

Cavity-assisted spin selection in one-dimensional conductors

Vivek Kumar¹, Joshua Coop¹, Yingshi Duo¹, Ian Farrer², David A. Ritchie³, and Sanjeev Kumar^{1,*}¹*Department of Electronic and Electrical Engineering, University College London, Torrington Place, London WC1E 7JE, United Kingdom*²*School of Electrical & Electronic Engineering, University of Sheffield, Mappin Street, Sheffield S1 3JD, United Kingdom*³*Cavendish Laboratory, J.J. Thomson Avenue, Cambridge CB3 0HE, United Kingdom*

(Received 30 December 2025; revised 17 April 2026; accepted 15 June 2026; published 7 July 2026)

Spontaneous spin polarization in quasi-one-dimensional (1D) electron systems is inherently fragile, often masked by structural disorder or potential anharmonicity. Here we report the deterministic stabilization of an exchange-driven spin gap, manifesting as a robust $0.5(2e^2/h)$ conductance plateau at zero magnetic field in a mesoscopic bilayer cavity. We demonstrate that this many-body phase is governed by a dual-parity protection mechanism. The spectral isolation of the tunnel-coupled bilayer energetically protects the ground state, while the symmetric harmonicity of the lateral cavity geometry shields the 1D van Hove singularity against transverse mode mixing. Breaking this spatial parity via asymmetric gating or localized central-gate screening violates the Stoner criterion for 1D ferromagnetism, quenching the $0.5(2e^2/h)$ state and restoring spin-degenerate transport. Our findings establish electrostatic spatial parity as a macroscopic, tunable lever for engineering correlated quantum phases in mesoscopic architectures.

DOI: [10.1103/b542-3g2c](https://doi.org/10.1103/b542-3g2c)

The on-demand electrical control of spin-polarized currents without external magnetic fields remains a cornerstone objective of both many-body physics and topological spintronics. In quasi-one-dimensional (1D) systems [1,2], the spontaneous lifting of spin degeneracy, manifested canonically as the “0.7 anomaly” in quantum point contacts (QPCs) or 1D quantum wires, provides a compelling signature of electron-electron interactions in the dilute limit [3–18]. This phenomenon is widely attributed to an exchange-driven instability, where the system minimizes its total energy by aligning spins as the kinetic energy is quenched in the low-density regime [19,20]. However, because this polarization relies primarily on density-driven fluctuations [16,21], the resulting state is intrinsically fragile, highly susceptible to thermal smearing, and lacks a precise tuning mechanism. Consequently, spontaneous spin polarization has largely remained a localized interaction effect [3] rather than a programmable macroscopic phase.

Transitioning from observing fleeting correlations to engineering robust quantum phases requires a degree of freedom beyond carrier density. Strongly tunnel-coupled double quantum wells provide such a lever by introducing a macroscopic layer-pseudospin architecture [22]. In these systems, interlayer tunneling hybridizes the layer states into molecular symmetric (S) and antisymmetric (AS) wave functions, separated by a tunneling gap Δ_{SAS} [23–30]. While this hy-

bridization fundamentally reshapes the interaction landscape, conventional split-gate architectures inherently break the very symmetries, both lateral and vertical, that are required to stabilize these delicate many-body ground states [31–43].

In this Letter, we demonstrate how macroscopic electrostatic parity governs the emergence and suppression of spontaneous spin polarization. By engineering a path-selective mesoscopic cavity on a tunnel-coupled GaAs/AlGaAs bilayer, we report the observation of a quantized $\sim 0.5(2e^2/h)$ conductance plateau at zero magnetic field. We show that this signature of a solitary, spin-polarized mode is strictly gated into existence by the local potential parity of the confinement. Our results establish a “dual-parity protection” mechanism, where lateral geometric harmonicity and vertical orbital symmetry converge to architect and control the many-body ground state. By utilizing a path-selective geometry to suppress macroscopic interference, we isolate the transport to a single, symmetry-protected 1D channel, revealing the explicit tunability of exchange correlations.

The experimental platform is based on a high-mobility GaAs/AlGaAs heterostructure grown via molecular beam epitaxy. The architecture comprises a tunnel-coupled bilayer formed by two 15 nm-wide GaAs quantum wells separated by a 3 nm-thin $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$ barrier. The top two-dimensional electron gas (2DEG) is situated at a nominal depth of ~ 283 nm below the heterostructure surface. Initial characterization was performed using low-field Shubnikov–de Haas (SdH) magnetotransport measurements [Fig. 1(b)]. A fast Fourier transform analysis of the SdH oscillations [Fig. 1(c)] reveals two distinct frequency components, corresponding to the molecularly hybridized subband densities $n_1 = 1.10 \times 10^{11} \text{ cm}^{-2}$ and $n_2 = 1.26 \times 10^{11} \text{ cm}^{-2}$. The calculated interlayer tunnel-coupling strength, $\Delta_{\text{SAS}} = \frac{2\pi\hbar^2}{m^*}(n_2 - n_1) \approx 1.8 \text{ meV}$ (m^* is the

*Contact author: sanjeev.kumar@ucl.ac.uk

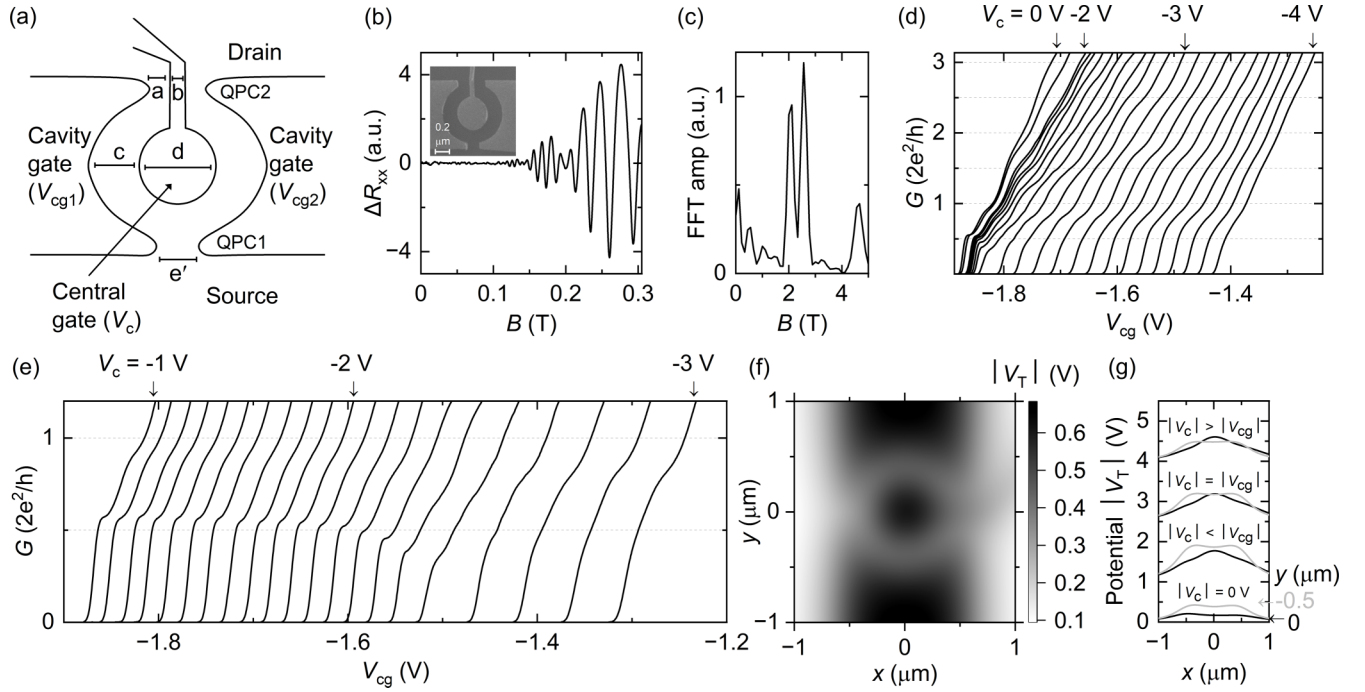


FIG. 1. (a) A schematic of the device shows a split-gate configuration with two cavity gates. It features two quantum point contacts (QPC1 and QPC2) positioned at the cavity's entrance and exit. The distance between the entrance and exit QPCs is $1.3 \mu\text{m}$. The QPCs have widths $e' = 0.25 \mu\text{m}$ and $2a + b = 0.5 \mu\text{m}$ ($a = 0.2 \mu\text{m}$ and $b = 0.1 \mu\text{m}$). The central gate has a diameter $d = 0.52 \mu\text{m}$. The maximum distance between the cavity gates at the geometric center is $2c + d = 1.2 \mu\text{m}$ ($c = 0.35 \mu\text{m}$). (b) Longitudinal resistance of the bilayer 2DEGs after background subtraction, ΔR_{xx} , as a function of magnetic field, B . The inset shows a scanning electron microscopy image of a representative device. (c) Fast Fourier transform (amplitude vs frequency, with frequency in magnetic field, B) of the Shubnikov-de Haas oscillations (ΔR_{xx} vs $1/B$). (d) Differential conductance, G , as a function of cavity gate voltage, V_{cg} , at various central gate voltages, V_c . The first two traces on the left are for $V_c = 0 \text{ V}$ and -1.5 V , respectively; traces for $-4 \text{ V} \leq V_c \leq -2 \text{ V}$ are in steps of 0.1 V . (e) A magnified view of the plot in (d); traces for $-3 \text{ V} \leq V_c \leq -1 \text{ V}$ in steps of 0.1 V , each consecutive trace has been offset horizontally by 0.02 V for clarity. The drop in conductance of the first plateau (and higher ones) on the right side indicates possible backscattering and asymmetry between the QPCs. (f) Total electrostatic potential, $|V_T|$, of a representative device at the 2DEG, located 275 nm beneath the cavity and central gates, for $|V_{cg1}| = |V_{cg2}| = 1.0 \text{ V}$ and $|V_c| = 1.5 \text{ V}$, shown as a 2D map in the xy plane. (g) Potential along x at $y = 0$ (black) and $y = -0.5 \mu\text{m}$ (gray) for different values of $|V_{cg}|$ ($= |V_{cg1}| = |V_{cg2}|$) and $|V_c|$. Four bias configurations are shown: $(|V_c|, |V_{cg}|) = (0 \text{ V}, 1.0 \text{ V})$, $(1.5 \text{ V}, 2.0 \text{ V})$, $(1.5 \text{ V}, 1.5 \text{ V})$, and $(1.5 \text{ V}, 1.0 \text{ V})$. For clarity, the corresponding traces are vertically offset by $0, 1.0, 2.5$, and 4.0 V , respectively, and appear from bottom to top as pairs of curves, each pair corresponding to $y = 0$ and $y = -0.5 \mu\text{m}$.

effective mass of the electron in GaAs; $\hbar$ is the reduced Planck's constant), confirms a robust bonding-antibonding energy gap. The bilayer system exhibits a high electron mobility $\mu \approx 1.2 \times 10^6 \text{ cm}^2/\text{Vs}$ and a corresponding elastic mean free path $l \approx 6 \mu\text{m}$, ensuring strictly ballistic transport across the sub-micron device active region. The mesoscopic cavity was defined using standard electron-beam lithography followed by the evaporation of Ti/Au Schottky gates. The device geometry consists of a path-selective cavity defined by a pair of $1.3 \mu\text{m}$ -long arc-shaped cavity gates. The lateral separation between the cavity gates varies from $0.25 \mu\text{m}$ at the entrance QPC1 to $1.2 \mu\text{m}$ at the cavity center, tapering to $0.5 \mu\text{m}$ at the exit QPC2. A circular central gate ($0.52 \mu\text{m}$ diameter) is positioned at the geometric center of the cavity, addressed via a $0.1 \mu\text{m}$ -wide rectangular metallic lead passing through the center of the exit QPC2 [see Figs. 1(a) and the inset of 1(b)].

To isolate the correlation physics of a single symmetry-protected channel, the drain ohmic contact is located on the lower side of this central gate lead at the exit QPC2. This

asymmetric global configuration defines a path-selective filter; by forcing electrons to traverse a single arm of the cavity, we suppress macroscopic Aharonov-Bohm interference and Fabry-Pérot resonances [Figs. 1(a) and the inset of 1(b)]. This design choice ensures that the measured conductance reflects the local potential parity governed by the cavity gates balance rather than single-particle interference effects [44–46].

The two-terminal differential conductance, $G = dI/dV$, was measured using standard low-frequency lock-in techniques with a $10 \mu\text{V}$ ac excitation at 77 Hz . Measurements were performed across multiple cooldowns in a cryogen-free ^3He evaporation cryostat with a base temperature of 300 mK . Reproducibility was verified across multiple thermal cooldowns and device iterations.

To quantify the spatial confinement and establish the baseline electrostatic landscape of the mesoscopic cavity, we performed numerical simulations of the 2D potential profile. The device geometry was modeled using an array of rectangular gates, following the analytical framework for surface gates on a GaAs heterostructure [47]. The electrostatic potential $\phi(x, y, d')$ at the 2DEG depth d' , generated

by a finite rectangular gate defined by coordinates $[x_1, x_2]$ and $[y_1, y_2]$, is given by $\frac{\phi(x,y,d')}{V_G} = g(x - x_1, y - y_1) + g(x - x_1, y_2 - y) + g(x_2 - x, y - y_1) + g(x_2 - x, y_2 - y)$, where V_G is the applied gate voltage and the geometric kernel $g(u, v) = \frac{1}{2\pi} \arctan(\frac{uv}{d'\sqrt{u^2 + v^2 + d'^2}})$.

Figure 1(f) presents the simulated 2D electrostatic potential map corresponding to a symmetric cavity configuration ($|V_{cg1}| = |V_{cg2}| = 1.0$ V) with a moderate central gate bias ($|V_c| = 1.5$ V). The spatial gradient clearly defines a path-selective, low-potential corridor that guides the adiabatic transport of electrons around the central barrier. In addition, the systematic control over the electron trajectory is illustrated by the longitudinal potential line cuts in Fig. 1(g), extracted at $y = 0$ (the geometric center) and $y = -0.5$ μm (the transport corridor). At $V_c = 0$ V, the global potential minimum remains fixed at $y = 0$, forming a symmetric, harmonic saddle point at the QPC bottlenecks. However, as the relative magnitude of V_c increases, the electrostatic potential actively repels the wave function, shifting the potential minima laterally. This simulated spatial evolution directly maps to the structural distortion and subsequent subband mixing observed in our transport data, confirming that tuning the gate parameters dynamically reengineers the local harmonicity of the confinement potential.

Figure 1(d) illustrates the evolution of conductance as the cavity gate voltage (V_{cg}) is swept for various central gate biases (V_c) ranging from 0 to -4.0 V. At zero central gate voltage, the conductance exhibits well-defined quantization at integer multiples of $2e^2/h$, alongside a well-shaped fractional plateau at $\sim 0.5(2e^2/h)$. The measured conductance evolves monotonically with the cavity gate voltage, remaining devoid of the oscillatory dips or resonant structures typically associated with mesoscopic cavities. This clean subband quantization rules out the formation of quasi-bound states or Fabry-Pérot-type single-particle interference [45,46,48,49]. Instead, it confirms that macroscopic scattering at the QPC-cavity interfaces is negligible and that our path-selective device architecture enforces adiabatic transport across the extended 1D constriction [48,50,51].

As V_c is made increasingly negative, the transport signatures evolve through two distinct regimes. For $0 \text{ V} \geq V_c > -1.5$ V, the $0.5(2e^2/h)$ plateau remains stable, demonstrating resilience against moderate perturbations to the longitudinal confinement. However, upon further increasing the negative bias V_c on the central gate, the pinch-off threshold shifts systematically towards more positive V_{cg} values, accompanied by a noticeable modulation of the subband quantization. In this regime of extreme spatial confinement, the electrostatic potential from the central gate severely distorts the bilayer's orbital architecture. Because the individual layer identities are already dissolved into molecular wave functions by the tunnel coupling, this transverse constriction induces mode mixing directly between the hybridized SAS subbands.

It may be noted that the $0.5(2e^2/h)$ plateau initially resists this perturbation but gradually shifts to lower conductance values. For $V_c < -3.0$ V, the $0.5(2e^2/h)$ plateau is substantially quenched, yielding to the reemergence of regular, spin-degenerate integer plateaus. This nonmonotonic transition, highlighted in the magnified view in Fig. 1(e), rules out

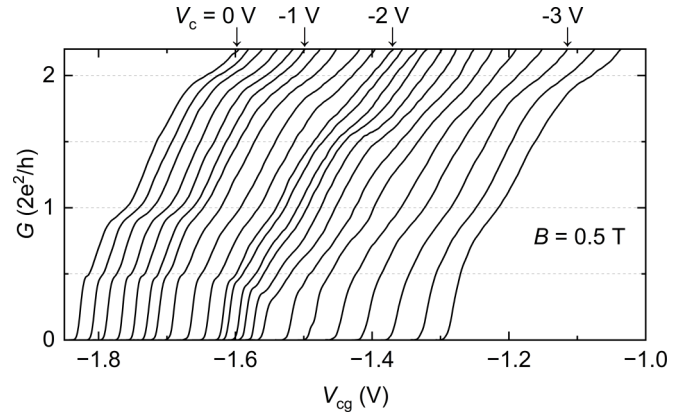


FIG. 2. Differential conductance, G , as a function of cavity gate voltage V_{cg} (when both cavity gates were swept together) at various central gate voltages V_c , in the presence of $B = 0.5$ T. Arrows at the top indicate the V_c values, with traces shown at equal intervals between them. For clarity, consecutive traces are horizontally offset by 0.02 V for $-2 \text{ V} \leq V_c < 0 \text{ V}$ and by 0.01 V for $V_c \leq -2 \text{ V}$.

trivial capacitive cross-talk or simple electrostatic pinch-off of the adjacent QPC2 by the central gate. A classical electrostatic pinch-off would strictly reduce the total transmission; it cannot spontaneously restore spin degeneracy or increase the conductance from a fractional to an integer state. Therefore, this specific transition uniquely confirms the dissolution of the many-body exchange correlation due to the geometrically induced anharmonicity.

Figure 2 presents the evolution of the conductance characteristics as a function of the cavity gate voltage under a moderate perpendicular magnetic field, $B = 0.5$ T, for varying V_c . At $V_c = 0$ V, the quantization resolves into robust integer steps of $2e^2/h$, accompanied by a highly pronounced fractional plateau at $0.5(2e^2/h)$ which exhibits remarkable resilience under magnetic confinement; for moderate central gate biases ($0 \geq V_c > -1.0$ V), the conductance traces remain virtually identical. As V_c is driven further negative ($V_c < -1.0$ V), the quantization of higher-order subbands is strongly modulated by the formation of hybrid magnetoelectric subbands. With B , electrons become increasingly localized by cyclotron motion which reduces the interlayer wave function overlap and subsequently weakens the hybridization [31,33] and introduces magnetic confinement. This magnetic harmonicity overrides the electrostatic anharmonicity induced by the central gate. By enforcing subband separability and suppressing structural mode mixing, the magnetic field acts as a geometric protector for the 1D van Hove singularity [52]. Consequently, the $0.5(2e^2/h)$ plateau is significantly strengthened and extended relative to the zero-field regime [18].

To unambiguously isolate the role of spatial parity in stabilizing the many-body ground state, we broke the device's lateral symmetry by decoupling the cavity gates. Figure 3 shows the conductance measured by sweeping the voltages on cavity gate 2 (V_{cg2}) and the central gate (V_c) together, while independently stepping the other cavity gate voltage, V_{cg1} . This asymmetric sweeping protocol allows us to systemati-

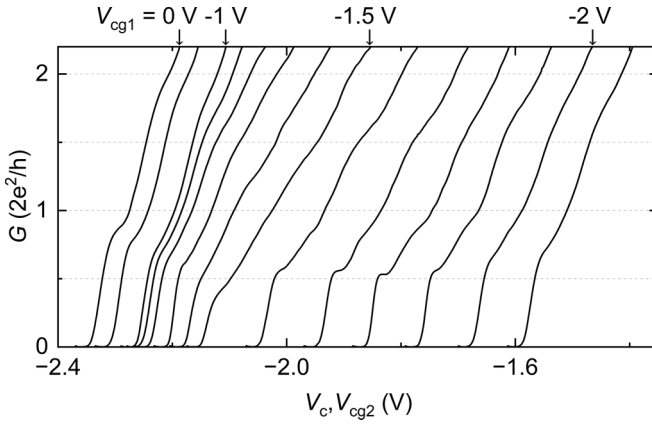


FIG. 3. Differential conductance, G , when V_{cg2} and V_c were swept together, at various fixed V_{cg1} values, indicated on the top of the plot, with traces shown at equal intervals between them.

cally tune the lateral electrostatic imbalance, parameterized as $\eta \equiv |V_{cg1} - V_{cg2}|$.

At $V_{cg1} = 0$ V, a significant transverse electrostatic asymmetry ($\eta \gg 0$) is imposed across the constriction. Consequently, while standard integer quantization is observed, the $0.5(2e^2/h)$ plateau is strikingly absent, in contrast to the symmetric sweeping protocol shown in Fig. 1. For $0 \text{ V} \geq V_{cg1} > -1.0$ V, the conductance features remain structurally similar but undergo an overall reduction in transmission. As V_{cg1} is further decreased toward -1.5 V, the increasing structural distortion exacerbates transverse mode mixing and backscattering. This geometrically induced anharmonicity severely smears the 1D density of states (DOS), leading to a visible degradation of the integer quantized plateaus.

Strikingly, an abrupt phase recovery occurs upon further tuning. Within a highly specific voltage window ($-1.6 \text{ V} \geq V_{cg1} \geq -1.9$ V), the effective electrostatic potential across the entrance QPC1, the cavity, and the exit QPC2 achieves a resonant spatial balance. At this point of exact spatial parity ($\eta \rightarrow 0$), the local harmonicity of the saddle point is temporarily restored. This rescues the 1D van Hove singularity from anharmonic mode mixing, thereby enabling the emergence of a robust $0.5(2e^2/h)$ plateau.

Finally, as V_{cg1} is driven beyond -1.9 V, the lateral parity is once again broken ($\eta > 0$). The re-introduction of geometric anharmonicity quenches the $0.5(2e^2/h)$ fractional feature and forces the system to revert to the spin-degenerate $2e^2/h$ plateau. This nonmonotonic evolution suggests that the $0.5(2e^2/h)$ signature is not a generic transport anomaly, but a tunable many-body phase that exists only when the geometric parity of the mesoscopic cavity conditions it.

We interpret the $0.5(2e^2/h)$ conductance plateau as the signature of an emergent, exchange-driven spin gap. In quasi-1D systems, the spontaneous lifting of spin degeneracy is governed by the competition between the 1D Coulomb interaction (exchange) energy, $E_{IE} = e^2 n_{1D} / 4\pi\epsilon_0\epsilon$, and the kinetic energy, $E_k = \pi^2 \hbar^2 n_{1D}^2 / 8m^*$, where ϵ is the dielectric constant of GaAs. To quantify this energy hierarchy, we

estimate the ground-state 1D electron densities (n_{1D}) of the constriction from the bulk 2D densities (n_{2D}) extracted via SdH oscillations. Assuming an infinite square-well confinement potential where the effective 1D channel width in the ground state is approximated by half the Fermi wavelength ($\lambda_{2D}/2$) for a singly occupied subband, the 1D density reduces to $n_{1D} \sim n_{2D} \lambda_{2D} / 2$ [6]. Utilizing the extracted bilayer densities, this yields $n_{1D} \approx 4.0 \times 10^5 \text{ cm}^{-1}$ and $4.4 \times 10^5 \text{ cm}^{-1}$ for the respective states. The corresponding Coulomb interaction energies evaluate to $E_{IE} \approx 4.4$ and 4.9 meV, which substantially eclipse the zero-point kinetic energies $E_k \approx 2.2$ and 2.7 meV.

The magnitude of the many-body correlation is characterized by the dimensionless 1D Wigner-Seitz parameter: $r_s^{1D} \approx \frac{1}{2a_B^* n_{1D}} \approx 1.25$, where a_B^* is the effective Bohr radius (10 nm in GaAs). The condition $a_B^* n_{1D} < 1$ (equivalent to $r_s^{1D} > 1$) suggests that the system is deeply entrenched in the strongly correlated limit. In this regime, the many-body energy gained by aligning spins, minimizing Coulomb repulsion via the Pauli exclusion principle, decisively outweighs the kinetic cost of occupying higher-momentum states [11,18,53–55].

The onset of this spontaneous polarization can be described by the Stoner criterion for 1D ferromagnetism, $D(E_F) \cdot J_{ex} > 1$, where $D(E_F)$ is the 1D DOS at the Fermi level and J_{ex} is the effective exchange integral [19,56–58]. While the Mermin-Wagner theorem [59] generally precludes long-range magnetic order in a thermodynamic 1D system, the stability of the polarized state in our device is ensured by the mesoscopic limit; the constriction length ($\sim 0.25 \mu\text{m}$) acts as a physical cutoff for the long-wavelength thermal fluctuations that would otherwise destabilize the phase. To explicitly evaluate this condition for our device, we approximate the 1D DOS as $D(E_F) \sim n_{1D} / 2E_k$ and the exchange interaction as $J_{ex} \sim E_{IE} / n_{1D}$, yielding the dimensionless Stoner product $\sim E_{IE} / 2E_k$. Utilizing our estimates in the low-density regime ($E_{IE} \approx 4.4$ meV and $E_k \approx 2.2$ meV), we find $E_{IE} / 2E_k \approx 1$. Because this bulk baseline approaches but does not exceed unity, the uniform 1D channel is primed yet strictly insufficient to spontaneously polarize. To formally cross the Stoner threshold, the system relies on the van Hove singularity [52] at the subband edge, where $D(E) \propto (E - E_0)^{-1/2}$, with E_0 being the zero-point confinement energy of the lowest transverse subband. This local divergence sharply amplifies $D(E_F)$, pushing the product above unity and explicitly driving the spin-gap opening. Since this threshold crossing depends entirely on a fragile singularity, the many-body phase is sensitive to any mechanism that smears the DOS. We propose that the stability of the $0.5(2e^2/h)$ feature is provided by a *dual-parity protection* mechanism, combining vertical orbital isolation with lateral geometric harmonicity.

The stability of the many-body phase is rooted in the $\Delta_{SAS} \approx 1.8$ meV tunneling gap, which significantly exceeds the 1D transverse confinement ($\hbar\omega \lesssim 1.0$ meV, estimated using source-drain bias spectroscopy). By energetically forbidding excitations to the AS subband, Δ_{SAS} acts as a rigorous *orbital vacuum*—a vertical buffer that suppresses intersubband scattering and protects the symmetric van Hove singularity. However, this orbital protection is only effective

if the lateral geometry acts as a geometric stabilizer. This structural stability is parameterized by the electrostatic tilt η , driving the system through two distinct transport regimes: (1) symmetry-protected harmony ($\eta \rightarrow 0$): Under symmetric biasing, the confinement approximates a nearly perfect harmonic saddle point. This parabolic geometry ensures subband separability and maximizes interlayer wave-function overlap, effectively amplifying J_{ex} . In the ground state, near the pinch-off, the preserved van Hove singularity triggers the Stoner instability, opening an exchange gap that rivals the subband spacing itself. This establishes the bilayer cavity not merely as a passive conduit, but as an active geometric lever for tuning many-body quantum phases in mesoscopic architectures. (2) Anharmonic mode mixing ($\eta > 0$): Conversely, the destruction of the $0.5(2e^2/h)$ plateau can be inevitably triggered by electrostatic perturbations that disrupt the delicate Stoner correlation, either through geometric asymmetry or extreme spatial confinement. When lateral asymmetry is introduced ($\eta > 0$), the transverse potential becomes heavily anharmonic. This geometrically induced anharmonicity drives significant mode-mixing between the transverse and longitudinal wave functions, effectively smearing the sharp van Hove singularity and suppressing $D(E_F)$. Simultaneously, applying a large negative bias to the central gate (V_c , as seen in Fig. 1) imposes extreme spatial confinement on the molecular states. Following the uncertainty principle, this constriction drastically increases the zero-point kinetic energy penalty, scaling as $\Delta E_k \propto W_{\text{eff}}^{-2}$, where W_{eff} is the effective 1D channel width. Furthermore, the proximate metallic central gate acts as a local electrostatic screen, actively reducing the long-range exchange interaction J_{ex} . Whether by suppressing the DOS via parity-mixing, which forces a structural transition from molecular hybridization back to layer-localized states, or by escalating the kinetic energy cost and screening J_{ex} , these perturbations inevitably drive the Stoner product below unity, thus quenching the spin gap and restoring spin-degenerate transport at $2e^2/h$.

A perpendicular magnetic field, $B = 0.5$ T introduces a diamagnetic confinement, $U_B = \frac{1}{2}m^*\omega_c^2 y^2$, where $\omega_c = eB/m^*$ is the cyclotron frequency, and yields a magnetic length $l_B = \sqrt{\hbar/(eB)} \approx 36$ nm and a cyclotron energy $\hbar\omega_c \approx 0.86$ meV. Importantly, these magnetic parameters closely match the electrostatic confinement parameters of the 1D channel, i.e., the transverse confinement energy $\hbar\omega \lesssim 1.0$ meV and the corresponding transverse confinement length $\ell_{\perp} = \sqrt{\hbar/m^*\omega} \approx 34$ nm. Because the fundamental magnetic and electrostatic length scales are virtually identical in this regime ($l_B \sim \ell_{\perp}$), the confinement potential undergoes resonant magnetoelectric hybridization [2,18,51,60].

While electrostatic spatial squeezing via the central gate introduces severe anharmonicity, the diamagnetic contribution remains intrinsically parabolic. By matching the energy scale of the channel ($\hbar\omega_c \sim \hbar\omega$), the magnetic field effectively overrides the electrostatic mode-mixing. Furthermore, while the cyclotron energy ($\hbar\omega_c \approx 0.86$ meV) is sufficient to enforce transverse harmonicity, it remains comfortably below the molecular tunneling gap ($\Delta_{\text{SAS}} \approx 1.8$ meV). This energy hierarchy ensures that the magnetic field geometrically stabilizes the 1D channel without severely collapsing the orbital

vacuum. This magnetically enforced harmonicity restores the sharp DOS van Hove singularity and reinforces the Stoner instability, significantly strengthening the $0.5(2e^2/h)$ state across a broader electrostatic phase space.

To assign the $0.5(2e^2/h)$ plateau to a many-body spin gap, we should systematically rule out classical geometric artifacts. In standard single-2DEG architectures, cavity mode-mixing drives purely ohmic transport, adding QPC resistances in series to yield a $0.5N(2e^2/h)$ sequence across all subbands [48,51,61]. Applying B to such classical devices induces adiabatic edge-state transport, bypassing cavity scattering and systematically eliminating the $0.5N(2e^2/h)$ artifacts, thereby reinstating the integer quantization. In contrast, zero-field transport in our symmetric bilayer cavity is intrinsically adiabatic, exhibiting clean integer quantization alongside a solitary $0.5(2e^2/h)$ many-body ground state. Applying $B = 0.5$ T provides magnetoelectric geometric stabilization (Fig. 2) that distinctly strengthens this selective fractional quantization rather than destroying it. This fundamentally opposite magnetic response explicitly rules out disorder-induced backscattering [62] and confirms the state is driven by exchange interactions rather than classical series resistance.

Furthermore, we assess the ballistic integrity of the cavity by comparing the characteristic transit timescales. For an electron density of $1.0 \times 10^{11} \text{ cm}^{-2}$, the Fermi velocity is $v_F \approx 1.4 \times 10^7 \text{ cm/s}$. The ballistic flight time across the $0.25 \mu\text{m}$ QPC is $t_{\text{QPC}} \approx 1.8$ ps, and the transit across the $1.3 \mu\text{m}$ cavity is $t_{\text{cav}} \approx 9.5$ ps. Both flight times are strictly bounded well below the momentum relaxation time $\tau_{\text{tr}} = \mu m^*/e \approx 46$ ps. This timescale hierarchy ($t_{\text{cav}} \ll \tau_{\text{tr}}$) confirms that electrons traverse the entire QPC-cavity-QPC architecture in a ballistic regime, allowing the macroscopic geometry to act as an extended, adiabatically continuous geometric stabilizer for the many-body phase.

While previous studies on vertically coupled 1D wires have reported conductance anomalies (0.7 or $0.5(2e^2/h)$) originating from hybrid low-energy modes or spontaneous spin polarization [31,63,64], the spatial fragility of these states has historically hindered systematic control. Furthermore, structural inversion asymmetry in double quantum wells can introduce Rashba spin-orbit interaction (SOI) [65,66], potentially inducing k -space subband splitting. However, while SOI may provide an underlying spin-admixture, it cannot account for the spatial parity dependence observed in our device. Instead, our results indicate that the reproducible $0.5(2e^2/h)$ quantization is fundamentally an exchange-driven phenomenon, enabled by the structural harmonicity of the cavity.

In conclusion, our results show that spontaneous spin polarization in mesoscopic cavity constrictions can be entirely governed by the spatial symmetry of the surrounding electrostatic environment. Rather than acting as a classical mode-randomizing chamber, our path-selective bilayer cavity functions as an active geometric stabilizer for the Stoner instability. We show that when lateral electrostatic harmonicity is maintained, it synergizes with the vertical orbital vacuum of the tunnel-coupled bilayer to protect the 1D van Hove singularity against anharmonic mode mixing. This dual-parity protection yields a stable $0.5(2e^2/h)$ exchange gap.

Conversely, we demonstrate that this delicate many-body phase can be quenched by breaking the spatial symmetry or introducing localized screening via the central gate. By proving that exchange-driven correlations can be toggled via macroscopic device geometry, this work provides a programmable electrostatic framework for generating, protecting, and manipulating spin-polarized ground states in future spintronic and topological quantum devices.

The work is funded by the United Kingdom Research and Innovation (UKRI), Future Leaders Fellowship (References MR/S015728/1 and MR/X006077/1). We thank M. Fu for assistance with the Hall and magnetoresistance experiments.

Data availability. The data that support the findings of this study are available from the corresponding author upon reasonable request.

-
- [1] B. J. van Wees, H. van Houten, C. W. J. Beenakker, J. G. Williamson, L. P. Kouwenhoven, D. van der Marel, and C. T. Foxon, Quantized conductance of point contacts in a two-dimensional electron gas, *Phys. Rev. Lett.* **60**, 848 (1988).
 - [2] D. A. Wharam, T. J. Thornton, R. Newbury, M. Pepper, H. Ahmed, J. E. F. Frost, D. G. Hasko, D. C. Peacock, D. A. Ritchie, and G. A. C. Jones, One-dimensional transport and the quantisation of the ballistic resistance, *J. Phys. C* **21**, L209 (1988).
 - [3] K. J. Thomas, J. T. Nicholls, M. Y. Simmons, M. Pepper, D. R. Mace, and D. A. Ritchie, Possible spin polarization in a one-dimensional electron gas, *Phys. Rev. Lett.* **77**, 135 (1996).
 - [4] S. Kumar, M. Pepper, D. Ritchie, I. Farrer, and H. Montagu, Formation of a non-magnetic, odd-denominator fractional quantized conductance in a quasi-one-dimensional electron system, *Appl. Phys. Lett.* **115**, 123104 (2019).
 - [5] S. Kumar, M. Pepper, S. N. Holmes, H. Montagu, Y. Gul, D. A. Ritchie, and I. Farrer, Zero-magnetic field fractional quantum states, *Phys. Rev. Lett.* **122**, 086803 (2019).
 - [6] V. Kumar, Y. Duo, P. See, J. P. Griffiths, D. A. Ritchie, I. Farrer, and S. Kumar, Correlation effects mediated by disorders in one-dimensional channels, *Phys. Rev. B* **112**, 035404 (2025).
 - [7] A. G. Pogosov, A. A. Shevyrin, D. A. Pokhobov, E. Yu Zhdanov, and S. Kumar, Suspended semiconductor nanostructures: Physics and technology, *J. Phys.: Condens. Matter* **34**, 263001 (2022).
 - [8] K. J. Thomas, J. T. Nicholls, N. J. Appleyard, M. Y. Simmons, M. Pepper, D. R. Mace, W. R. Tribe, and D. A. Ritchie, Interaction effects in a one-dimensional constriction, *Phys. Rev. B* **58**, 4846 (1998).
 - [9] T. Rejec and Y. Meir, Magnetic impurity formation in quantum point contacts, *Nature (London)* **442**, 900 (2006).
 - [10] K.-F. Berggren and M. Pepper, Electrons in one dimension, *Philos. Trans. R. Soc. A* **368**, 1141 (2010).
 - [11] S. Kumar and M. Pepper, Interactions and non-magnetic fractional quantization in one-dimension, *Appl. Phys. Lett.* **119**, 110502 (2021).
 - [12] R. Crook, J. Prance, K. J. Thomas, S. J. Chorley, I. Farrer, D. A. Ritchie, M. Pepper, and C. G. Smith, Conductance quantization at a half-integer plateau in a symmetric GaAs quantum wire, *Science* **312**, 1359 (2006).
 - [13] P. Debray, S. M. S. Rahman, J. Wan, R. S. Newrock, M. Cahay, A. T. Ngo, S. E. Ulloa, S. T. Herbert, M. Muhammad, and M. Johnson, All-electric quantum point contact spin-polarizer, *Nat. Nanotechnol.* **4**, 759 (2009).
 - [14] P. Chuang, S.-C. Ho, L. W. Smith, F. Sfigakis, M. Pepper, C.-H. Chen, J.-C. Fan, J. P. Griffiths, I. Farrer, H. E. Beere *et al.*, All-electric all-semiconductor spin field-effect transistors, *Nat. Nanotechnol.* **10**, 35 (2015).
 - [15] R. Davies, I. V. Lerner, and I. V. Yurkevich, Resonant fractional conductance through a 1D Wigner chain, *Commun. Phys.* **7**, 67 (2024).
 - [16] D. J. Reilly, T. M. Buehler, J. L. O'Brien, A. R. Hamilton, A. S. Dzurak, R. G. Clark, B. E. Kane, L. N. Pfeiffer, and K. W. West, Density-dependent spin polarization in ultra-low-disorder quantum wires, *Phys. Rev. Lett.* **89**, 246801 (2002).
 - [17] S. M. Cronenwett, H. J. Lynch, D. Goldhaber-Gordon, L. P. Kouwenhoven, C. M. Marcus, K. Hirose, N. S. Wingreen, and V. Umansky, Low-temperature fate of the 0.7 structure in a point contact: A Kondo-like correlated state in an open system, *Phys. Rev. Lett.* **88**, 226805 (2002).
 - [18] Y. Duo, J. Coop, I. Farrer, D. A. Ritchie, and S. Kumar, Magnetoelectric subbands in the one-dimensional to quasi-one-dimensional confined regime, *Phys. Rev. B* **113**, 245304 (2026).
 - [19] E. C. Stoner, Collective electron ferromagnetism, *Proc. R. Soc. Lond. A* **165**, 372 (1938).
 - [20] C.-K. Wang and K.-F. Berggren, Spin splitting of subbands in quasi-one-dimensional electron quantum channels, *Phys. Rev. B* **54**, R14257(R) (1996).
 - [21] K.-F. Berggren and I. I. Yakimenko, Effects of exchange and electron correlation on conductance and nanomagnetism in ballistic semiconductor quantum point contacts, *Phys. Rev. B* **66**, 085323 (2002).
 - [22] S. H. Abedinpour, M. Polini, A. H. MacDonald, B. Tanatar, M. P. Tosi, and G. Vignale, Theory of the pseudospin resonance in semiconductor bilayers, *Phys. Rev. Lett.* **99**, 206802 (2007).
 - [23] J. P. Eisenstein, Exciton condensation in bilayer quantum Hall systems, *Annu. Rev. Condens. Matter Phys.* **5**, 159 (2014).
 - [24] J. Shabani, T. Gokmen, Y. T. Chiu, and M. Shayegan, Evidence for developing fractional quantum Hall states at even denominator 1/2 and 1/4 fillings in asymmetric wide quantum wells, *Phys. Rev. Lett.* **103**, 256802 (2009).
 - [25] J. T. Nicholls, N. P. R. Hill, B. Kardynal, N. Turner, E. H. Linfield, D. A. Ritchie, C. H. W. Barnes, G. A. C. Jones, and M. Pepper, The investigation of 1D and 2D phenomena using double-layer electron systems, *Physica E* **3**, 52 (1998).
 - [26] A. F. Croxall, K. Das Gupta, C. A. Nicoll, H. E. Beere, I. Farrer, D. A. Ritchie, and M. Pepper, Possible effect of collective modes in zero magnetic field transport in an electron-hole bilayer, *Phys. Rev. B* **80**, 125323 (2009).
 - [27] A. Siddiki, Self-consistent Coulomb picture of an electron-electron bilayer system, *Phys. Rev. B* **75**, 155311 (2007).

- [28] S. Faniel, E. Tutuc, E. P. De Poortere, C. Gustin, A. Vlad, S. Melinte, M. Shayegan, and V. Bayot, Thermopower of interacting GaAs bilayer hole systems in the reentrant insulating phase near $\nu = 1$, *Phys. Rev. Lett.* **94**, 046802 (2005).
- [29] Y. Zhang, J. K. Jain, and J. P. Eisenstein, Tunnel transport and interlayer excitons in bilayer fractional quantum Hall systems, *Phys. Rev. B* **95**, 195105 (2017).
- [30] C. Wang, A. Gupta, S. K. Singh, Y. J. Chung, L. N. Pfeiffer, K. W. West, K. W. Baldwin, R. Winkler, and M. Shayegan, Even-denominator fractional quantum Hall state at filling factor $\nu = 3/4$, *Phys. Rev. Lett.* **129**, 156801 (2022).
- [31] K. J. Thomas, J. T. Nicholls, M. Y. Simmons, W. R. Tribe, A. G. Davies, and M. Pepper, Controlled wave-function mixing in strongly coupled one-dimensional wires, *Phys. Rev. B* **59**, 12252 (1999).
- [32] K. J. Thomas, J. T. Nicholls, W. R. Tribe, M. Y. Simmons, A. G. Davies, D. A. Ritchie, and M. Pepper, Bonding and antibonding states in strongly coupled ballistic one-dimensional wires, *Physica E* **6**, 581 (2000).
- [33] S. Ichinokura, T. Hatano, W. Izumida, K. Nagase, and Y. Hirayama, Electrical control of tunnel coupling between vertically coupled quantum point contacts, *Appl. Phys. Lett.* **103**, 062106 (2013).
- [34] S. F. Fischer, G. Apetriti, U. Kunze, D. Schuh, and G. Abstreiter, Magnetotransport spectroscopy of spatially coincident coupled electron waveguides, *Phys. Rev. B* **71**, 195330 (2005).
- [35] S. F. Fischer, G. Apetriti, U. Kunze, D. Schuh, and G. Abstreiter, Tunnel-coupled one-dimensional electron systems with large subband separations, *Phys. Rev. B* **74**, 115324 (2006).
- [36] Y. Jompol, C. J. B. Ford, I. Farrer, G. A. C. Jones, D. Anderson, D. A. Ritchie, T. W. Silk, and A. J. Schofield, Probing e-e interactions in a periodic array of GaAs quantum wires, *Physica E* **40**, 1220 (2008).
- [37] Y. Jompol, C. J. B. Ford, J. P. Griffiths, I. Farrer, G. A. C. Jones, D. Anderson, D. A. Ritchie, T. W. Silk, and A. J. Schofield, Probing spin-charge separation in a Tomonaga-Luttinger liquid, *Science* **325**, 597 (2009).
- [38] K. L. Hudson, A. Srinivasan, O. Goulko, J. Adam, Q. Wang, L. A. Yeoh, O. Kloch, I. Farrer, D. A. Ritchie, A. Ludwig, *et al.*, New signatures of the spin gap in quantum point contacts, *Nat. Commun.* **12**, 5 (2021).
- [39] S. Kumar, K. J. Thomas, L. W. Smith, M. Pepper, G. L. Creeth, I. Farrer, D. Ritchie, G. Jones, and J. Griffiths, Many-body effects in a quasi-one-dimensional electron gas, *Phys. Rev. B* **90**, 201304(R) (2014).
- [40] L. W. Smith, A. R. Hamilton, K. J. Thomas, M. Pepper, I. Farrer, J. P. Griffiths, G. A. C. Jones, and D. A. Ritchie, Compressibility measurements of quasi-one-dimensional quantum wires, *Phys. Rev. Lett.* **107**, 126801 (2011).
- [41] E. Tutuc, E. P. De Poortere, S. J. Papadakis, and M. Shayegan, In-plane magnetic field-induced spin polarization and transition to insulating behavior in two-dimensional hole systems, *Phys. Rev. Lett.* **86**, 2858 (2001).
- [42] O. M. Auslaender, H. Steinberg, A. Yacoby, Y. Tserkovnyak, B. I. Halperin, K. W. Baldwin, L. N. Pfeiffer, and K. W. West, Spin-charge separation and localization in one dimension, *Science* **308**, 88 (2005).
- [43] G. Gumbs, Tunneling of two interacting electrons in a quantum wire, *Solid State Commun.* **128**, 443 (2003).
- [44] C. Yan, S. Kumar, M. Pepper, P. See, I. Farrer, D. Ritchie, J. Griffiths, and G. Jones, Interference effects in a tunable quantum point contact integrated with an electronic cavity, *Phys. Rev. Appl.* **8**, 024009 (2017).
- [45] A. A. Kozikov, D. Weinmann, C. Rössler, T. Ihn, K. Ensslin, C. Reichl, and W. Wegscheider, Electron backscattering in a cavity: Ballistic and coherent effects, *Phys. Rev. B* **94**, 195428 (2016).
- [46] S. E. Ulloa, E. Castaño, and G. Kirczenow, Ballistic transport in a novel one-dimensional superlattice, *Phys. Rev. B* **41**, 12350 (1990).
- [47] J. H. Davies, I. A. Larkin, and E. V. Sukhorukov, Modeling the patterned two-dimensional electron gas: Electrostatics, *J. Appl. Phys.* **77**, 4504 (1995).
- [48] S.-q. Yuan and B.-y. Gu, Effect of geometry-induced scattering on the quantum conductance in double-quantum-point constrictions connected in series by a cavity, *J. Appl. Phys.* **73**, 7496 (1993).
- [49] Y. Takagaki, M. ElHassan, A. Shailos, C. Prasad, J. P. Bird, D. K. Ferry, K. H. Ploog, L.-H. Lin, N. Aoki, and Y. Ochiai, Magnetic-field-controlled electron dynamics in quantum cavities, *Phys. Rev. B* **62**, 10255 (2000).
- [50] D. A. Wharam, M. Pepper, H. Ahmed, J. E. F. Frost, D. G. Hasko, D. C. Peacock, D. A. Ritchie, and G. A. C. Jones, Addition of the one-dimensional quantised ballistic resistance, *J. Phys. C* **21**, L887 (1988).
- [51] C. W. J. Beenakker and H. van Houten, Magnetotransport and nonadditivity of point-contact resistances in series, *Phys. Rev. B* **39**, 10445(R) (1989).
- [52] L. Van Hove, The occurrence of singularities in the elastic frequency distribution of a crystal, *Phys. Rev.* **89**, 1189 (1953).
- [53] J. S. Meyer and K. A. Matveev, Wigner crystal physics in quantum wires, *J. Phys.: Condens. Matter* **21**, 023203 (2009).
- [54] A. Chaplik, Instability of quasi-one-dimensional electron chain and the “string-zigzag” structural transition, *Pis'ma Zh. Eksp. Teor. Fiz.* **31**, 275 (1980) [*JETP Lett.* **31**, 252 (1980)].
- [55] H. Montagu, I. Farrer, D. Ritchie, and S. Kumar, Spin polarised quantum conductance in 1D channels, *Appl. Phys. Express* **18**, 015002 (2025).
- [56] W. E. Liu, S. Chesi, D. Webb, U. Zülicke, R. Winkler, R. Joynt, and D. Culcer, Generalized Stoner criterion and versatile spin ordering in two-dimensional spin-orbit coupled electron systems, *Phys. Rev. B* **96**, 235425 (2017).
- [57] S. Liu, C. Wang, B. Wang, Y. Jia, and J. Cho, Flat-band ferromagnetism in the quasi-one-dimensional electride Y_2Cl_3 induced by hole doping, *Phys. Rev. B* **110**, 024413 (2024).
- [58] T. Cao, Z. Li, and S. G. Louie, Tunable magnetism and half-metallicity in hole-doped monolayer GaSe, *Phys. Rev. Lett.* **114**, 236602 (2015).
- [59] N. D. Mermin and H. Wagner, Absence of ferromagnetism or antiferromagnetism in one-or two-dimensional isotropic Heisenberg models, *Phys. Rev. Lett.* **17**, 1133 (1966).
- [60] K.-F. Berggren, T. J. Thornton, D. J. Newson, and M. Pepper, Magnetic depopulation of 1D subbands in a narrow 2D electron gas in a GaAs/AlGaAs heterojunction, *Phys. Rev. Lett.* **57**, 1769 (1986).
- [61] L. P. Kouwenhoven, B. J. van Wees, W. Kool, C. J. P. M. Harmans, A. A. M. Staring, and C. T. Foxon, Transition from

- Ohmic to adiabatic transport in quantum point contacts in series, [Phys. Rev. B **40**, 8083\(R\) \(1989\)](#).
- [62] P. L. McEuen, B. W. Alphenaar, R. G. Wheeler, and R. N. Sacks, Resonant transport effects due to an impurity in a narrow constriction, [Surf. Sci. **229**, 312 \(1990\)](#).
- [63] D. Terasawa, S. Norimoto, T. Arakawa, M. Ferrier, A. Fukuda, K. Kobayashi, and Y. Hirayama, Conductance quantization and shot noise of a double-layer quantum point contact, [Phys. Rev. B **101**, 115401 \(2020\)](#).
- [64] P. Wójcik and J. Adamowski, Spin filtering effect generated by the inter-subband spin-orbit coupling in the bilayer nanowire with the quantum point contact, [Sci. Rep. **7**, 45346 \(2017\)](#).
- [65] Y. A. Bychkov and É. I. Rashba, Properties of a 2D electron gas with lifted spectral degeneracy, [Pis'ma Zh. Eksp. Teor. Fiz. **39**, 66 \(1984\)](#) [[JETP Lett. **39**, 78 \(1984\)](#)].
- [66] E. A. de A. e. Silva, G. C. La Rocca, and F. Bassani, Spin-orbit splitting of electronic states in semiconductor asymmetric quantum wells, [Phys. Rev. B **55**, 16293 \(1997\)](#).