# Magnetically Controllable Two-Dimensional Spin Transport in a 3D Crystal

Two-dimensional quantum materials have become a new paradigm in condensed matter physics, offering exciting device applications. Stabilizing and controlling these phases, however, has proven challenging. Here, we propose an innovative method to realize an externally controllable quasi-two-dimensional electronic state with topologically non-trivial spin textures in a three-dimensional perovskite. We further explore their potential implementations in various spintronic applications.

Over the past few years, my group at the University of Manchester has closely collaborated with Professor Rodion Belosludov's team at IMR on several projects focused on modeling emergent quantum phenomena in two-dimensional (2D) materials [1-3]. This collaboration has leveraged the state-of-the-art computational facilities at IMR's Center for Computational Materials Research (CCMS). My visit during the summer of 2023 provided an exceptional opportunity to solidify our joint research on a specific group of Perovskite compounds, establishing them as ideal spintronic candidates for 2D spin transport with novel topological properties [4].

During this visit, our research focused on $Eu_{0.5}TaO_3$, a prototypical system related to conventional $ABO_3$ perovskites such as $SrTiO_3$ and KTaO3. In $Eu_{0.5}TaO_3$, however, the A site is half-filled by the magnetic rare-earth element Eu. As a result, the primitive cell of $Eu_{0.5}TaO_3$ consists of two distorted TaO3 octahedra sandwiching a Eu layer, stacked alternately along the crystalline c-axis. This structure leads to the system being dubbed a *fractional* double perovskite [4].

A key feature of $Eu_{0.5}TaO_3$ is its strong atomic spin-orbit interaction from Ta ions. When combined with the local inversion asymmetry of their TaO3 octahedra, this interaction creates two spatially separated Rashba fields with opposite chiralities, as shown in Figure 1. Additionally, the large local Eu *4f*-orbital magnetic moments facilitate a delicate yet profound magnetic exchange coupling with the Ta charge carriers through a proximity-induced mechanism known as the Ruderman-Kittel-Kasuya-Yosida (RKKY) exchange interaction. Our first-principles calculations revealed [4] that by controlling the interplay between the intrinsic Rashba fields experienced by the charge carriers and the RKKY exchange coupling they mediate among the local Eu magnetic moments through an external magnetic field, they can form quasi-2D energy pockets with topologically non-trivial characteristics, manifested as alternating monopole-anti-monopole-like spin textures, as shown in Fig. 1.

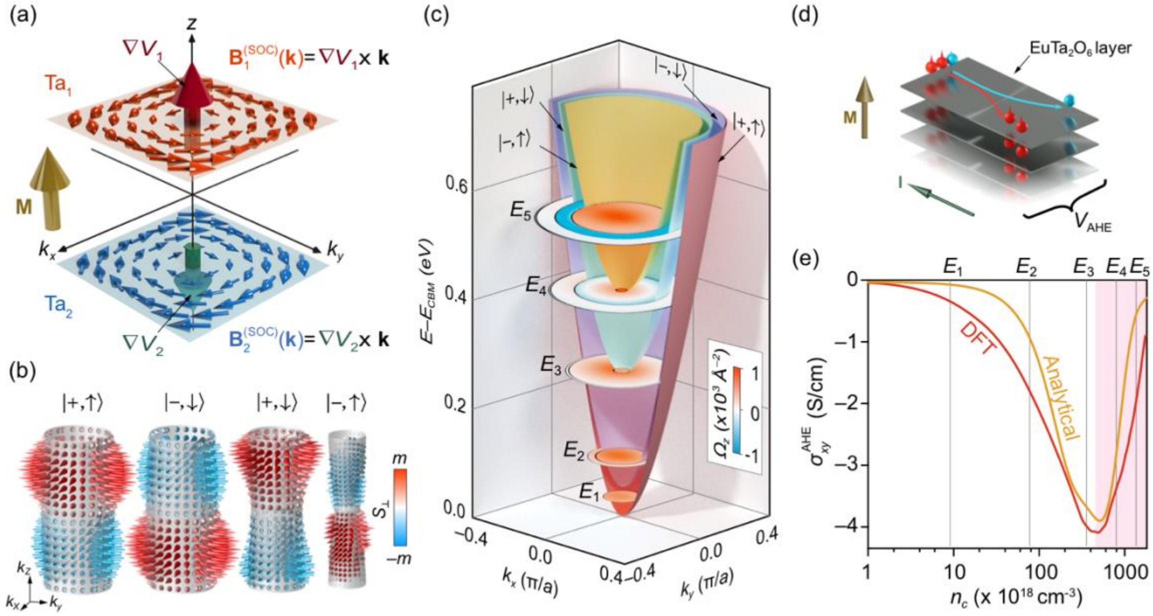


Fig 1. (a) Rashba fields and (b) monopole-anti-monopole-like spin textures in Eu0.5TaO3 conduction bands. The Berry-curvature-projected low-energy electronic structure of Eu0.5TaO3 (c), forming quasi-2D electron gases (d). The resulting Anomalous Hall conductivity is shown in (e).

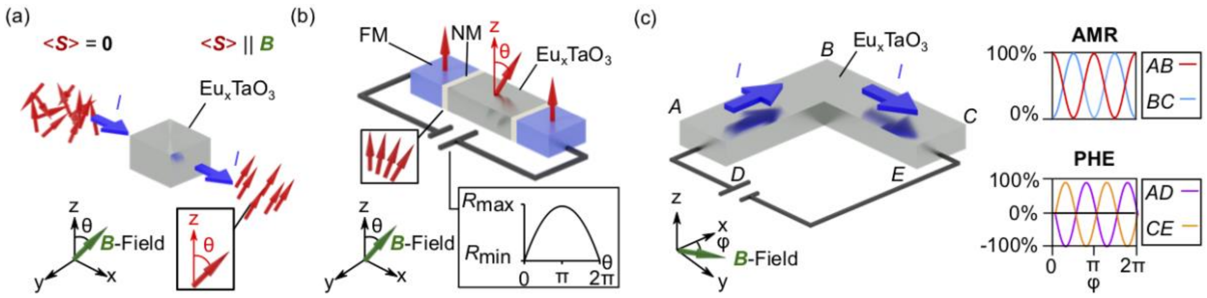


Fig. 2. Spintronic device applications for EuxTaO3. (a) Spin polarizer, generic non-spin polarized current enters material and is spin-polarized along the applied magnetic field *B*. (b) Inter-facial spin valve, $Eu_xTaO_3$ has itinerant ferromagnetic (FM) contacts at either end, with a thin non-magnetic (NM) layer separating them. As transport across the FM-NM-$Eu_xTaO_3$ junction leads to spin scattering, as shown in the inset, adjusting the polar angle of *B*, and thus adjusting the relative angle between the magnetizations, manipulates the resistance across the device. (c) Spin transistor, current flows around the device from *A* to *C* under the influence of an angularly variable *B*.

Focusing on transport phenomena, we demonstrated that this quasi-2D behavior leads to various anomalies in charge conductivity, including divergent quantum oscillations and an oscillating Seebeck effect. Both effects were proposed as possible probes to observe the interplay experimentally. Furthermore, our calculations suggest that this system and similar materials could exhibit an intrinsic Anomalous Hall Effect (AHE) with a non-monotonic dependence on the charge carrier, offering the possibility of a tunable AHE [4]; See Fig. 1. The origin of this AHE is not fully explained and remains a key area of our ongoing research collaboration.

The remarkable level of controllability over the fermiology and magnetic properties of Eu0.5TaO3 makes this system an ideal candidate for realizing quasi-2D electron gases, applicable in cutting-edge spintronic devices. Inspired by these findings, we proposed several device applications incorporating Eu0.5TaO3, such as spin polarizers, spin transistors, and interfacial spin valves [4], as shown in Fig. 2.

Building on these findings, we are currently investigating the topological properties of fractional perovskites in more detail and searching for similar materials exhibiting such quantum properties. Through our collaboration with colleagues at IMR, we are confident that our findings can pave the way for establishing a new platform for spintronics with advanced device functionalities suitable for future energy and quantum information technologies.

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