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Observation of Spin-Orbit Coupling in Clean Carbon Nanotubes
FERDINAND KUEMMETH, SHAHAL ILANI, PAUL MCEUEN, DAN RALPH, Physics Department, Cornell University, Ithaca, NY 14850 — The electronic states in defect-free carbon nanotubes (NTs) are widely believed to be four-fold degenerate, due to independent spin and orbital symmetries, and also to possess electron-hole symmetry. We report measurements demonstrating that in clean NTs the spin and orbital motion of electrons are coupled, thereby breaking all of these symmetries. This spin-orbit coupling is directly observed as a splitting of the four-fold degeneracy of a single electron in an ultra-clean quantum dot. Application of a parallel magnetic field reveals that the coupling favours parallel alignment of the orbital and spin magnetic moments for electrons and anti-parallel alignment for holes. We further show that SO coupling determines the filling order in the many-electron ground states, in a way different than that expected from electron-electron interactions. At low magnetic fields we find that the two-electron ground state is neither a spin-triplet nor a spin-singlet, but a Slater determinant in which the spin and orbital wavefunction are entangled. Our findings have important implications for spintronic applications in NTs and provide a mechanism for all-electrical control of spins.

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