Direct observation of Dirac nodal-line fermions in P-square net superconductor, $ZrP_{1.24}Se_{0.57}$

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In recent years, Dirac nodal-line fermions in superconducting materials have attracted much attention due to expectation for novel transport properties [1]. For instance, a Dirac nodal-line semimetal (DNLS), $PbTaSe_2$, exhibits Dirac velocity of 4.0×10^5 m/s and superconductivity with critical temperature (T_c) of 3.8 K [2]. However, in order to realize low-loss and fast electronics, the nodal-line superconductors which exhibit higher Dirac velocity and higher T_c are desired. Here, we focus on a recently-discovered layered-phosphide-chalcogenide superconductor, $ZrP_{2-x}Se_x$ (T_c = 6.2 K) [3]. This material is isostructural with ZrSiS, which is known as a typical DNLS. While the first-principles calculation has predicted that a nodal line is present in the band structure of $ZrP_{2-x}Se_x$ [4], no experimental evidence has been reported so far. In this study, we performed an angle-resolved photoemission spectroscopy (ARPES) study of high-quality single crystals of $ZrP_{1.24}Se_{0.57}$, using soft X-ray (SX) and vacuum ultraviolet (VUV) synchrotron radiations at BL25SU of SPring-8 and BL-1of HiSOR, respectively.

The band dispersions of $ZrP_{1.24}Se_{0.57}$ observed by VUV-ARPES along the X-Γ-X and M-Γ-M lines are shown in Figs. 1(a) and (b), respectively. Two electron pockets, γ and δ, centered at the Γ point, and an electron pocket, ε, centered at the X point are observed, as shown in Fig. 1(a). We observed that two steep and straight dispersions cross with each other at -1.3 eV with Dirac velocity of 1.2×10^6 m/s, and that the crossing point forms a closed nodal-loop in the k_x-k_y plane. The experimental band structures is well reproduced by tight-binding calculation of a free-standing P square net.

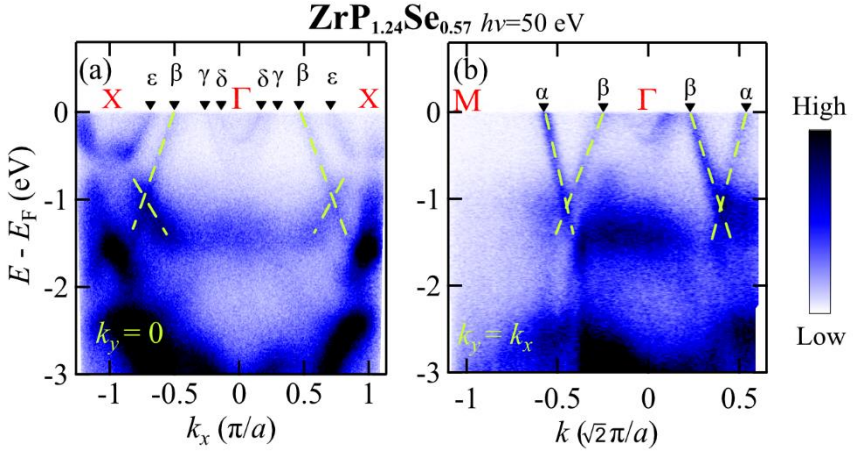

FIGURE 1. Experimental *E*-*k* plots along the (a) X-Γ-X and (b) M-Γ-M, respectively, with $h\nu$ = 50 eV for $ZrP_{1.24}Se_{0.57}$.

In summary, we have demonstrated that $ZrP_{1.24}Se_{0.57}$ is a nodal-line superconductor. The fast Dirac fermions of 1.2×10^6 m/s in $ZrP_{1.24}Se_{0.57}$ arises from the nonsymmorphic P square net, and surpass the velocity record held by the point-node Dirac fermions in graphene. Our finding provides a new playground for emergent exotic phenomena, and will lead to a discovery of elusive Majorana fermions.

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