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Multicomponent Magnetic Domain Walls in Rhombohedral Graphene

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Spatial textures of magnetic order, such as domain walls and skyrmions, are fundamental objects in magnetism. In rhombohedral multilayer graphene, magnetic order involves spin and valley degrees of freedom, opening the possibility of qualitatively new spatial textures. Here, we explore this possibility through a microscopic study of a one-dimensional domain wall in the valley-imbalanced quarter-metal phase of rhombohedral graphene. We uncover two different classes of domain walls. One resembles a conventional magnetic domain wall, locally rotating between the two bulk states, whereas the other is intrinsically multicomponent and explores states that are not occupied in either bulk domain. Which texture is realized is controlled by the competition between intervalley Hund's coupling and spin-orbit coupling, and we identify experimental signatures to distinguish them. For a superconducting junction formed across the wall, we further show that the superconducting phase difference couples directly to the intervalley-coherent phase of the texture, allowing precession of this internal phase to generate a voltage. This mechanism provides an explanation for the resistive domain walls recently observed in chiral superconductors [arXiv2605.13303] and predicts accompanying magnetization oscillations that could be detected using GHz-frequency AC probes. Our theory establish a microscopic connection between multicomponent magnetic textures, their internal dynamics, and superconducting transport.

Introduction.— In a conventional metallic ferromagnet (e.g. nickel), the local order parameter is a three-dimensional spin magnetization, and a domain wall is described as a smooth rotation of this vector between two bulk orientations [1–7]. In macroscopic magnetic materials, domain formation is determined by the competition between exchange, magnetic anisotropy, and long-range magnetostatic interactions. Dividing a uniform state into smaller domains reduces its magnetostatic energy at the cost of creating domain walls [8–11]. Magnetism in rhombohedral graphene is fundamentally different in two respects. First, because the electron system is atomically thin, the conventional magnetostatic driving force for domain formation is strongly reduced. Second, the magnetization is not carried by spin alone: in the presence of an electric displacement field, spontaneous valley polarization also produces a substantial orbital magnetization [12–17]. At low carrier densities and low temperature, interactions can spontaneously polarize the spin and valley degrees of freedom, producing a quarter-metal state in which only one of the four spin-valley flavors is occupied [18–20]. Recent experiments have directly imaged magnetic domains in this regime [13, 21] and further suggest that the domain structure of the parent quarter metal is inherited by the chiral superconducting phase [22–25]. Nevertheless, the microscopic structure of the domain walls remains largely unexplored. In particular, it is not known whether intrinsic spin-orbit coupling keeps spin and valley locked throughout the wall, as in transition-metal dichalcogenides [26], or whether they “unlock” inside the wall?

In this work, we address this question using a momentum-space micromagnetic calculation in rhombohedral graphene and a long-wavelength CP^3 theory. We uncover two qualitatively distinct classes of spin-valley domain walls, separated by a continuous transition driven by the competition between spin-orbit coupling and intervalley Hund's exchange, as shown in Fig. 1. This transition occurs entirely within the domain

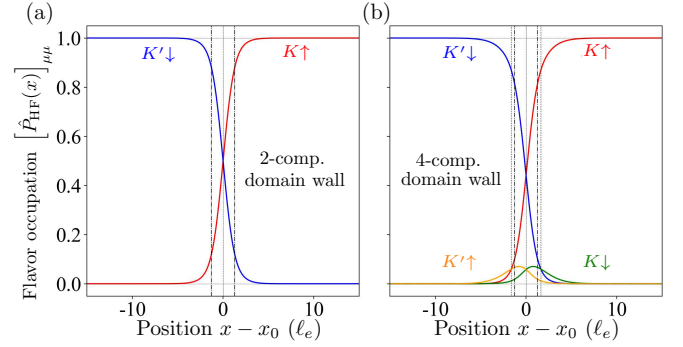


Figure 1. Two- and four-component domain walls in the valley-imbalanced quarter metal, determined by the competition between spin-orbit coupling λ_{soc} and intervalley Hund's coupling $g_{\perp}|n_e|$. In (a), $\lambda_{\text{soc}} \gg g_{\perp}|n_e|$ the magnetic texture only has two flavors, whereas in (b), $\lambda_{\text{soc}} \ll g_{\perp}|n_e|$ allows all four flavors to participate inside the wall. The curves show the diagonal component of the local spin-valley order parameter $[\hat{P}_{\text{HF}}(x)]_{\mu\mu}$.

wall while the adjoining bulk ferromagnetic states remain unchanged. We identify experimental signatures that distinguish the two textures and further examine what becomes of these domain walls when chiral superconductivity develops in the adjoining domains. In this regime, the system forms an $S|IVC|S$ junction, in which the intervalley-coherent domain-wall region acts as a magnetic weak link between two chiral superconductors. The resulting Josephson coupling directly links the superconducting phase difference to the internal intervalley-coherent phase of the magnetic texture.

Microscopic spin-valley domain walls.— Because the low-energy electrons carry four spin-valley flavors, their local magnetic order is described by a 4×4 Hermitian matrix. Excluding the total charge density, this matrix contains $4^2 - 1 = 15$ independent order parameters. Rather than parameterizing this large space and assuming a particular form for the domain wall [27], we determine the texture using unrestricted

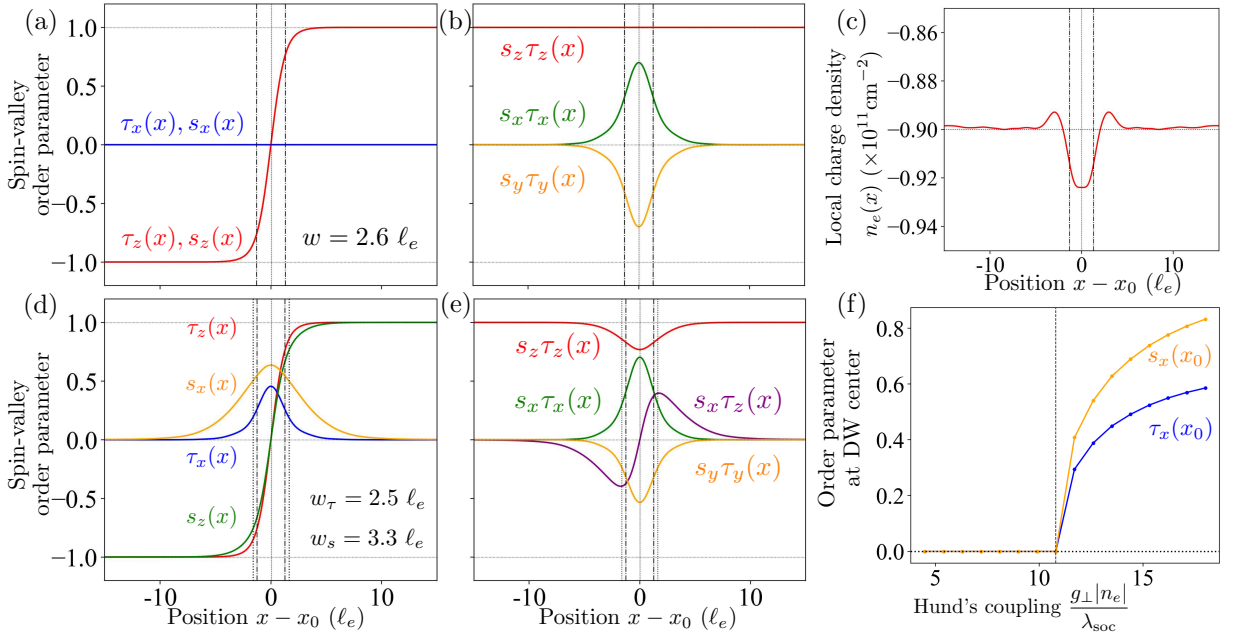


Figure 2. Self-consistent HF solutions of the two-component and the four-component spin-valley domain walls. (a–c) Results for the two-component domain wall at $g_{\perp} = 0$ centered at $x = x_0$. (a,b) Local Spin-valley texture shows that the spin and valley polarizations reverse simultaneously while remaining locked throughout the domain wall, giving rise to $s_z \tau_z(x) = 1$ throughout the space. The characteristic length scale is the average hole spacing, $\ell_e = 1/\sqrt{\pi|n_e|} \approx 20$ nm, and the domain-wall width $w = 2.6 \ell_e$ is indicated by the vertical dash-dotted lines. (c) Corresponding local charge density $n_e(x)$, showing only a weak redistribution of charge across the domain wall. The horizontal dashed line indicates the average charge density n_e . (d,e) Spin-valley texture of the four-component domain wall at $g_{\perp}|n_e|/\lambda_{\text{soc}} = 13.5$ shows intervalley coherence (τ_x) and transverse spin polarization (s_x) develop near the domain-wall center, partially releasing spin-valley locking ($s_z \tau_z < 1$) and producing distinct spin and valley domain-wall widths. The spin and valley widths are $w_s = 3.3 \ell_e$ (dotted lines) and $w_{\tau} = 2.5 \ell_e$ (dash-dotted lines), respectively. (f) $s_x(x_0)$ and $\tau_x(x_0)$ at the domain wall center continuously grow beyond a critical coupling $g_{\perp}^*|n_e|/\lambda_{\text{soc}} \approx 11$.

Hartree–Fock (HF) theory. This allows the charge density and all spin, valley, and mixed spin-valley order parameters to vary self-consistently in space.

We use rhombohedral bilayer graphene as a minimal model to identify magnetic domain-wall physics that we expect to persist in systems with other numbers of layers. We consider a one-dimensional domain wall for which the order parameter varies along x while translational symmetry is preserved along y . To solve the problem numerically, periodic boundary conditions are imposed along the x direction, such that the magnetic supercell forms a closed ring of circumference L . The periodic geometry therefore contains two equivalent domain walls separating the two degenerate bulk ferromagnetic states, with reciprocal vectors $G = 2\pi m/L$. The in-plane coordinate axes are defined by taking $\mathbf{e}_x$ and $\mathbf{e}_y$ to be parallel and perpendicular, respectively, to the graphene Dirac-point momentum $\mathbf{K}$ measured from the Γ point. In this basis, the self-consistent Hartree–Fock (HF) Hamiltonian is

$$H_{G\alpha,G'\beta}^{\text{MF}}(k_y) = \delta_{GG'} \left[\hat{H}_{\alpha\beta}^{\text{SWMc}}(G\mathbf{e}_x + k_y\mathbf{e}_y) + \hat{H}_{\alpha\beta}^{\text{SOC}} \right] + \Sigma_{G\alpha,G'\beta}^{\text{HF,C}}(k_y) + \Sigma_{G\alpha,G'\beta}^{\text{HF,Hund}}, \quad (1)$$

where α, β collectively label the spin (s), valley (τ), layer (l), and the A/B sublattice (σ) degrees of freedom. The first two terms describe the microscopic SWMc band structure[18] and

intrinsic spin-orbit coupling[20], while the last two are the HF self-energies arising from long-range Coulomb interactions and intervalley Hund’s exchange. Details of the Hamiltonian and its numerical implementation are given in Ref. [28]. We first identify the density and displacement field for which the uniform HF ground state is a spin- and valley-polarized quarter metal[29]. Intrinsic spin-orbit coupling locks the relative spin and valley orientations and reduces the fourfold flavor degeneracy to a time-reversal-related pair, which we denote by $K \uparrow$ and $K' \downarrow$. We then initialize the density matrix with a texture connecting these two states and solve Eq. (1) self-consistently. The initial wall width parameter is estimated as $\xi \sim \sqrt{\rho_s/\mathcal{K}}$, where ρ_s is the spin-valley stiffness and $\mathcal{K}$ is the magnetic anisotropy energy, both extracted from constrained uniform HF calculations [28].

The converged eigenvalues and eigenvectors,

$$H_{G\alpha,G'\beta}^{\text{MF}}(k_y) z_{nG'\beta}(k_y) = \mathcal{E}_n(k_y) z_{nG\alpha}(k_y), \quad (2)$$

determine the one-body density matrix $\hat{\rho}(k_y) = \sum_n n_F(\mathcal{E}_n(k_y)) |z_n(k_y)\rangle \langle z_n(k_y)|$. To isolate the spin-valley order carried by the doped electrons, we define the doped-carrier density matrix $\hat{\rho}$ by restricting the band sum in $\hat{\rho}$ to the

single-particle states of those doped carriers:

$$\tilde{\rho}_{G\alpha,G'\beta}(k_y) = \sum_{n \in \mathcal{D}(k_y)} n_F(\mathcal{E}_n(k_y)) z_{nG\alpha}(k_y) z_{nG'\beta}^*(k_y). \quad (3)$$

Here $\mathcal{D}(k_y)$ is the set of states filled as the chemical potential is raised/lowered from charge neutrality to its physical (HF) value. Fourier transforming this density matrix along x and tracing over the layer and sublattice degrees of freedom gives the normalized local spin-valley order parameter

$$[\hat{P}_{\text{HF}}(x)]_{\mu\nu} = \frac{1}{n_e(x)L} \int \frac{dk_y}{(2\pi)} \sum_{G,G'} \sum_a \tilde{\rho}_{G\mu a, G'\nu a}(k_y) e^{i(G-G')x}, \quad (4)$$

where $a \equiv (l, \sigma)$ runs through all the sublattices and $n_e(x)$ is the doped local charge density such that $\text{Tr} \hat{P}_{\text{HF}}(x) = 1$. Here, $\mu, \nu \in \{K \uparrow, K' \uparrow, K \downarrow, K' \downarrow\}$. The diagonal elements of $\hat{P}$ give the local occupations of the four spin-valley flavors, as shown in Fig. 1, and the local spin-valley order parameters are

$$s_i \tau_j(x) = \text{Tr} [\hat{P}_{\text{HF}}(x) \hat{s}_i \hat{\tau}_j]. \quad (5)$$

This construction determines the complete spin-valley texture without assuming a particular rotation path across the domain wall.

The main results of our microscopic calculations are summarized in Fig. 2. When spin-orbit coupling dominates the intervalley Hund's coupling, $\lambda_{\text{soc}} \gg g_{\perp}|n_e|$, spin and valley remain locked throughout the wall. The texture is confined to the two-dimensional subspace favored by spin-orbit coupling, $K \uparrow$ and $K' \downarrow$. As shown in Figs. 2(a) and 2(b), the spin-orbit locking condition $s_z \tau_z(x) = 1$ remains satisfied at every position. We refer to this solution as the two-component domain wall. Although the two flavors form a superposition of opposite spin inside the domain wall, they belong to opposite valleys, and their coherence produces no net in-plane spin polarization. The wall therefore carries no static in-plane spin moment and has no direct linear Zeeman coupling to an in-plane magnetic field. This texture is adiabatically connected to the spin-valley-locked domain walls previously studied in transition-metal-dichalcogenides Chern insulators [26]. An important distinction is that the quarter-metal phase considered here is metallic and exhibits charge-density fluctuations across the wall, as shown in Fig. 2(c).

The domain wall structure changes qualitatively in the opposite, Hund-dominated limit, $g_{\perp}|n_e| \gg \lambda_{\text{soc}}$. Intervalley Hund's exchange favors parallel spin alignment in the two valleys and therefore admixes the other two flavors that are unoccupied in either bulk domains, $K \downarrow$ and $K' \uparrow$. The resulting spin-valley texture is shown in Figs. 2(d) and (e). The reduction of $s_z \tau_z(x)$ below unity reflects a local spin-orbit-energy cost, which is compensated by the gain in intervalley exchange energy and accompanied by the emergence of transverse spin polarization $s_x(x)$ and intervalley coherence $\tau_x(x)$. Spin and valley are therefore no longer locked and develop distinct spatial profiles, with the spin-domain-wall width slightly exceeding the

valley-domain-wall width. As shown in Fig. 2(f), these additional order parameters turn on continuously above a critical Hund's coupling $g_{\perp}|n_e|/\lambda_{\text{soc}} \sim 11$, demonstrating a continuous transition from the two-component to the four-component domain wall.

As shown in companion experimental studies [30, 31], the two textures exhibit distinct magnetotransport signatures: the 4-component domain wall carries a net in-plane spin moment and supports a ferro-Josephson effect whose critical current varies linearly with the applied in-plane magnetic field. Although our microscopic calculations focus on rhombohedral graphene, the same domain-wall physics may also arise in graphene moiré superlattices. This broader applicability motivates the universal long-wavelength theory outlined below and developed further in [28].

CP³ theory and its limitation.— A natural long-wavelength description, analogous to those used for magic-angle twisted bilayer graphene [32] and quantum Hall ferromagnets [33], represents the local spin-valley polarization by a normalized four-component spinor $|\psi(x)\rangle$, or equivalently by the rank-one projector

$$\hat{P}(x) = |\psi(x)\rangle\langle\psi(x)|, \quad \hat{P}^2 = \hat{P}, \quad \text{Tr} \hat{P} = 1, \quad (6)$$

whose order-parameter manifold is CP^3 . We test this description using the reduced spin-valley density matrix $\hat{P}_{\text{HF}}(x)$ obtained from the microscopic HF solution. As shown in Fig. 3(a), $\hat{P}_{\text{HF}}$ is nearly idempotent in the bulk but becomes mixed inside the domain wall, as diagnosed by the finite value of $\text{Tr}(\hat{P}_{\text{HF}} - \hat{P}_{\text{HF}}^2)$. Microscopically, this arises because the intervalley coherence and layer-sublattice degrees of freedom become entangled inside the domain wall. The CP^3 theory therefore captures the qualitative spin-valley texture but not the full microscopic quasiparticle wavefunctions. For example, the idealized CP^3 texture would have predicted $|s_x \tau_x(x_0)| = |s_y \tau_y(x_0)| = 1$ at the center of two-component domain wall (Fig. S6 in Ref. [28]), whereas their magnitudes are reduced in the microscopic HF solution (Fig. 2b).

Chiral superconductivity across domain walls.— One of the most striking aspects of chiral superconductivity in the quarter-metal regime is the apparent intertwining of magnetism and superconductivity [23, 34–36]. In Ref. [34], it was found that the nominally zero-resistance state shows resistance spikes ($R_{xx} \ll h/e^2$) near the coercive field associated with magnetization reversal of the parent quarter metal. NanoSQUID imaging further reveals that the chiral domain structure of the superconducting phase is inherited from its valley-polarized parent metal and that the domain walls are resistive [23]. These observations suggest that, below T_c , a normal-state spin-valley domain wall evolves into a weak link between superconducting domains of opposite chirality.

This picture raises two basic questions. First, what produces the observed resistance? A conventional $S|N|S$ junction can carry a dissipationless Josephson current mediated by Andreev bound states, even when the normal region has finite resistance. The presence of a normal domain-wall region is therefore not, by itself, sufficient to produce a voltage across

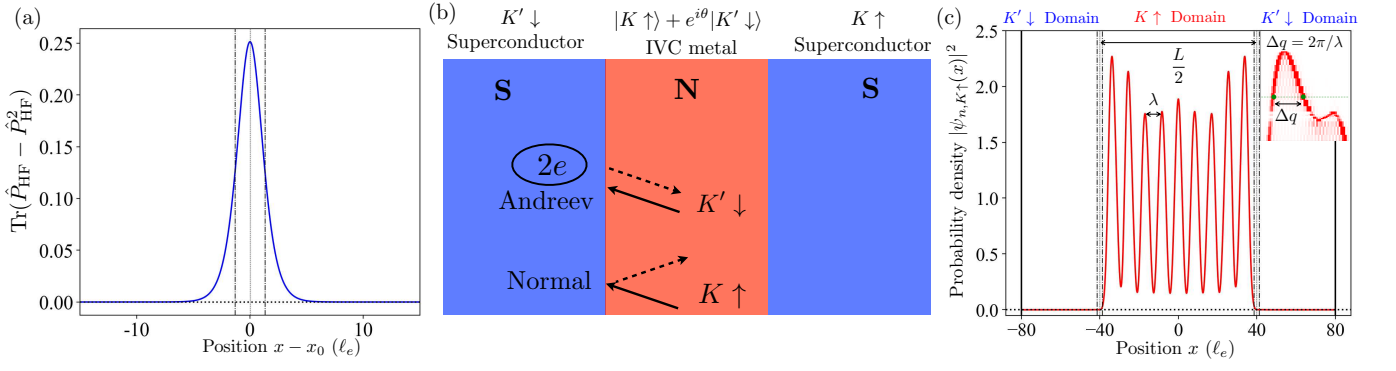


Figure 3. (a) Deviation of the microscopic HF spin-valley projector from the pure-state condition, quantified by $\text{Tr}(\hat{P}_{\text{HF}} - \hat{P}_{\text{HF}}^2)$. A finite value near the domain-wall center demonstrates that the local spin-valley density matrix is mixed, in contrast to the pure projector assumed in the CP^3 theory. (b) Schematic of spin-valley-selective scattering across an $S|N|S$ junction, where time-reversal-related chiral superconductors are separated by an intervalley-coherent (IVC) normal-metal, $\propto |K \uparrow\rangle + e^{i\theta}|K' \downarrow\rangle$. The IVC region coherently mixes the two valley flavors, enabling normal reflection and intervalley-assisted Andreev conversion. (c) Probability density $|\psi_{n,K\uparrow}(x)|^2$ of a representative Bloch state at $\mathcal{E}_n(k_y = 0) - \mu = 5.6$ meV in the $K \uparrow$ domain. The bulk oscillation originates from the interference of two dominant Fourier components separated by momentum difference Δq , giving an oscillation wavelength $\lambda = 2\pi/\Delta q$.

the junction. Moreover, because the domain wall is only a few interparticle spacings wide, the junction can, in principle, support a supercurrent below its critical current.

Second, when Cooper pairs tunnel across the domain wall, what microscopic process converts pairs with center-of-mass momentum $2K$ into pairs with momentum $2K'$ [37]? Although the domain wall breaks translational symmetry, it varies over the interparticle spacing, which is much larger than the atomic scale, and therefore cannot by itself provide the large momentum transfer required for intervalley conversion. We argue below that these two questions have a common resolution: the superconducting phase couples dynamically to the intervalley-coherent phase within the domain wall.

Let's consider the superconducting junction shown in Fig. 3(b). The left and right regions are time-reversal-related chiral superconductors with order parameters $\Delta_L = |\Delta_L|e^{i\phi_L}$, $\Delta_R = |\Delta_R|e^{i\phi_R}$ formed respectively from electrons in the K and K' valleys. We model the domain-wall as a non-superconducting intervalley-coherent state with order parameter $M \equiv \langle c_K^\dagger c_{K'} \rangle = |M|e^{i\theta}$ where θ is the intervalley-coherent phase. To an excellent approximation, the low-energy Hamiltonian separately conserves the electron numbers in the two valleys. Because the microscopic Hamiltonian is invariant under independent valley rotations, $c_\tau \rightarrow e^{i\alpha_\tau} c_\tau$ ($\tau = K, K'$), the phases of the three order parameters transform as

$$(\phi_L, \phi_R, \theta) \rightarrow (\phi_L + 2\alpha_K, \phi_R + 2\alpha_{K'}, \theta + \alpha_{K'} - \alpha_K). \quad (7)$$

Consequently, the Josephson energy can depend on the phases only through the valley-invariant combination

$$\Phi = \varphi - 2\theta, \quad \varphi = \phi_R - \phi_L - \frac{2e}{\hbar} \int_L^R \mathbf{A} \cdot d\ell \quad (8)$$

To leading harmonic order, the phase-dependent free energy then takes the form

$$F = F_J + F_U = -E_J \cos(\varphi - 2\theta) - E_U \cos(3\theta), \quad (9)$$

where E_J describes Josephson coupling energy across the domain wall and E_U is the pinning potential generated by 3-body Umklapp processes, whose strength is estimated in Ref. [38]. The corresponding Josephson current is

$$I_s = \frac{2e}{\hbar} \frac{\partial F}{\partial \varphi} = I_c \sin \Phi, \quad I_c = \frac{2eE_J}{\hbar}. \quad (10)$$

Because θ enters the same invariant phase combination, Josephson coupling exerts a torque on the intervalley-coherent phase,

$$\tau_\theta = -\frac{\partial F}{\partial \theta} = \frac{\hbar}{e} I_s - 3E_U \sin(3\theta). \quad (11)$$

The voltage drop across the junction is related to the dynamics of both phase variables through the Josephson relation,

$$V = \frac{\hbar}{2e} \dot{\varphi} = \frac{\hbar}{2e} (\dot{\Phi} + 2\dot{\theta}). \quad (12)$$

This equation implies there are two distinct critical currents. The first is the usual Josephson critical current, $I_c = \frac{2eE_J}{\hbar}$, above which Φ starts precessing. The second is the depinning current of the intervalley-coherent phase, $I'_c = \frac{3eE_U}{\hbar}$, above which θ starts precessing. A fully stationary state therefore exists only when the applied current $I < \min(I_c, I'_c)$. Thus, for the $S|IVC|S$ junction, even below the conventional Josephson critical current, the junction can become resistive once IVC order parameter is non-stationary. Our analysis therefore suggests that the resistance observed in Ref. [23] may originate either from conventional Josephson breakdown or from current-driven dynamics of the intervalley-coherent phase, depending on which critical current is smaller. A possible test is to measure the nonlinear IV characteristic: below the depinning threshold, Andreev bound states carry a dissipationless supercurrent; above threshold, phase precession generates a finite voltage. Importantly, IVC precession also produces GHz

oscillations of orbital magnetization which can be detected using AC probes [38].

Interference pattern.— Beyond their collective dynamics, the metallic domain walls also produce interference pattern for the stationary quasiparticle states. As shown in Fig. 3(c), the probability density $|\psi_{K\uparrow}(x)|^2$ of a stationary state in a $K\uparrow$ domain bounded by two $K'\downarrow$ domains shows pronounced spatial oscillations. These oscillations arise from interference between the two equal-energy momenta $k_{x,1}$ and $k_{x,2}$ shown in the inset. Their separation, $\Delta q = |k_{x,1} - k_{x,2}|$, determines the interference wavelength: $\lambda = \frac{2\pi}{\Delta q}$ and $N\lambda \sim \frac{L}{2}$. Here $L/2$ is the length of the $K\uparrow$ domain and N is the number of oscillation periods across it. For the state shown in Fig. 3(c), $N = 9$. This energy-dependent interference pattern provides a microscopic signature of metallic domain structure that could be detected using spatially resolved probes.

Summary and outlook.— We have developed a micromagnetic theory in momentum-space to study magnetic textures in rhombohedral graphene and uncovered two qualitatively distinct multicomponent spin-valley domain walls. Their competition is determined by the competition between spin-orbit coupling and intervalley Hund's exchange and occurs entirely within the wall while the adjoining bulk states remain unchanged. This work provides a starting point for studying more general spin-valley textures [39], including skyrmions, as well as interactions between domain walls and quasiparticles.

Note added.— During the preparation of this manuscript, we became aware of a related work Ref. [40] on domain walls in rhombohedral multilayer graphene. That work studies transport across a prescribed valley-domain-wall texture, while we determine the domain-wall structure microscopically. Ref. [41] develops a theory of hydrodynamic transport across orbital-ferromagnetic domain walls. Refs. [30, 31] report experimental evidence of unconventional transport across such domain walls.

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Competing interests statement.— The authors declare no competing interests.

Ethics declaration.— Not applicable.

Data availability.— All data generated or analyzed during this study are included in this published article (and its Supplementary Information files).

Code availability.— The custom Python code used for the microscopic Hartree-Fock calculations and the CP^3 continuum-theory calculations in this study is available at <https://github.com/mainakdasphys/multicomponent-magnetic-domain-walls-in-rhombohedral-graphene>.

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- [1] M. R. Scheinfein, J. Unguris, R. J. Celotta, and D. T. Pierce, "Influence of the surface on magnetic domain-wall microstructure," *Phys. Rev. Lett.*, vol. 63, pp. 668–671, Aug 1989.
- [2] M. R. Scheinfein, J. Unguris, J. L. Blue, K. J. Coakley, D. T. Pierce, R. J. Celotta, and P. J. Ryan, "Micromagnetics of domain walls at surfaces," *Phys. Rev. B*, vol. 43, pp. 3395–3422, Feb 1991.
- [3] S. Middelhoeck, "Domain walls in thin ni-fe films," *Journal of Applied Physics*, vol. 34, no. 4, pp. 1054–1059, 1963.
- [4] H.-H. Yang, N. Bansal, P. Rüßmann, M. Hoffmann, L. Zhang, D. Go, Q. Li, A.-A. Haghighirad, K. Sen, S. Blügel, M. Le Tacon, Y. Mokrousov, and W. Wulfhekel, "Magnetic domain walls of the van der waals material fe3gete2," *2D Materials*, vol. 9, p. 025022, mar 2022.
- [5] B. Huang, G. Clark, E. Navarro-Moratalla, D. R. Klein, R. Cheng, K. L. Seyler, D. Zhong, E. Schmidgall, M. A. McGuire, D. H. Cobden, W. Yao, D. Xiao, P. Jarillo-Herrero, and X. Xu, "Layer-dependent ferromagnetism in a van der waals crystal down to the monolayer limit," *Nature*, vol. 546, no. 7657, pp. 270–273, 2017.
- [6] C. Gong, L. Li, Z. Li, H. Ji, A. Stern, Y. Xia, T. Cao, W. Bao, C. Wang, Y. Wang, Z. Q. Qiu, R. J. Cava, S. G. Louie, J. Xia, and X. Zhang, "Discovery of intrinsic ferromagnetism in two-dimensional van der waals crystals," *Nature*, vol. 546, no. 7657, pp. 265–269, 2017.
- [7] M. Alimohammadian and B. Sohrabi, "Observation of magnetic domains in graphene magnetized by controlling temperature, strain and magnetic field," *Scientific Reports*, vol. 10, no. 1, p. 21325, 2020.
- [8] W. F. Brown, *Micromagnetics*. Interscience tracts on physics and astronomy, no. 18, New York: Interscience Publishers, 1963.
- [9] W. F. Brown Jr and A. E. LaBonte, "Structure and energy of one-dimensional domain walls in ferromagnetic thin films," *Journal of Applied Physics*, vol. 36, no. 4, pp. 1380–1386, 1965.
- [10] A. Hubert and R. Schäfer, *Magnetic domains : the analysis of magnetic microstructures*. Berlin : Springer, 1998.
- [11] G. Venkat, D. A. Allwood, and T. J. Hayward, "Magnetic domain walls: types, processes and applications," *Journal of Physics D: Applied Physics*, vol. 57, p. 063001, nov 2023.
- [12] F. R. Geisenhof, F. Winterer, A. M. Seiler, J. Lenz, T. Xu, F. Zhang, and R. T. Weitz, "Quantum anomalous hall octet driven by orbital magnetism in bilayer graphene," *Nature*, vol. 598, no. 7879, pp. 53–58, 2021.
- [13] O. I. Sheekey, T. B. Arp, B. A. Foutty, R. Zhang, T. Tan, L. F. W. Holleis, Y. Guo, S. S. Kalantire, C. Zhang, M. Zakharyan, D. Gong, A. Keough, Y. Choi, Y. Choi, S. Xu, T. Xie, B. H. Alexander, M. Hocking, Q. Cao, M. E. Huber, T. Taniguchi, K. Watanabe, C. Jin, E. Lantagne-Hurtubise, A. Sharpe, T. Devakul, and A. F. Young, "Visualizing orbital magnetism in electron doped rhombohedral multilayer graphene," 2026.
- [14] T. Han, Z. Lu, G. Scuri, J. Sung, J. Wang, T. Han, K. Watanabe, T. Taniguchi, L. Fu, H. Park, and L. Ju, "Orbital multiferroicity in pentalayer rhombohedral graphene," *Nature*, vol. 623,

- no. 7985, pp. 41–47, 2023.
- [15] J. Deng, J. Xie, H. Li, T. Taniguchi, K. Watanabe, J. Shan, K. F. Mak, and X. Liu, “Superconductivity and ferroelectric orbital magnetism in semimetallic rhombohedral hexalayer graphene,” 2026.
 - [16] C. Huang, T. M. R. Wolf, W. Qin, N. Wei, I. V. Blinov, and A. H. MacDonald, “Spin and orbital metallic magnetism in rhombohedral trilayer graphene,” *Phys. Rev. B*, vol. 107, p. L121405, Mar 2023.
 - [17] M. Das and C. Huang, “Unconventional metallic ferromagnetism: Nonanalyticity and sign-changing behavior of orbital magnetization in rhombohedral trilayer graphene,” *Phys. Rev. B*, vol. 109, p. L060409, Feb 2024.
 - [18] H. Zhou, T. Xie, A. Ghazaryan, T. Holder, J. R. Ehrets, E. M. Spanton, T. Taniguchi, K. Watanabe, E. Berg, M. Serbyn, *et al.*, “Half-and quarter-metals in rhombohedral trilayer graphene,” *Nature*, vol. 598, no. 7881, pp. 429–433, 2021.
 - [19] T. Arp, O. Sheekey, H. Zhou, C. Tschirhart, C. L. Patterson, H. Yoo, L. Holleis, E. Redekop, G. Babikyan, T. Xie, *et al.*, “Intervalley coherence and intrinsic spin-orbit coupling in rhombohedral trilayer graphene,” *Nature Physics*, vol. 20, no. 9, pp. 1413–1420, 2024.
 - [20] N. Auerbach, S. Dutta, M. Uzan, Y. Vituri, Y. Zhou, A. Y. Meltzer, S. Grover, T. Holder, P. Emanuel, M. E. Huber, Y. Myasoedov, K. Watanabe, T. Taniguchi, Y. Oreg, E. Berg, and E. Zeldov, “Isospin magnetic texture and intervalley exchange interaction in rhombohedral tetralayer graphene,” *Nature Physics*, vol. 21, no. 11, pp. 1765–1772, 2025.
 - [21] R. Zhang, B. A. Foutty, O. Sheekey, T. Arp, S. Xu, T. Xie, Y. Guo, H. Stoyanov, S. Gu, A. Keough, E. Redekop, C. Zhang, T. Taniguchi, K. Watanabe, M. E. Huber, C. Jin, E. Berg, and A. F. Young, “Imaging the meissner effect and local superfluid stiffness in a graphene superconductor,” 2026.
 - [22] T. Han, Z. Lu, Z. Hadjri, L. Shi, Z. Wu, W. Xu, Y. Yao, A. A. Cotten, O. Sharifi Sedeh, H. Weldeyesus, J. Yang, J. Seo, S. Ye, M. Zhou, H. Liu, G. Shi, Z. Hua, K. Watanabe, T. Taniguchi, P. Xiong, D. M. Zumbühl, L. Fu, and L. Ju, “Signatures of chiral superconductivity in rhombohedral graphene,” *Nature*, vol. 643, no. 8072, pp. 654–661, 2025.
 - [23] S. Dutta, N. Auerbach, T. Han, Y. Zhou, G. Shavit, N.-S. Kander, Y. Myasoedov, M. E. Huber, K. Watanabe, T. Taniguchi, *et al.*, “Reconfigurable chiral superconductivity,” *arXiv preprint arXiv:2605.13303*, 2026.
 - [24] Z. Hua, S. Ye, P. Pattanankanvijit, G. Shi, T. Han, E. Aitken, J. Yang, J. Seo, H. Liu, R. Hao, K. Xiao, J. Guo, V. T. Phong, K. Watanabe, T. Taniguchi, C. Huang, C. Lewandowski, L. Ju, P. Xiong, and Z. Lu, “Multi-knob switchable chiral superconductivity quartet in rhombohedral graphene,” 2026.
 - [25] S. S. Kalantre, B. H. Alexander, J. May-Mann, J. Herzog-Arbeitman, M. Hocking, Q. Cao, K. Watanabe, T. Taniguchi, D. Goldhaber-Gordon, A. J. Mannix, T. Devakul, Y. H. Kwan, D. E. Parker, and A. Sharpe, “Fermiology and the candidate chiral superconductor in rhombohedral tetralayer graphene,” 2026.
 - [26] W.-X. Qiu and F. Wu, “Topological magnons and domain walls in twisted bilayer mote_2 ,” *Phys. Rev. B*, vol. 112, p. 085132, Aug 2025.
 - [27] C. Huang, N. Wei, and A. H. MacDonald, “Current-driven magnetization reversal in orbital chern insulators,” *Phys. Rev. Lett.*, vol. 126, p. 056801, Feb 2021.
 - [28] See Supplemental Material for details of mean-field construction of uniform and domain wall solutions, and reconstruction of domain wall profiles using CP^3 theory.
 - [29] J. M. Koh, A. Thomson, J. Alicea, and E. Lantagne-Hurtubise, “Symmetry-broken metallic orders in spin-orbit-coupled bernal bilayer graphene,” *Phys. Rev. B*, vol. 110, p. 245118, Dec 2024.
 - [30] R. Su, Z. Gao, C. Coleman, M. Kuirri, D. Waters, K. Watanabe, T. Taniguchi, M. Yankowitz, N. Wei, C. Huang, A. H. MacDonald, and J. Folk, “Signatures of a ferro-josephson effect in twisted graphene,” *arXiv:2608.25257*, 2026.
 - [31] Z. Gao, C. Coleman, S. Folk, R. Su, M. Kuirri, K. Watanabe, T. Taniguchi, N. Wei, C. Huang, and J. Folk, “Metastable magnetic domains and the anomalous $b_{\parallel} = 0$ resistance peak in twisted double bilayer graphene,” *arXiv:2608.25263*, 2026.
 - [32] Y. H. Kwan, G. Wagner, N. Chakraborty, S. H. Simon, and S. Parameswaran, “Domain wall competition in the chern insulating regime of twisted bilayer graphene,” *Physical Review B*, vol. 104, no. 11, p. 115404, 2021.
 - [33] Y. Lian, A. Rosch, and M. Goerbig, “ $\text{Su}(4)$ skyrmions in the $\nu = \pm 1$ quantum hall state of graphene,” *Physical Review Letters*, vol. 117, no. 5, p. 056806, 2016.
 - [34] T. Han, Z. Lu, Z. Hadjri, L. Shi, Z. Wu, W. Xu, Y. Yao, A. A. Cotten, O. Sharifi Sedeh, H. Weldeyesus, *et al.*, “Signatures of chiral superconductivity in rhombohedral graphene,” *Nature*, vol. 643, no. 8072, pp. 654–661, 2025.
 - [35] Z. Hua, S. Ye, P. Pattanankanvijit, G. Shi, T. Han, E. Aitken, J. Yang, J. Seo, H. Liu, R. Hao, *et al.*, “Multi-knob switchable chiral superconductivity quartet in rhombohedral graphene,” *arXiv preprint arXiv:2607.06520*, 2026.
 - [36] O. I. Sheekey, T. B. Arp, B. A. Foutty, R. Zhang, T. Tan, L. F. Holleis, Y. Guo, S. S. Kalantre, C. Zhang, M. Zakharyan, *et al.*, “Visualizing orbital magnetism in electron doped rhombohedral multilayer graphene,” *arXiv preprint arXiv:2605.30316*, 2026.
 - [37] Q. Qin and C. Wu, “Chiral finite-momentum superconductivity in the tetralayer graphene,” *Chinese Physics Letters*, vol. 43, p. 030708, mar 2026.
 - [38] M. Das and C. Huang, “Momentum space ac josephson effect and intervalley coherence in multilayer graphene,” *Nature Communications*, vol. 17, no. 1, p. 1079, 2025.
 - [39] Y. Zhu, Z. Li, Y. Xu, Y. Ling, Z. Lin, Z. Chen, Z. Liu, H. Fu, and X. Lin, “Charge excitations at landau level crossings in $\text{wse}_2/\text{sub}_2/\text{sub}_2$ -encapsulated bilayer graphene,” *Chin. Phys. Lett.*, vol. 43, no. 2, pp. 020714–020714, 2026.
 - [40] V. T. Phong, E. Prada, P. San-Jose, F. Guinea, and E. J. Mele, “Valley valves at domain walls in symmetry-broken rhombohedral graphene,” *arXiv preprint arXiv:2606.14878*, 2026.
 - [41] A. Panigrahi and K. Nazaryan, “Viscocoherent transport: Chiral selection of hydrodynamic vortices by berry curvature,” *arXiv:2608.26102*, 2026.
 - [42] G. Xu and C. Huang, “Influence of the dirac sea on phase transitions in monolayer graphene under strong magnetic fields,” *Phys. Rev. B*, vol. 111, p. 125127, Mar 2025.

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