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Coupling of spin and orbital motion of electrons in carbon nanotubes

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Electrons in atoms possess both spin and orbital degrees of freedom. In non-relativistic quantum mechanics, these are independent, resulting in large degeneracies in atomic spectra. However, relativistic effects couple the spin and orbital motion, leading to the well-known fine structure in atomic spectra. The electronic states in defect-free carbon nanotubes are widely believed to be four-fold degenerate, owing to independent spin and orbital symmetries, and also to possess electron–hole symmetry. Here we report measurements demonstrating that 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 ultra-clean quantum dots. The coupling favors parallel alignment of the orbital and spin magnetic moments for electrons and antiparallel alignment for holes. Our measurements are consistent with recent theories that predict the existence of spin–orbit coupling in curved graphene and describe it as a spin-dependent topological phase in nanotubes. Work done in collaboration with F. Kuemmeth, S. Ilani, and D. C. Ralph