Low-energy electron-boson coupling in Sr_2RuO_4

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Recently, spin-triplet superconductivity, in which individual electron spins are aligned in parallel in the electron pairs that form the superconductivity, has attracted much attention. Since most superconductors are spin-singlet superconductors with antiparallel electron spins, the elucidation of the mechanism of electron pair formation in spin-triplet superconductors is expected to provide essential guidelines for designing room-temperature superconductors. The ruthenium oxide superconductor Sr_2RuO_4 has been extensively studied as a strong candidate for the spin-triplet superconductors. In particular, angle-resolved photoemission spectroscopy (ARPES) experiments have been widely believed to observe the electron-boson (phonon, magnetic fluctuation, etc.) coupling as a sudden change of the band dispersion, which might be involved in pair formation. Indeed, many previous ARPES results reported the existence of electron-boson interactions fingerprinted by a "kink" structure in the γ-band derived from Ru $4d_{xy}$ orbital. On the other hand, the latest high-resolution ARPES study, which measured the electronic states near the Fermi energy (E_F), reported that the electrons and bosons are not strongly coupled [1]. Such a discrepancy could be attributed to the fact that the existing ARPES measurements only focused on the near-E_F region and could not accurately evaluate electron correlations with an energy scale 10 to 100 times larger than that of the boson mode ($\lesssim$100 meV). This suggests that we need to observe not only the band structures in the vicinity of the E_F but also the entire band structure for the accurate identification of coupling components by ARPES. In this regard, to separate and evaluate multiple types of the many-body effects, we have performed both soft X-ray (SX-) and vacuum ultra-violet (VUV-) ARPES by observing the entire band structure and detailed band structure in the vicinity of the E_F, respectively. SX- and VUV-ARPES experiments were performed at SPring-8 BL25SU and SSRL BL5-2, respectively, and preliminary VUV-ARPES experiments were performed at HiSOR BL-1.

Figures 1(a) and 1(b) show the Fermi surface and ARPES images using $h\nu$ = 450 eV (SX) and 65 eV (VUV), respectively. In both SX-ARPES and VUV-ARPES results, the observed Fermi surfaces clearly show the three band-structures (α, β, and γ), originating in the bulk Ru $4d$ t_{2g} orbitals. First, we focus on the SX-ARPES image in the X-M-X direction, where the α band was observed entirely and showed a parabolic dispersion shape. This enables us to evaluate the electron correlation effects accurately because the α band shows negligible dependence on the perpendicular momentum (k_z) as well as the spin-orbit coupling in this direction. Next, we focus on the γ band in the Γ/Z-M direction because it shows the largest effective mass, namely, the electrons most strongly affected by the many-body interaction there. Then, we have determined the γ band dispersion by fitting the momentum distribution curves (MDCs) as shown in the blue-filled circles in Fig. 1(c), where a phenomenological model dispersion is also shown. The model dispersion was calculated by including the electron correlation effects with the estimated strength from the SX-ARPES results. One can see that the experimental dispersion is not reproduced by the model calculations, including the electron correlation effects. This indicates that the electron-boson coupling should be considered to explain the mass renormalization effects in the γ band.

The electron-boson coupling could be more visualized in the real part of the self-energy shown in Fig. 1(d), induced by taking the energy difference between the experimental and model dispersion. Interestingly, we found a clear shoulder structure at ~ -8 meV, corresponding to the energy of the kink structure in the band dispersion as indicated by the orange line in Fig. 1(c). The kink energy is consistent with the Σ_3 phonon mode, the in-plane rotation of the RuO_6 octahedron, as observed by a neutron scattering experiment [2]. In addition, a strong coupling between the Σ_3 phonon mode and ferromagnetic fluctuations has been suggested by a scanning tunneling microscopy and theoretical study [3]. Therefore, we believe that our results reveal the strong electronic coupling to the ferromagnetic fluctuations mediated by the Σ_3 phonon mode. This may suggest the formation of the spin-triplet electron pair mediated by a magnon-phonon coupling.

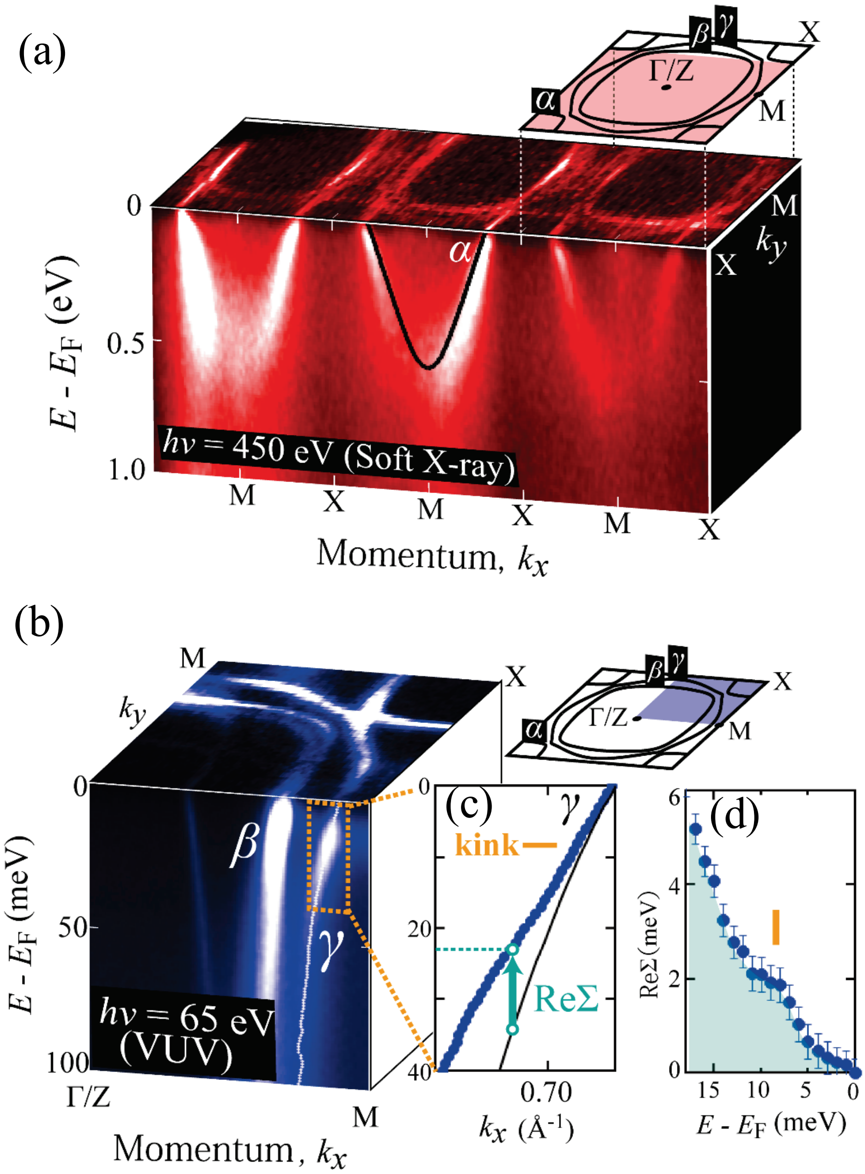

FIGURE 1. (a) SX-ARPES data: Fermi surface and band dispersion along the M-X-M direction taken with a photon energy of 450 eV below 35 K with the circular polarization. The solid black line represents a phenomenological model dispersion ($\lambda_{EEI} = 1.0$). (b) VUV-ARPES data: Fermi surface and band dispersion along the Γ/Z-M direction taken with a photon energy of 65 eV below 10 K with the *p*-polarization. (c) The γ band dispersion in the vicinity of the E_F determined by the MDC fitting. (d) Real-part of the self-energy very close to the E_F.

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