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Altermagnetic Proximity Effect

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Proximity effects complement conventional materials design by enabling interfacial properties absent in any constituent. Here, we uncover an altermagnetic proximity effect (AMPE), distinct from ferromagnetic and antiferromagnetic proximity, in which the hallmark momentum-alternating spin splitting of an altermagnet is transferred across an interface into an adjacent nonmagnetic layer—a process we term "altermagnetization." Using first-principles calculations and model analysis, we identify the AMPE in heterostructures based on the prototypical van der Waals altermagnet V_2Se_2O, where a proximitized monolayer PbO acquires altermagnetic band splitting and real-space spin textures, with systematic tunability via interlayer spacing and magnetic configuration. We further demonstrate that the AMPE enables valley-dependent spin splitting in the semiconductor PbS and realizes topological superconductivity in the *s*-wave superconductor $NbSe_2$, both inheriting the altermagnetic spin texture. Finally, we validate the generality and experimental feasibility of the AMPE by realizing it in a broader class of established altermagnets, including V_2Se_2O derivatives, Ruddlesden-Popper perovskites, and the metallic CrSb. Our results identify the AMPE as a universal proximity mechanism and a versatile platform for engineering emergent quantum phenomena in heterostructures.

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Proximity effects allow a material to acquire properties of its neighbors, becoming magnetic, superconducting, topologically nontrivial, or exhibiting enhanced spin-orbit coupling [1–3]. Magnetic proximity effects, particularly in ferromagnets, are widely used to generate spin splitting and tune magnetic parameters that include anisotropy, coercivity, and exchange bias [3–11]. Antiferromagnetic proximity, in turn, relies on interfacial hybridization without fringing fields, enabling ultrafast spin dynamics and symmetry-enforced transport [1,12,13]. These mechanisms underpin modern spintronics, valleytronics, topological states, and heterostructures of superconductors and magnets [14–19].

A growing class of unconventional magnets [20–28], often termed altermagnets (AMs) [29–40], exhibits properties beyond common ferromagnets and antiferromagnets, most notably momentum-dependent alternating spin splitting without net magnetization. This nonrelativistic spin splitting and its tunability expand the opportunities in spintronics [41–45], multiferroics [46–56], topotronics [57–62], and superconductivity [63–68]. A central challenge now lies in understanding if this distinctive magnetic order, rooted in antiferromagnetic (AFM) sublattices linked by symmetries involving rotations [29–32] can be transferred across an interface into otherwise nonmagnetic (NM) layers. Establishing whether AMs generate a distinct proximity effect, rather than simply mimicking ferromagnetic or antiferromagnetic proximity, is key to assessing their impact. Equally important is clarifying if this proximity channel can enable unexplored phenomena, particularly in van der Waals (vdW) heterostructures, where proximity effects are most tunable [69–73].

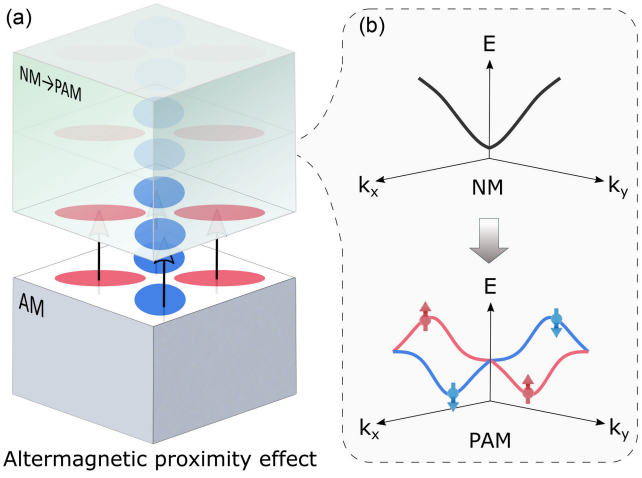


FIG. 1. Schematic of the AMPE. (a) Altermagnetism penetrating an NM layer. (b) Band evolution of the NM layer as it becomes a PAM.

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In this Letter, we address these questions by introducing the altermagnetic proximity effect (AMPE) as in Fig. 1 in which the momentum-alternating spin splitting intrinsic to AMs is imprinted onto a neighboring nonmagnetic layer through an interfacial process we term "altermagnetization." Combining first-principles calculations with model analysis, we establish the AMPE in heterostructures formed from the prototypical altermagnetic V_2Se_2O and monolayer PbO: the PbO layer becomes altermagnetized, as evidenced by the induced altermagnetic band splitting and real-space spin densities, whose systematic evolution with interlayer spacing and magnetic configuration demonstrates both robustness and tunability of the AMPE. We then illustrate broader consequences of this effect by showing that the AMPE can generate valley-dependent spin splitting in PbS and enable a topological superconductivity in $NbSe_2$. Finally, by extending our analysis beyond the V_2Se_2O platform to additional altermagnetic classes, including V_2Se_2O derivatives, Ruddlesden-Popper perovskites, and the metallic CrSb, we establish the AMPE as a distinct and universal proximity mechanism and a viable route for engineering multifunctional quantum states in heterostructures.

Our proposed AMPE is schematically illustrated in Fig. 1(a). When an NM material is placed in contact with an altermagnet, the extension of electronic wave functions across the interface can imprint the characteristic alternating spin splitting of the AM onto the NM layer. This interfacial process drives a transition from the NM state to a proximitized altermagnet (PAM), in which originally spin-degenerate bands acquire momentum-dependent spin polarization [Fig. 1(b)]. As with other proximity effects [1], the AMPE is short ranged and decays with distance from the interface. Two-dimensional vdW systems, with atomically thin layers and clean interfaces, thus provide an ideal platform to exploit this AMPE and to design the corresponding highly tunable functionalities.

While most experimentally confirmed AMs exist as bulk crystals or thin films [33–36], V_2Se_2O stands out as a famous vdW candidate [26,74]. Its intercalated metallic derivatives have also been experimentally identified as AMs [35,36], further highlighting its versatility. V_2Se_2O crystallizes in a square lattice where the two V sublattices form a checkerboard AFM configuration linked by C_{4z} symmetry [Fig. 2(a)]. This symmetry yields the hallmark AM features, as confirmed by our calculations showing alternating spin densities in real space and momentum-dependent spin splitting [Fig. 2(c)]. To demonstrate the AMPE of V_2Se_2O, we select PbO as the adjacent NM layer. PbO is a well-established semiconductor with a simple, well-characterized crystal structure and spin-degenerate bands [75,76], as shown in our calculations [Fig. 2(b)]. Importantly, PbO and V_2Se_2O both form 2D square lattices with a minimal lattice mismatch of just 0.7%, making PbO an ideal and clean reference to isolate and analyze the AMPE from V_2Se_2O.

To investigate the emergence of the AMPE, we computed the total energies of several stacking configurations of the PbO/V_2Se_2O heterostructure (see Supplemental Material [77]) and identified the most stable arrangement shown in Fig. 2(a). The corresponding band structure [Fig. 2(d)] indicates that both constituents largely preserve their intrinsic electronic features under vdW coupling. Strikingly, however, the PbO layer now exhibits pronounced momentum-dependent spin splitting [Figs. 2(d)–2(f)], in sharp contrast to its pristine spin-degenerate state [Fig. 2(b)], demonstrating that PbO is transformed into a PAM-PbO through AMPE. The induced spin splitting displays a characteristic altermagnetic signature: spin degeneracy is preserved along $\Gamma - M$, while opposite spin polarizations appear along $M - X - \Gamma$ and $\Gamma - Y - M$, consistent with the underlying order of V_2Se_2O. Moreover, the real-space spin density of PAM-PbO mirrors the symmetry of the V_2Se_2O substrate, providing direct evidence that PbO inherits the altermagnetic character of V_2Se_2O. To confirm this, we further convert V_2Se_2O into a conventional AFM configuration by rearranging its spin sublattices [Fig. 2(i); see Supplemental Material [77]]. In this case, the sublattices are related by translation or inversion symmetry, eliminating the alternating spin splitting. As expected, the induced splitting in PbO disappears [Fig. 2(i)], while its spin density develops an AFM feature, indicating a conventional AFM proximity effect. This control case further illustrates the AMPE of V_2Se_2O.

To further elucidate how PbO is influenced by the AMPE of V_2Se_2O, we analyze the interfacial interaction and charge redistribution in their vdW heterostructure. The planar-averaged charge density difference $\Delta q(z)$, together with the real-space redistribution shown in Fig. 2(g), indicates a slight interfacial charge transfer from PbO to V_2Se_2O. Such a modest charge transfer has a negligible effect on the altermagnetic ground state of V_2Se_2O, as further corroborated by the doping simulations in Supplemental Material [77]. Because the strength of proximity effects is highly sensitive to interlayer spacing, we evaluate the evolution of the spin splitting ΔE_S as a function of the separation d between PbO and V_2Se_2O. As shown in Fig. 2(h), the induced ΔE_S decreases monotonically with increasing d, accompanied by a corresponding reduction of the spin density, confirming the short-range nature of the AMPE. Taken together, these results provide unambiguous evidence for the AMPE from multiple, mutually consistent perspectives.

Valleytronics—Beyond charge and spin, the valley degree of freedom provides a powerful route toward valleytronic devices and robust topological states [15,83–86]. A common strategy to lift valley degeneracy is to apply an external magnetic field, but the typically small g-factors of semiconductors limit its effectiveness. Magnetic proximity effects offer an alternative by introducing valley asymmetry [1,10,11]. Valley phenomena in AMs have recently

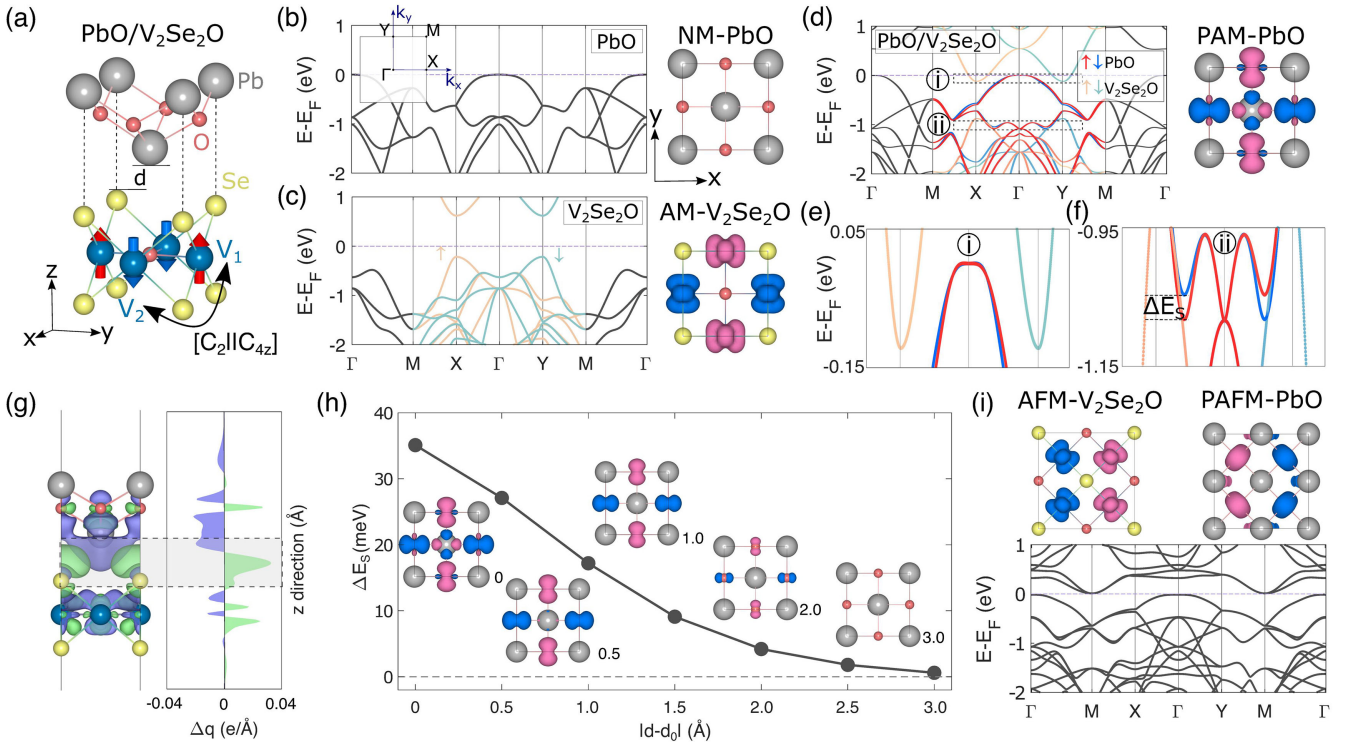


FIG. 2. (a) Crystal structure of PbO/V_2Se_2O heterostructure. The spin sublattices of V_2Se_2O are connected by $[C_2\|C_{4z}]$ symmetry. (b)–(d) Calculated bands and spin densities of pristine monolayers PbO and V_2Se_2O, and their heterostructure. The inset in (b) shows the first Brillouin zone. (e),(f) Enlarged views of the regions labeled "(i)" and "(ii)" in (d). (g) Differential charge density of the PbO/V_2Se_2O heterostructure and its planar average, $\Delta q(z)$. Green (purple) indicates charge accumulation (depletion) and the isosurface value is 5×10^{-4} e/bohr^3. (h) Spin splitting ΔE_S in (f) with the spin densities, as a function of the interlayer distance d in (a), where d_0 is the equilibrium value. (i) Same as (d) but for a proximitized AFM PbO (PAFM-PbO), realized when PbO is placed on a $\sqrt{2} \times \sqrt{2}$ V_2Se_2O supercell in a conventional AFM state. For all bands, black denotes spin-degenerate states; red and blue indicate spin-up and spin-down bands of the PAM component (PbO), while yellow and green represent the corresponding bands of the V_2Se_2O component.

attracted growing attention [26,87–89]. In particular, monolayer V_2Se_2O has been predicted to host a unique symmetry-paired spin-valley locking that links spin and valley space with real space, enabling giant piezomagnetism and large noncollinear spin currents [26].

Motivated by this, we explore whether such valley physics can be transferred into an NM material through the AMPE, using a PbS/V_2Se_2O heterostructure as an example [Fig. 3(a)]. Monolayer PbS, known for its rich topological, valleytronic, and optoelectronic properties [90], exhibits spin-valley degeneracy in its pristine state [Fig. 3(b)]. When coupled to V_2Se_2O, PbS inherits the altermagnetic feature of symmetry-paired spin-valley locking through the AMPE, as evidenced by the characteristic spin splitting in Fig. 3(c) and the corresponding rotation-symmetry-linked spin-density patterns shown in Supplemental Material [77]. This pairing enables strain-tunable valley polarization: breaking the mirror symmetry between the X and Y valleys converts them from degenerate to polarized states. Uniaxial strain along x or y shifts their relative energies in opposite directions, producing a controllable valley splitting that grows monotonically under either compressive or tensile strain [Fig. 3(e)]. This effect is substantial even under moderate strain—for example, 3% tensile strain along x yields a 152 meV valence-band splitting [Fig. 3(d), Supplemental Material [77]], far exceeding the thermal energy at 300 K. Such a robust splitting ensures stable valley polarization and enables practical control of valley populations through mechanical or substrate engineering. These results demonstrate that the AMPE provides a general route to induce spin-valley polarization in otherwise nonmagnetic materials. By combining interfacial coupling with strain engineering, one can realize electrically and mechanically tunable valley functionalities, opening new opportunities for spintronic and valleytronic applications in AM-based heterostructures.

Topological superconductivity—Proximity effects provide one of the most promising routes to realize topological superconductivity and host Majorana modes (MM), essential for fault-tolerant quantum computing [91–93]. The conventional platform, an s-wave superconductor proximitized into a semiconductor with strong spin-orbit coupling under an

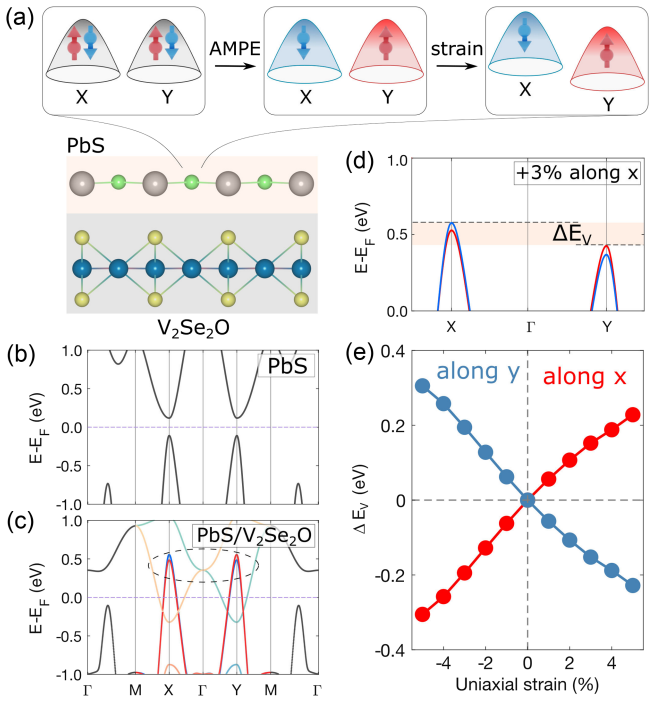


FIG. 3. (a) Schematic of the PbS/V_2Se_2O heterostructure illustrating the AMPE- and strain-induced spin and valley splitting in a monolayer PbS. (b),(c) Calculated bands of the monolayer PbS and PbS/V_2Se_2O heterostructure. (d) Bands of the AM-proximitized monolayer PbS under 3% uniaxial tensile strain along the x axis, showing valley splitting, ΔE_V. (e) Strain-dependent ΔE_V. Band color codes as in Fig. 2.

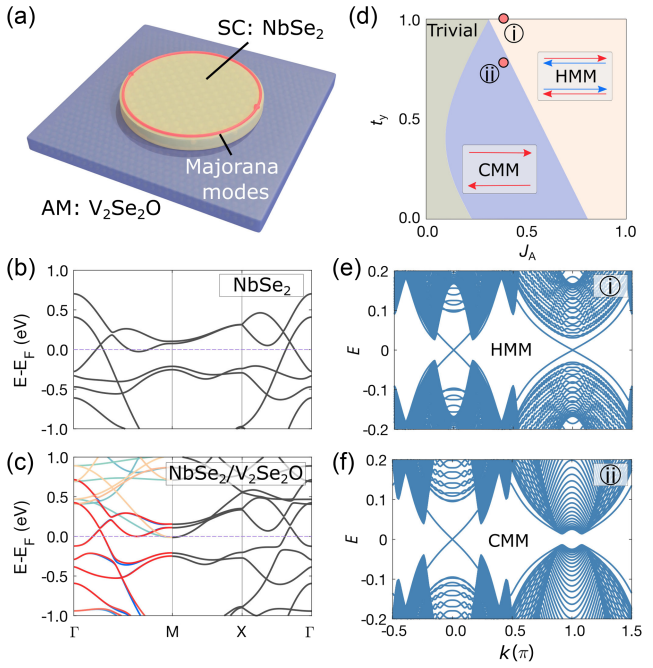


FIG. 4. (a) Schematic transformation of an s-wave superconductor $NbSe_2$ into a topological superconductor hosting edge MM (red circle) via the AMPE from V_2Se_2O. (b),(c) Bands of a $NbSe_2$ supercell, and the $NbSe_2/V_2Se_2O$ heterostructure. (d) Topological phase diagram of the PAM-$NbSe_2$ obtained from Eq. (1). (e),(f) Ribbon spectra of PAM-$NbSe_2$ showing helical and chiral MM (HMM and CMM). Parameters are $t_x = 1$, $\mu = 0.6$, $\lambda_R = 0.2$, $J_A = 0.4$, $\Delta = 0.2$. $t_y = 1$ in (e) and $t_y = 0.8$ in (f). Band color codes as in Fig. 2.

external magnetic field, has yielded multiple signatures of topological superconductivity [92]. However, this approach requires applied magnetic fields that compete with superconductivity. In contrast, the AMPE offers a distinct advantage: it induces momentum-dependent spin splitting without net magnetization or external fields, thus preserving the superconducting gap while enabling new routes to engineer topological superconducting states [64–66].

To explore this possibility, we consider a platform composed of the well-studied vdW s-wave superconductor $NbSe_2$ placed on V_2Se_2O [Fig. 4(a)]. In this configuration, the AMPE-induced splitting from V_2Se_2O is expected to modify the pairing of $NbSe_2$ and can drive it into a topological superconductor hosting edge MM. Our first-principles calculations confirm that pristine $NbSe_2$ exhibits spin-degenerate bands [Fig. 4(b)], while in the $NbSe_2/V_2Se_2O$ heterostructure these bands acquire altermagnetic spin splitting as seen in Fig. 4(c) and Supplemental Material [77], demonstrating that the AMPE penetrates the superconducting layer without introducing net magnetization.

To analyze the superconducting properties of proximitized $NbSe_2$, we construct an effective model in the Nambu basis,

$$\begin{aligned} H_{\mathrm{BdG}} = {} & (t_x \cos k_x + t_y \cos k_y - \mu)\sigma_0\tau_z \\ & + \lambda_R(\sin k_y \sigma_x\tau_z - \sin k_x \sigma_y\tau_z) \\ & + J_A(\cos k_x - \cos k_y)\sigma_z\tau_0 + \Delta\sigma_0\tau_x, \end{aligned} \tag{1}$$

where $\sigma_i(\tau_i)$ are Pauli matrices in spin (particle-hole) space. The model includes kinetic hopping terms $t_{x/y}$, chemical potential μ, s-wave pairing Δ, the AMPE strength J_A, and the Rashba spin-orbit coupling strength λ_R, which arises from broken out-of-plane mirror symmetry at the interface and is essential for driving $NbSe_2$ into a topological superconducting phase [94,95], as detailed in Supplemental Material [77].

From gap-closing conditions and the calculated topological invariants [77,96], we obtain the phase diagram in Fig. 4(d). For isotropic hopping ($t_x = t_y$), crystalline symmetry enforces a valley degeneracy that, with suitable J_A, yields a helical topological superconductor hosting pairs of helical MMs at the edges [Fig. 4(e)]. Breaking this crystalline relation ($t_x \neq t_y$) lifts the valley degeneracy, allowing valley-selective topological transitions: one valley becomes topological while the other remains trivial. The edge spectrum then contains a single chiral MM per

boundary [Fig. 4(f)]. This symmetry-controlled switch between helical and chiral MMs within a single platform is a key advantage of AMPE-based designs. Because altermagnetism can be flexibly tuned by various dynamic means [31,32,97], the AMPE enables controllable manipulation of MMs, offering unprecedented opportunities for their fusion and braiding [98–100] central to topological quantum computing.

Beyond the V_2Se_2O-based heterostructures, we further demonstrate that the AMPE is a generic interfacial mechanism by realizing it in heterostructures between other nonmagnetic layers and diverse altermagnetic platforms, including V_2Se_2O derivatives, Ruddlesden-Popper perovskites (e.g., $Ca_3Mn_2O_7$ [49]), and the experimentally established metallic altermagnet CrSb [34], as detailed in Supplemental Material [77]. These results further reinforce both the generality and experimental feasibility of the AMPE.

Our proposed AMPE shifts the role of AMs from intrinsic or bulk mechanisms to an interfacial route. This conceptual advance significantly broadens their scope, enabling their momentum-alternating spin textures to be harnessed in otherwise NM systems. Just as ferromagnetic proximity can induce energy splittings beyond those achievable with external fields [1], the AMPE offers comparable advantages while avoiding stray fields and net magnetization. This field-free distinction is especially crucial for proximity-induced topological superconductivity, where conventional Zeeman-based schemes are often limited to semiconductors with large g-factors even under magnetic textures and fringing fields [100,101].

More broadly, the tunable spin and symmetry properties of altermagnets make the AMPE a versatile platform for realizing emergent states that would otherwise demand complex materials or multiple proximity effects [1]. A natural outlook is to identify the governing factors and control knobs of the AMPE strength, as well as the characteristic energy and timescales for reconfiguring altermagnetic order. Such efforts will be essential for assessing the feasibility of dynamical control over spin-dependent and topological responses [14,95], opening new opportunities to manipulate quantum phases in both normal and superconducting states.

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Data availability—The data that support the findings of this letter are openly available [102].

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