

Moiré-resonant surface state in ultrathin RuO₂(110)

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RuO₂ has emerged as a prototypical candidate for *altermagnetism*. In the face of daunting evidence for magnetic order in the bulk, the focus naturally shifted to surfaces and ultrathin films, where Coulomb interactions are dimensionally quenched and electron correlations strongly enhanced. Here, we examine atomically ordered, ultrathin RuO₂(110) grown on Ru(0001) using a combination of scanning tunneling microscopy (STM), density functional theory, and density matrix renormalization group methods. We observe a nonmagnetic charge order that is imprinted by the incommensurate moiré stacking with the substrate and enhanced by the electronic Fermi-surface scattering within the flat-band surface state. We further identify a nonmagnetic, metastable $c(2 \times 2)$ surface reconstruction that arises from surface phonon softening and can be toggled reversibly via STM tip manipulation. Spin-polarized STM measurements, however, reveal no evidence of magnetic order on the RuO₂(110) surface. Our findings of a nonmagnetic charge modulation position ultrathin RuO₂(110) as an intriguing platform for exploring moiré-assisted electronic orders.

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The binary oxide RuO₂ has emerged as a material of multifold significance, drawing attention for both its exceptional catalytic properties and its proposed role as a functional Dirac semimetal with allegedly unconventional magnetic behavior [1–4]. Historically valued for its performance in electrochemical water splitting and its stability as a contact material [1,5,6], RuO₂ has more recently been identified as a potential prototype of *altermagnetism*—a novel magnetic phase where the presence of alternating magnetic moments within the unit cell combined with the absence of an antiunitary symmetry enables spin-split magnon excitations and thus hybridizes characteristics of conventional ferro- and antiferromagnets [7,8].

Although several experimental studies have reported findings not inconsistent with an altermagnetic interpretation [4,9–12], the existence of intrinsic magnetism in stoichiometric RuO₂ remains highly contested. Theoretical work has suggested that strong Fermi-surface nesting in RuO₂ could drive spin-density wave instabilities [2,13–16], and early

neutron and resonant x-ray scattering studies appeared to support collinear magnetic order [17–19]. Recent and more sensitive muon spin rotation and neutron scattering measurements, however, have excluded the presence of long-range magnetic order or sizable local moments in both bulk and thin film samples [20–22]. Moreover, transport anomalies initially attributed to an anomalous Hall effect [4,9] can now be reconciled from nonmagnetic mechanisms [23,24], while purported time-reversal symmetry breaking in the band structure [25] has been challenged by the absence of measurable spin splitting [26]. Numerous additional studies have raised further skepticism about altermagnetism in bulk RuO₂ [27–30].

As a result, recent theoretical efforts have increasingly focused on ultrathin films and surface-specific magnetic phenomena, with particular attention to the thermodynamically stable RuO₂(110) surface. This is because the associated dimensionality reduction, combined with an expected breakdown of the Fermi liquid paradigm due to enhanced electron correlations [31], has been promoted as a possible mechanism for surface magnetic instabilities [32–35].

In this context, spin-polarized scanning tunneling microscopy and spectroscopy (SP-STM/STS) have been proposed as powerful tools to probe emergent surface magnetism with atomic-scale resolution [35–37]. However, such spin-sensitive, atomically resolved measurements have remained experimentally challenging. A key limitation has been the

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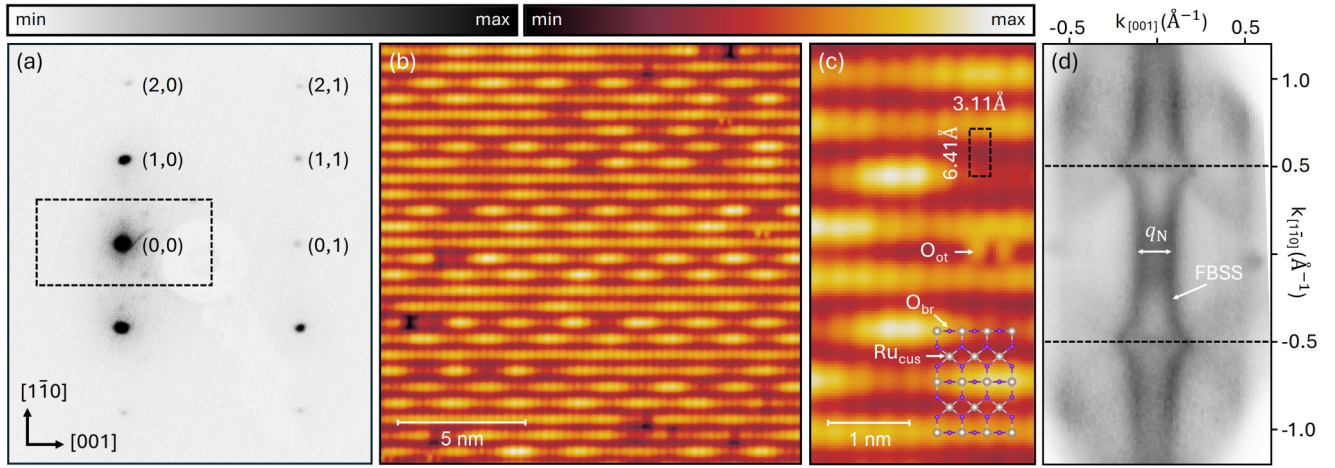


FIG. 1. Surface characterization of the stoichiometric $\text{RuO}_2(110)$ thin film grown on $\text{Ru}(0001)$: (a) Room-temperature LEED measurement ($E_{\text{kin}} = 80$ eV) of a large single domain of $\text{RuO}_2(110)$; the surface Brillouin zone is indicated in black. (b) STM constant current topography map showing an extended $\text{RuO}_2(110)$ terrace ($I_T = 500$ pA, $V_{\text{bias}} = 5$ mV). (c) Magnified view of panel (b) overlaid with the ball-and-stick model of the unreconstructed stoichiometric $\text{RuO}_2(110)$, exposing $[001]$ -oriented $\text{Ru}-\text{O}_{\text{br}}$ chains separated by rows of undercoordinated Ru_{cus} [1]. Oxygen atoms are marked in purple and ruthenium atoms in gray. (d) ARPES Fermi-surface map from a single domain, measured at the MAESTRO beamline of the Advanced Light Source with 69 eV p -polarized photons at $< 3 \times 10^{-10}$ mbar and 40 K.

absence of high-quality, atomically ordered $\text{RuO}_2(110)$ surfaces: Despite yielding high-quality bulk films, conventional epitaxial methods—including magnetron sputtering, molecular beam epitaxy, and pulsed laser deposition—often fall short of achieving the defect-free surface order required for large-scale STM/STS [38]. A well-established alternative involves the controlled oxidation and reactive segregation of RuO_2 on single-crystalline $\text{Ru}(0001)$, producing ultrathin, stoichiometric $\text{RuO}_2(110)$ films with excellent atomic order and minimal defect density [1,39]. This approach offers two key advantages: (1) It enables high-resolution STM/STS measurements that resolve the local electronic structure of the $\text{RuO}_2(110)$ surface and (2) self-passivation restricts RuO_2 to thicknesses where correlation effects are expected to be most pronounced, potentially giving rise to emergent electronic or spin instabilities.

Our results reveal surface-terminating chains of Ru and O that host a nested, quasi-one-dimensional flat-band surface state (FBSS), characterized by a local density of states (LDOS) peak near the Fermi energy—consistent with prior angle-resolved photoemission spectroscopy (ARPES) observations on bulk-truncated $\text{RuO}_2(110)$ [3,14,15,40]. This FBSS is modulated by a moiré potential originating from the underlying ruthenium substrate, the strength of which can be tuned by varying the RuO_2 film thickness.

The moiré potential induces a surface charge modulation that resonates with Fermi-surface nesting of the FBSS, without evidence for a corresponding spin modulation: Within its limits, spin-polarized STM reveals no magnetic contrast, consistent with our Density Matrix Renormalization Group (DMRG) calculations. Additionally, we identify a metastable, previously unreported $c(2 \times 2)$ surface reconstruction that can be reversibly toggled using the STM tip and originates from a structural relaxation, as corroborated by density functional theory (DFT). Together, these findings reveal intriguing complex structural and electronic phenomena on the $\text{RuO}_2(110)$

surface yet argue against its propensity toward magnetic instabilities.

I. FERMION SURFACE NESTING IN $\text{RuO}_2(110)$

The C_{3v} symmetry of the $\text{Ru}(0001)$ substrate permits the growth of three rotational domains of $\text{RuO}_2(110)$. Fine-tuning of the growth conditions (see Secs. S1 and S2 in the Supplemental Material [41]), however, achieves selective formation of millimeter-scale single-domain $\text{RuO}_2(110)$ films. Low-energy electron diffraction [LEED, Fig. 1(a)] confirms the long-range crystalline order, while atomically resolved STM topography images [Fig. 1(b)] reveal well-ordered terraces with typical widths of several tens of nanometers.

A magnified view [Fig. 1(c)] resolves the characteristic surface structure, consistent with the ball-and-stick model of the stoichiometric $\text{RuO}_2(110)$ surface [1]. In particular, the surface features quasi-one-dimensional $[001]$ -oriented $\text{Ru}-\text{O}_{\text{br}}$ chains separated by rows of undercoordinated Ru_{cus} sites. As previously reported [3,14,35], the hybridization of $\text{Ru } 4d_z$ and $\text{O}_{\text{br}} 2p_z$ orbitals in these chains gives rise to an FBSS that disperses along the $[001]$ direction and is flat in the $[1\bar{1}0]$ direction. This FBSS is clearly observed in ARPES measurements on our ultrathin, $\lesssim 3$ nm $\text{RuO}_2(110)/\text{Ru}(0001)$ films [Fig. 1(d)]. Notably, ARPES displays the canonical (110)-oriented Fermi surface known from cleaved bulk RuO_2 [14,26,40], indicating that the band structure is largely unaffected by quantum confinement at this thickness. The Fermi surface is dominated by two linear features of the FBSS oriented along the $[1\bar{1}0]$ direction. Its near-parallel geometry enables strong Fermi-surface nesting, suggesting an enhanced susceptibility to electronic instabilities and a possible breakdown of Fermi liquid behavior due to electron interactions (see Sec. S6.2 in the Supplemental Material [41]). The corresponding nesting vector is determined to be $q_N \approx 0.24 \pm 0.04 \text{ \AA}^{-1}$.

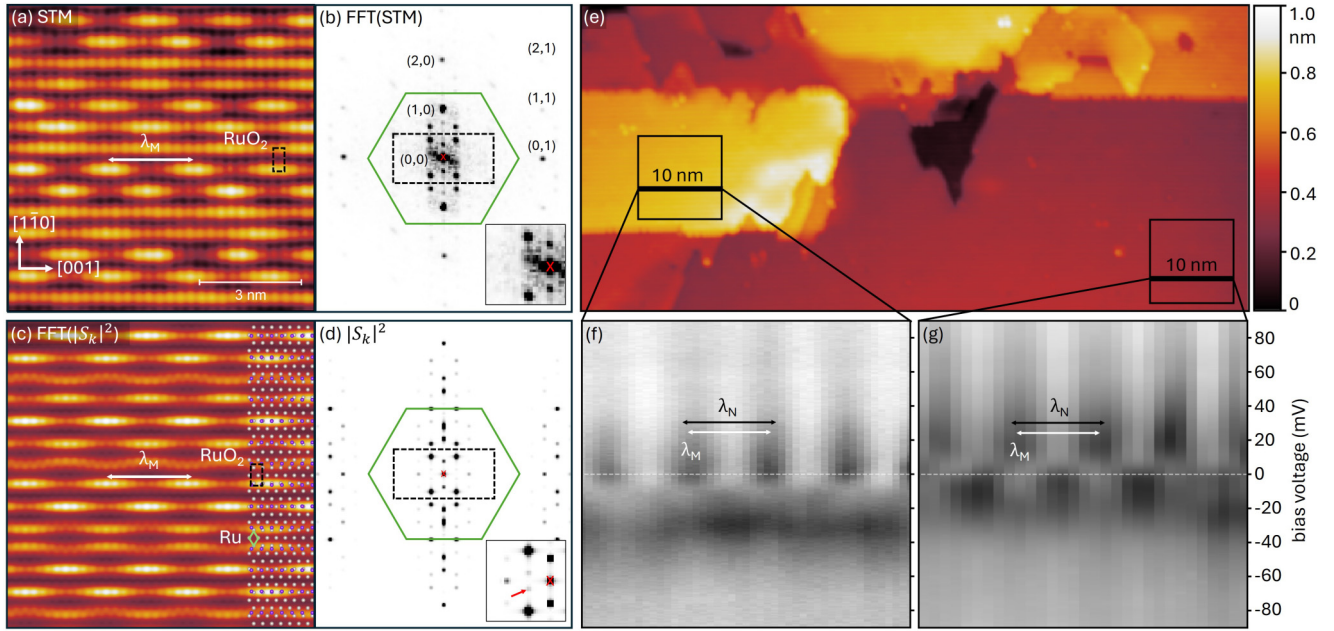


FIG. 2. Moiré pattern arising from the lattice mismatch of the $\text{RuO}_2(110)$ thin film and the $\text{Ru}(0001)$ substrate: (a) STM constant current topography map showing real-space moiré pattern ($I_T = 500$ pA, $V_{\text{bias}} = 5$ mV). (b) FFT of the STM measurement depicted in panel (a). The green and black lines mark the boundaries of the $\text{Ru}(0001)$ and $\text{RuO}_2(110)$ surface Brillouin zones, respectively. (c) Real-space simulation of the moiré pattern, i.e., FFT of the structure factor $|S_q|^2$ in panel (d) calculated via Eq. (1). The Ru atom positions of the $\text{Ru}(0001)$ substrate and $\text{RuO}_2(110)$ surface are indicated by gray and purple circles, respectively. (e) STM constant current topography map exposing different apparent heights of the RuO_2 film ($I_T = 10$ pA, $V_{\text{bias}} = -500$ mV). Corresponding dI/dV STS line spectroscopy along the $[001]$ direction of the two different regions is shown in panels (f) and (g) ($I_T = 10$ pA, $V_{\text{bias}} = -500$ mV, $V_{\text{rms}} = 2$ mV, $\delta_z = -0.27$ nm).

II. SUBSTRATE-INDUCED MOIRÉ MODULATION

Having established the synthesis of atomically ordered $\text{RuO}_2(110)$ surfaces with an electronic structure consistent with cleaved single crystals, we now turn to two notable features observed in the STM topography of Figs. 1(b) and 1(c) [39,42,43]:¹

(1) The registry shift between some occasional on top O_{ot} atoms and the $\text{Ru}-\text{O}_{\text{br}}$ chains [42] indicates that our low bias voltage ($V_{\text{bias}} = 5$ mV) STM measurements predominantly resolve the Ru positions. This contrasts earlier work at higher bias voltages (~ -1 V) that resolved the O_{br} positions [39].

(2) The $\text{Ru}-\text{O}_{\text{br}}$ chains, which host the FBSS, show a distinct apparent height beating on the order of 30 pm. The magnitude and phase of this beating vary from chain to chain.

While the sensitivity of low bias voltages to Ru-derived density of states [3] explains point (1), point (2) requires a more detailed examination: Applying a two-dimensional (2D) fast Fourier transform (FFT) to the quasiperiodic modulation observed in the STM topography [Fig. 2(a)] reveals additional peaks within the first Brillouin zone [Fig. 2(b)], which are inconsistent with the $\text{RuO}_2(110)$ lattice alone. These are

rationalized by the incommensurate lattice of the underlying $\text{Ru}(0001)$ substrate, which imprints a moiré potential on the $\text{RuO}_2(110)$ surface [44,45] [see inset of Fig. 2(c)]. This induces a surface charge density modulation that can be expressed in terms of a moiré structure factor (see Sec. S3 in the Supplemental Material [41]):

$$S_q = \sum_{\mathbf{G}_{\text{Ru}}} \sum_{\mathbf{G}_{\text{RuO}_2}} \delta(\mathbf{q} - \mathbf{G}_{\text{Ru}} - \mathbf{G}_{\text{RuO}_2}) f(\mathbf{G}_{\text{RuO}_2}), \quad (1)$$

with atomic scattering factor $f(\mathbf{G}_{\text{RuO}_2})$ [46], and reciprocal lattice vectors $\mathbf{G}_{\text{RuO}_2}$ and $\mathbf{G}_{\text{Ru}}$ of film and substrate.

The calculated $|S_q|^2$ [Fig. 2(d)] matches remarkably well with the experimental FFT [Fig. 2(b)], as well as the LEED pattern [$E_{\text{kin}} = 80$ eV, $T = 300$ K, Fig. 1(a)]. To compare with real-space data, we performed an inverse FFT of Fig. 2(d), applying a Gaussian filter to simulate STM resolution. The resulting image [Fig. 2(c)] is in excellent agreement with the measured topography [Fig. 2(a)], revealing a leading moiré wavelength of $\lambda_M = 22.9 \pm 2.0$ Å, i.e., ≈ 7.6 lattice constants along the chain direction.

To investigate the thickness dependence of the moiré modulation, we prepared a stepped $\text{RuO}_2(110)$ film with terraces of varying apparent heights. A representative STM image [Fig. 2(e)] shows an apparently thicker region (bright orange) and an apparently thinner region (dark orange).

In the thicker region, spatially resolved dI/dV spectra [Fig. 2(f)] reveal a modulated LDOS, with peaks near zero bias. They alternate in intensity with the spatial period of λ_M —a clear fingerprint of moiré-induced LDOS trapping.

¹According to a private communication with Michael Schmid (TU Vienna), the authors of Ref. [39] occasionally observed a periodic corrugation in ultrathin $\text{RuO}_2(110)/\text{Ru}(0001)$ films using room-temperature STM at a bias voltage of -30 mV. This corrugation is consistent with our observations (2), although these results have not been published.

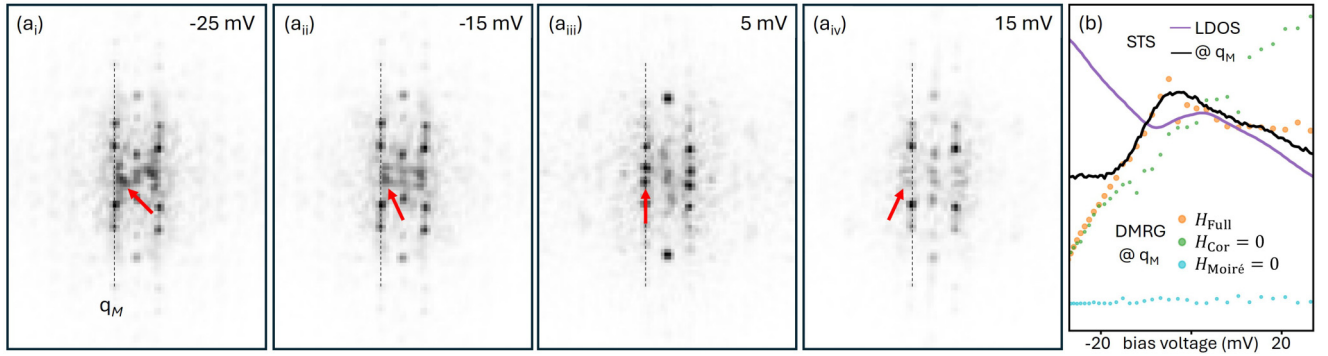


FIG. 3. Moiré interaction with FBSS: (a) FFT of constant current dI/dV maps collected at bias voltages from $V_{\text{bias}} = -25$ to 15 mV ($I_T = 500$ pA, $V_{\text{rms}} = 5$ mV). The red arrow indicates a dispersing moiré peak. (b) LDOS integrated over the entire area (purple) of an STS grid measurement, as compared to LDOS integrated only over the moiré frequencies (black) at q_M as indicated in panel (a), [the grid scan was measured on the thicker region of Fig. 2(e) with $I_T = 10$ pA, $V_{\text{bias}} = -500$ mV, $V_{\text{rms}} = 2$ mV, and $\delta_z = -0.27$ nm]. While the total LDOS exhibits maxima at -30 mV and near zero bias, the moiré features exhibit a resonance at -5 mV. The markers show the oscillation amplitude at q_M calculated by DMRG for the FBSS without moiré (turquoise), for noninteracting FBSS and moiré (green) and for interacting FBSS and moiré (orange), the latter of which reproduces the experimentally observed resonance (black).

Additionally, a second LDOS feature appears at -30 meV, which shows almost no spatial modulation and aligns with the FBSS binding energy observed in ARPES [see Figs. S1 and S2(c) in the Supplemental Material [41]]. This indicates a substrate-decoupled surface electronic structure of $\text{RuO}_2(110)$ in the thicker region [14].

In contrast, the thinner region shows these LDOS features shifted upward by ≈ 20 meV, now located at bias voltages of -10 and 20 meV [Fig. 2(g)]. Both signatures exhibit a clear, inversely phased spatial modulation with period λ_M , indicating stronger coupling to the underlying $\text{Ru}(0001)$ substrate and a more pronounced influence of the moiré potential. This suggests a progressive attenuation of the moiré potential with increasing film thickness and underscores the decisive role of the substrate in shaping the $\text{RuO}_2(110)$ thin film's surface electronic structure.

III. RESONATING FERMI-SURFACE SCATTERING

Building on our interpretation of the moiré-induced surface charge modulation, we note that a contrast inversion between STM images taken at opposite bias polarities—similar to Fig. 2(g)—is often regarded as a hallmark of charge density wave order [47–49], i.e., of a Fermi-surface instability. We, however, reconcile this modulation by a resonant coupling between the moiré potential and the Fermi-surface nesting, corroborated by a striking correspondence: The moiré wave vector $q_M = 2\pi/\lambda_M \approx 0.27 \pm 0.02 \text{ \AA}^{-1}$, as extracted from STM data, closely matches the Fermi-surface nesting vector $q_N \approx 0.24 \pm 0.04 \text{ \AA}^{-1}$ identified within the FBSS via ARPES [Fig. 1(d)] [14]. This near-coincidence naturally implies a contribution of the Fermi-surface nesting within the FBSS to the observed moiré scattering features:

Indeed, we find that the electronic fluctuations encoded in the bare susceptibility $\chi(\mathbf{q})$ can constructively interfere with the moiré potential when both wave vectors are commensurate. In this sense, the Coulomb interaction can drive a resonant response by coupling the moiré potential to $\chi(\mathbf{q})$, which itself is a property of the noninteracting band structure.

To explore this possibility experimentally, Fig. 3(a) presents two-dimensional Fourier transforms (FFTs) of dI/dV maps, which reflect the local density of states near the Fermi level, acquired at bias voltages of $V_{\text{bias}} = -25, -15, 5$, and 15 mV. As expected, the FFTs qualitatively reproduce the peak pattern associated with the static moiré modulation observed in the STM topography [Fig. 2(c)]. Notably, however, the intensity profile of the corresponding moiré scattering peaks at q_M [black curve in Fig. 3(b)]—measured by STS-grid spectroscopy—exhibits a pronounced bias-voltage dependence, reaching a maximum at -5 meV. This behavior is qualitatively distinct from a corresponding dip in the total surface density of states, which we obtained by integration over all wave vectors of the dataset (purple curve). This discrepancy indicates that the resonance is not driven by the LDOS itself, but instead reflects a moiré-induced interaction with Fermi-surface nesting in the FBSS, occurring at band fillings where q_M and q_N coincide—a phenomenon that, to the best of our knowledge, has not been previously reported.

To theoretically examine this resonance, we employed the DMRG method, well suited for probing quasi-one-dimensional strongly correlated systems [50,51]. We constructed a minimal Hamiltonian model incorporating key features of the $\text{RuO}_2(110)$ surface: (1) a tight-binding term (H_{Kin}) derived from the DFT surface band structure and adapted to the FBSS ARPES results [3,14], (2) a periodically modulated on-site energy representing the moiré potential ($H_{\text{Moiré}}$), and (3) a two-particle interaction term capturing electronic correlations (H_{Cor}). The total Hamiltonian reads (see Sec. S6.1 in the Supplemental Material [41])

$$H_{\text{Full}} = H_{\text{Kin}} + H_{\text{Moiré}} + H_{\text{Cor}}. \quad (2)$$

The prominent anisotropy of the electronic single-particle spectrum in Fig. 1(d) suggests weakly coupled $\text{Ru}-\text{O}_{\text{br}}$ chains to dominate the low-energy physics of the $\text{RuO}_2(110)$ surface. This intuition is substantiated by the almost one-dimensional (1D) electronic fluctuation spectrum characterized by the bare susceptibility $\chi(\mathbf{q})$ (see Sec. S6.2 in the Supplemental Material [41]) and motivates us to start our analysis by considering

an isolated Ru—O_{br} chain along the [001] axis. Using open boundary conditions, we solve the model for varying FBSS binding energies by tuning the chemical potential. As an analog to the experimental LDOS, we compute the expectation value of the site-resolved electronic density $\langle \hat{n}_i \rangle = \langle \hat{n}_{i\uparrow} + \hat{n}_{i\downarrow} \rangle$.

Consistent with experiment, $\langle \hat{n}_i \rangle$ displays a periodic modulation along the investigated 1D chain [see Fig. S9(c) in the Supplemental Material [41]]. Its FFT amplitude, plotted as a function of energy and momentum, reveals two main features: a dominant, nondispersing peak at $q_M = 2\pi/\lambda_M = 0.27 \text{ \AA}^{-1}$, matching the experimentally determined moiré period, and a quadratically dispersing mode associated with Friedel oscillations from the FBSS (see Sec. S6.4 in the Supplemental Material [41]) [52]. The strength of the charge modulation at q_M is plotted as function of binding energy in Fig. 3(b) (orange curve), and indeed reproduces the characteristic resonance at -5 mV observed experimentally (black curve), where the Fermi wave vector q_N perfectly matches the moiré period q_M .

While in the real material the moiré potential and Fermi-surface nesting are intrinsically intertwined, the DMRG framework allows us to disentangle their respective roles (see Sec. S6.4 in the Supplemental Material [41]). When Fermi-surface scattering is suppressed by setting $H_{\text{Cor}} = 0$, a charge modulation with the correct periodicity q_M is recovered; however, the resonant enhancement is absent (green curve). Conversely, when the moiré potential is switched off ($H_{\text{Moiré}} = 0$), electronic correlations alone are insufficient to drive a charge instability at q_M , and only residual Friedel oscillations arising from the open boundary conditions remain (turquoise curve).

Extending our 1D analysis to the full 2D surface model, we find that charge ordering along the [001] axis is indeed consistent with the resonant behavior of the isolated chains. The interchain ordering is governed exclusively by the moiré potential $H_{\text{Moiré}}$, whereas the weak interchain coupling contained in H_{Kin} and H_{Cor} plays only a marginal role due to the pronounced anisotropy of the FBSS. Taken together, these results demonstrate that the charge modulation is primarily driven by the moiré potential, while electronic correlations at the Fermi surface substantially enhance this modulation and give rise to the experimentally observed resonance in STS. Consequently, we do not expect charge ordering at q_M on the bulk-truncated RuO₂(110) surface.

For completeness, let us also focus on the four distinct peaks that are indicated by red arrows in the FFTs of Fig. 3(a), peaks that are predicted by our structure factor model [inset of Fig. 2(d)]. Unlike the other moiré peaks, these features exhibit a pronounced energy-dependent momentum shift: As the bias voltage increases from -25 to 15 mV , the peaks shift from $0.87q_M$ to $1.08q_M$, a currently unexplained energy dispersion that is about twice as steep as expected for quasiparticle interference of the FBSS.

IV. EMERGENT SURFACE RECONSTRUCTION

In addition to the charge-ordering phenomena discussed above, STM topography measurements on a subset of samples [Fig. 4(a)] reveal a pronounced $c(2 \times 2)$ periodic modulation. This reconstruction is characterized by an alternating

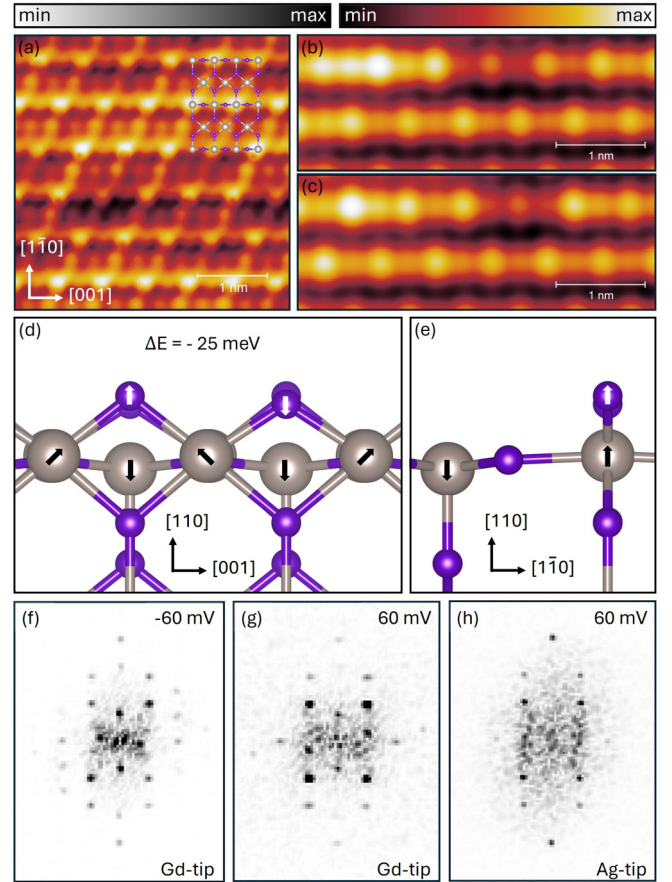


FIG. 4. RuO₂(110) surface instabilities: (a) Constant current STM topography scan showing a $c(2 \times 2)$ reconstruction of the RuO₂(110) surface ($I_T = 1000 \text{ pA}$, $V_{\text{bias}} = -15 \text{ mV}$). (b), (c) Constant current STM topography scans on the same area taken before and after switching between the two metastable reconstructions ($I_T = 20 \text{ pA}$, $V_{\text{bias}} = -15 \text{ mV}$). (d), (e) $c(2 \times 2)$ surface reconstruction of RuO₂(110) as found by DFT slab calculations. FFT of constant current dI/dV scans measured with spin polarized Gd tip at (f) $V_{\text{bias}} = -60 \text{ mV}$ and (g) $V_{\text{bias}} = 60 \text{ mV}$ ($I_T = 200 \text{ pA}$, $V_{\text{rms}} = 5 \text{ mV}$). (h) Corresponding FFT of unpolarized Ag-tip scan showing qualitatively similar results, indicating the peak's origin to be nonmagnetic.

intensity pattern of surface Ru sites, effectively doubling the RuO₂(110) surface unit cell.

As shown in Figs. 4(b) and 4(c), two symmetry-equivalent metastable configurations of this $c(2 \times 2)$ pattern can be reversibly switched with tunneling currents of $I_T = 100 \text{ pA}$, demonstrating the bistable nature of the surface reconstruction.

A previous study under ambient conditions attributed a similar 2×2 reconstruction on RuO₂(110) to the adsorption of CO molecules at oxygen bridge sites [43]. This interpretation, however, is incompatible with our observations, since CO adsorption is known to quench the FBSS [3], which remains clearly discernible in our measurements. Instead, our DFT calculations for a clean RuO₂(110) surface slab reveal a structural reconstruction that intrinsically doubles the surface unit cell [Figs. 4(d) and 4(e)], is driven by a surface phonon softening, and is $\approx 25 \text{ meV}$ more stable than the un-

reconstructed 2×2 surface unit cell (see Sec. S6.5 in the Supplemental Material [41]).

V. NO EVIDENCE FOR MAGNETIC SURFACE INSTABILITY

Finally, none of our experimental observations provide evidence for magnetic order in the RuO₂ thin films, consistent with the nonmagnetic ground states obtained from DMRG. Even when considering on-site Coulomb repulsions exceeding both FBSS bandwidth and *ab initio* bulk values [20], neither of the considered models exhibits any tendency toward long-range magnetic order in the spin expectation value $S_i^z = \langle \hat{n}_{i\uparrow} - \hat{n}_{i\downarrow} \rangle / 2$. Instead, all computed ground states remain spin singlets without any local magnetization.

In light of recent theoretical predictions of surface magnetism on RuO₂(110) [33–35], we explicitly probed potential magnetic order using spin-polarized STM measurements performed with a Gd-coated tip. The magnetic sensitivity of the tip was independently verified on a Gd reference surface (see Fig. S6 in the Supplemental Material [41]). Within the experimental resolution, no significant differences were observed between data acquired with the spin-polarized tip [Figs. 4(f) and 4(g)] and those obtained using an unpolarized Ag tip [Fig. 4(h)]. In particular, we find no indications of spin-density waves, magnetic domains, or spin-polarized surface states.

We note that the subatomic magnetic order with small magnetic moments predicted in the context of altermagnetism in Ref. [35] approaches the sensitivity limits of spin-polarized STM (spatial resolution $\approx 3 \text{ \AA}$, magnetic resolution $\approx 0.3 \mu_B$) [53–57]. The absence of a measurable spin contrast therefore constitutes an important experimental benchmark for future studies addressing possible magnetic ordering on RuO₂(110).

Experimental signatures of altermagnetism in epitaxial RuO₂ thin films have primarily been reported for RuO₂ grown on TiO₂(110), where substantial strain and symmetry breaking are imposed on the (110) surface [12,33,58–60]. In contrast, Ref. [29] reports ARPES measurements on RuO₂ thin films grown on metallic Ru substrates, which, similar to our results, are consistent with a nonmagnetic surface band

structure. This apparent substrate dependence raises questions about the intrinsic nature of altermagnetism in RuO₂ thin films and highlights the need for a more systematic investigation of substrate-induced effects.

Irrespective of this open issue, our study establishes ultra-thin RuO₂ films as a versatile platform for correlated electron physics, in which tunable electronic and structural instabilities intertwine to give rise to ordering phenomena and surface reconstructions that, within the limits of our experimental resolution, remain nonmagnetic.

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DATA AVAILABILITY

The data supporting the findings of this article are not publicly available but are available from the authors upon reasonable request.

- [1] H. Over, Surface chemistry of ruthenium dioxide in heterogeneous catalysis and electrocatalysis: From fundamental to applied research, *Chem. Rev.* **112**, 3356 (2012).
- [2] Y. Sun, Y. Zhang, C.-X. Liu, C. Felser, and B. Yan, Dirac nodal lines and induced spin Hall effect in metallic rutile oxides, *Phys. Rev. B* **95**, 235104 (2017).
- [3] V. Jovic *et al.*, Momentum for catalysis: How surface reactions shape the RuO₂ flat surface state, *ACS Catal.* **11**, 1749 (2021).
- [4] Z. Feng *et al.*, An anomalous Hall effect in altermagnetic ruthenium dioxide, *Nat. Electron.* **5**, 735 (2022).
- [5] Y. Lee, J. Suntivich, K. J. May, E. E. Perry, and Y. Shao-Horn, Synthesis and activities of rutile IrO₂ and RuO₂ nanoparticles for oxygen evolution in acid and alkaline solutions, *J. Phys. Chem. Lett.* **3**, 399 (2012).
- [6] R. G. Vadimsky, R. P. Frankenthal, and D. E. Thompson, Ru and RuO₂ as electrical contact materials: Preparation and environmental interactions, *J. Electrochem. Soc.* **126**, 1017 (1979).
- [7] L. Šmejkal, J. Sinova, and T. Jungwirth, Emerging research landscape of altermagnetism, *Phys. Rev. X* **12**, 040501 (2022).
- [8] L. Šmejkal, J. Sinova, and T. Jungwirth, Beyond conventional ferromagnetism and antiferromagnetism: A phase with nonrelativistic spin and crystal rotation symmetry, *Phys. Rev. X* **12**, 031042 (2022).
- [9] T. Tschirner *et al.*, Saturation of the anomalous Hall effect at high magnetic fields in altermagnetic RuO₂, *APL Mater.* **11**, 101103 (2023).
- [10] X. Zhou *et al.*, Crystal thermal transport in altermagnetic RuO₂, *Phys. Rev. Lett.* **132**, 056701 (2024).
- [11] Y. Guo *et al.*, Direct and inverse spin splitting effects in altermagnetic RuO₂, *Adv. Sci.* **11**, 2400967 (2024).
- [12] S. G. Jeong *et al.*, Metallicity and anomalous Hall effect in epitaxially strained, atomically thin RuO₂ films, *Proc. Natl. Acad. Sci. USA* **122**, e2500831122 (2025).

- [13] L. F. Mattheiss, Electronic structure of RuO_2 , OsO_2 , and IrO_2 , *Phys. Rev. B* **13**, 2433 (1976).
- [14] V. Jovic *et al.*, Dirac nodal lines and flat-band surface state in the functional oxide RuO_2 , *Phys. Rev. B* **98**, 241101 (2018).
- [15] V. Jovic *et al.*, The Dirac nodal line network in non-symmorphic rutile semimetal RuO_2 , [arXiv:1908.02621](https://arxiv.org/abs/1908.02621).
- [16] K.-H. Ahn, A. Hariki, K.-W. Lee, and J. Kuneš, Antiferromagnetism in RuO_2 as d -wave Pomeranchuk instability, *Phys. Rev. B* **99**, 184432 (2019).
- [17] T. Berlijn *et al.*, Itinerant antiferromagnetism in RuO_2 , *Phys. Rev. Lett.* **118**, 077201 (2017).
- [18] Z. Zhu *et al.*, Anomalous antiferromagnetism in metallic RuO_2 determined by resonant x-ray scattering, *Phys. Rev. Lett.* **122**, 017202 (2019).
- [19] S. W. Lovesey, D. D. Khalyavin, and G. van der Laan, Magnetic properties of RuO_2 and charge-magnetic interference in Bragg diffraction of circularly polarized x-rays, *Phys. Rev. B* **105**, 014403 (2022).
- [20] A. Smolyanyuk, I. I. Mazin, L. Garcia-Gassull, and R. Valentí, Fragility of the magnetic order in the prototypical altermagnet RuO_2 , *Phys. Rev. B* **109**, 134424 (2024).
- [21] P. Keßler *et al.*, Absence of magnetic order in RuO_2 : Insights from μSR spectroscopy and neutron diffraction, *npj Spintron.* **2**, 50 (2024).
- [22] L. Kiefer *et al.*, Crystal structure and absence of magnetic order in single-crystalline RuO_2 , *J. Phys.: Condens. Matter* **37**, 135801 (2025).
- [23] F. Pawula *et al.*, Multiband transport in RuO_2 , *Phys. Rev. B* **110**, 064432 (2024).
- [24] X. Peng *et al.*, Universal scaling behavior of transport properties in non-magnetic RuO_2 , *Commun. Mater.* **6**, 177 (2025).
- [25] O. Fedchenko *et al.*, Observation of time-reversal symmetry breaking in the band structure of altermagnetic RuO_2 , *Sci. Adv.* **10**, eadj4883 (2024).
- [26] J. Liu *et al.*, Absence of altermagnetic spin splitting character in rutile oxide RuO_2 , *Phys. Rev. Lett.* **133**, 176401 (2024).
- [27] D. T. Plouff *et al.*, Revisiting altermagnetism in RuO_2 : A study of laser-pulse induced charge dynamics by time-domain terahertz spectroscopy, *npj Spintron.* **3**, 17 (2025).
- [28] S. W. Lovesey, D. D. Khalyavin, and G. van der Laan, Magnetic structure of RuO_2 in view of altermagnetism, *Phys. Rev. B* **108**, L121103 (2023).
- [29] S. Hahn *et al.*, Off-stoichiometric surface reconstruction in the altermagnetic candidate $\text{RuO}_2(100)/\text{Ru}(10\bar{1}0)$, *Phys. Rev. B* **111**, 214431 (2025).
- [30] A. Smolyanyuk, L. Šmejkal, and I. I. Mazin, Origin of the anomalous Hall effect in Cr-doped RuO_2 , *Phys. Rev. B* **111**, 064406 (2025).
- [31] T. Giamarchi, *Quantum Physics in One Dimension* (Oxford University Press, Oxford, 2003).
- [32] S. Brahimi, D. P. Rai, and S. Lounis, Confinement-induced altermagnetism in RuO_2 thin films, *J. Phys.: Condens. Matter* **37**, 395801 (2025).
- [33] S. G. Jeong, I. H. Choi, S. Nair, L. Buiarelli, B. Pourbahari, J. Young Oh, B. Y. X. Lin, J. M. LeBeau, N. Bassim, D. Hirai, A. Seo, W. S. Choi, R. M. Fernandes, T. Birol, L. Zhao, J. S. Lee, and B. Jalan, Altermagnetic polar metallic phase in ultra-thin epitaxially-strained RuO_2 films, *Proc. Natl. Acad. Sci. USA* **123**, e2526641123 (2026).
- [34] E. Torun, C. M. Fang, G. A. de Wijs, and R. A. de Groot, Role of magnetism in catalysis: $\text{RuO}_2(110)$ surface, *J. Phys. Chem. C* **117**, 6353 (2013).
- [35] D. Q. Ho, D. Q. To, R. Hu, G. W. Bryant, and A. Janotti, Symmetry-breaking induced surface magnetization in nonmagnetic RuO_2 , *Phys. Rev. Mater.* **9**, 094406 (2025).
- [36] H.-R. Hu, X. Wan, and W. Chen, Quasiparticle interference in altermagnets, *Phys. Rev. B* **111**, 035132 (2025).
- [37] P. Sukhachov and J. Linder, Impurity-induced Friedel oscillations in altermagnets and p -wave magnets, *Phys. Rev. B* **110**, 205114 (2024).
- [38] P. Keßler *et al.*, Epitaxial RuO_2 and IrO_2 films by pulsed laser deposition on $\text{TiO}_2(110)$, *APL Mater.* **12**, 101110 (2024).
- [39] H. Over *et al.*, Atomic-scale structure and catalytic reactivity of the $\text{RuO}_2(110)$ surface, *Science* **287**, 1474 (2000).
- [40] M. H. Visscher, S. Buchberger, B. Saika, S. Mo, L. Richter, M. Leandersson, C. Polley, A. P. Mackenzie, and P. D. C. King, Disentangling bulk and surface electronic structure using targeted cleave planes in RuO_2 , [arXiv:2605.06798](https://arxiv.org/abs/2605.06798).
- [41] See Supplemental Material at <https://link.aps.org/supplemental/10.1103/cvqr-4wkd> for details, which includes Refs. [1,3,14,32–35,39,41,44–46,50–52,55,60–81].
- [42] H. Over, A. Seitsonen, E. Lundgren, M. Schmid, and P. Varga, Experimental and simulated STM images of stoichiometric and partially reduced $\text{RuO}_2(110)$ surfaces including adsorbates, *Surf. Sci.* **515**, 143 (2002).
- [43] M. Rössler, S. Günther, and J. Winterlin, Scanning tunneling microscopy of the $\text{RuO}_2(110)$ surface at ambient oxygen pressure, *J. Phys. Chem. C* **111**, 2242 (2007).
- [44] Y. Kim, A. Seitsonen, and H. Over, The atomic geometry of oxygen-rich $\text{Ru}(0001)$ surfaces: coexistence of $(1 \times 1)\text{O}$ and $\text{RuO}_2(110)$ domains, *Surf. Sci.* **465**, 1 (2000).
- [45] Y. D. Kim, S. Schwegmann, A. P. Seitsonen, and H. Over, Epitaxial growth of $\text{RuO}_2(100)$ on $\text{Ru}(10\bar{1}0)$: Surface structure and other properties, *J. Phys. Chem. B* **105**, 2205 (2001).
- [46] L.-M. Peng, Electron atomic scattering factors and scattering potentials of crystals, *Micron* **30**, 625 (1999).
- [47] P. Mallet *et al.*, Contrast reversal of the charge density wave STM image in purple potassium molybdenum bronze $\text{K}_{0.9}\text{Mo}_6\text{O}_{17}$, *Phys. Rev. B* **60**, 2122 (1999).
- [48] P. Mallet, H. Guyot, J. Y. Veuillen, and N. Motta, Charge-density-wave STM observation in $\eta\text{-Mo}_4\text{O}_{11}$, *Phys. Rev. B* **63**, 165428 (2001).
- [49] M. Spera *et al.*, Insight into the charge density wave gap from contrast inversion in topographic STM images, *Phys. Rev. Lett.* **125**, 267603 (2020).
- [50] S. R. White, Density matrix formulation for quantum renormalization groups, *Phys. Rev. Lett.* **69**, 2863 (1992).
- [51] U. Schollwöck, The density-matrix renormalization group in the age of matrix product states, *Ann. Phys.* **326**, 96 (2011).
- [52] S. R. White, I. Affleck, and D. J. Scalapino, Friedel oscillations and charge density waves in chains and ladders, *Phys. Rev. B* **65**, 165122 (2002).
- [53] J. Tersoff and D. R. Hamann, Theory and application for the scanning tunneling microscope, *Phys. Rev. Lett.* **50**, 1998 (1983).

- [54] P. Kurz, G. Bihlmayer, and S. Blügel, Magnetism and electronic structure of hcp Gd and the Gd(0001) surface, *J. Phys.: Condens. Matter* **14**, 6353 (2002).
- [55] P. Härtl, M. Leisegang, and M. Bode, Magnetic domain structure of epitaxial Gd films grown on W(110), *Phys. Rev. B* **105**, 174431 (2022).
- [56] C. J. Chen, Origin of atomic resolution on metal surfaces in scanning tunneling microscopy, *Phys. Rev. Lett.* **65**, 448 (1990).
- [57] C. J. Chen, Tunneling matrix elements in three-dimensional space: The derivative rule and the sum rule, *Phys. Rev. B* **42**, 8841 (1990).
- [58] A. K. Rajapitamahuni *et al.*, Thickness-dependent insulator-to-metal transition in epitaxial RuO₂ films, *Phys. Rev. Mater.* **8**, 075002 (2024).
- [59] Y. Zhang *et al.*, Observation of mirror-odd and mirror-even spin texture in ultra-thin epitaxially-strained RuO₂ films, [arXiv:2509.16361](https://arxiv.org/abs/2509.16361).
- [60] A. Akashdeep *et al.*, Surface-localized magnetic order in RuO₂ thin films revealed by low-energy muon probes, *Appl. Phys. Lett.* **128**, 022406 (2026).
- [61] H. Schäfer, G. Schneidereit, and W. Gerhardt, Zur Chemie der Platinmetalle. RuO₂ Chemischer Transport, Eigenschaften, thermischer Zerfall, *Z. Anorg. Allg. Chem.* **319**, 327 (1963).
- [62] H. Over *et al.*, Visualization of atomic processes on ruthenium dioxide using scanning tunneling microscopy, *ChemPhysChem* **5**, 167 (2004).
- [63] B. Herd, M. Knapp, and H. Over, Atomic scale insights into the initial oxidation of Ru(0001) using molecular oxygen: A scanning tunneling microscopy study, *J. Phys. Chem. C* **116**, 24649 (2012).
- [64] A. Goriachko and H. Over, The nanostructuring of atomically flat Ru(0001) upon oxidation and reduction, *Nanoscale Res. Lett.* **11**, 534 (2016).
- [65] Y. He, D. Langsdorf, L. Li, and H. Over, Versatile model system for studying processes ranging from heterogeneous to photocatalysis: Epitaxial RuO₂(110) on TiO₂(110), *J. Phys. Chem. C* **119**, 2692 (2015).
- [66] Y. D. Kim *et al.*, Characterization of various oxygen species on an oxide surface: RuO₂(110), *J. Phys. Chem. B* **105**, 3752 (2001).
- [67] F. A. Cotton and J. T. Mague, The crystal and molecular structure of tetragonal ruthenium dioxide, *Inorg. Chem.* **5**, 317 (1966).
- [68] H. Swanson, R. Fuyat, and G. Ugrinic, Standard X-ray diffraction powder patterns, NBS CIRCULAR 539, Vol. IV, Technical Report, National Bureau of Standards, 1955.
- [69] G. Kresse and J. Furthmüller, Efficient iterative schemes for *ab initio* total-energy calculations using a plane-wave basis set, *Phys. Rev. B* **54**, 11169 (1996).
- [70] G. Kresse and D. Joubert, From ultrasoft pseudopotentials to the projector augmented-wave method, *Phys. Rev. B* **59**, 1758 (1999).
- [71] P. E. Blöchl, Projector augmented-wave method, *Phys. Rev. B* **50**, 17953 (1994).
- [72] J. P. Perdew *et al.*, Atoms, molecules, solids, and surfaces: Applications of the generalized gradient approximation for exchange and correlation, *Phys. Rev. B* **46**, 6671 (1992).
- [73] J. P. Perdew, K. Burke, and M. Ernzerhof, Generalized gradient approximation made simple, *Phys. Rev. Lett.* **77**, 3865 (1996).
- [74] S. R. White, Density matrix renormalization group algorithms with a single center site, *Phys. Rev. B* **72**, 180403(R) (2005).
- [75] M. Fishman, S. R. White, and E. M. Stoudenmire, The ITensor software library for tensor network calculations, *SciPost Phys. Codebases*, 4 (2022).
- [76] M. Fishman, S. R. White, and E. M. Stoudenmire, Codebase release 0.3 for ITensor, *SciPost Phys. Codebases*, 4-r0.3 (2022).
- [77] A. S. Minkin *et al.*, Interlayer interaction, shear vibrational mode, and tribological properties of two-dimensional bilayers with a commensurate moiré pattern, *Phys. Rev. B* **108**, 085411 (2023).
- [78] M. Dürrnagel, J. Beyer, R. Thomale, and T. Schwemmer, Unconventional superconductivity from weak coupling, *Eur. Phys. J. B* **95**, 112 (2022).
- [79] N. Chepiga and F. Mila, Lifshitz point at commensurate melting of chains of Rydberg atoms, *Phys. Rev. Res.* **3**, 023049 (2021).
- [80] S. Basak and A. Ptok, Lattice dynamics of altermagnetic ruthenium oxide RuO₂, *Acta Phys. Pol. A* **145**, 93 (2024).
- [81] I. H. Choi *et al.*, Strain-induced dynamic spin-phonon coupling in epitaxial RuO₂ films, [arXiv:2509.23969](https://arxiv.org/abs/2509.23969).
- [82] <https://www.gauss-centre.eu>.
- [83] <https://www.lrz.de>.