# Probing Quantum Anomalous Hall States in Twisted Bilayer WSe<sub>2</sub> via Attractive Polaron Spectroscopy

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Moiré superlattices in semiconductors are predicted to exhibit a rich variety of interaction-induced topological states. However, experimental demonstrations of such topological states, apart from MoTe<sub>2</sub> superlattices [1–8], have remained scarce [9, 10]. Here, we report the first optical detection of quantum anomalous Hall (QAH) states in twisted WSe<sub>2</sub> homobilayer (tWSe<sub>2</sub>). Specifically, we employ polarization-resolved attractive polaron spectroscopy on a dual-gated,  $2^{\circ}$  tWSe<sub>2</sub> and observe direct signatures of spontaneous time-reversal symmetry breaking at hole filling v = 1. Together with a Chern number (*C*) measurement via Streda formula analysis, we identify this magnetized state as a topological state, characterized by C = 1. Furthermore, we demonstrate that these topological and magnetic properties are tunable via a finite displacement field, between a QAH ferromagnetic state and an antiferromagnetic state. Our findings position tWSe<sub>2</sub> as a highly versatile, stable, and optically addressable platform for investigating topological order and strong correlations in two-dimensional landscapes.

# Introduction

Twisted transition metal dichalcogenide (TMD) bilayers have emerged as a highly tunable platform for investigating correlated electronic phases in two dimensions. In these systems, the presence of periodic moiré potentials — arising from lattice mismatch — produces strong interaction and non-trivial topology, resulting in a wide array of exotic many-body states. These include superconductivity [11, 12], ferroelectric order [13], Mott insulators [14–17], generalized Wigner crystals [14, 18, 19], and a growing set of topological phases, such as integer and fractional quantum spin Hall [20] and quantum anomalous Hall (QAH) states [1–8].

QAH phases are especially appealing as they exhibit topological properties even in the absence of an external magnetic field. Examples includes integer and fractional QAH states in MoTe<sub>2</sub> [1–8], and integer QAH in twisted MoTe<sub>2</sub>–WSe<sub>2</sub> heterobilayers [21]. Remarkably, QAH effect has been reported in tWSe<sub>2</sub> at 1.2° twist angle [9], as well as superconductivity at 3.6° and 5° angles [11, 12]. Despite these advances, tWSe<sub>2</sub> remains largely underexplored even though it offers practical advantages, including enhanced air stability and visible-frequency optical transitions — features that make it an excellent platform for scalable device engineering and optical interrogation.

Specifically, the magnetic and topological nature of correlated states in this system remains largely uncharted. For instance, clear signatures of spontaneous time-reversal symmetry breaking at integer fillings, and probe of the phase diagram in tWSe<sub>2</sub> has yet to be observed.

Here, we report the first optical detection of the quantum anomalous Hall effect in tWSe2, using attractive

polaron (AP) spectroscopy [22]. Polarization-resolved reflection near the AP resonance reveals clear signatures of spontaneous magnetization at hole filling v = 1. Using the Streda formula, we identify this state as a Chern insulator with Chern number C = 1, as prediced earlier [23, 24]. Our optical measurement establishes the presence of a topological states on a macroscopic level, which is inaccessible via local scanning probes [9]. Furthermore, we demonstrate that an applied vertical displacement field tunes the system from a QAH ferromagnetic phase to an antiferromagnetic state.

# **Attractive Polaron Spectroscopy**

Our sample is  $2^{\circ}$  twisted WSe<sub>2</sub> with a hexagonal structure whose superlattice periodicity is approximately 9.4 nm (see Extended Data Fig. 2 for calibration of twisting angle). The two sublattices in a moiré unit cell are denoted by MX and XM, respectively, as shown in Fig. 1a (see Extended Data Fig. 1 for the calculated electronic structure). We employ a dual-gate geometry to enable independent control of both the hole filling factor, *v*, and the perpendicular displacement field (*D*). Tuning *D* controls the interlayer potential difference in tWSe<sub>2</sub>.

The attractive polaron in our system is a composite excitation between an exciton in one valley and a hole in the opposite valley, as shown schematically in Fig. 1b. Therefore, the polarization-resolved optical response at AP resonance reveals the hole occupancy in the opposite valley [22].

To identify and characterize the AP resonance, we measure the reflection contrast (*RC*) spectrum as a function of v, which exhibits several resonances (Fig. 1c). Near the charge-neutral regime, we identify tWSe<sub>2</sub> intralayer excitons at 1.694 eV, and the red-shifting resonance (upon doping until v = 1) as the AP. We note that oscillator strength is transferred to other species near v = 2. By analyzing the doping-dependent derivative of *RC*, we identify two sign reversals at v = 1 and v = 3 (Fig. 1d), marking the peak of the oscillator strength of the AP. By integrating the AP intensity (within the horizontal dashed lines indicated in Fig. 1c), we observe that its oscillator strength increases monotonically with v up to v = 1, then decreases between v = 1 and v = 2, as shown in Fig. 1e. The same trend repeats between v = 2 and v = 4.

To qualitatively understand the observed characteristics of AP, we use the fact that its oscillator strength scale with the number of singly occupied states in the valence moiré bands [22]. In other words, any creation of vacant and doubly occupied states transfers the AP oscillator strength to other species outside of the AP's integrated frequency range. Here, we note that at v = 1, there is a single hole per moiré unit cell, and therefore, gives the maximum number of singly occupied states for the topmost moiré valence band  $v_1$  (Fig. 1b). The observed repeating oscillator strength trend for v > 2 in Fig. 1e follows a similar explanation for the second moiré band  $v_2$ , which is gapped from the  $v_1$  (see Extended Data Fig. 1).

#### Spontaneous magnetization at v = 1

To optically detect spontaneous magnetization of the system, we measure polarization-resolved *RC* under zero magnetic field (Fig. 2a-b) and construct the reflection magnetic circular dichroism (RMCD) as a function of v at 66 mK, as shown in Fig. 2c. Since the RC from  $\sigma_-$  and  $\sigma_+$  excitations selectively probe the occupation of doped charges in the +K and -K valleys, respectively, any valley and spin imbalance will lead to a different optical response in the two polarizations. Remarkably, we observe that the *RC* exhibits a pronounced peak for  $\sigma_-$  excitation at v = 1, while a dip is observed for  $\sigma_+$  within the AP energy range, a direct indication of spontaneous time-reversal symmetry breaking. To be more quantitative, the RMCD measurement in Fig. 2c captures the out-of-plane magnetization of the doped charges. The magnetization peaks at v = 1 (see Fig. 2d for *RC* spectra), while it remains negligible at other fillings.

Crucially, in addition to spontaneous RMCD under a zero field, we observe a magnetic hysteresis loop

at v = 1, which indicates the presence of ferromagnetism (FM), with a coercive magnetic field of approximately 50 mT, as shown in Fig. 2e. The observed emergent magnetism can be understood in the mean-field approximation, where electron-electron interactions generate an effective exchange splitting between the two valleys, yielding FM around v = 1 as only one valley is occupied, as schematically illustrated in Fig. 2f. The hysteresis disappears at a higher temperature of around 1.2 K, see Extended Data Fig. 3. Notably, our observation of FM at v = 1 in tWSe<sub>2</sub> is similar to the general trend seen in MoTe<sub>2</sub>; however, here we report the absence of FM at v = 3, in contrast to MoTe<sub>2</sub>.

#### Identifying the quantum anomalous Hall state with Streda formula

To directly determine the topological properties of our system, we measure the magnetic field- and dopingdependence of the optical spectra and extract the topological invariant from the Streda formula [1, 25–27]. Specifically, we track the frequency-integrated oscillator strength, as a function of magnetic field  $\mu_0 H$  and gate voltage (see Extended Data Figs. 4, 5, 6 for details). In particular, the AP spectroscopy performed at v > 0 allows us to track the density shift of correlated states as a function of the magnetic field  $\mu_0 H$ , as shown in Fig. 3a. The local maxima therein for each  $\mu_0 H$  is extracted and shown in Fig. 3b, and the slope of each line indicates the Chern number (*C*) of the corresponding state.

The polaron peak at v = 1 marks a correlated insulating state whose density shifts linearly as a function of the magnetic field, with a slope that matches C = 1, according to the Streda formula. Together with the emergence of FM at this filling, we attribute this state to an integer QAH phase. Upon reversal of the magnetic field, the magnetization reverses, which also leads to a reversal of the Chern number to C = -1, manifesting a valley contrasting Chern number for the many-body ground state. Compared to twisted MoTe<sub>2</sub>, the lack of an experimentally observed QAH phase in earlier experiments employing twisted WSe<sub>2</sub> [28] may be attributed to its significantly lower ferromagnetic transition temperature,  $T_C < 1.2 K$ , in contrast to  $T_C \approx$ 10 K in MoTe<sub>2</sub>. We also note that at twist angles smaller than the current studies, such as  $\theta \leq 1.5^\circ$ , tWSe<sub>2</sub> can suffer a stronger lattice relaxation effect compared to tMoTe<sub>2</sub>. This can lead to high twist angle disorder, as was the case in earlier local probe measurement [9].

In contrast to the QAH state at v = 1, the peak at v = 3 indicates a correlated insulating state that does not disperse with increasing magnetic field, which therefore suggests a zero Chern number (C = 0). Intriguingly, the absence of RMCD signal could potentially point to a non-trivial magnetic ordering that is intervalley coherent or antiferromagnetic in nature, which has not been observed previously in higher moiré bands [8, 20, 29], or potentially a non-abelian spin Hall insulator, as theoretically predicted [30].

# Displacement field tuning: from QAH FM to AFM

With QAH physics at v = 1 established under a zero displacement field, we further investigate the robustness and tunability of this Chern insulating state with a finite displacement field  $D/\varepsilon_0$ . First, in Fig. 4a, we present the RMCD diagram with respect to v and  $D/\varepsilon_0$  at zero magnetic field and 66 mK. We observe a prominent RMCD response at around v = 1, where the RMCD signal persists up to  $\sim 18$  mV/nm. This region of a prominent RMCD response establishes the ferromagnetic regime in the overall phase diagram of tWSe<sub>2</sub>. At a slightly elevated magnetic field of 0.1 T, the ferromagnetic phase becomes further stabilized across a broader regime (Extended Data Fig. 8). Notably, ferromagnetic order is stabalized near the van Hove singularity , suggesting enhanced interaction strength due to the high density of states(Extended Data Fig. 8) [11, 12, 28].

Focusing on the displacement-field-dependence of the RMCD at v = 1, we observe that the magnetization of the system quenches above a critical displacement field of 18 mV/nm, as indicated by the dashed line in

Fig. 4b. Meanwhile, near this critical displacement field, we also observe a divergent magnetic susceptibility, consistent with a field-controlled magnetic phase transition (Fig. 4b, see Extended Data Fig. 7 for spectrally resolved data).

To understand the origin of this magnetic phase transition, we measure the magnetic susceptibility of the sample by performing temperature-dependent RMCD measurements and extract the Curie-Weiss temperature  $T_{CW}$  (see Extended data Fig. 9 for details). Intriguingly, we observe a clear sign-change of the Curie-Weiss temperature  $T_{CW}$ , as shown in Fig. 4c, from positive to negative with increasing *D*. This indicates a transition from FM to antiferromagnetic (AFM) order [31, 32] in our system, due to a change in the lattice geometry as shown schematically in the inset of Fig. 4d. Together, these findings reveal a field-tunable magnetic phase transition linked to the underlying topological properties of the correlated moiré system.

## Conclusion

In summary, we have reported the first optical detection of the QAH states in a tWSe<sub>2</sub> system and demonstrated displacement-field tunability of the underlying magnetic order, showcasing transitions between quantum anomalous Hall ferromagnetic and antiferromagnetic phases. These results highlight tWSe<sub>2</sub> as a uniquely versatile platform, combining visible-frequency optical access with air stability and fabrication simplicity—features that open new directions for probing correlated and topological quantum phases in moiré systems.

Looking ahead, several exciting research avenues can be built upon our findings. One promising direction is the exploration of fractional Chern insulators [33], which have recently been observed in tMoTe<sub>2</sub> [1– 4, 34–36], and may be realized in tWSe<sub>2</sub> given its favorable material properties. Moreover, the presence of different Chern numbers in higher moire bands compared to MoTe<sub>2</sub> may lead to the realization of other correlated states [37].

More intriguing is the realization of recently predicted topological excitons [38], accessible in a modified device architecture designed to host long-lived interlayer excitons. The coexistence of strong exciton-exciton interactions [16, 17, 39, 40] and tunable excitonic band topology [38] offers a compelling pathway toward the realization of bosonic fractional Chern insulators [41–43]. Such long-sought phase are bosonic analogue of fermionic fractional Chern insulators [44–48], which has remained unobserved in any system to date. More generally, this system could be considered as a promising candidate for optical probe and manipulation of strongly-correlated electron-photon systems [49, 50]. Specifically, interesting prospects are optical detection and manipulation of topological states [51, 52].

#### Methods

### **Device fabrication:**

The device was made by "tear-and-stack" technique using the standard polymer-based dry transfer method. With picking up the top gate graphite, top gate hBN, tWSe<sub>2</sub>, bilayer hBN spacer, half over-lapped MoSe<sub>2</sub> monolayer in sequence and dropped down onto a pre-prepared hBN-Graphite bottom gate on a 285 nm SiO<sub>2</sub>/Si substrate. Followed by electron beam lithography and metal deposition for the gate and contacts (5 nm Cr, 70 nm Au). All the monolayers are identified via optical contrast. The top (~ 17.8 nm) and bottom (~ 24.6 nm) dielectric hBN thickness are confirmed by atomic force microscopy.

### **Optical measurements:**

Optical measurements were performed using confocal microscopy in an optically accessible dilution fridge (BlueFors) with vertical magnetic fields up to 9T and temperatures down to 60 mK [53]. A halogen lamp was used as the light source. The input light was spectrally filtered to 650 to 900 nm range. A low-temperature microscope objective was used to focus the light onto the sample. The light intensity on the sample was kept around 0.14 nW/ $\mu$ m<sup>2</sup> to minimize its effects on the electronic states. The reflected light was collected by the same objective and analyzed by a spectrometer equipped with a charge coupled device array to obtain spectrum. The RC spectrum is defined as  $(R - R_0)/R$ , where  $R_0$  the reference spectrum was taken for the sample at a high doping density with quenched excitonic resonances. For all the zero magnetic field data presented in Fig. 2 and 4, we polarize the system with a positive vertical magnetic field and then ramp back to perform the zero magnetic field measurement. The RMCD was used to study the magnetic properties of the samples. A combination of a linear polarizer and a quarter-wave plate was used to generate circularly polarized light ( $\sigma_{-}$  and  $\sigma_{+}$ ) on the sample. The RMCD spectrum is defined as  $\frac{\sigma_{-} - \sigma_{+}}{\sigma_{-} + \sigma_{+}}$ .

For the AP spectroscopy, we integrate the reflectance over a range of wavelengths (738-741.2 nm, or equivalently, 1.673 - 1.680 eV) that focuses on the attractive polaron resonance of tWSe<sub>2</sub>. The same wavelength range was used to obtain the average of the absolute value of RMCD. The magnetic susceptibility was evaluated from the slope of MCD at zero magnetic field.

For the streda formula data presented in Fig. 3, we use *RC* under  $\sigma^-$  excitation for the positive magnetic field detection, and  $\sigma^+$  excitation for the negative magnetic field detection.

#### **Twisted Angle Calibration:**

We calibrate the twisted angle of the tWSe<sub>2</sub> presented in the main text using the quantum oscillations observed optically under an out-of-plane magnetic field of 8.8T. In Extended Data Fig. 2, we present the doping dependent *RC* response of a monolayer tWSe<sub>2</sub> under  $\sigma_+$  excitation. The oscillation signal formed as a result of the formation of the Landau levels (LLs). The LL period is determined to be 0.244 V for the single gate response, from which we deduce a hole density change of  $1.75 \times 10^{12}$  cm<sup>-2</sup> per volt for data presented in the main text. Combining with the moiré period  $\Delta V_M$  extracted from the doping dependent *RC* data, we obtain a moiré density  $n_M$  of  $1.31 \times 10^{12}$  cm<sup>-2</sup>. The twisted angle calibration is further corroborated by the doping density calibration, as described in the next section.

#### **Doping density calibration:**

A parallel-plate capacitor model is used to calculate the gate-induced carrier density n and displacement

field *D* based on the applied gate voltages. The gate capacitances per area of the top and bottom gates,  $C_{t/b} = \varepsilon_{hBN}\varepsilon_0/d_{t/b}$ , are determined by the hBN thickness  $d_{t/b}$  and dielectric constant. We use  $\varepsilon_{hBN} = 3.89$ here. The sample doping density *n* can be calculated as  $n = (C_tV_t + C_bV_b)$ , where  $V_t$  and  $V_b$  are the voltages applied to the top and bottom gates. The displacement field is defined as  $D = (C_tV_t - C_bV_b)/2\varepsilon_0 - D_{offset}$ , where  $\varepsilon_0$  is the vacuum permittivity and the subtracted value is the built-in offset.

#### Data availability

All of the data that support the findings of this study are reported in the main text and Supplementary Information. Source data are available from the corresponding authors on reasonable request.

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#### **Competing interests**

The authors declare no competing interests.

#### Contributions

B.G., Y.Z., and M.H. conceived the project. B.G. performed the optical measurements and analyzed the data. M.X. did the theoretical calculation. M.X. and T.S.H. contributed to the theoretical understanding. L.Z. and B.G. fabricated the device. L.Z., M.G., D.S., P.U., G.A., R.M., M.J.M, and S.S. assisted with the experiment. S.J. and H.J. exfoliated the TMD flakes. T.T. and K.W. provided the bulk h-BN crystals. All authors contributed the writing of the manuscript. Y.Z. and M.H. supervised the work. All authors discussed the results and contributed to the manuscript.

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Fig.1: Optical response of the twisted WSe<sub>2</sub> homobilayer.

FIG. 1. **a**, Illustration of the moiré pattern in a R-stacked twisted WSe<sub>2</sub> homobilayer. Orange and red circles denote the high-symmetry atomic registries MX and XM, respectively (see inset). **b**, Schematic of an attractive polaron (AP) formed by an exciton in one valley (here at K') and a hole in the opposite valley (K). The exciton consists of an electron in the lowest conduction moiré band (dashed) and a hole in the topmost valence moiré band ( $V_1$ ). A second valence moiré band,  $V_2$ , is separated from  $V_1$ . **c**, Reflection contrast (RC) spectrum, defined as  $\frac{R-R_0}{R_0}$ , at temperature 4K. The hole-filling fraction v is tuned by gates (see Methods for calibration). The horizontal dashed lines (and arrows) indicate the integrated energy range of the attractive polaron. **d**, Derivative of RC with respect to v. **e**, Doping dependence of the integrated AP intensity ( $R_{AP}$ ).



FIG. 2. RC as a function of energy and hole filling fraction v under  $\mathbf{a}$ ,  $\sigma^-$  and  $\mathbf{b}$ ,  $\sigma^+$  excitation, respectively.  $\mathbf{c}$ , Spectrally resolved reflection magnetic circular dichroism (RMCD) at various v.  $\mathbf{d}$ , Polarization-resolved reflection spectrum at v = 1.  $\mathbf{e}$ , Magnetic hysteresis loop measured at v = 1; green and orange indicate the scan directions with respect to the magnetic field ( $\pm \Delta B$ ).  $\mathbf{f}$ , Schematic of the *many-body* bands at v = 1, incorporating electrostatic interaction at the mean-field level [54].  $v_1$  and  $v_2$  denote the first and the second moiré valance bands, respectively. All the data were taken at T = 66 mK.

Fig.2: Spontaneous magnetization at V = 1.

Fig. 3: Identifying the QAM states with the Streda formula



FIG. 3. **a**, Integrated AP intensity as a function of magnetic field *B* and hole filling fraction *v*. **b**, Extracted maxima of the integrated spectrum intensity at each *B* near  $v \simeq 0, 1, 3$ , indicated by purple, blue, and orange dots, respectively. Red and dark green lines near v = 1 and v = 3 indicate a linear fit for the blue and orange data points, from which the slope indicates Chern number C = 1 for v = 1, and C = 0 for v = 3.



FIG. 4. **a**, Integrated AP intensity as a function of the displacment field *D* and hole filling fraction *v* at magnetic field B = 0 and temperature T = 66 mK. **b**, (Red, left y-axis) Reflection magnetic circular dichroism (RMCD) as a function of the displacement field  $\frac{D}{\varepsilon_0}$  at B = 0. (Blue, right y-axis) derivative of RMCD with respect to magnetic field *B* at B = 0 measured as a function of  $\frac{D}{\varepsilon_0}$ . **c**, Magnetic susceptibility as function of temperature for two displacement field values. **d**, Curie-Weiss temperature  $T_{CW}$  as a function of  $\frac{D}{\varepsilon_0}$ . Linear fitting error bars are also shown. The inset schematics indicate the (bottom) QAH FM phase and the (top) AFM phase, respectively.

#### Fig. 4: Displacement field tuning: from QAH FM to AFM.



FIG. 1. Extended Data Fig.1 |Electronic structure of tWSe<sub>2</sub>. (a) Valley-projected moiré bandstructure obtained from the noninteracting continuum model at twist angle  $\theta = 2^{\circ}$  and zero displacement field D = 0. (b) The real space electron density distribution for filling the first (v<sub>1</sub>) and the second (v<sub>2</sub>) moiré bands. The parameters of the continuum model are taken from [23].



FIG. 2. Extended Data Fig.2 |Calibration of the twisted angle. a, Derivative of polarization-solved reflection  $(R_+)$  with respect to bottom gate voltage  $V_{bot}$  with spectral resolution at a monolayer WSe<sub>2</sub> spot. The black dashed lines indicate the energy window within which we obtain the landau oscillations. b, Extracted voltages where we get the minima  $\frac{dRC}{dV}$  within the dashed line region in panel **a**. Magnetic field 8.8*T* is used for this data.



FIG. 3. Extended Data Fig 3.|Temperature dependence of the QAH ferromagnetic phase at v = 1. RMCD signal hysteresis loop under v = 1 at 66mK, 300mK, and 1.2K.



FIG. 4. Extended Data Fig4. | a-f, Doping dependent *RC* under  $\sigma^-$  excitation at 0, 1, 2, 3, 4, 5 T. The AP intensity maximum shifts gradually from v = 1 to a  $v = 1 + \varepsilon$  as increasing the magnetic field. This indicates that the correlated state at v = 1 shifts with increasing the  $\mu_0 H$  field.



FIG. 5. Extended Figure 5. |Details about AP spectroscopy. a, Integrated AP intensity at various magnetic fields at 0, 1, 3, 5 T. b, Derivative of *RC* with respect to doping level. We can identify the peak position at v = 1 shift as a function of the external magnetic field, while it remains around the same doping level at v = 3 as changing  $\mu_0 H$ .



FIG. 6. Extended Figure 6. [Extraction of v = 0. a, Spectrally resolved doping dependent *RC* map at both electron and hole doping regime under 5 T. The dashed line indicates the energy range within which the intrinsic exciton sits and be integrated to obtain b.  $V_{top}$  change as a function of  $V_{bot}$  to dope the system while keeping the displacement field 0. b, Integrated intrinsic exciton at 0, 1, 3, 5T. c Integrated intrinsic exciton (X) oscillation strength as a function of  $\mu_0 H$ .



FIG. 7. Extended Figure 7. |Polarization resolved displacement field dependent *RC*. **a**, Spectrally resolved reflection contrast (RC) with displacement field (*D*) at  $\sigma_{-}$  (upper)  $\sigma_{+}$  (lower) excitations. **b**, The corresponding RMCD with respect to the data shown in **a**.



FIG. 8. Extended Figure 8. |v - D dependent RMCD under 0.1T. a, the integrated energy range is the same as the one shown in the main text. The magnetism get stabilized around the van Hove singularity region, and also shown at v = 3. b Simulation of DOS as a function of v - D. The corresponding electronic structure is obtained from the moiré continuum model as in Extended Fig. 1.



FIG. 9. Extended Figure 9. |Extraction of Curie-Weiss temperature at various displacement fields. Evolution of RMCD with respect to magnetic field ( $\mu_0 H$ ) and temperature (color) at various displacement field D = 0.75, 29.75, 58.75 mV/nm a-c. d-f The corresponding inverse susceptibility as a function of temperature with respect to the data shown in a-c. The dahsed line is the fitted data to extract the Curie-Weiss temperature.