chiba 277-8581, Japan*

Abstract

We have studied the electronic structures of URu_2Si_2 employing ultrahigh-resolution laser angle-resolved photoemission spectroscopy. The change of photoemission spectra is investigated across the hidden-order transition, and the emergence of a narrow band is clearly observed near the Fermi level for both (π, 0) and (π, π) directions. In addition, it is shown that tuning of light's polarization allows the signal of a hole-like dispersive feature to enhance. These observations prove that laser angle-resolved photoemission spectroscopy is an effective tool for studying the evolution of electronic structures across the hidden-order transition in URu_2Si_2.

Key words:
Electronic structure, Laser angle-resolved photoemission spectroscopy, URu_2Si_2, Hidden order
PACS: 71.20.-b, 71.27.+a, 74.70.Tx, 79.60.-i

1. Introduction

URu_2Si_2 is a heavy fermion superconductor ($T_c \sim 1.5$ K) that shows unknown second-order phase transition at 17.5 K [1, 2, 3]. This unknown phase transition was formally considered as the formation of spin-density wave, but this possibility was ruled out by the fact that observed moment ($\sim 0.03\ \mu_B$) is too small to account for the entropy release [4]. Even today, order parameter of this second-order transition is still unknown. Since the hidden-order state appears in the proximity of superconductivity and magnetism, understanding of the hidden-order state in URu_2Si_2 would offer new insights in the physics of correlated systems.

To understand the underlying nature of 'hidden-order' state, it is important to address whether the modification of electronic states occurs or not across the second-order transition. Angle-resolved photoemission spectroscopy (ARPES) is potentially a powerful tool to address such question, but the earlier efforts were unsuccessful owing to the achievable energy resolution at that time. Very recently, the results of high-resolution ARPES across the hidden-order transition are reported for the first time and show the emergence of a heavy quasiparticle band near the Fermi level in the hidden-order phase [5]. However, higher energy resolution can be obtained in the recent experiment [6], and it may be possible to improve the quality in data by employing a state-of-art ARPES.

In this report, we report the electronic states of URu_2Si_2 measured by a state-of-art laser ARPES. We show that the heavy quasiparticle band can be observed with bright clarity, which demonstrates the power of laser ARPES for resolving the narrow feature near the Fermi level. Moreover, we find that employment of linearly-polarized light enhances the signal of a hole-like dispersive feature observed in our measurements. These data prove that laser ARPES is an effective tool for studying the electronic states in the hidden-order state of URu_2Si_2.

2. Experimental

Single crystals of URu_2Si_2 were prepared by the Czochralski method as described elsewhere [7, 8]. ARPES spectra were recorded with laser ARPES system at the Institute for Solid State Physics, The University of Tokyo, where the system consists of a vacuum ultraviolet laser (photon energy of 6.994 eV) and a Gammadata-Scienta R4000WAL electron analyzer. we obtained (001) surface by *in situ* cleaving where the base pressure of the main chamber was kept better than 4×10^{-11} Torr throughout the experiment. Binding energies of spectra and sample temperature were calibrated in reference to the Fermi edge of a gold film evaporated near the sample, and the total energy resolution was set at 2 meV.

3. Results and Discussion

3.1. Band Dispersion in the Hidden-Order State of URu_2Si_2

Figure 1(a) and 1(b) show ARPES intensity plots at 7 K and at 25 K, respectively, measured along (π, 0) direction of the

*Corresponding author.
Email address: dns421103@s.okayama-u.ac.jp (Rikiya Yoshida)

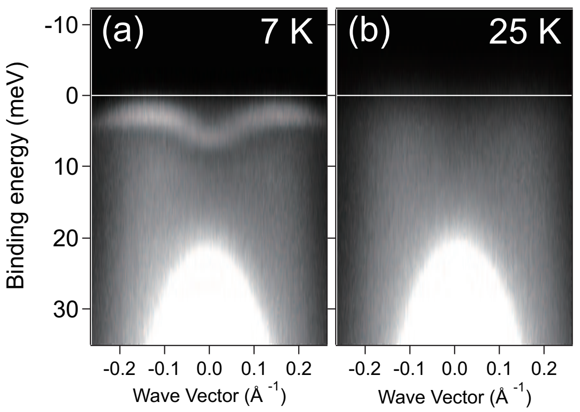

Figure 1: Laser ARPES data on URu_2Si_2 measured along (π, 0) direction with circularly-polarized light: (a) ARPES intensity plot at 7 K, and (b) at 25 K.

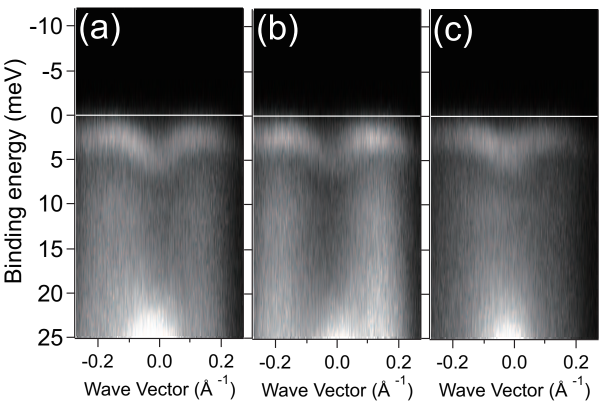

Figure 2: Polarization dependence of ARPES intensity plots measured along (π, π) direction at 7 K: (a) with circularly-polarized light, (b) with *s*-polarized light, and (c) with *p*-polarized light.

body-centered tetragonal Brillouin zone. In these plots, we observe a dispersive feature extending toward the Fermi level and photoemission intensities at higher binding energy. The latter signal has been assigned as a surface state by the previous work [5]. Moreover, a signal from a narrow quasiparticle band near the Fermi level appears in the spectrum at 7 K. We estimate the velocity of quasiparticles to be 30 meV Å from the slope between 0 Å^{-1} and 0.15 Å^{-1}, in agreement with previous ARPES estimate . We also estimate k_F of the dispersive feature from the intensity plot at 25 K, yielding $k_F \sim 0.12$ Å^{-1}. This value is slightly smaller than what has been reported for a hole-like band observed in the previous work [5], but the deviation may come from the difference in the position of momentum space along k_z. The most striking point in our higher-resolution measurement is that the heavy quasiparticle band is observed much clearer than the previous work. When it comes to the spectrum at 25 K, however, such narrow feature disappears completely. This fact unambiguously ensures the existence of narrow band near the Fermi level in the hidden-order state of URu_2Si_2.

3.2. Polarization Dependence

Figure 2(a)-(c) display ARPES intensity plots at 7 K taken for (π, π) direction with different polarizations. It is noted that the appearance of the narrow band in (π, π) direction confirms that the observed change is applicable to the wide region of momentum space. In our data with different polarizations, it is remarkable that the intensity of the dispersive feature becomes clear with *s*-polarized light (Figure 2(b)). However, it is not the case for circularly-polarized light (Figure 2(a)) or *p*-polarized light (Figure 2(c)). Although careful discussions with reference to theoretical calculations would be necessary, this observation can be applicable to determine the character of the dispersive feature and also proves the usability of laser ARPES for the investigation of URu_2Si_2.

4. Conclusion

In summary, we have shown the appearance of a narrow band near the Fermi level in the hidden-order state and the polarization dependence of a dispersive feature. Our data show laser ARPES is an promising tool to investigate the detail of electronic structures in the hidden-order state of URu_2Si_2. Further investigations are in progress and will be published in a separate paper.

Acknowledgements

We are grateful to I. Kawasaki, H. Yamagami, H. Harima, K. Miyake, T. Shimojima, K. Okazaki, Y. Ishida, W. Malaeb, and K. Machida for valuable comments. This work is supported by a Grant-in-Aid for Scientific Research on Innovative Areas "Heavy Electrons" (No. 20102002 and No. 20102003) and Grant- in-Aid for Scientific Research (S) (No. 20224015) of Ministry of Education, Culture, Sports, Science and Technology, Japan. Photoemission experiments were carried out under the Visiting Researcher's Program of the Institute for Solid State Physics, the University of Tokyo. R. Y. acknowledges the financial support from Research Fellowship of the Japan Society for the Promotion of Science.

References

[1] T. T. M. Palstra, A. A. Menovsky, J. van den Berg, A. J. Dirkmaat, P. H. Kes, G. J. Nieuwenhuys, and J. A. Mydosh, Phys. Rev. Lett. **55** (1985) 2727.
[2] W. Schlabitz, J. Baumann, B. Pollit, U. Rauchschwalbe, H. M. Mayer, U. Ahlheim, and C. D. Bredl, Z. Phys. B: Condens. Matter **62** (1986) 171.
[3] M. B. Maple, J. W. Chen, Y. Dalichaouch, T. Kohara, C. Rossel, M. S. Torikachvili, M. W. McElfresh, and J. D. Thompson, Phys. Rev. Lett. **56** (1986) 185.
[4] W. J. L. Buyers, Physica B **223-224** (1996) 9.
[5] A. F. Santander-Syro, M. Klein, F. L. Boariu, A. Nuber, P. Lejay, and F. Reinert, Nature Phys. **5** (2009) 637.
[6] T. Kiss, T. Shimojima, K. Ishizaka, A. Chainani, T. Togashi, T. Kanai, X.-Y. Wang, C.-T. Chen, S. Watanabe, and S. Shin, Rev. Sci. Instrum. **79** (2008) 023106.
[7] H. Ohkuni *et al.*, Phil. Mag. B **79** (1999) 1045.
[8] Y. Haga Y, H. Sakai, and S. Kambe, J. Phys. Soc. Jpn. **76** (2007) 051012.