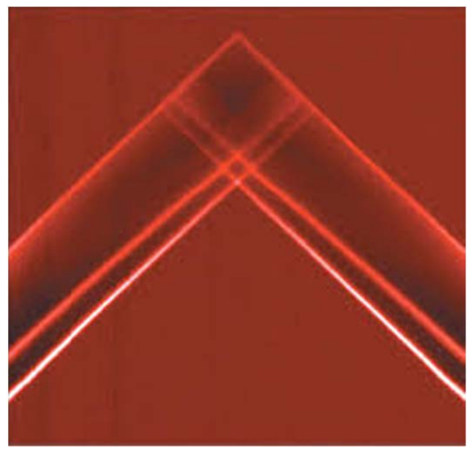
Coupling of spin and orbital motion of electrons in carbon nanotubes

Kuemmeth, Ferdinand, et al. "Coupling of spin and orbital motion of electrons in carbon nanotubes." Nature 452.7186 (2008): 448.

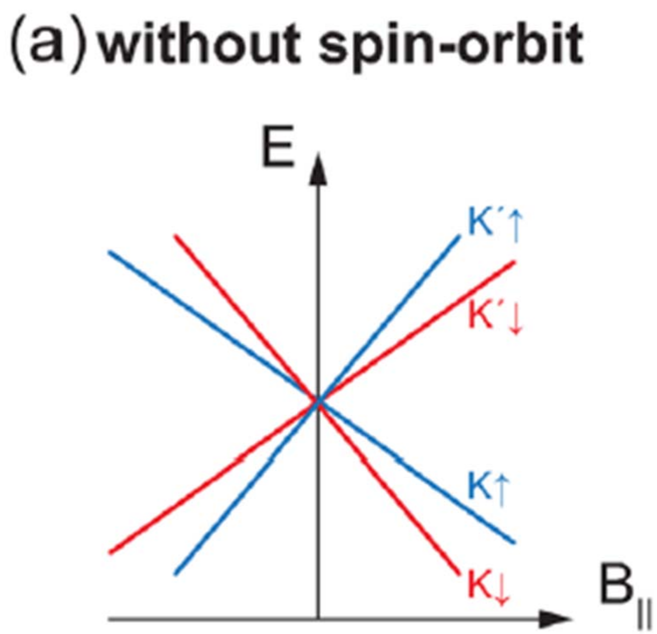


Ivan Velkovsky, Xiaoning Wang, Junyi Wu, Shengzhu Yin, Matthew Ziemann

Carbon Nanotubes are Useful in Spintronics

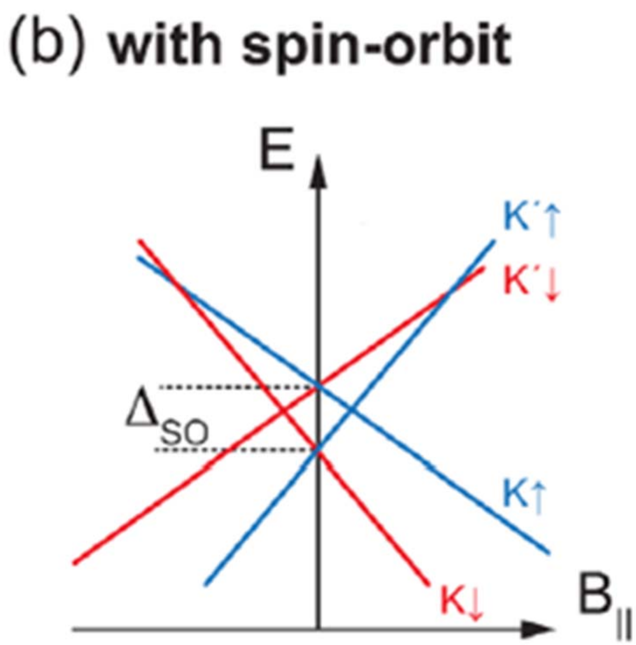
- Spintronics is an emerging field to replace charge-based electronics with spin-based ones
- Graphene and carbon nanotubes have unique properties (Dirac dispersion, clockwise and counter-clockwise orbits in nanotubes) that may be used for spintronics
- Spin states in carbon are stable, making it an attractive material

Spin States are Degenerate in Graphene



- Carbon nanotube devices have a spin state and orbital state, leading to a possible 4-fold degeneracy in the non-relativistic limit
- Degeneracy can be broken by external magnetic field, which splits the spectrum into 4

Spin-orbital Coupling will Break Degeneracy



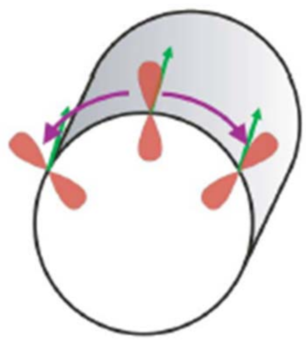
- Spin-orbital coupling also breaks the degeneracy at zero field, giving two two-fold degenerate states instead of one four-fold state.
- Paper shows that this coupling is significant in very clean nanotube devices

Spin-orbit Coupling in Curved Graphenes

Theoretical work by Ando and Hernando pointed out that in curved graphene, the spin-orbit coupling is not weak

- Previous work on curved graphene ignored spin-orbit coupling
- This wasn't observed experimentally because of disorder
- The current paper discusses work on cleaner curved graphene samples

Model



$$k_z \pi d \to k_z - 2\pi S_{||}\phi_{SO}/\phi_0$$

The spin-dependent topological flux is indeed invariant under scaling of the diameter

$$E = \pm v_F \sqrt{k_z^2 + k_{||}^2} - \frac{g}{2}\mu_B S_{||} B_{||}$$

$$k_z = \pm \frac{E_{gap}}{2v_F} + \frac{2}{d}\frac{\phi_{AB}}{\phi_0} + S_{||}\frac{2}{d}\frac{\phi_{SO}}{\phi_0}$$

Kuemmeth, Ferdinand, et al. "Coupling of spin and orbital motion of electrons in carbon nanotubes." Nature 452.7186 (2008): 448.
Ando, T. Spin–orbit interaction in carbon nanotubes. J. Phys. Soc. Jpn. 69,1757–1763 (2000).

Electron-hole Symmetry

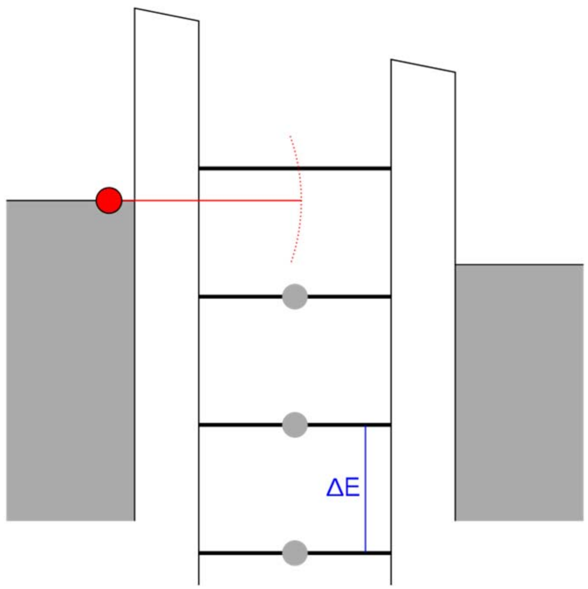
- Many work before this paper believed that electron-hole symmetry

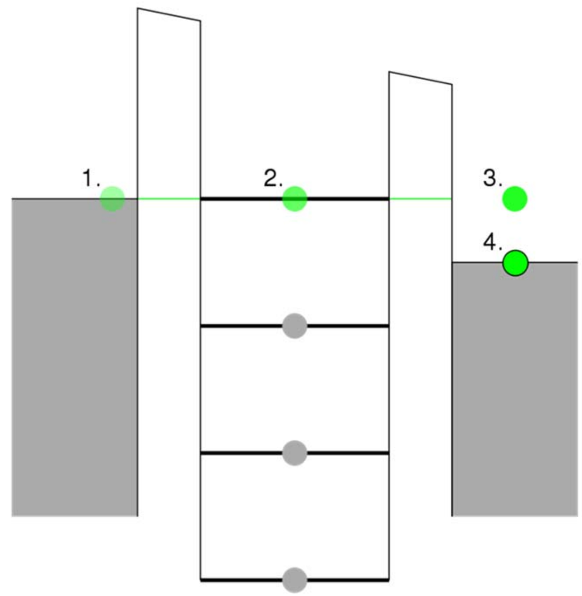
  Holds in defect-free carbon nanotubes

- However, the previous equation (SO interaction, applied B field) indicates

  That this symmetry is broken

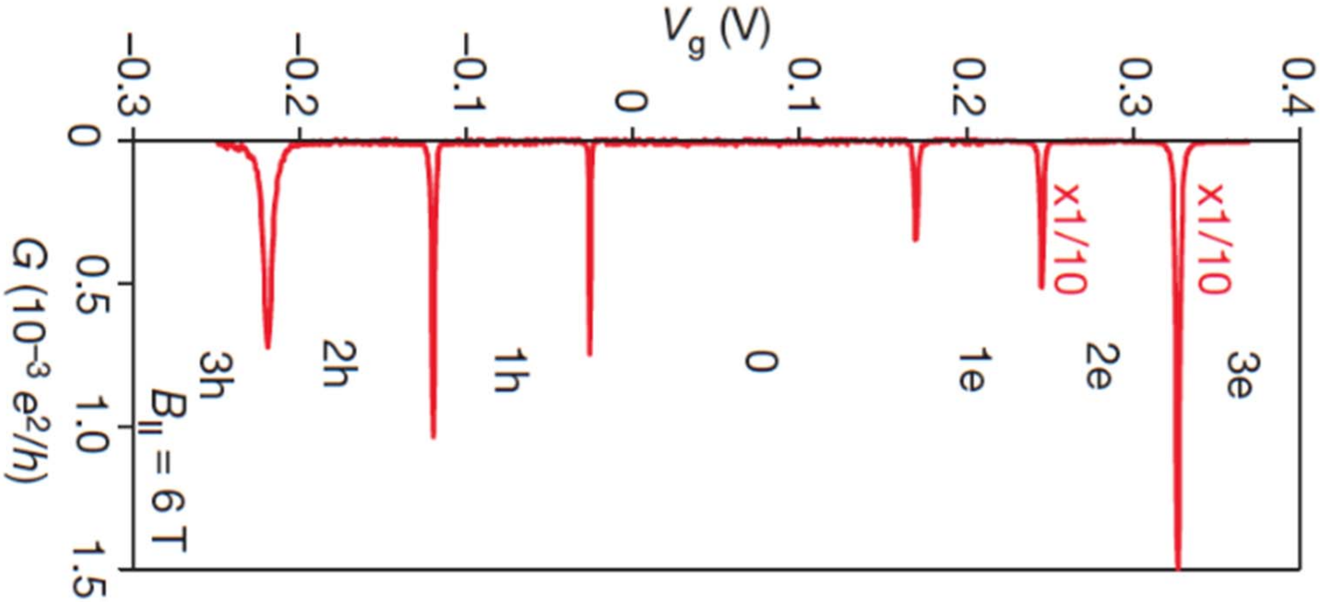
Measure Transport through Quantum Dot Device





- When lower energy levels are occupied, no electrons can pass
- Energy levels are lowered when gate voltage increases

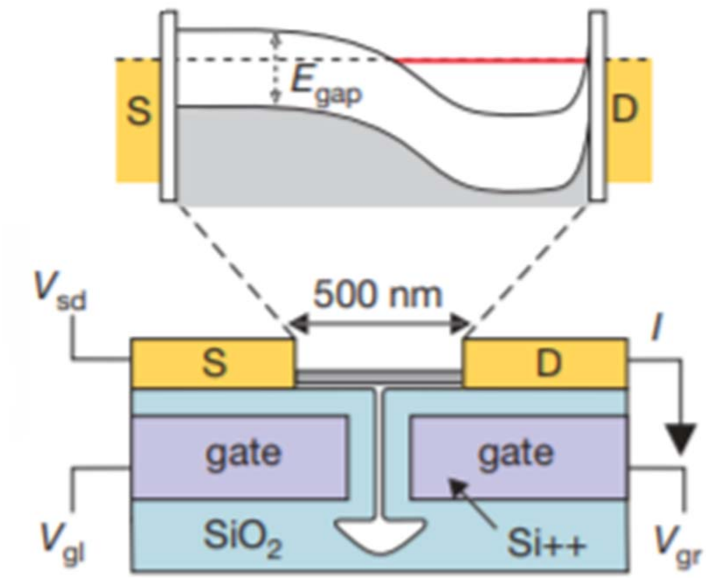
Identification of First Electron or First Hole



- Linear conductance (G) is a function of V_g
- Each peak indicates the addition of a single electron/hole

Introduction	Background	**Method**	Result	Significance	Critique

New Quantum Dot Device Reduces Disorder

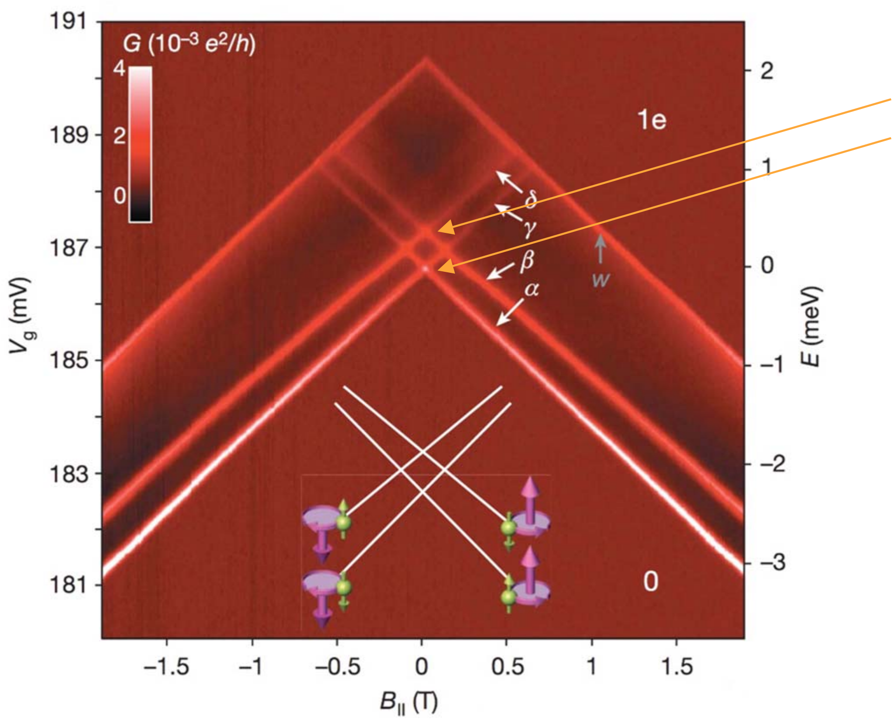


$$G(V_g) = dI/dV_{sd}$$

- Bottom gating fabrication method→ Reduce disorder-induced splitting of the orbital degeneracy
- Double gates → Prove that the measurement is Independence of quantum dot location
- High magnetic field in Coulomb peaks → Exclude electron-electron interactions

Introduction	Background	**Method**	Result	Significance	Critique

SO Coupling Observed in a Single Electron in Nanotube Dot

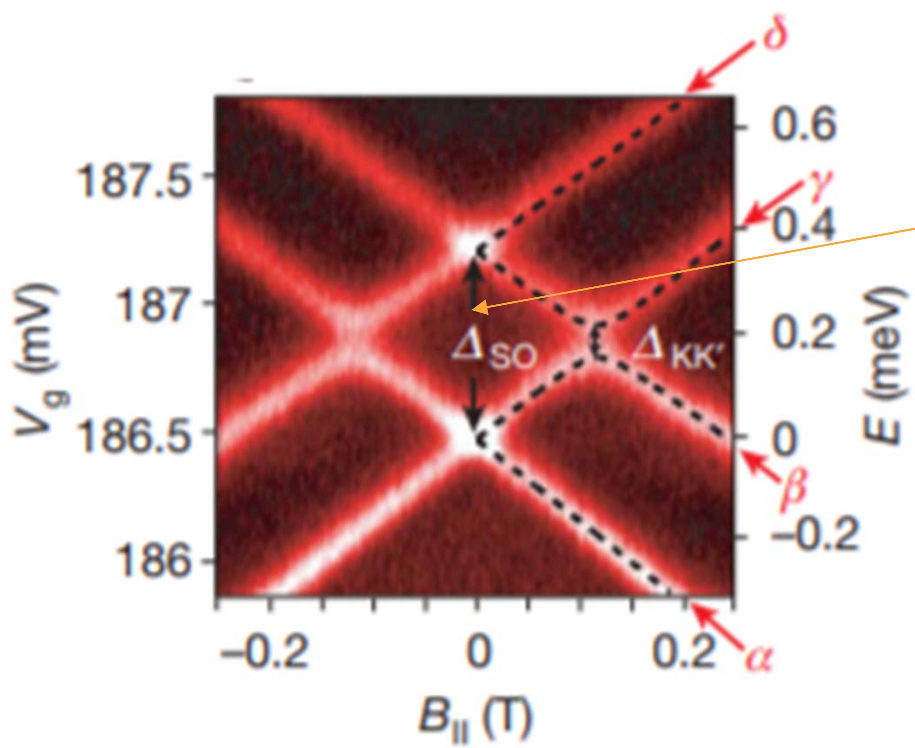


- At B=0 the four-fold degeneracy is split into two Kramer doublets

- As B increases, energy splitting between state α and β increases due to Zeeman splitting

Introduction	Background	Method	**Result**	Significance	Critique

Small Disorder-induced Mixing Allows Observation of SO Coupling



- Δ_{SO} >> $\Delta_{KK'}$

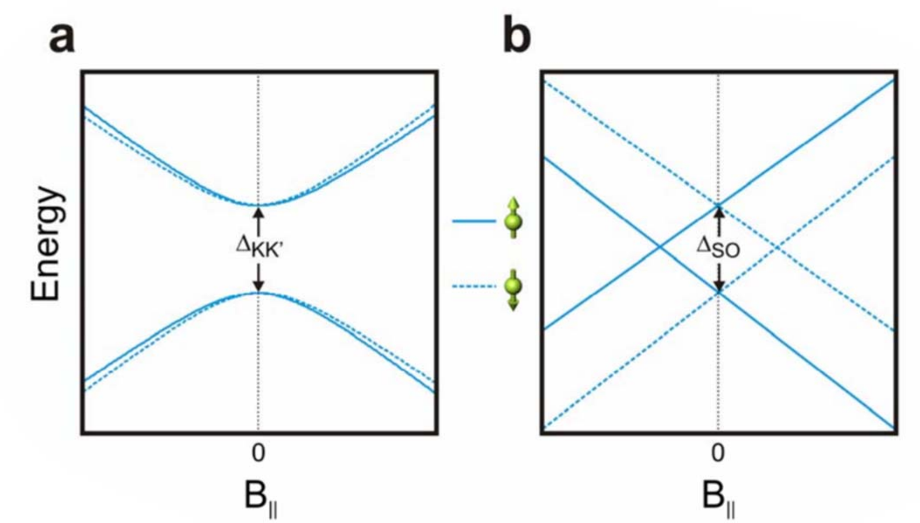
  Δ_{SO} - zero field splitting due to SO coupling

  Δ_{KK} - splitting due to K-K' mixing

$$\Delta_{SO_{theory}} = 0.32meV$$
$$\Delta_{SO_{expriment}} = 0.37 \pm 0.02meV$$
$$\Delta_{KK'} = 65\mu eV$$

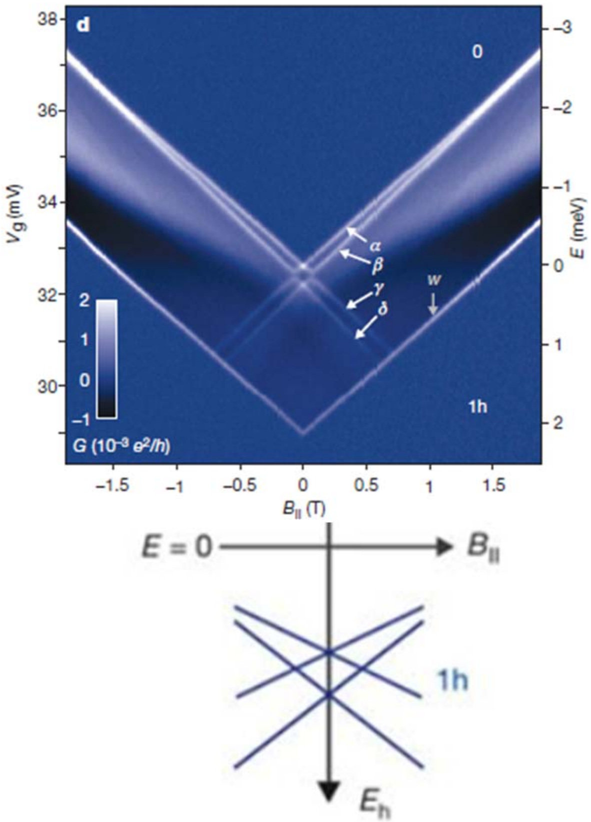
Introduction	Background	Method	**Result**	Significance	Critique

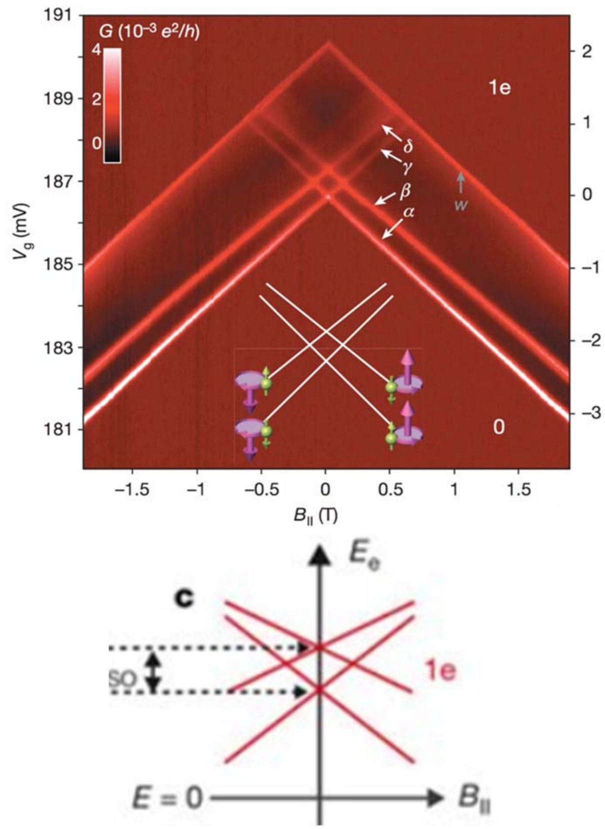
Spin-orbit Coupling vs. K-K’ Scattering



- The four-fold degeneracy in nanotubes can be broken by extrinsic sources such as disorder
- If $\Delta_{SO} \sim \Delta_{KK'}$, disorder-induced splitting will mask the intrinsic SO coupling

SO Coupling Breaks Electron-hole Symmetry





- Not symmetric around E=0

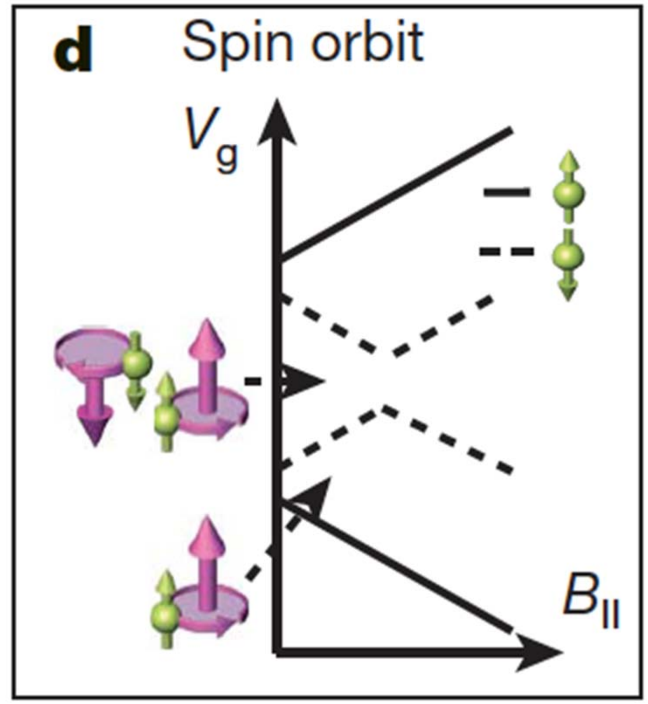
Introduction	Background	Method	**Result**	Significance	Critique

Significance

- First experiment demonstration of spin–orbit coupling in carbon nanotubes
- Predicted by Ando and Hernando in 2000, but never detected due to disorder
- Raise interesting questions about electron-hole symmetry
- This spin-orbit coupling effect is not strong enough to rule out carbon nanotubes as medium for spintropics, but could be exploited to allow electron spin to be manipulated by electrical means

Critique on clarity

- Insufficient explanation of experimental design
- Too little evaluation of the results
- Confusing figures labeling



Introduction	Background	Method	Result	Significance	**Critique**

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By: Oreg, Yuval; Refael, Gil; von Oppen, Felix
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CHEMICAL SOCIETY REVIEWS Volume: 40 Issue: 6 Pages: 3336-3355 Published: 2011

Times Cited: 552
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Electrical control of a confined electron spin in a silicene quantum dot

Impact & Direction of the Field

- Discovery completes picture of non-interacting, single particle physics in nanotubes
- One of first experimental applications of ultraclean nanotube devices
- Further work explores 2-electron and many-electron behaviors, and different quantum dot leads (e.g. superconducting).
- Spintronics moving towards organic molecules, graphene, and topological insulators

Reference

1. Kuemmeth, F., Ilani, S., Ralph, D. C. & McEuen, P. L. Coupling of spin and orbital motion of electrons in carbon nanotubes. *Nature* **452**, 448–452 (2008).
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3. Ando, T. *Spin-Orbit Interaction in Carbon Nanotubes*. *Journal of the Physical Society of Japan* **69**, (2000).
4. Laird, E. A. *et al.* Quantum transport in carbon nanotubes. (2015). doi:10.1103/RevModPhys.87.703
5. *Wikipedia Coulomb Blockade: The free encyclopedia*. from https://en.wikipedia.org/wiki/Coulomb_blockade