Gate-dependent spin–orbit coupling in multielectron carbon nanotubes

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Spin-orbit coupling in CNTs

• curvature of graphene lattice $\rightarrow$ radial electric field $\rightarrow$ parallel or antiparallel orientation of spin and orbital momentum is favored (depending on sign of spin-orbit splitting $\Delta_{SO}$).

• $g_{\text{orb}} > g_{\text{electron}}$

• spin-orbit splitting $\Delta_{SO}$ (as seen in perpendicular field) is given by the underlying structure:
  – carbon (atomic): $\sim 8$ meV
  – graphene: $\sim 1$ $\mu$eV
  – nanotube: greatly enhanced due to coupling between $\pi$ and $\sigma$ bands

Kuemmeth et al., Nature 452 (2008)
Sample fabrication

- highly doped Si, capped with 500 nm SiO$_2$
- nanotubes are single-wall (CVD grown: H$_2$, Ar, CH$_4$)
- e-beam: Au/Pd (40/10 nm) electrodes spaced by 400 nm
- Attocube ANRv51 piezo rotator
- $^3$He/$^4$He dilution refrigerator with $T_{\text{base}} \sim 100$ mK
Coulomb diamonds: Four-electron shells

• factor 2 from electron spin
• factor 2 from isospin \((K, K')\) – \(e^-\) going around clockwise and anticlockwise
Nanotube energy spectrum (theory)

- (a) Zeeman splitting proportional to $B$ and $g_{\text{electron}}$: $B_{\parallel}$ couples to orbital magnetic moment: $g_{\text{orb}} > g_{\text{electron}}$.
- (b) $\Delta_{KK} \rightarrow$ “avoided crossing” at $B = 0$
- (c) $B_{\text{perp}}$ does not couple $K$ and $K'$: “Kramer doublets” do not split
- (d) Asymmetric splitting of $\alpha, \beta$ vs $\gamma, \delta$ in $B_{\parallel}$. Zeeman splitting is suppressed in $B_{\text{perp}}$ by $\Delta_{SO}$.

Kuemmeth et al., Nature 452 (2008)

$\Delta_{SO} \neq 0$

\begin{align*}
\Delta_{K} & = 0 \\
\Delta_{SO} & = 0
\end{align*}

$\Delta_{K} > 0$

$\Delta_{SO} > 0$

$\Delta_{SO} / \Delta_{K}$

$E_{\uparrow} - E_{\downarrow}$

\[ E_{\uparrow}^{K} - E_{\downarrow}^{K} \]
Cotunneling spectroscopy

- (a) B=0, ~180 electrons. Arrows point at horizontal lines truncating the diamonds, arising from significant cotunneling due to strong tunnel coupling
- (b) find inelastic cotunneling processes by varying $V_{sd}$
- (c) scale bar: $0.1e^2/h$

→ By taking the derivative of the lines in (c), one can make the states visible (large change in $dl/dV$ points at resonant cotunneling process)
Cotunneling spectroscopy

- (f) ground state transition at $B_{||} = 1.1$ T: zero-bias Kondo peak (inset)
- $\Delta_{SO}$ is directly expressed by avoided crossings in g-i.
Tuning $\Delta_{SO}$ with $V_g$

- Valence band (holes)
- Conduction band (electrons)

$\Delta_{SO}$ (meV)

$V_g$ (V)
Conclusion

- nice Coulomb diamonds in a CNT multielectron QD
- cotunneling spectroscopy in parallel and perpendicular magnetic fields
- theoretical model that explains and matches the measured band structures very well
- attempt to find a $V_g$-dependence of the spin-orbit coupling, measured for electrons and holes
Valid here for the valence band! For the conduction band, the signs are opposite. So, as shown in figure 2d, here $\Delta_{SO} > 0$. 

Additional figures