Antilocalization, a positive correction to classical conductivity, is commonly observed in mesoscopic conductors with strong spin-orbit coupling [1,2], and has been well studied in low-dimensional systems over the past two decades [3–8]. In quantum wires (1D) and dots (0D), the combination of coherence and spin-orbit coupling is a topic of renewed interest in part due to numerous quantum information processing proposals—from spin qubits to Majorana modes—where these ingredients play a fundamental role [9–12]. Antilocalization in 1D systems has been investigated in detail both theoretically [13–15] and experimentally [16–19]. In 0D systems, antilocalization in both the opened and nearly isolated Coulomb blockade regime has been studied theoretically [20,21], but to date experiments have only addressed the open-transport regime, where Coulomb effects play a minor role [22,23].

The hole gas formed in the Ge core of a Ge/Si core-shell nanowire [24] is an attractive system for exploring the coexisting effects of coherence, confinement, and spin-orbit coupling. Tunable quantum dots have been demonstrated in this system [25,26], band structure calculations indicate strong spin-orbit coupling [27], and antilocalization has been demonstrated in the open-transport regime [28].

In this Letter, we investigate full distributions of Coulomb blockade peak height as a function of magnetic field in a gated Ge/Si core-shell nanowire. The low-field distributions are consistent with random matrix theory [21] of Coulomb blockade transport through a 0D system with symplectic symmetry (valid for strong spin-orbit coupling), and inconsistent with predictions for orthogonal symmetry (low spin-orbit coupling). The high-field peak height distribution is found to be a scaled version of the low-field distribution, as expected from theory. However, the observed scale factor, \( \sim 2.3 \), is significantly larger than the theoretical factor of 1.4 [21]. Temperature dependence of the peak-height variance is consistent with theory using a value for orbital level spacing measured independently via Coulomb blockade spectroscopy. Consistent bounds on the spin-orbit length, \( l_{so} \lesssim 20 – 25 \text{ nm} \), are found in the Coulomb blockade and open transport regimes.

Coulomb blockade of transport through a 0D system occurs when temperature, voltage bias, and lifetime broadening are small compared to the charging energy, \( kT, V \), and \( l_{so} \ll e^2/C \), where \( V = V_b + V_{ac} \) is the (dc + ac) bias across the device, \( C \) is the dot capacitance, \( e \) is the electron charge, and \( l_{so} \approx r_{\text{escape}}^{-1} \) is the tunnel rate out of the system. When, in addition, \( kT, V, \) and \( l_{so} \) are less than the orbital level spacing, \( \Delta \), tunneling occurs through a single (ground-state) wave function. In this latter case, Coulomb blockade conductance peaks fluctuate in height from peak to peak (cf. Fig. 1, bottom trace), depending on the coupling of the ground-state wave function to modes in the leads. The principle experimental result of this Letter is that the distribution of Coulomb peak heights reveals the presence of strong spin-orbit coupling, and allows a bounding on the spin-orbit strength consistent with measurements performed in the same wire in the open regime (Fig. 1, top trace). The zero-field distribution is found to differ markedly from that measured in GaAs quantum dots, where spin-orbit coupling is relatively weak [29]. We first review random matrix theory results that relate peak statistics to wave function symmetries, then present experimental results for a gated Ge/Si nanowire sample in the Coulomb blockade and open wire regimes.

For disordered or chaotic dots, the statistics of couplings between the modes in the leads and wave functions in the dot can be calculated from random matrix ensembles for the dot Hamiltonian: orthogonal (\( \beta = 1 \)) for time-reversal symmetric systems, unitary (\( \beta = 2 \)) for systems with broken time-reversal symmetry, and symplectic (\( \beta = 4 \))
for time-reversal symmetric systems with broken spin rotation symmetry. Including spin-orbit and Zeeman coupling yields an extended random matrix theory with two more parameters, $s$ and $\Sigma$, in addition to the usual Dyson parameter $\beta$ [20]. The parameter $s$, reflecting Kramers degeneracy, decreases from 2 to 1 with sufficient applied magnetic field; the parameter $\Sigma$, reflecting the mixing of Kramers-split levels, increases from 1 (unmixed) to 2 (mixed) with a sufficient combination of spin-orbit coupling and magnetic field. These ensembles have been investigated experimentally in the open-transport regime [30].

Writing $\Gamma = \Gamma_l + \Gamma_r$ for left and right leads, the Coulomb peak height for $\Gamma \ll kT$ is given by

$$g_p = \frac{2e^2}{h} \frac{\chi_1}{kT\Gamma_l + \Gamma_r} = \frac{e^2}{h} \frac{\Gamma}{2kT\chi_1},$$

(1)

where $\alpha = 4\Gamma_l\Gamma_r/[\Gamma_l(\Gamma_l + \Gamma_r)]$ fluctuates from peak to peak with statistics that depend on $\beta$, $\Sigma$, and $s$, and $\chi_{s=1} = 1/8$ and $\chi_{s=2} = 3 - 2\sqrt{2}$ account for effects of Kramers degeneracy on Coulomb blockade [31]. At zero magnetic field, the distribution of $\alpha$ for weak spin-orbit coupling is given by [21,31,32]

$$P_{\beta=1,\Sigma=1,s=2}(\alpha) = \sqrt{\frac{1}{\alpha \Gamma}} e^{-\alpha},$$

(2)

whereas for strong spin-orbit coupling it is given by

$$P_{\beta=4,\Sigma=1,s=2}(\alpha) = 16e^3 e^{-2\alpha} \left[ K_0(2\alpha) + \left( 1 + \frac{1}{4\alpha} \right) K_1(2\alpha) \right],$$

(3)

where $K_0$ and $K_1$ are modified Bessel functions. The distributions have $\bar{\alpha} = 1/2$ and $\bar{\alpha} = 4/5$ for weak and strong spin-orbit coupling, respectively.

A consequence of the equality

$$P_{\beta=2,\Sigma=2,s=1}(\alpha) = P_{\beta=4,\Sigma=1,s=2}(\alpha)$$

(4)

is that for strong spin-orbit coupling, the peak height distribution at high field is expected to be a scaled version of the zero-field distribution, decreased by the ratio $\chi_{s=2}/\chi_{s=1} \sim 1.4$ [21] due to lifting of Kramers degeneracy. This is in contrast to the weak spin-orbit case, where the high-field distribution differs markedly in shape from the zero-field distribution, and the high-field mean height is increased by a factor of 4/3 compared to zero field [32], consistent with experiment [29,33].

The measured device was formed from a Ge/Si core-shell nanowire (10 nm Ge core, 2 nm Si shell) [34] placed on an array of Cr/Au bottom gates (2 nm/20 nm thick, 20 nm wide, 60 nm pitch) patterned by electron beam lithography on a native-oxide Si wafer, then covered with 25 nm of HfO$_2$ (grown by atomic layer deposition at 180°C) before depositing the wires. Patterned Ti/Pd Ohmic contacts were deposited following a 3 s buffered HF etch. Conductance was measured in a dilution refrigerator with electron temperature $T \sim 100$ mK using standard lock-in techniques with ac excitation $V_{ac} = 100 \mu V$, except where noted. The lock-in excitation was chosen to be as large as possible without altering the peak height distribution. An in-line resistance of 4.2 kΩ was subtracted from all data.

A typical orbital level spacing of $\Delta \sim 0.2$ meV was measured from Coulomb blockade spectroscopy, as shown in Fig. 1, inset. The number of holes $N_H$ in the Coulomb blockade regime was estimated to be roughly 600, based on counting Coulomb oscillations. The length of the quantum dot was in the range $L = 200–600$ nm, corresponding to the length of the middle segment of the wire. For wire width $w = 10$ nm, this gives $M = 4w/\lambda_F = 4–6$, occupied transverse modes, using a 3D estimate for the Fermi wavelength, $\lambda_F = (2\pi^2Lw^2/3N_H)^{1/3} \sim 6–9$ nm. The elastic scattering length $l = h\mu/\lambda_F e = 35–50$ nm and mobility $\mu \sim 800$ cm$^2$/Vs were extracted from the slope of the pinch-off curve (Fig. 4, inset) using $g = (\pi v_F^2/4L)\mu e$ [24,28]. Values in the open regime differ somewhat, as discussed below.

Figure 1 shows the two-terminal conductance of the nanowire as a function of a common voltage on gates 2, 3, and 4, denoted $V_{2-4}$, for a common voltage on gates 1 and 5, $V_{1,5}$, corresponding to open regime (top trace) and tunneling regime (bottom trace). $V_{2-4}$ tune the hole density, while $V_1$ tunes the left barrier and $V_3$ tunes the right barrier. Coulomb blockade peaks appear when left and right barriers have conductance less than $2e^2/h$. The open regime shows weak dependence on gate voltage, with an onset of Coulomb oscillations as conductance decreases; the tunneling regime showed well-defined Coulomb
blockade peaks with fluctuating heights. The heights of neighboring peaks appear correlated over roughly two peaks, even at the lowest temperatures, similar to [29], which decreases the effective ensemble size.

Representative sets of Coulomb blockade peaks at \( B \sim 0 \) and \( 6 \) T [Fig. 2(a),(b)] show a decrease in average peak height at high field, as expected for strong spin-orbit coupling. As temperature was increased above \( \Delta \), fluctuations in peak height decreased rapidly, consistent with a simple model that assumes resonant transport through multiple, uniformly spaced levels [35] [Fig. 2(c)]. Note that the same ensemble was used for each temperature. This presumably accounts for the correlated departures from theory at low temperature. The discrepancy with theory at high temperature is unexplained, and is reminiscent of [36].

Peak height histograms for \( m = 142 \) Coulomb peaks (see the Supplemental Material [37]) show the evolution of the distribution as a function of magnetic field [Fig. 3(a)]. The observed decreasing average peak height at higher fields—Coulomb blockade antilocalization—as well as the maximum in the distribution away from zero height at all fields, are both signatures of strong spin-orbit coupling.

Figures 3(b) and 3(c) show peak height distributions \( P(g_p) = (\bar{a}/g_p^2)P_{\Sigma x} (\bar{a} g_p^2) = N/(mW) \), where \( W \) is the bin width and \( N \) is the bin count in Fig. 3(a), at low and high magnetic fields. The low-field data in Fig. 3(b) agree with the theoretical distribution for strong spin-orbit coupling (\( \beta = 4 \)), with the mean peak height taken from Fig. 3(a), and are inconsistent with the theoretical distribution for weak spin-orbit coupling (\( \beta = 1 \)). The high-field data in Fig. 3(c) are consistent with a scaled version of the low-field theoretical distribution, as expected for strong spin-orbit coupling, but with a scale factor of \( \sim 2.3 \) rather than the theoretically predicted factor of 1.4. The reason for this discrepancy—qualitative scaling, but not by the predicted factor—is not understood, but may result from changes in tunnel rates out of the dot or changes in density of states in the leads, which are also likely segments of the nanowire.

We have also examined the distributions of Coulomb peak spacings, another statistical property that, in principle, contains information about symmetries of wave functions [39]. The measured distributions appear Gaussian with similar widths for zero and higher magnetic fields, with a standard deviation of 0.5 meV. This width is comparable to the single-particle level spacing, as seen in previous experimental studies [39,40]. We note that peak spacing distributions are more susceptible to experimental noise than peak height distributions, so it is not surprising that peak height distributions show field dependence while spacing distributions do not. Symplectic statistics associated with strong spin-orbit coupling have been measured in the spacings between excited states in metallic quantum dots [41].

To compare antilocalization in the Coulomb blockade regime to the open-wire regime, we tuned the device to more negative gate voltages, where Coulomb blockade oscillations were absent [see Fig. 1(a)]. The number of holes was larger in the open regime, \( N_{\phi} \sim 1700 \) and \( \lambda_F \sim 6 \) nm, again determined by counting Coulomb
from the two contacts, each set to the diffusion constant, and for the magnetoconductance of the wire, where the last two terms of Eq. (5) do not play an important role, and, in principle, could be dropped. We retain these terms, though they have no discernible effect on the fits, for consistency with the existing literature [16,19,28,45] for \( w < l_e \).

The transport scattering length \( l_s = 2D/v_f \), where \( v_f \) is the Fermi velocity, the dephasing length \( l_\phi \), and the spin precession length \( l_{s0} \), then appear as [13,15] \( D\tau_\phi = l_\phi^2/2 \), \( D\tau_c = l_c/l_e/2 \), \( D\tau_B = C_1l_B^2/w^3 + C_2l_s/l_B^2/w^2 \), and \( D\tau_{so} = C_3l_s/l_B^2/w^2 \), where \( l_B^2 = h/eB \). Contants \( C_1 = 4\pi(9.5) \), \( C_2 = 3(24/5) \) apply for diffusive (specular) boundary scattering [13], and we interpolate between these values for specularity \( \epsilon \) between zero (fully diffusive) and one (fully specular). We use the specular value \( C_3 = 130(15) \), lacking a theoretical value for diffusive boundary scattering. The ratio of scattering lengths depends on specularity and sample width \( l_s/l_e = F(w/l_e,\epsilon) \), with \( F(\epsilon, 1) = 1 \) [46]. These expressions require \( l_s < w < l_e \), the former barely satisfied for \( l_s = 6 \) nm.

Four free parameters \( l_s \), \( g_{so} \), \( l_e \), and \( l_\phi \), are used to fit theory to data. The transport scattering length is found from \( l_s = (4L/\pi w^2)h\lambda_{so}/\lambda_F n e^2 \), where \( n = 4N_H/\pi w^2 L \) is the 3D hole density (a reasonable model, given six occupied transverse modes). Specularity can then be found by inverting \( l_s/l_e = F(w/l_e,\epsilon) \), and the Fermi wavelength can be found from the 3D density, \( \lambda_F = (8\pi/3n)^{1/3} \). As seen in Fig. 4, the model fits the data very well, and gives the following ranges for transport parameters \( g_{so} = 0.2–0.7 e^2/h \), \( l_e < 10 \) \( \mu m \), \( l_s = 15–25 \) nm, \( \phi_0 = (0.2–1.2) \) \( \mu m \), specularity in the range \( \epsilon = 0.4–1 \), and \( l_{so} < 20 \) nm. (Allowing \( l_{so} > 20 \) nm gives good fits only with \( l_e > 10 \) \( \mu m \), which we rule out as unphysical.)

As a comparison between open and nearly isolated regimes, we note that the observation of antilocalization in Coulomb blockade implies \( \epsilon_{so} \geq \Delta \), where \( \epsilon_{so} \) is the spin-orbit energy in the dot [21]. To convert this into a spin-orbit length we assume the simple relation \( \epsilon_{so} = h^2/(2m^*l_{so}^2) \) [27] and the bulk heavy-hole effective mass \( m^* = 0.28m_c \). This gives \( l_{so} < 25 \) nm, consistent with the open regime measurement of \( l_{so} < 20 \) nm.

It is interesting to consider the reason for the large magnetic field scale associated with antilocalization in both regimes. Flux cancellation due to boundary scattering is known to enhance the effective magnetic length [13]. Flux cancellations of the effective spin-orbit magnetic field can also occur [15]. These effects roughly cancel out, and the field scale for antilocalization is then \( l_B = l_{so} \), or \( B^* = h/(e^2l_{so}^2) = 3 \) T for \( l_{so} = 15 \) nm.

In summary, we have presented an experimental study of Coulomb blockade peak height statistics in a Ge/Si nanowire. Peak height distributions as well as the field dependence of average peak height (antilocalization) are consistent with the effects of strong spin-orbit coupling. However, the observed decrease in average peak height with applied magnetic field is larger than expected. Magnetoconductance of the same device configured as an open wire yields consistent results. Further investigation of the spin-orbit strength in this system could come from spectroscopic measurements of orbital anticrossings in a

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FIG. 4. Two-terminal conductance \( g \) in the open-wire regime as a function of magnetic field \( B \) (points) along with theory, based on Eq. (5), including contact resistance. Fit bounds spin-orbit length, \( l_{so} < 20 \) nm. Inset: pinch-off curve at bias \( V_B = 10 \) mV. Saturation at \( g \sim 0.3e^2/h \) indicates decreasing mobility in the open regime (see text).
quantum dot, or from electric-dipole spin resonance measurements in a Ge/Si double quantum dot. Combined with the expectation of long spin dephasing times in Ge/Si quantum dots, the strong spin-orbit coupling found in this work makes Ge/Si nanowire quantum dots attractive for spin qubit applications.

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[34] The device shown in Fig. 1 is lithographically identical to the one studied here. However, in the measured device the nanowire forms a smaller angle with $B$ of $31^\circ$ determined from optical microscopy.
[46] $F$ is given by [47]:

$$F(x, e) = 1 - \frac{12}{\pi} (1 - e^2) \sum_{i=1}^{\infty} \nu e^{-\nu} \int_0^1 dx \sqrt{1 - x^2} S_4(\nu kx),$$

where $S_4(\lambda) = \int_0^{\pi/2} d\theta e^{-\lambda \sin \theta} \cos ^3 \theta \sin \theta$.