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SU(4) Kondo Effect in Carbon Nanotube Quantum Dots: Kondo Effect without Charge Quantization

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Carbon nanotubes present an ideal system for investigating quantum electronic transport at the nanoscale. In our nanotube quantum dots, we can control the contact transparency and thereby can tune the electronic conductance from the well-developed Coulomb blockade to the Kondo regime. We work with high quality nanotubes, where quantum-mechanical orbitals are doubly-degenerate, forming four-electron "shells". For electrons tunneling within the nanotube, the orbital quantum number is preserved and the tunneling Hamiltonian possesses SU(4) symmetry. We present our observations of the SU(4) Kondo effect for one, two, and three electrons in a shell. Surprisingly, as the contacts are made more transparent and the charge quantization is completely suppressed, we still observe the SU(4) Kondo effect. This behavior is different from the SU(2) Kondo effect which is destroyed by charge fluctuations. The hallmark of the new transport regime is the surprising lack of single-electron features at low temperature, which are uncovered as the temperature is raised. Recent numerical calculations demonstrate a very good agreement with our measurements.