

Electron-hole asymmetry and shell filling in carbon nanotube quantum dots on boron nitride

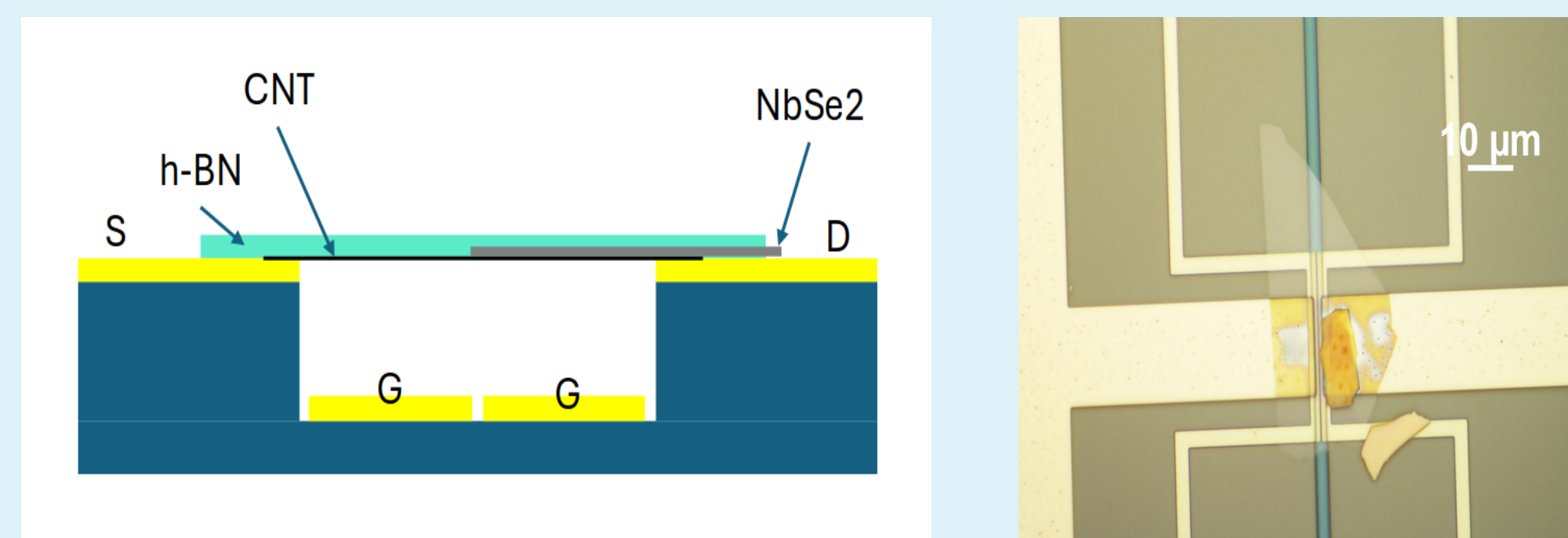
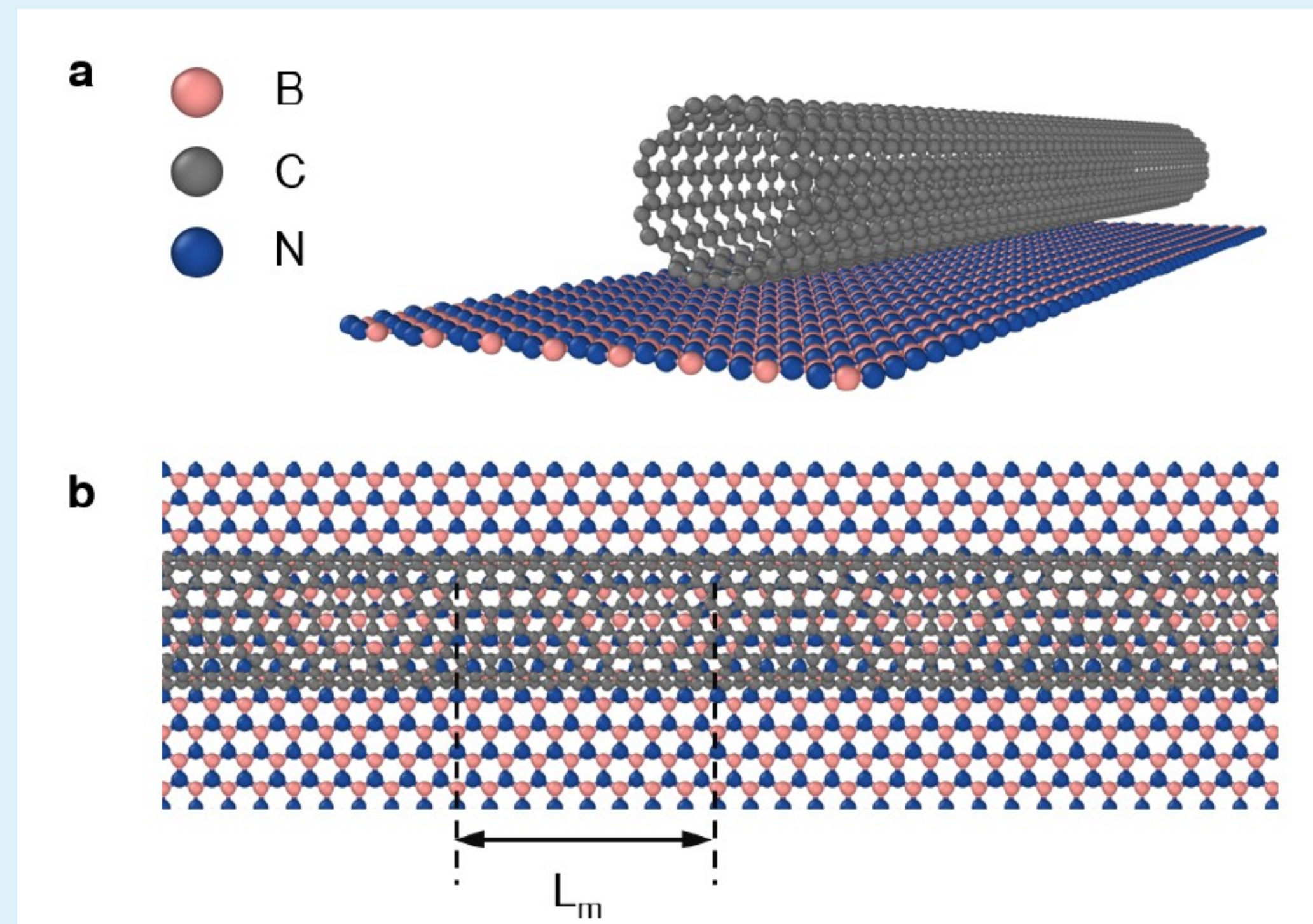
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Introduction and Motivation

- The emergence of strongly correlated states in magic-angle twisted bilayer graphene has driven interest in moiré potentials for quantum system engineering. Carbon nanotubes (CNTs) on epitaxial boron nitride offer a unique one-dimensional testing ground for this physics.
- Conductance measurements from our collaborators demonstrate varying peak spacings that capture the discrete charging and shell-filling behavior of the CNT quantum dot.
- We developed a phenomenological model that accurately predicts this shell-filling hierarchy. A core requirement for experimental agreement is a small but vital asymmetry between electron and hole charging energies.
- Fitting successive conductance peaks allows us to map how interaction parameters vary against the chemical potential.
- This framework successfully differentiates electron addition from hole removal, proving that electron-hole charging asymmetry is fundamentally necessary to understand shell-filling in periodically confined 1D systems.

Experiment and Schematic



- CNT is placed on hexagonal BN spanning ~60 supercells. Image obtained from [1]. $\Lambda_{\text{moiré}} = 16$ nm
- A source-drain bias voltage is applied to measure current.
- Voltage on the gate V_{BG} allows for the tuning of the charge carriers within the tube.

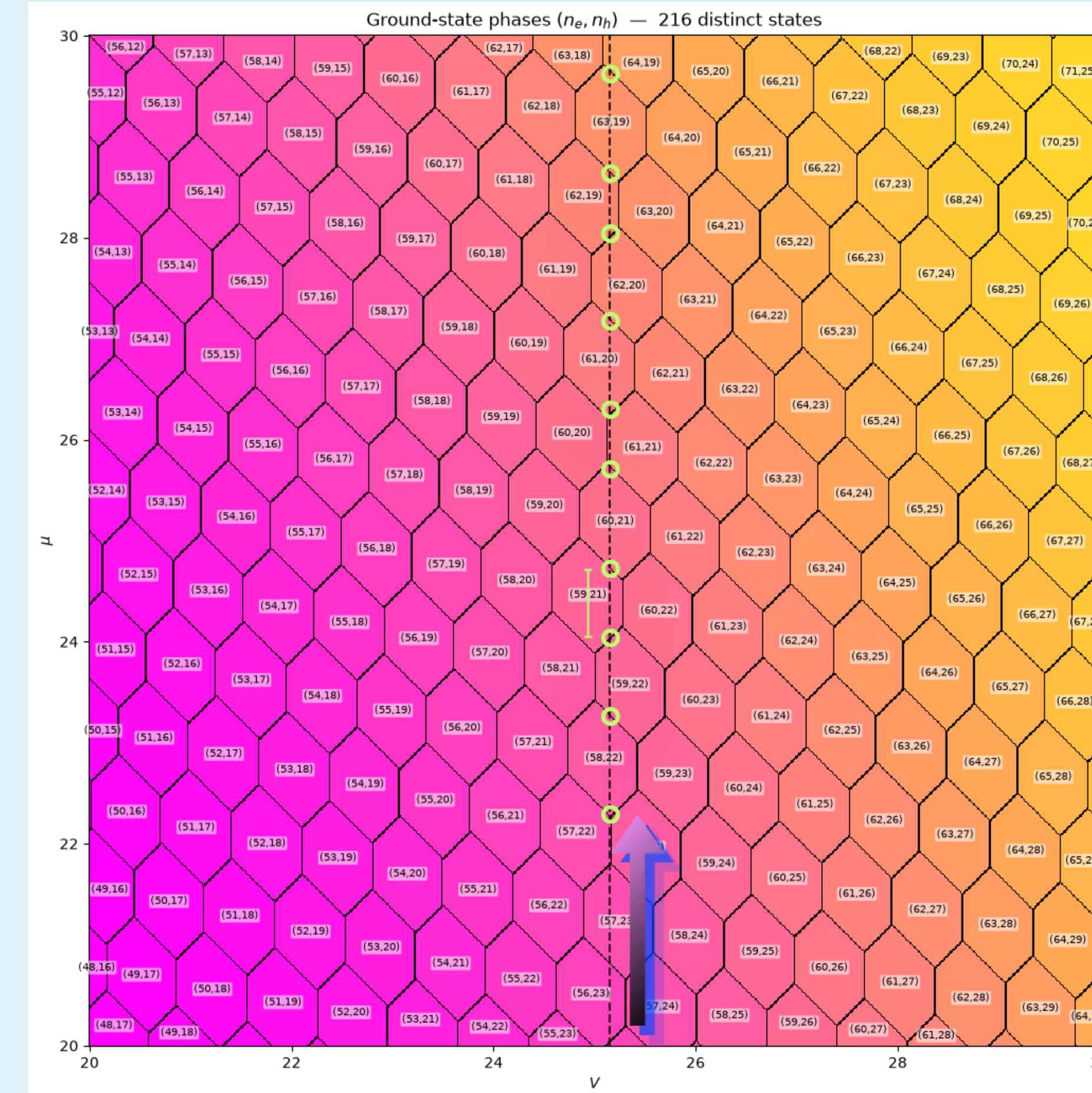
Phenomenological Model

Our proposed model has the Hamiltonian:

$$H(n_e, n_h) = \frac{1}{2} \epsilon_{\text{ce}} n_e^2 + \frac{1}{2} \epsilon_{\text{ch}} n_h^2 - \epsilon_{\text{int}} n_e n_h - \mu (n_e - n_h) - v (n_e + n_h)$$

- n = number of electrons or holes
- $\epsilon_{\text{ce}}, \epsilon_{\text{ch}}, \epsilon_{\text{int}}$ = charging energies of the electron, hole and interaction strength
- μ = chemical potential
- v = amplitude of the periodic potential of the superlattice
- Examine the system at different numbers of charge carriers.
- First, solve for the ground states of this model over a range of different μ and v .
- This is done by fixing the charging energies and interaction parameter $\epsilon_{\text{ce}}, \epsilon_{\text{ch}}, \epsilon_{\text{int}}$.
- This yields a phase diagram displaying Coulomb blockades with varying electron and hole configurations.

Charging energies and interaction is detuned



- Select any constant value of v in the model and increase μ .
- Stepping up in μ traverses through Coulomb blockades sequentially. n_e increases or n_h decreases.
- Each boundary crossed marks an increase in the total charge. This shows up as a conductance peak. The distance from one boundary crossing to the next depends on the shape of the Coulomb blockades.
- Coulomb blockade shape is a function of $\epsilon_{\text{ce}}, \epsilon_{\text{ch}}, \epsilon_{\text{int}}$ but is constant across μ and v .
- We get a distribution in the distances between conductance peaks.

Data and Analysis



- Conductance G versus back- voltage V_{BG} measurements display roughly 293 distinct conductance peaks.
- Spacing between consecutive peaks measures addition energy required to add successive charge carriers to the system.
- In a particle-hole symmetric 1D system, the addition energy displays a strictly periodic, symmetric shell-filling sequence, but not seen here.
- Qualitative agreement between the simulated peak spacings and the experimental data when introducing asymmetry between the electron and hole charging energies.
- This broken symmetry geometrically tilts the incompressible honeycomb domains in the phase diagram, demonstrating that electron-hole charging asymmetry is essential for capturing the complex shell-filling behavior.
- Tracking the transitions resolves whether a given conductance resonance corresponds to electron addition or a hole removal event

References and Acknowledgements

- B. Flebus and A. H. MacDonald, Electronic structure of carbon nanotubes on graphene substrates, Phys. Rev. B 99, 235413 (2019)
- D. S. Novikov, Electron properties of carbon nanotubes in a periodic potential, Phys. Rev. B 72, 235428 (2005).

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