Carbon nanotubes (CNTs), semiconducting nanowires, and edge channels of the quantum Hall effect are ideal quasi-one-dimensional (1D) systems to study both electron correlations and quantum interference. In fact, various many-body effects, including Coulomb blockade [3–5], Wigner phases [6–9], and Kondo physics [10–21], as well as Fabry-Pérot and Mach-Zehnder oscillations resulting from electron interference [22–28], have been observed in these multimode 1D systems. It is possible to switch from interaction- to interference-governed transport regimes by tuning the tunnel couplings at the interface between the wire and the electrodes, $\Gamma_s$ and $\Gamma_D$, for the source ($S$) and drain ($D$) electrodes. Which transport regime dominates crucially depends on how large the tunneling broadening $\hbar \Gamma = \hbar (\Gamma_s + \Gamma_D)$ is compared to other energy scales, in particular, to the charging energy $E_C$, being the electrostatic cost to add another (charged) electron to the wire [29]. In the so-called quantum dot limit, characterized by $\hbar \Gamma \ll E_C$, tunneling events in and out of the wire are rare and Coulomb charging effects are dominant. They give rise to Coulomb blockade phenomena and incoherent single-electron tunneling in the regime $\hbar \Gamma < k_B T \ll E_C$. By decreasing temperature, one expects coherent single-electron tunneling for $k_B T \approx \hbar \Gamma \ll E_C$, where the width of the Coulomb peaks is determined by $\Gamma$; at even lower temperatures, when spin-fluctuations become relevant, the Kondo effect emerges as the dominant transport mechanism. In the opposite limit of large transmission, $\hbar \Gamma \gg E_C$, interference effects give rise to the characteristic Fabry-Pérot patterns, which can be easily calculated from a noninteracting single-particle scattering approach [22]. The focus of this Letter is the intermediate transmission regime $\hbar \Gamma \sim E_C \gg k_B T$ when no clear hierarchy of energy scales exists.

An experimental hallmark of both interaction- and interference-dominated transport is the modulation of the conductance when sweeping the electrochemical potential, that is, by varying the gate voltage $V_g$. In the incoherent tunneling regime, the alternance of single-electron tunneling and Coulomb blockade physics results in finite conductance peaks with a period in $V_g$ of about $e/C_g$ [2], where $-e$ is the (negative) electron charge, and $C_g$ is the capacitance between the nanotube and the gate electrode; see Fig. 1(a). In contrast, in the interference-dominated regime, the conductance modulation of the Fabry-Pérot oscillations arises from the electron wave phase...
accumulated during a round trip along the wire. The presence of valley and spin degrees of freedom in CNTs gives rise to interferometers with oscillation period $\Delta V_g = 4e/C_g$ [22].

In this Letter, we improve the quality of nanotube devices to an unprecedented level. We discover a crossover of the conductance oscillation period between $e/C_g$ and $4e/C_g$ upon sweeping temperature. Above liquid helium temperature, the period is $e/C_g$ with oscillation amplitudes pointing to coherent single-electron tunneling in an open quantum dot configuration. At low temperature, the period becomes $4e/C_g$, and the oscillations feature typical characteristics of Fabry-Pérot interference. These unexpected data are a clear signature of the interplay between interaction and quantum interference.

Experimental results.—We grow nanotubes by chemical vapor deposition on prepatterned electrodes [30]. The nanotube is suspended between two metal electrodes; see Fig. 1. We clean the nanotube in the dilution fridge at base temperature by applying a high constant source-drain voltage $V_{sd}$ for a few minutes (see Sec. I of the Supplemental Material [31]). This current-annealing step cleans the nanotube surface from contamination molecules adsorbed when the device is in contact with air. The energy gap of the two nanotubes discussed in this Letter is on the order of 10 meV (for details, see the Supplemental Material [31]). The length of the two suspended nanotubes inferred by scanning electron microscopy (SEM) is about 1.5 $\mu$m.

Figure 1(b) shows the modulation of the differential conductance $G_{\text{diff}}$ of device I as a function of $V_g$ in the hole-side regime at 15 mK. Rapid conductance oscillations are superimposed on slow modulations. Since the conductance remains always large, that is, above $e^2/h$, we attribute the rapid oscillation to the Fabry-Pérot interference with period in gate voltage being $\Delta V_g = 4e/C_g$. The slow modulation may be caused by the Sagnac interference [25,26], the additional backscattering due to a few residual adatoms on the CNT, the symmetry breaking of the electronic wave function by the planar contacts of the device, or any combination of these (for further discussion, see Sec. I and II A of the Supplemental Material [31]).

A crossover to a regime dominated by the charging effect in an open interacting quantum dot is observed upon increasing temperature. Specifically, by sweeping the temperature from 15 mK to 8 K, the amplitude of the oscillations gets smaller. Further, the oscillation period gets four times lower, changing from $4e/C_g$ at 15 mK to $e/C_g$ at 8 K; see Figs. 2(a) and 2(c)–2(e). The period in $V_g$ is calibrated in units of $e/C_g$ using the measurements in the electron-side regime, where regular Coulomb oscillations are observed at 8 K, as shown in Fig. 2(b). The same behavior is observed in device II; Figs. 3(a) and 3(b). The $4e/C_g$ oscillations vanish at $\sim 3$ K in both devices, whereas the $e/C_g$ oscillation amplitude is suppressed to almost zero below $\sim 1$ K in device I and below $\sim 0.1$ K in device II; see Figs. 2(f) and 3(b).

Our interpretation of a temperature-induced crossover between two seemingly distinct transport regimes is confirmed by measured maps of the differential conductance as a function of source-drain and gate voltages at $T = 15$ mK and $T = 8$ K, as shown in Figs. 4(a) and 4(d), respectively. The low-temperature data feature the regular chess-board-like Fabry-Pérot interference pattern [22], while the high-temperature data show smeared Coulomb diamonds. Such measurements further allow us to extract important energy scales for our device. The characteristic bias $V_{sd}$ indicated by the arrow in Fig. 4(a) yields a single-particle excitation energy $\Delta E = eV_{sd} \approx 1.7$ meV. This value is consistent with what is expected from a nanotube with length $L \approx 1.5 \mu$m. Assuming the linear dispersion $\varepsilon(k) = hv_F k$, with longitudinal quantization $k_n = n\pi/L$ and the Fermi velocity $v_F = 10^6$ m/s, it yields $\Delta E = \varepsilon(k_{n+1}) - \varepsilon(k_n) = hv_F \pi/L \approx 1.4$ meV. The charging energy is estimated from the charge stability diagram measurements at 8 K, Fig. 4(d); from the Coulomb diamond, indicated by the dashed lines, a charging energy $E_C \approx 3.6$ meV is extracted. Further, we estimate $\hbar \Gamma \approx E_C$ because of the strong smearing of the diamonds in Fig. 4(d) and the weak conductance modulation at 8 K in Fig. 2(a). The energy hierarchy in our experiment is thus $E_C \approx \hbar \Gamma \approx \Delta E \gg k_BT$.

The evolution of the 15 mK conductance oscillations as a function of the source-drain bias shows that both oscillations coexist over a large bias range, albeit with modulated strengths; see Figs. 4(a)–4(c). The main trend is that
the oscillation period changes from \(4e/C_g\) at zero bias to \(e/C_g\) at high bias. By contrast, the evolution in the perpendicular magnetic field shows that the conductance peaks are split in two, with the splitting in gate voltage being linear in magnetic field; see Figs. 3(c) and 3(d).

This is attributed to the Zeeman splitting, since the associated \(g\) factor is \(2.4 \pm 0.4\). The error in the estimation arises from the uncertainty in the lever arm. These data indicate degeneracy of the four electron levels associated to the spin and valley degrees of freedom.

Discussion.—We examine possible origins of the temperature-induced period change. Let us first assume that interactions are not important. Then, upon lowering temperature, noninteracting Fabry-Pérot oscillations are expected to emerge when the thermal smearing becomes smaller than the single-particle excitation energy. However, thermal smearing is associated to a characteristic temperature \(T_{\text{th}} \sim \Delta E/k_B \approx 20\ \text{K}\), which is rather different from the measured crossover temperature \(T_C \sim 3\ \text{K}\) in Figs. 2(f) and 3(c). In addition, thermal smearing cannot explain the emergence at temperatures above \(T_C\) of the \(e/C_g\) oscillations due to coherent single-electron tunneling. Therefore, thermal decoherence is not at the origin of the measured period change. This is further supported by single-particle Fabry-Pérot interference calculations, based on an accurate tight-binding modeling of CNTs, that we carried out. We also considered the complementary regime and investigated whether charge fluctuations could be the cause of our finding. However, when using an interacting multilevel quantum dot with fourfold degenerate energy levels in the regime \(E_C \approx \hbar\Gamma\), we could not reproduce the measured fourfold variation of the period. Both the single-particle and the interacting calculations are described in the Sec. II of the Supplemental Material [31].
In the Kondo effect, the tunneling coupling is low compared to the charging energy to allow full localization of the charge within the dot, but it is large enough compared to the Kondo energy to enable both spin and valley fluctuations [11]. This results in a crossover from charging effects at high temperature to the increased conductance of Kondo resonances at zero temperature, with a fourfold enhancement of the oscillation period [13,29,38]. In contrast to our observations, though, in the SU(4) Kondo effect, the conductance alternates between large values close to 4$e^2/h$ at oscillation maxima and almost zero at minima [18,38]; see also Sec. I b of the Supplemental Material [31]. In our annealed devices, the tunneling coupling is large; $h\Gamma \approx E_C$. The charge is no longer strongly localized within the dot. As a result, our devices are in a regime where there are also charge fluctuations in the nanotube, in addition to spin and valley fluctuations. This might be at the origin of the crossover of the conductance oscillation period observed in this Letter, similar to what happens in the SU(4) Kondo regime [13,29,38], but with conductance minima clearly distinct from zero. We emphasize that the zero-source-drain bias, low-temperature $G_{\text{diff}}(V_g)$ data alone do not allow one to distinguish between noninteracting and correlated Fabry-Pérot oscillations. However, the smooth modulation between $e/C_g$ and $4e/C_g$ oscillations upon increasing the bias [see Fig. 4(c)] further supports our hypothesis of correlated Fabry-Pérot regime.

Conclusion.—Our Letter provides a comprehensible phenomenology of transport in nanotubes when both interference and interaction are involved. The findings presented in this Letter have been possible thanks to the high quality of the devices, since otherwise disorder leads to irregular $G_{\text{diff}}(V_g)$ modulations that are difficult to interpret. The main results are summarized as follows: (i) We measure a fourfold enhancement of the oscillation period of $G_{\text{diff}}(V_g)$ upon decreasing temperature, signaling a crossover from coherent single-electron tunneling to Fabry-Pérot interference; both oscillations coexist at the crossover temperature. (ii) Upon increasing the source-drain bias at low temperature, both oscillations coexist over a large bias range. (iii) The Sagnac-like modulation pinpoints the quantum interference nature of the Fabry-Pérot oscillations at zero bias. (iv) The magnetic field data suggest a fourfold spin and orbital degeneracy at zero magnetic field.

The unexpected temperature-induced crossover, possibly related to charge, spin, and valley fluctuations, raises an important question: How does the strength of charge fluctuations compare to that of spin and valley fluctuations in our experiment? Indeed, when the electron transmission approaches one in open fermion channels, the electron shot noise is suppressed to zero [39], indicating that there are no longer any charge, spin, and valley fluctuations in nanotubes; by contrast, in the lower $\Gamma$ limit of SU(4) Kondo, spin and valley fluctuate, but not the charge. It is then natural to ask how the crossover temperature in our devices compares with the well-known Kondo temperature of closed quantum dots. However, a quantitative description

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of our experiment constitutes a theoretical challenge. It will be interesting to measure shot noise [40–43] and the backaction of the electromechanical coupling [44,45] to further characterize these correlated Fabry-Pérot oscillations.

We thank B. Thibeault at UCSB for fabrication help, W.J. Liang, P. Recher, D. Mantelli, and F. Dolcini for discussions. This work is supported by ERC advanced Grant No. 692876, the Cellex Foundation, the CERCA program from the Generalitat de Catalunya, AGAUR (Grant No. 2017SGR1664), Severo Ochoa (Grant No. SEV-2015-0522), MICINN Grant No. RTI2018-097953-B-I00 and the Fondo Europeo de Desarrollo Regional. We acknowledge support by the Deutsche Forschungsgemeinschaft within SFB 1277 B04.


