Observation of Edge States in Topological Tellurium by μ-ARPES

Trigonal tellurium (Te), composed of helical chains, has long attracted attention due to its unique optoelectric and magnetoelectric properties, together with its non-trivial bulk band topology represented by Weyl fermions. Recent theories have further predicted that individual Te helices serve as a novel state of matter: a one-dimensional topological insulator (1D TI) phase, which has remained elusive in solids. Here, using advanced angle-resolved photoemission spectroscopy with micro-focused synchrotron light, we report the discovery of unusual electronic states that support the 1D TI nature of Te helix chains, specifically the formation of bound states at their endpoints.

Topological insulators (TIs), distinguished from conventional material classifications, are fascinating materials that are insulating in their bulk but exhibit topologically protected metallic states at their surface or edge [1-3]. These materials are predicted to possess intriguing electronic, transport, and quantum properties that strongly depend on their crystal dimensionality (1D, 2D, or 3D). While the experimental confirmation of 2D and 3D TIs, such as HgTe/CdTe and Bi_2Se_3, promptly followed their theoretical proposals, the experimental realization of their 1D counterpart in stable solid-state systems has remained elusive, despite over four decades of intensive exploration since the initial conceptualization of its fundamental principles [4]. This persistent challenge primarily stems from the scarcity of naturally occurring materials with an intrinsic 1D structure, and among those available, the absence of an ideal platform to manifest the nontrivial topology. Consequently, the experimental discovery of a 1D TI within a pristine 1D structure has been a central issue in condensed matter physics.

In this study, we present experimental signature for the 1D TI nature of a tellurium (Te) helix chain (**Fig. 1(a)**) [5]. Crucially, this experimental observation was made possible by the state-of-the-art angle-resolved photoemission spectroscopy (ARPES) system, specifically the micro-focused ARPES (μ-ARPES) [6] with an approximately 10-μm diameter beam, at BL-28A. The high spatial resolution and scanning imaging technique, offered by this system, were essential in our discovery.

As depicted in **Figs. 1(b)** and **(c)**, real-space mapping of the μ-ARPES intensity near the Fermi level on the Te(0001) surface, which is oriented perpendicular to the Te chains, revealed a strong spatial modulation of the electronic states. Remarkably, the most intense signals were concentrated near crystal edges,

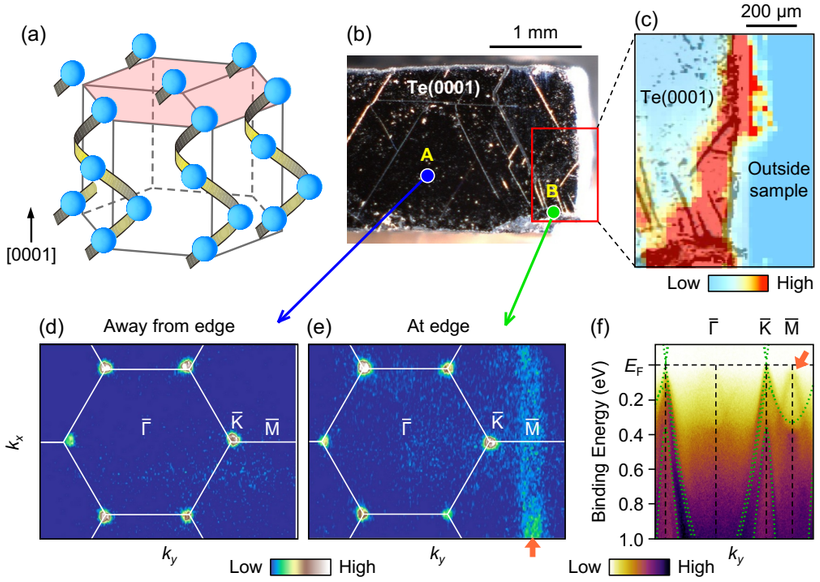

Figure 1: (a) Schematic of Te crystal. **(b)** Optical microscope image of Te(0001) surface prepared by ion beam sputtering [10]. **(c)** Spatial map of ARPES intensity near the Fermi level (E_F) in the region enclosed by red rectangle in **(b)**. **(d)** ARPES intensity at E_F plotted as a function of in-plane wave vector (k_x and k_y), measured at the center of a large terrace of the crystal [position A shown by blue circle in **(b)**]. **(e)** Same as **(d)**, but measured at the crystal edge [position B shown by green circle in **(b)**]. **(f)** ARPES intensity plot as a function of binding energy and k_y measured along the $\bar{\Gamma}$-$\bar{K}$-$\bar{M}$ cut of **(e)**.

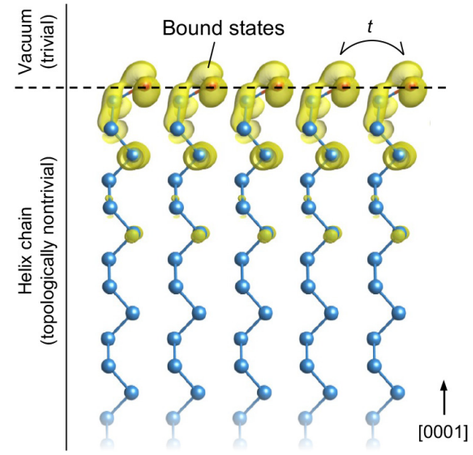

Figure 2: Side view of the helix chains at the edge of Te crystal, together with calculated charge density distribution of bound states (yellow sphere).

indicating the potential formation of novel edge-localized states. A direct comparison of the Fermi surfaces measured at the crystal's center (**Fig. 1(d)**) and its edge (**Fig. 1(e)**) elucidates this point: while both regions share small Fermi pockets originating from the bulk bands of Te at each H point [7], a distinct, straight 1D pattern elongated uniaxially along the k_x direction appeared exclusively at the edge (**Fig. 1(e)**). This observation allows us to definitively attribute the strong signals at the edge in **Fig. 1(c)** to the presence of unique 1D electronic states. Furthermore, our measurements of the band dispersion reveal that the 1D states exhibit a clear hole-like band dispersing only along k_y (**Fig. 1(f)**). This spectral signature demonstrates that electrons forming the 1D states are highly restricted to move along the crystal edge (which is elongated horizontally in **Fig. 1(b)**), indicating that the observed 1D states are true edge states.

Our comprehensive theoretical calculations, which show good agreement with the experimental findings, propose that the observed edge states arise from the formation of topological bound states at the endpoints of open Te chains at the crystal edge (**Fig. 2**), followed by coherent electron hopping that forms a continuous 1D band structure. The absence of such states at the center of the Te(0001) surface is consistently explained by the dimerization of Te chains, which effectively removes the chain's endpoints and thus eliminates the conditions for bound-state formation. The formation of these bound states at the endpoints of open Te chains, consistent with recent theoretical proposals [8, 9], strongly supports the topologically nontrivial character, namely, the 1D TI nature, of the Te helix. The discovery of these novel topological states, enabled by the advanced capabilities of μ-ARPES, represents a crucial step towards developing novel functionalities. These advancements pave the way for future spintronic nanodevices, including the exciting prospect of creating quantum-dot systems for cutting-edge applications such as spin-orbit qubits.

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