Nodeless electron pairing in CsV_3Sb_5-derived kagome superconductors

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Overview

The kagome lattice, consisting of corner-shared triangles (inset of Fig. 1), is an exciting platform for emergent quantum phenomena, since its electronic structure is featured with a flat band, a Dirac cone, and van Hove singularities. Recently, superconductivity that intertwines with charge density wave (CDW) has been observed in kagome metals AV_3Sb_5 (A = K, Rb, Cs) [1-2]. To illuminate the pairing mechanism and the interplays between multiple phases, a fundamental issue is to determine the superconducting (SC) gap symmetry. However, it remains elusive owing to the existence of several conflicting experimental results [2] and lack of a momentum-dependent measurements of SC gap structure. Angle-resolved photoemission spectroscopy (ARPES) has been proved to be a powerful tool to directly measure the SC gap in the momentum space [3]. Nevertheless, the relatively low transition temperature (T_c) renders the precise ARPES determination of the gap in the SC state extremely challenging.

In this work, we utilize an ultrahigh-resolution and low-temperature laser-ARPES, together with a chemical substitution of V in CsV_3Sb_5, that raises T_c, to precisely measure the gap structure in the SC state. Considering the accessibility in terms of temperature and possible influence of CDW, we select $Cs(V_{0.93}Nb_{0.07})_3Sb_5$ and $Cs(V_{0.86}Ta_{0.14})_3Sb_5$ for the SC gap measurement (denoted as Nb0.07 and Ta0.14, respectively). The Nb0.07 sample exhibits T_c of 4.4 K and a CDW transition at T_{CDW} = 58 K, whereas the Ta0.14 sample exhibits a T_c of 5.2 K, but no clear CDW transition (Fig. 1). Our results uncover the SC gap structures of both samples are isotropic, regardless of the disappearance of CDW, hinting at a robust nodeless pairing in CsV_3Sb_5-derived kagome superconductors [4].

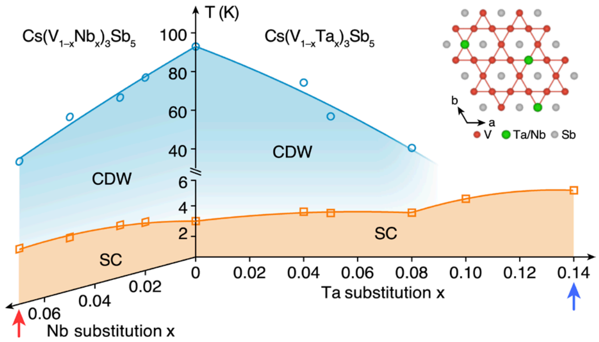

Fig. 1. Phase diagram of substituted CsV_3Sb_5. The inset illustrates Ta or Nb substitutions by V atoms in V-Sb layer.

Results

We first map out the Fermi surface (FS). Fig. 2**a** shows a joint FS of the Ta0.14 sample by combing three segments, which is consistent with whole-FS mapping using a larger photon energy [4]. Three FS sheets – a circular electron-like pocket (marked as α) and a hexagonal hole-like pocket (marked as β) at Brillouin Zone (BZ) center Γ point, and a triangle pocket (marked as δ) at the BZ corner K point – are well distinguished. This makes the determination of the Fermi momentum (k_F) reliable.

Before investigating the SC gap structure, we confirm the spectral evidence of the superconductivity. Using the Ta0.14 sample as an example, the temperature-dependent EDCs of a cut on β FS are shown in Fig. 2**b**. Apparently, at $T = 2$ K, far below T_c, the emergent quasiparticle peak around the Fermi level (E_F) clearly indicates the opening of an SC gap. With temperature gradually increasing, the growing intensity at E_F and the approaching peaks suggest that the SC gap becomes smaller and eventually closes. The fitted SC gap amplitudes versus temperature are summarized in the inset of Fig. 2**b**. The estimated T_c of approximately 5.2 K

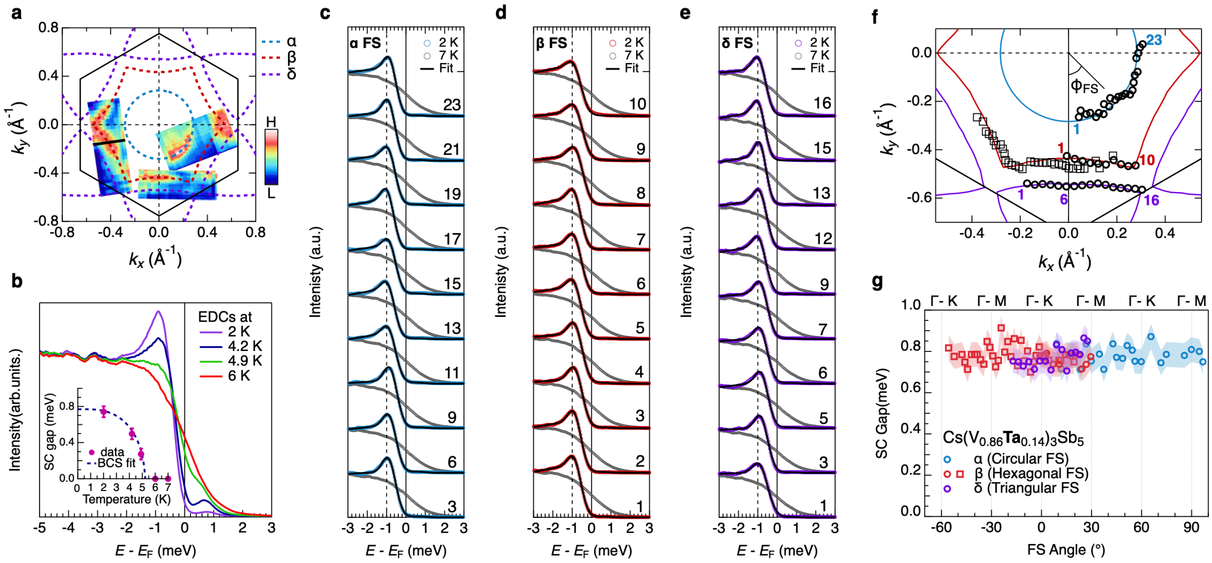

Fig. 2. Isotropic superconducting gap in $Cs(V_{0.86}Ta_{0.14})_3Sb_5$. **a**. Fermi surface mappings. **b**. Temperature-dependent EDCs at k_F in a cut marked as a black line in **a**. **c-e**, EDCs at k_F along with the a, b, and d FS, respectively. **f**, Positions of examined k_F. **g**, SC gap amplitude from the fits to EDCs at k_F. The shaded areas represent the error bars.

is consistent with the bulk T_c determined by resistivity measurements, demonstrating the high quality of the samples and the high precision of our SC gap measurements.

We then study the momentum dependence of the SC gap in the Ta0.14 sample with the CDW order fully suppressed. The EDCs at k_F of α, β and δ FSs are presented in Figs. **2c-e**. Near E_F, the leading edges of the EDCs at 2 K all show a shift compared to that at 7 K. Moreover, they universally show a strong coherence peak at the same binding energy, indicating an isotropic SC gap structure. Fitting these EDCs to a Bardeen–Cooper–Schrieffer (BCS) spectral function, the quantitatively extracted gap amplitudes of the different FSs have rarely fluctuated amplitudes with an average Δ_{Ta} of 0.77 ± 0.06 meV (Fig. 2**g**), yielding a ratio 2 Δ_{Ta}/k_BT_c of 3.44 ± 0.27 (where k_B is the Boltzmann constant).

Next, we turn to examine the SC gap structure of the Nb0.07 sample, where T_{CDW} gets slightly suppressed. After checking the FS topology like that of the Ta0.14 sample, we take the EDCs at k_F positions of three FSs. By fitting them with a BCS spectral function, quantitatively, the SC gap amplitudes remain nearly isotropic (Fig. 3**a**). The averaged gap amplitude Δ_{Nb} is 0.54 ± 0.06 meV, giving out a weaker ratio $2\Delta_{Nb}/k_BT_c$ of 2.83 ± 0.32. By turning the photon energy from 5.8 eV to 7eV, we further study the z-direction momentum (k_z) dependence of the SC gap. We find that the SC gap remains nearly the same at these two k_z planes within our experimental uncertainties. Giving the direct momentum-resolved capability of ARPES and the prominent features of SC gap opening, our data reveal a nodeless, nearly isotropic and orbital-independent SC gap in both Nb0.07 and Ta0.14 samples (Fig. 3**a, b**).

Discussion and outlook

As shown in Fig. 3**c**, the isovalent substitutions of Nb/Ta for V atoms can be viewed as effective in-plane negative pressure, which suppresses the CDW order while it enhances the superconductivity. Our results uncover a fact that the same isotropic SC gap structure on suppression of CDW, different from the observation of a nodal-to-nodeless in the sister compounds KV_3Sb_5 and RbV_3Sb_5 under hydrostatic pressure [5], suggesting a probably weak CDW-SC competition in CsV_3Sb_5.

Our results allow us further to discuss the pairing symmetry. The robust isotropic SC gaps with small

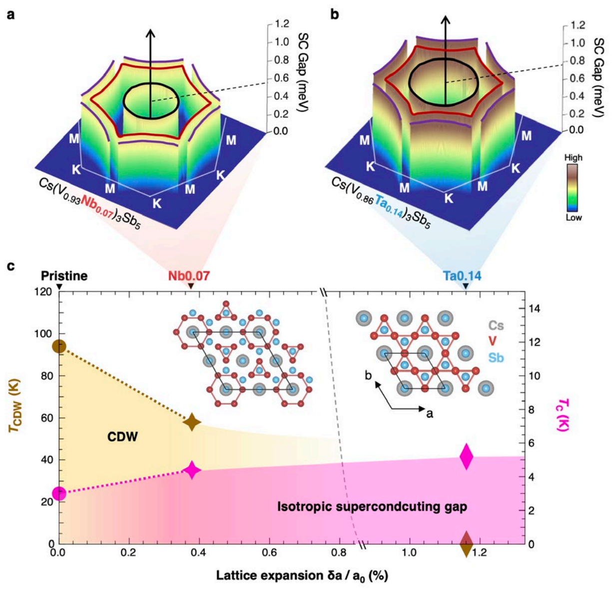

Fig. 3. Robust isotropic SC gap on suppression of CDW. **a,b**, Schematic momentum-dependent SC gap of the Nb0.07 and Ta0.14 samples, respectively. **c**, Schematic phase diagram as function of the lattice expansion due to substitutions. Here, δa is the change of the in-plane lattice constant relative to pristine CsV_3Sb_5.

$2\Delta/k_BT_c$ seem to be consistent with a conventional *s*-wave pairing. This is also supported by the observed band dispersion kinks stemming from electron-phonon couplings, as well as the positive correlation between the coupling strength and T_c [6]. Precisely, these results do not rule out other nodeless pairing states due to the lack of phase information in ARPES measurements. Particularly, the observation of increased muon spin relaxation rate on CDW-suppressed CsV_3Sb_5 by pressure provide evidence for the potential presence of time-reversal-symmetry-breaking superconductivity [7], highlighting the need for further examination. In addition, a direct ARPES investigation on pristine CsV_3Sb_5 will be more helpful to further pin down the pairing symmetry.

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