

***d*-wave surface altermagnetism in centrosymmetric collinear antiferromagnets**Ersoy Şaşıoğlu ^{*}, Ingrid Mertig , and Samir Lounis *Institute of Physics and Halle-Berlin-Regensburg Cluster of Excellence CCE, Martin Luther University Halle-Wittenberg, 06120 Halle (Saale), Germany*

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Broken inversion symmetry at the surfaces of centrosymmetric collinear antiferromagnets lifts the combined inversion and time-reversal symmetry (PT) and can enable nonrelativistic d -wave spin splitting, termed surface altermagnetism. Combining symmetry analysis with first-principles calculations, we show that inversion breaking alone is necessary but not sufficient for this effect. Instead, surface altermagnetism emerges only when no degeneracy-protecting symmetry survives at the surface that exchanges the two antiferromagnetically coupled sublattices. We demonstrate this mechanism for the G -type antiferromagnets V_3Al and $BaMn_2Sb_2$, and contrast it with $MnPt$, where the translation-time-reversal symmetry (tT) survives at the surface and preserves spin degeneracy despite broken inversion symmetry. We further show that the mechanism applies across multiple classes of centrosymmetric antiferromagnets and remains robust against spin-orbit coupling, although relativistic spin mixing in heavier-element compounds may reduce the observable spin polarization. These results establish a symmetry-based route toward realizing robust nonrelativistic momentum-dependent spin polarization at antiferromagnetic surfaces and interfaces.

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Antiferromagnets (AFMs) possessing combined inversion and time-reversal symmetry (PT) exhibit spin-degenerate electronic bands in the absence of spin-orbit coupling (SOC). The recent discovery of altermagnetism has challenged this paradigm by demonstrating that collinear compensated magnets can host large nonrelativistic spin splittings when their magnetic space groups break PT while preserving the equivalence of opposite-spin sublattices through crystal rotations or mirror operations [1–4]. The resulting momentum-dependent spin polarization follows characteristic d -, g -, or i -wave symmetries dictated by the underlying lattice and has been realized in several classes of transition-metal compounds [5–10]. Experimentally, altermagnetic band splittings have now been directly resolved in α -MnTe, CrSb, and the metallic room-temperature d -wave altermagnet KV_2Se_2O using angle-resolved photoemission spectroscopy and complementary transport probes, establishing altermagnets as a distinct class of compensated magnets with nonrelativistic spin polarization [11–14]. Motivated by this discovery, altermagnetism has rapidly evolved into an active research field, encompassing symmetry-based classifications, large-scale materials screening, and first-principles studies of bulk and low-dimensional systems [15–31].

An important and largely unexplored question is whether analogous nonrelativistic altermagnetic spin splitting can also emerge at the *surfaces* of otherwise PT -symmetric

AFMs. While recent theoretical and materials-driven studies have firmly established altermagnetism in bulk and low-dimensional periodic systems, the role of surfaces, where translational symmetry is explicitly broken, remains poorly understood. Recent theoretical work has begun to examine surface electronic structures of intrinsically altermagnetic bulk materials [32]; however, the emergence of altermagnetic spin splitting at the surfaces of bulk PT -symmetric AFMs, where altermagnetism is absent in the bulk, has not been established. Surface termination inherently breaks inversion symmetry and thereby removes the bulk PT symmetry even in centrosymmetric C - and G -type AFMs whose electronic bands are spin degenerate in the absence of SOC. Unlike relativistic Rashba or Dresselhaus effects, which originate from SOC in noncentrosymmetric crystals [33,34], the surface-induced spin splitting discussed here emerges already in the absence of SOC from the local antiferromagnetic exchange field. SOC may subsequently modify the detailed surface electronic structure through spin mixing and additional relativistic splittings, but it is not the primary microscopic origin of the effect. Unlike conventional ferromagnetic exchange splitting, the resulting nonrelativistic spin polarization exhibits a symmetry-enforced momentum-dependent sign change in momentum space. Whether surface-induced inversion breaking alone is sufficient to generate a symmetry-dictated momentum-dependent spin polarization analogous to that of bulk altermagnets, or whether additional symmetries surviving the surface termination continue to protect spin degeneracy, therefore remains an open question.

In this work we show that surface inversion breaking in centrosymmetric AFMs, while necessary, is not sufficient to induce surface altermagnetism. Instead, surface altermagnetism emerges only when no symmetry survives at the surface that both exchanges the two antiferromagnetically

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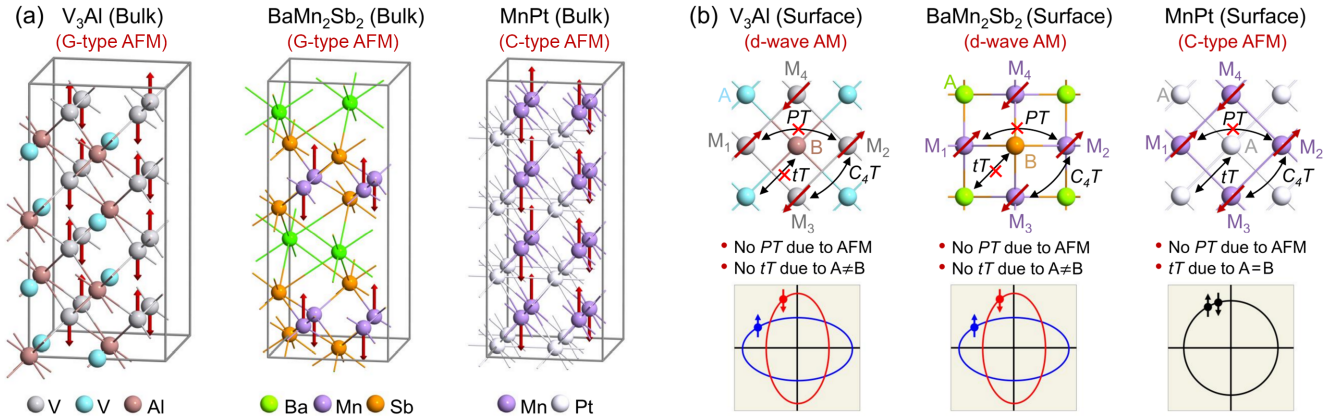


FIG. 1. Bulk and surface magnetic structures illustrating the symmetry conditions for surface altermagnetism. (a) Bulk magnetic configurations of the centrosymmetric AFMs V_3Al and $BaMn_2Sb_2$ (G -type) and $MnPt$ (C -type). All bulk phases preserve combined PT symmetry and therefore exhibit spin-degenerate electronic bands in the absence of SOC. Arrows indicate the magnetic moment orientations. (b) Top view of the surface and subsurface layers for representative (001) surface terminations. Each surface magnetic layer contains two antiferromagnetically coupled magnetic atoms. For V_3Al and $BaMn_2Sb_2$, the checkerboard arrangement of inequivalent subsurface nonmagnetic atoms produces distinct local environments for the two surface magnetic sublattices. Consequently, no symmetry remains that exchanges the two sublattices while protecting spin degeneracy. Although the antiunitary symmetry C_4T is preserved, it does not exchange the two antiferromagnetic surface sublattices and therefore does not enforce spin degeneracy, allowing a symmetry-permitted nonrelativistic d -wave spin splitting, schematically illustrated by the surface Fermi surfaces. In contrast, the $MnPt$ surface retains the translation–time-reversal symmetry tT , which exchanges the two surface sublattices and preserves spin degeneracy, despite the absence of inversion. The indicated symmetry operations summarize the distinct magnetic symmetry of the representative surface terminations.

coupled sublattices and protects spin degeneracy. Using symmetry analysis and first-principles calculations, we demonstrate this mechanism for representative centrosymmetric AFMs, including the Heusler compound V_3Al and the 122 pnictide $BaMn_2Sb_2$. In these systems the absence of such a degeneracy-protecting symmetry permits a nonrelativistic d -wave momentum-dependent spin splitting localized within the outermost magnetic layers. We further show that this mechanism applies across representative classes of centrosymmetric AFMs and remains robust against SOC, although relativistic spin mixing can reduce the observable spin polarization in heavier-element compounds.

For surface terminations satisfying these symmetry conditions, the leading nonrelativistic spin splitting transforms according to a d -wave representation dictated by the surface magnetic point group [3,6]. First-principles calculations confirm that this symmetry-allowed spin splitting emerges at realistic antiferromagnetic surfaces, exhibits the characteristic momentum-dependent sign reversal of altermagnetism, and remains strongly localized within the outermost magnetic layers. These results identify centrosymmetric AFMs as a previously unexplored platform for nonrelativistic surface and interface altermagnetism. Surface altermagnetism follows the same general symmetry principles as bulk altermagnetism [3,5]. The distinction lies not in a different symmetry criterion but in the reduced magnetic symmetry of the terminated surface, which determines whether the symmetries protecting spin degeneracy survive. The present work therefore clarifies how surface termination governs the emergence of nonrelativistic surface spin splitting in otherwise PT -symmetric AFMs.

To elucidate the symmetry mechanism underlying surface altermagnetism, Fig. 1 contrasts the bulk and surface magnetic structures of representative centrosymmetric AFMs. All

materials considered are collinear C - or G -type AFMs that preserve the combined inversion and time-reversal symmetry (PT) in the bulk. As shown in Fig. 1(a), the bulk magnetic structures of V_3Al , $BaMn_2Sb_2$, and $MnPt$ are fully compensated and antiferromagnetically ordered. In the following we focus on the (001) surface, for which each magnetic layer contains two antiferromagnetically coupled magnetic moments.

At a surface, inversion symmetry is inherently broken and the combined PT symmetry is therefore absent even in centrosymmetric AFMs. However, as illustrated in Fig. 1(b), breaking PT alone is not sufficient to generate altermagnetic spin polarization. Spin degeneracy may still be protected by symmetries that relate the two antiferromagnetically coupled surface sublattices. In the representative systems considered here, spin degeneracy is protected only if the surface retains a symmetry that exchanges the two antiferromagnetically coupled sublattices. $MnPt$ provides such an example through the translation–time-reversal symmetry tT .

The role of these symmetries is illustrated by the top views of the surface and subsurface layers shown in Fig. 1(b). The magnetic atoms are labeled M_1 and M_2 (spin-up) and M_3 and M_4 (spin-down), while the nonmagnetic atoms in the surface unit cell are denoted by A and B . For V_3Al and $BaMn_2Sb_2$, the surface termination breaks inversion symmetry, as indicated by the absence of a PT operation relating the two spin-up magnetic moments M_1 and M_2 . Moreover, the subsurface layer exhibits a checkerboard arrangement of chemically distinct nonmagnetic sites A and B , producing different local environments for the two surface magnetic sublattices. Importantly, such local inequivalence is necessary but not sufficient for surface altermagnetism. The decisive requirement is that no symmetry survives, which both exchanges the two antiferromagnetically coupled surface sublattices and protects spin degeneracy. Although the antiunitary operation

TABLE I. Representative centrosymmetric collinear AFMs illustrating the symmetry mechanism governing surface altermagnetism (see Supplemental Material [35] for an extended survey of candidate materials across representative structural families). All materials preserve combined PT symmetry in the bulk and therefore exhibit spin-degenerate electronic bands in the absence of SOC. Surface altermagnetism (AM) is symmetry allowed only when the surface termination removes the symmetry that protects the spin degeneracy while exchanging the two antiferromagnetically coupled surface sublattices. The column “ Σ present” indicates whether such a symmetry survives at the surface (e.g., $\Sigma = tT$ in MnPt).

Material	Class	AFM type	Σ present	AM
V ₃ Al	L2 ₁ Heusler	G-type	No	Yes
BaMn ₂ Sb ₂	122 pnictide	G-type	No	Yes
MnPt	L1 ₀ intermetallic	C-type	Yes (tT)	No
LaMnPO	1111 oxypnictide	C-type	No	Yes
LaFeO ₃	Perovskite oxide	G-type	Yes	No
K ₂ NiF ₄	Layered perovskite	G-type	Yes	No

C_4T remains and maps M_3 onto M_2 , it does not exchange the two antiferromagnetically coupled surface sublattices and therefore does not protect spin degeneracy. Consequently, the surface electronic states are free to develop the characteristic nonrelativistic momentum-dependent spin splitting of surface altermagnetism.

In contrast, for MnPt the nonmagnetic surface sites A and B are equivalent (both corresponding to Pt atoms) so that the local environments of the two surface magnetic sublattices remain identical. Consequently, a half translation that exchanges the two magnetic sublattices remains a symmetry of the surface. This symmetry is realized as the antiunitary translation–time-reversal symmetry tT , which protects spin degeneracy despite the absence of inversion symmetry. As a result, the surface electronic structure of MnPt remains spin degenerate, and no altermagnetic spin splitting develops. This example demonstrates that surface inversion breaking alone does not guarantee surface altermagnetism. Rather, the decisive factor is whether the terminated surface retains a symmetry that exchanges the two antiferromagnetically coupled sublattices and thereby protects spin degeneracy.

The symmetry considerations discussed above have direct implications for materials selection. Table I summarizes representative compounds from several structural classes of centrosymmetric collinear AFMs considered in this work (an extended list is provided in Supplemental Material [35]). All listed materials preserve combined PT symmetry in the bulk and therefore exhibit spin-degenerate electronic bands in the absence of SOC. Surface altermagnetism emerges only when the surface termination removes any symmetry that both exchanges the two antiferromagnetically coupled surface sublattices and protects spin degeneracy. This condition is fulfilled for V₃Al, BaMn₂Sb₂, and LaMnPO, whereas MnPt, LaFeO₃, and K₂NiF₄ remain spin degenerate because their representative surface terminations retain the corresponding degeneracy-protecting symmetry. These examples demonstrate that the occurrence of surface altermagnetism is not determined solely by the C - or G -type magnetic order, but by the magnetic symmetry of the terminated surface. When

symmetry permits surface altermagnetism, the magnitude of the resulting spin splitting remains material dependent and reflects the electronic character of the surface states. Together, Fig. 1 and Table I summarize the symmetry mechanism for the representative centrosymmetric AFMs investigated in this work. We now test the symmetry analysis described above using first-principles electronic-structure calculations for representative AFMs that satisfy the surface symmetry conditions for altermagnetism, namely, the absence of a symmetry that both exchanges the two antiferromagnetically coupled surface sublattices and protects spin degeneracy. We focus on the G -type AFMs V₃Al and BaMn₂Sb₂, identified in Fig. 1 and Table I as prototypical systems in which surface altermagnetism is symmetry allowed. The calculations are based on density-functional theory within the generalized gradient approximation, treating magnetism in the collinear nonrelativistic limit [36–38]. Surface electronic structures are obtained from slab geometries constructed along the (001) direction. In symmetric slabs, the two opposing surface terminations are related by the underlying G -type antiferromagnetic order, such that the corresponding surface states exhibit opposite spin polarizations. Consequently, their spin splittings cancel in the total band structure, preserving global spin degeneracy. Although the underlying splitting can always be recovered from surface- or layer-resolved projections, we employ asymmetric slab geometries for clarity, allowing the surface altermagnetic spin splitting to appear directly in the calculated band structure. Corresponding results for symmetric slabs, together with additional computational details, are provided in Supplemental Material [35]. Unless stated otherwise, SOC is neglected to isolate the nonrelativistic spin splitting originating from the antiferromagnetic exchange field. Additional calculations including SOC are presented below and in Supplemental Material [35].

Figure 2(a) shows the bulk and surface band structures of V₃Al along the in-plane $X-\Gamma-Y$ high-symmetry path of the orthorhombic surface Brillouin zone ($a = b$). V₃Al is a high- T_N antiferromagnet, with a reported Néel temperature of about 600 K, and has been proposed as a spin-gapless antiferromagnet [39–42]. The bulk electronic structure is strictly spin degenerate and exhibits a Dirac-like dispersion near the X point, with the Dirac node located approximately 60 meV below the Fermi level. At the surface, where no symmetry-protecting spin degeneracy survives, pronounced nonrelativistic spin splitting develops in states localized within the outermost magnetic layers. The Dirac cones shift toward the X and Y points and become pinned close to the Fermi level, with opposite spin polarization on the two linear branches. The resulting spin splitting reaches up to 0.32 eV, giving rise to metallic Dirac surface states with a pronounced momentum-dependent spin polarization.

An electronically distinct manifestation of surface altermagnetism is found in BaMn₂Sb₂, shown in Fig. 2(b). BaMn₂Sb₂ is a layered antiferromagnetic semiconductor with a bulk band gap of approximately 0.3 eV and a reported Néel temperature of about 450 K [43–45]. While the bulk electronic structure remains fully spin degenerate, the surface develops two Dirac points located approximately 20 meV above the Fermi level along the $\Gamma-X$ and $\Gamma-Y$ directions. In the absence of SOC, these Dirac states are fully spin polarized in

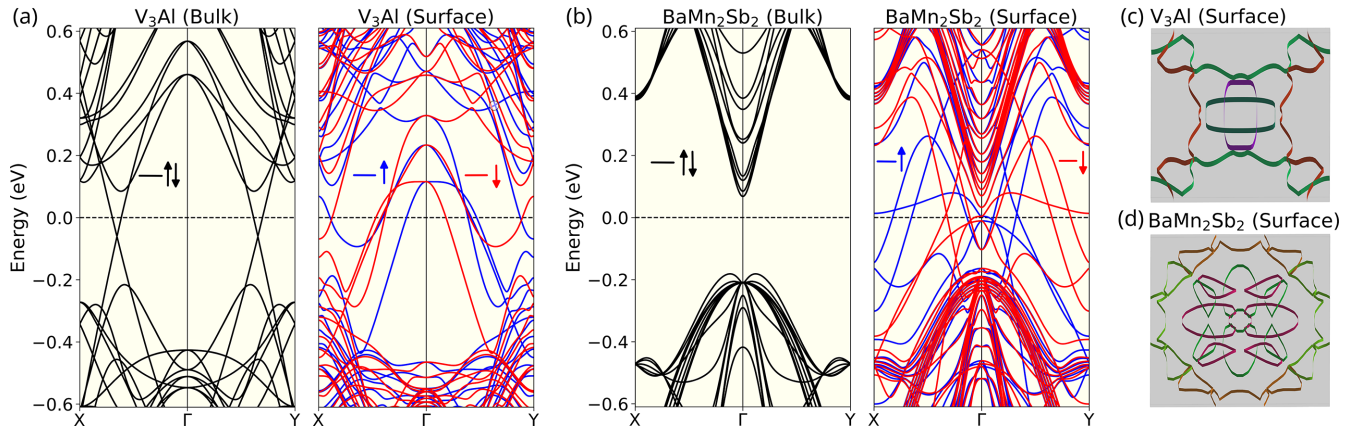


FIG. 2. Surface electronic structure of the centrosymmetric AFMs V_3Al and $BaMn_2Sb_2$. (a) Bulk and surface band structures of the G -type AFM V_3Al calculated along the in-plane $X-\Gamma-Y$ high-symmetry path. The surface bands are obtained from a 20-layer slab, while the bulk reference is calculated using the corresponding 20-layer bulk supercell for direct comparison. The bulk bands remain spin degenerate owing to combined PT symmetry, whereas the surface develops pronounced nonrelativistic spin splitting in surface-localized states. (b) Same as (a), but for the G -type AFM $BaMn_2Sb_2$. (c), (d) Spin-resolved two-dimensional Fermi surfaces of the asymmetric slabs for V_3Al and $BaMn_2Sb_2$, respectively. The characteristic fourfold angular modulation with alternating spin polarization constitutes the momentum-space fingerprint of d -wave surface altermagnetism.

a momentum-selective manner: bands along $\Gamma-X$ carry one spin character, whereas those along $\Gamma-Y$ carry the opposite one. The resulting spin splitting reaches approximately 0.35 eV near the Fermi level, demonstrating that pronounced nonrelativistic spin polarization can emerge even at the surface of a small-gap antiferromagnetic semiconductor, in sharp contrast to its spin-degenerate bulk electronic structure.

The momentum-dependent spin polarization discussed above has a direct manifestation at the Fermi level. Figures 2(c) and 2(d) show the spin-resolved two-dimensional Fermi surfaces obtained from asymmetric slab calculations. In $BaMn_2Sb_2$, only two surface-derived bands cross the Fermi level, giving rise to a comparatively simple multilobed Fermi surface with alternating spin polarization. By contrast, several surface bands contribute near the Fermi level in V_3Al , resulting in a more intricate Fermi-surface texture; for clarity, only two representative bands per spin channel are shown. Despite these differences in electronic structure, both materials exhibit a pronounced fourfold angular modulation with alternating spin character, providing a direct momentum-space fingerprint of the underlying d -wave surface altermagnetism.

Having established the symmetry origin and momentum-space fingerprints of surface altermagnetism, we now turn to its spatial localization. Figure 3 presents layer-resolved fat-band representations for the asymmetric V_3Al slab, projected onto the first three magnetic V layers of the V-V-terminated surface. The nonrelativistic d -wave spin splitting near the Fermi level is dominated by holelike surface states localized within the outermost magnetic layer, which carries most of the spectral weight. The same spin-split surface states remain visible in the subsurface layers with rapidly decreasing spectral weight, while their dispersion and spin splitting remain essentially unchanged. Deeper inside the slab, the surface-state weight becomes negligible and the electronic structure continuously approaches the PT -protected spin-degenerate bulk limit. Because the metallic surface states are partially

delocalized, a unique layer-resolved energy splitting cannot be defined. Instead, the decay of their spectral weight provides a direct and physically transparent measure of the penetration of surface altermagnetism into the bulk.

To exclude finite-size effects associated with the asymmetric slab geometry, we also performed semi-infinite Green's-function calculations for the V-V-terminated $V_3Al(001)$ surface. As shown in Supplemental Material [35], the resulting surface spectral function reproduces the same holelike spin-split states obtained from the slab calculations, confirming that the characteristic d -wave spin splitting is an intrinsic property of the V-V termination rather than an artifact of slab thickness or charge redistribution between the two slab surfaces. Additional layer-resolved projections for both terminations of V_3Al and $BaMn_2Sb_2$ are presented in

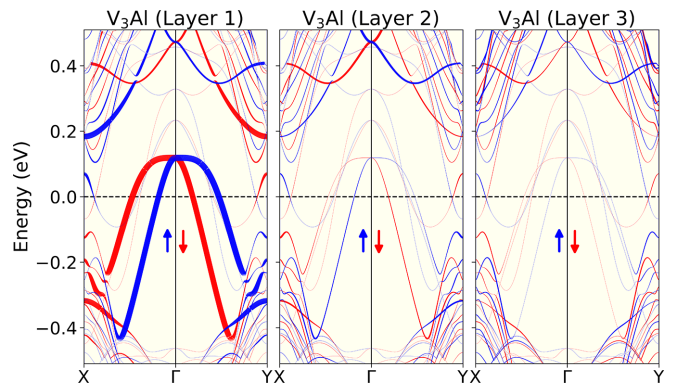


FIG. 3. Layer-resolved surface altermagnetic states in V_3Al . Fat-band representations of the asymmetric 20-layer V_3Al slab projected onto the first three magnetic V layers, shown along the in-plane $X-\Gamma-Y$ path. The surface magnetic layer (layer 1) hosts pronounced nonrelativistic d -wave altermagnetic spin splitting near the Fermi level with dominant spectral weight. The same split surface-derived states persist in the subsurface layers (layers 2 and 3) with rapidly decreasing weight.

Supplemental Material [35]. In both compounds the magnetic-atom-terminated surfaces host strongly localized spin-split states confined essentially to the first surface unit cell, whereas the nonmagnetic-atom terminations exhibit more extended states with pronounced *d*-wave spin splitting penetrating deeper into the crystal. The corresponding surface dispersions further display distinct electron- and holelike character, demonstrating the strong dependence of the surface electronic structure on the termination.

To assess the robustness of surface altermagnetism against relativistic effects, we additionally performed calculations including SOC for both V_3Al and $BaMn_2Sb_2$ (see Supplemental Material [35]). In V_3Al , SOC produces only negligible modifications of the nonrelativistic *d*-wave spin splitting owing to the weak atomic SOC of the constituent elements. In contrast, for the MnSb-terminated $BaMn_2Sb_2$ surface, SOC induces noticeable spin mixing and additional splitting of crossing surface bands, thereby reducing the spin polarization while preserving the characteristic *d*-wave momentum dependence. For the Ba-terminated surface, however, relativistic effects remain weak. Furthermore, noncollinear calculations including SOC reveal no surface spin canting in either V_3Al or $BaMn_2Sb_2$, consistent with the dominance of nearest-neighbor antiferromagnetic exchange interactions over relativistic magnetic interactions. These results demonstrate that surface altermagnetism is robust against SOC, although the experimentally observable spin polarization may be reduced by relativistic spin mixing in heavier-element compounds.

The symmetry analysis presented here provides practical guidelines for identifying surface altermagnetism in centrosymmetric AFMs. Additional candidate materials spanning representative structural families are listed in Supplemental Material [35]. The strong surface localization and nonrelativistic origin of the effect further suggest that analogous electronic states may also emerge at antiferromagnetic interfaces and heterostructures where inversion symmetry is locally broken. Surface altermagnetism should therefore be directly accessible to surface-sensitive probes such as angle-resolved photoemission spectroscopy and scanning tunneling microscopy. Although the present work focuses on idealized surface terminations, the structural relaxations discussed in Supplemental Material [35] do not reveal any tendency toward surface reconstruction in the representative systems considered here. Surface roughness, reconstruction, and

disorder may nevertheless modify the detailed surface electronic structure and the magnitude of the spin splitting. However, the underlying momentum-dependent spin polarization is expected to remain robust as long as the magnetic order and the relevant surface symmetries are preserved. These results establish centrosymmetric AFMs as a promising platform for exploring symmetry-controlled spin phenomena at surfaces and interfaces.

In summary, we establish surface altermagnetism as a symmetry-controlled phenomenon emerging at the surfaces of centrosymmetric collinear AFMs. Combining symmetry analysis with first-principles calculations, we show that surface inversion breaking alone is not sufficient to induce momentum-dependent spin splitting. Instead, the effect emerges only when the surface no longer retains a symmetry that both exchanges the two antiferromagnetically coupled sublattices and protects spin degeneracy. We demonstrate this mechanism for V_3Al and $BaMn_2Sb_2$, which host robust *d*-wave altermagnetic surface states, despite fully spin-degenerate bulk electronic structures, while MnPt remains spin degenerate because the tT symmetry survives at the surface. The resulting states are strongly localized within the outermost magnetic layers and originate from a nonrelativistic exchange-driven spin splitting that emerges already in the absence of SOC. Calculations including SOC further show that the characteristic *d*-wave momentum dependence remains robust, although relativistic spin mixing can reduce the experimentally observable spin polarization in heavier-element compounds. These results provide practical guidelines for identifying surface altermagnetism in centrosymmetric AFMs and establish antiferromagnetic surfaces and interfaces as a promising platform for symmetry-controlled momentum-dependent spin polarization.

Note added. Recently, we became aware of a complementary study based on surface spin-group analysis and database screening of candidate materials for surface altermagnetism [46].

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Data availability. The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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- [1] L.-D. Yuan, Z. Wang, J.-W. Luo, and A. Zunger, Prediction of low-Z collinear and noncollinear antiferromagnetic compounds having momentum-dependent spin splitting even without spin-orbit coupling, *Phys. Rev. Mater.* **5**, 014409 (2021).
 - [2] L. Šmejkal, R. González-Hernández, T. Jungwirth, and J. Sinova, Crystal time-reversal symmetry breaking and spontaneous Hall effect in collinear antiferromagnets, *Sci. Adv.* **6**, eaaz8809 (2020).
 - [3] 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).
 - [4] L. Šmejkal, A. H. MacDonald, J. Sinova, S. Nakatsuji, and T. Jungwirth, Anomalous Hall antiferromagnets, *Nat. Rev. Mater.* **7**, 482 (2022).
 - [5] Y. Guo, Y. Zhang, R. González-Hernández, L. Šmejkal, J. Sinova, and T. Jungwirth, Spin-split collinear antiferromagnets:

- A large-scale *ab initio* study, *Mater. Today Phys.* **32**, 100991 (2023).
- [6] I. I. Mazin, Altermagnetism in MnTe: Origin, predicted manifestations, and routes to detwinning, *Phys. Rev. B* **107**, L100418 (2023).
 - [7] T. Jungwirth, J. Sinova, P. Wadley, D. Kriegner, H. Reichlova, F. Krizek, H. Ohno, and L. Šmejkal, Altermagnetic spintronics, *arXiv:2508.09748*.
 - [8] S. Giuli, C. Mejuto-Zaera, and M. Capone, Altermagnetism from interaction-driven itinerant magnetism, *Phys. Rev. B* **111**, L020401 (2025).
 - [9] Z. Feng *et al.*, An anomalous Hall effect in altermagnetic ruthenium dioxide, *Nat. Electron.* **5**, 735 (2022).
 - [10] Z. Lin, D. Chen, W. Lu, X. Liang, S. Feng, K. Yamagami, J. Osiecki, M. Leandersson, B. Thiagarajan, J. Liu, *et al.*, Bulk band structure of RuO₂ measured with soft x-ray angle-resolved photoemission spectroscopy, *Phys. Rev. B* **111**, 134450 (2025).
 - [11] S. Lee, S. Lee, S. Jung, J. Jung, D. Kim, Y. Lee, B. Seok, J. Kim, B. G. Park, L. Šmejkal, C.-J. Kang, and C. Kim, Broken Kramers degeneracy in altermagnetic MnTe, *Phys. Rev. Lett.* **132**, 036702 (2024).
 - [12] S. Reimers, L. Odenbreit, L. Šmejkal, V. N. Strocov, P. Constantinou, A. B. Hellenes, R. Jaeschke Ubierno, W. H. Campos, V. K. Bharadwaj, A. Chakraborty, T. Denneulin, W. Shi, R. E. Dunin-Borkowski, S. Das, M. Kläui, J. Sinova, and M. Jourdan, Direct observation of altermagnetic band splitting in CrSb thin films, *Nat. Commun.* **15**, 2116 (2024).
 - [13] B. Jiang, M. Hu, J. Bai, Z. Song, C. Mu, G. Qu, W. Li, W. Zhu, H. Pi, Z. Wei, Y. Sun, Y. Huang, X. Zheng, Y. Peng, L. He, S. Li, J. Luo, Z. Li, G. Chen, H. Li, *et al.*, A metallic room-temperature d-wave altermagnet, *Nat. Phys.* **21**, 754 (2025).
 - [14] N. Biniskos, M. dos Santos Dias, S. Agrestini, D. Sviták, K.-J. Zhou, J. Pospíšil, and P. Čermák, Systematic mapping of altermagnetic magnons by resonant inelastic x-ray circular dichroism, *Nat. Commun.* **16**, 9311 (2025).
 - [15] L.-D. Yuan, Z. Wang, J.-W. Luo, E. I. Rashba, and A. Zunger, Giant momentum-dependent spin splitting in centrosymmetric low-Z antiferromagnets, *Phys. Rev. B* **102**, 014422 (2020).
 - [16] J. Söderquist and T. Olsen, Two-dimensional altermagnets from high throughput computational screening: Symmetry requirements, chiral magnons, and spin-orbit effects, *Appl. Phys. Lett.* **124**, 182409 (2024).
 - [17] B. Brekke, A. Brataas, and A. Sudbø, Two-dimensional altermagnets: Superconductivity in a minimal microscopic model, *Phys. Rev. B* **108**, 224421 (2023).
 - [18] R. Xu, Y. Gao, and J. Liu, Chemical design of monolayer altermagnets, *Natl. Sci. Rev.* **13**, nwaf528 (2026).
 - [19] T. Jungwirth, J. Sinova, R. M. Fernandes, Q. Liu, H. Watanabe, S. Murakami, S. Nakatsuji, and L. Šmejkal, Symmetry, microscopy and spectroscopy signatures of altermagnetism, *Nature (London)* **649**, 837 (2026).
 - [20] X. Wan, S. Mandal, Y. Guo, and K. Haule, High-throughput search for metallic altermagnets by embedded dynamical mean field theory, *Phys. Rev. Lett.* **135**, 106501 (2025).
 - [21] P.-H. Chang, K. D. Belashchenko, and I. I. Mazin, Inverse Lieb materials: Altermagnetism and more, *npj Quantum Mater.* **11**, 49 (2026).
 - [22] R. Bhattarai, P. Minch, and T. D. Rhone, High-throughput screening of altermagnetic materials, *Phys. Rev. Mater.* **9**, 064403 (2025).
 - [23] S. Brahimi, D. Prakash Rai, and S. Lounis, Confinement-induced altermagnetism in RuO₂ ultrathin films, *J. Phys.: Condens. Matter* **37**, 395801 (2025).
 - [24] L. Bai, W. Feng, S. Liu, L. Šmejkal, Y. Mokrousov, and Y. Yao, Altermagnetism: Exploring new frontiers in magnetism and spintronics, *Adv. Funct. Mater.* **34**, 2409327 (2024).
 - [25] R. Tamang, S. Gurung, D. P. Rai, S. Brahimi, and S. Lounis, Altermagnetism and altermagnets: A brief review, *Magnetism* **5**, 17 (2025).
 - [26] J. Matsuda, H. Watanabe, and R. Arita, Multiferroic collinear antiferromagnets with hidden altermagnetic spin splitting, *Phys. Rev. Lett.* **134**, 226703 (2025).
 - [27] P. A. McClarty and J. G. Rau, Landau theory of altermagnetism, *Phys. Rev. Lett.* **132**, 176702 (2024).
 - [28] J. Sivianes, F. J. dos Santos, and J. Ibañez-Azpiroz, Optical signatures of spin symmetries in unconventional magnets, *Phys. Rev. Lett.* **134**, 196907 (2025).
 - [29] D. Jo, D. Go, Y. Mokrousov, P. M. Oppeneer, S.-W. Cheong, and H.-W. Lee, Weak ferromagnetism in altermagnets from alternating g-tensor anisotropy, *Phys. Rev. Lett.* **134**, 196703 (2025).
 - [30] Q. Song, S. Stavrić, P. Barone, A. Droghetti, D. S. Antonenko, J. W. F. Venderbos, C. A. Occhialini, B. Ilyas, E. Ergeçen, N. Gedik, *et al.*, Electrical switching of a *p*-wave magnet, *Nature (London)* **642**, 64 (2025).
 - [31] Y. Fukaya, B. Lu, K. Yada, Y. Tanaka, and J. Cayao, Superconducting phenomena in systems with unconventional magnets, *J. Phys.: Condens. Matter* **37**, 313003 (2025).
 - [32] R. M. Sattigeri, G. Cuono, and C. Autieri, Altermagnetic surface states: Towards the observation and utilization of altermagnetism in thin films, interfaces and topological materials, *Nanoscale* **15**, 16998 (2023).
 - [33] E. I. Rashba, Properties of semiconductors with an extremum loop. I. Cyclotron and combinational resonance in a magnetic field perpendicular to the plane of the loop, *Fiz. Tverd. Tela* **2**, 1224 (1960) [*Sov. Phys. Solid State* **2**, 1109 (1960)].
 - [34] G. Dresselhaus, Spin-orbit coupling effects in zinc blende structures, *Phys. Rev.* **100**, 580 (1955).
 - [35] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/mkk5-b53m> for computational details, an extended symmetry-based survey of representative centrosymmetric collinear antiferromagnets, and supporting calculations for V₃Al and BaMn₂Sb₂, including layer-resolved surface electronic structures, semi-infinite surface calculations, structural relaxation, and calculations including spin-orbit coupling.
 - [36] S. Smidstrup, T. Markussen, P. Vancaeyveld, J. Wellendorff, J. Schneider, T. Gunst, B. Verstichel, D. Stradi, P. A. Khomyakov, U. G. Vej-Hansen, M.-E. Lee, S. T. Chill, F. Rasmussen, G. Penazzi, F. Corsetti, A. Ojanperä, K. Jensen, M. L. N. Palsgaard, U. Martinez, A. Blom, *et al.*, QuantumATK: An integrated platform of electronic and atomic-scale modelling tools, *J. Phys.: Condens. Matter* **32**, 015901 (2020).
 - [37] J. P. Perdew, K. Burke, and M. Ernzerhof, Generalized gradient approximation made simple, *Phys. Rev. Lett.* **77**, 3865 (1996).
 - [38] M. J. van Setten, M. Giantomassi, E. Bousquet, M. J. Verstraete, D. R. Hamann, X. Gonze, and G.-M. Rignanese, The PSEUDODOJO: Training and grading a 85 element optimized norm-conserving pseudopotential table, *Comput. Phys. Commun.* **226**, 39 (2018).

- [39] I. Galanakis, Ş. Tırpancı, K. Özdoğan, and E. Şaşıoğlu, Itinerant *G*-type antiferromagnetism in $D0_3$ -type V_3Z ($Z = \text{Al, Ga, In}$) compounds: A first-principles study, *Phys. Rev. B* **94**, 064401 (2016).
- [40] S. Khmelevskyi, First-principles modeling of longitudinal spin fluctuations in itinerant electron antiferromagnets: High Néel temperature in the $V_3\text{Al}$ alloy, *Phys. Rev. B* **94**, 024420 (2016).
- [41] M. Tas, E. Şaşıoğlu, C. Friedrich, S. Blügel, and I. Galanakis, Design of $L2_1$ -type antiferromagnetic semiconducting full-Heusler compounds: A first principles DFT + GW study, *J. Appl. Phys.* **121**, 053903 (2017).
- [42] X. Chen, Y. Huang, J. Liu, H. Yuan, and H. Chen, Effects of Ga substitution on electronic and thermoelectric properties of gapless semiconductor $V_3\text{Al}$, *RSC Adv.* **9**, 3847 (2019).
- [43] J. An, A. S. Sefat, D. J. Singh, and M.-H. Du, Electronic structure and magnetism in BaMn_2As_2 and BaMn_2Sb_2 , *Phys. Rev. B* **79**, 075120 (2009).
- [44] N. S. Sangeetha, V. Smetana, A.-V. Mudring, and D. C. Johnston, Antiferromagnetism in semiconducting SrMn_2Sb_2 and BaMn_2Sb_2 single crystals, *Phys. Rev. B* **97**, 014402 (2018).
- [45] Q. Zhang, Z. Diao, H. Cao, A. Saleheen, R. Chapai, D. Gong, S. Stadler, and R. Jin, Structure-property relationship in layered BaMn_2Sb_2 and $\text{Ba}_2\text{Mn}_3\text{Sb}_2\text{O}_2$, *Phys. Rev. B* **99**, 184416 (2019).
- [46] C. Lange, R. Jaeschke-Ubiergo, A. Chakraborty, X. H. Verbeek, L. Šmejkal, J. Sinova, and A. Mook, Emergent altermagnetism at surfaces of antiferromagnets: Full symmetry classification and material identification, [arXiv:2602.08773](https://arxiv.org/abs/2602.08773).