PhD THESIS DEFENSE: A non-linear carbon nanotube mechanical resonator near the quantum ground state of motion.

ROGER TORMO QUERALT

November 18, 2024
11:00
Auditorium and Online (Teams)

This thesis describes the design, fabrication, and measurement of gate-defined quantum dots embedded in suspended carbon nanotubes. The mechanical vibrations of the nanotube couple strongly to the quantum dots by modulating the gate-defined electrostatic potential. The quantum dot charge states and mechanical vibrations are characterized using transport measurements and a capacitively coupled superconducting microwave resonator.
The samples are fabricated using a novel nanofabrication protocol developed within our group, enabling ultra-clean carbon nanotubes, as short as 560 nm, to be suspended over five gating electrodes. This compact geometry is advantageous for producing near-gigahertz

frequency nanotube mechanical resonators in their ground state of motion at cryostat temperatures of 10 mK. According to our electrostatic finite-element simulations, this layout could also enhance the screening of substrate charge fluctuators, which are a major source of dephasing for quantum dot-based charge qubits.

The carbon nanotubes are investigated in a dilution refrigerator at 30 mK. Single, double, and triple quantum dots are electrostatically localized within the nanotube through the applied voltages at the gate electrodes. Transport measurements reveal exceptionally high-quality charge stability diagrams in the various quantum dot configurations.

In the double quantum dot configuration, we focus on the inter-dot charge transition where an electron tunneling between the two dots forms a charge qubit with a gate-tunable energy. The charge qubit is detected by probing a superconducting microwave resonator connected galvanically to a gate electrode and capacitively coupled to the electric dipole moment of the double quantum dot. The microwave cavity consists of a 100 nm thick niobium spiral resonator with a resonance frequency of 1.475 GHz and a high characteristic impedance of 640 ?. The suspended carbon nanotubes exhibit high-frequency, highly coherent mechanical modes with typical resonance frequencies ranging from tens to hundreds of MHz. Electron tunneling through the quantum dots embedded in the resonator exerts a back-action force on the mechanical motion, resulting in a mechanical resonance frequency softening. Frequency softenings of up to 20% were observed in the first flexural mode of two distinct devices, characterized by the frequencies of 240 MHz and 35 MHz. From the frequency softening, an electromechanical coupling of 920 MHz and 500 MHz was estimated for each device, demonstrating operation in the deep ultrastrong coupling regime. However, the coupling mechanism in this system relies on an incoherent tunneling process, which precludes its application in any quantum protocol. The second flexural mode of the carbon nanotube, characterized by 515 MHz, presents electromechanical couplings up to 410 MHz when coupled to a charge qubit transition, confirming operation in the ultrastrong coupling regime. This significant electromechanical coupling induces non-linear effects down to motional amplitudes roughly ten times the nanotube's zero-point motion, which are detected using the microwave cavity that is sensitive to the squared displacement of the mechanical resonator. The large non-linearities observed in these devices near the mechanical groun state highlight the potential of carbon nanotube electromechanical systems for quantu applications, including nanomechanical qubits, expanded quantum motion delocalisation and quantum sensing

Monday November 18, 11:00h. ICFO Auditorium
Thesis Director: Prof. Dr. Adrian Bachtold and Dr. Christoffer Moller
Hosted by: Academic Affairs