Broken SU(4) symmetry in a Kondo-correlated carbon nanotube[1]

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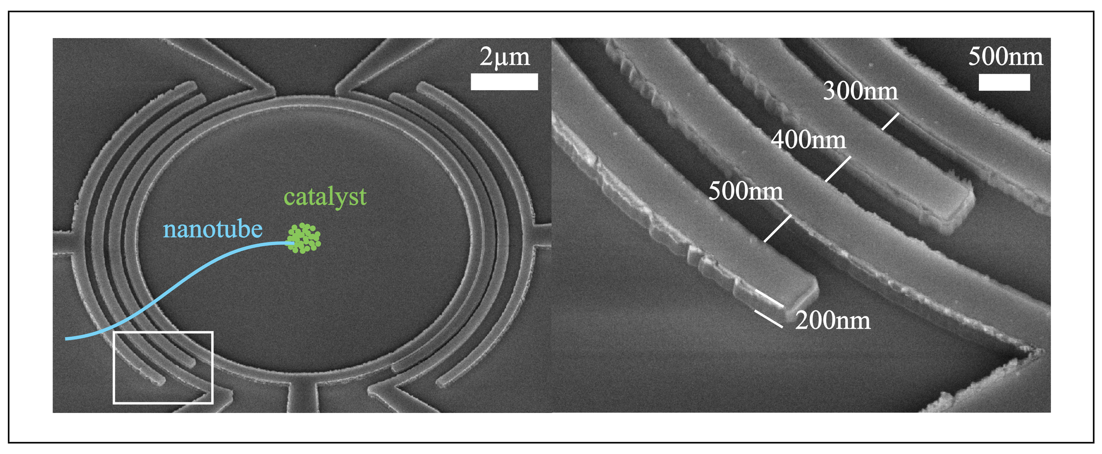
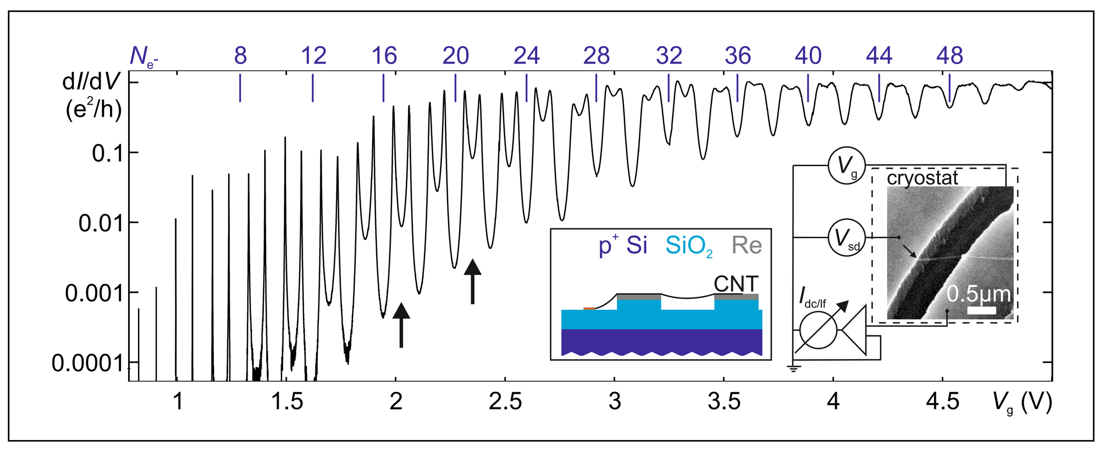
Ultraclean carbon nanotubes



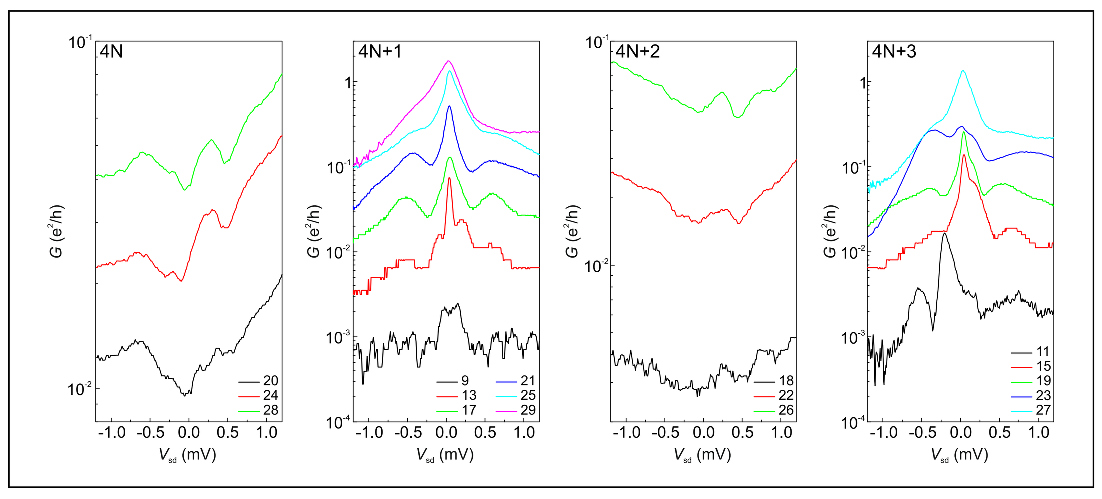
- first preparation of contacts, trenches, catalyst ...
- then growth of nanotubes across contacts
- no contamination / damage by later fabrication steps [2, 3, 4]

Electronic characterization



- clean few-electron system, Coulomb blockade
- Kondo enhanced conductance in odd valleys [5]

Non-equilibrium features

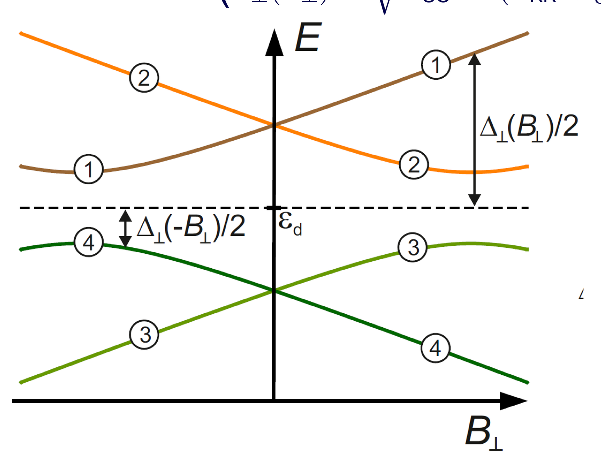


- clear four-fold periodicity in electron number N_{el}
- zero-bias anomaly in odd-N_{el} valleys [6, 7, 8]
- pronounced satellite peaks at finite V_{sd}

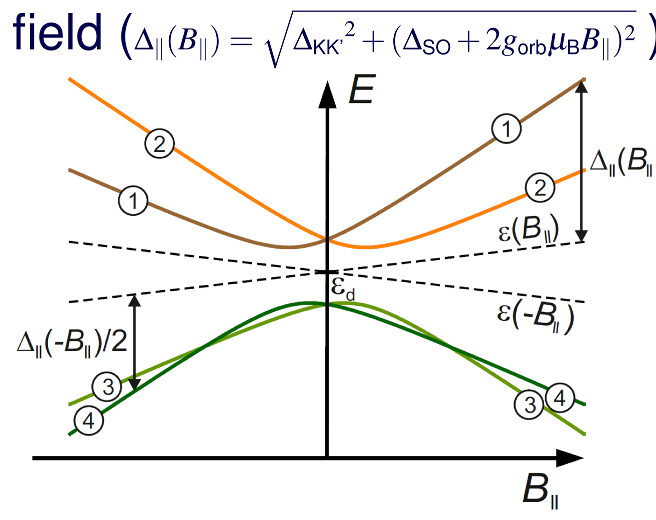
Single-particle Hamiltonian [9]

$$\hat{H}_{\mathrm{CNT}} = \varepsilon_d \hat{I}_\sigma \otimes \hat{I}_\tau + \frac{\Delta_{\mathrm{KK'}}}{2}\hat{I}_\sigma \otimes \hat{\tau}_z + \frac{\Delta_{\mathrm{SO}}}{2}\hat{\sigma}_z \otimes \hat{\tau}_x + \frac{1}{2} g_s \mu_{\mathrm{B}} |\vec{B}| (\cos\varphi\, \hat{\sigma}_z + \sin\varphi\, \hat{\sigma}_x) \otimes \hat{I}_\tau + g_{\mathrm{orb}} \mu_{\mathrm{B}} |\vec{B}| \cos\varphi\, \hat{I}_\sigma \otimes \hat{\tau}_x$$

- perpendicular field ($\Delta_\perp(B_\perp) = \sqrt{\Delta_{\mathrm{SO}}{}^2 + (\Delta_{\mathrm{KK'}} + g_s \mu_{\mathrm{B}} B_\perp)^2}$):

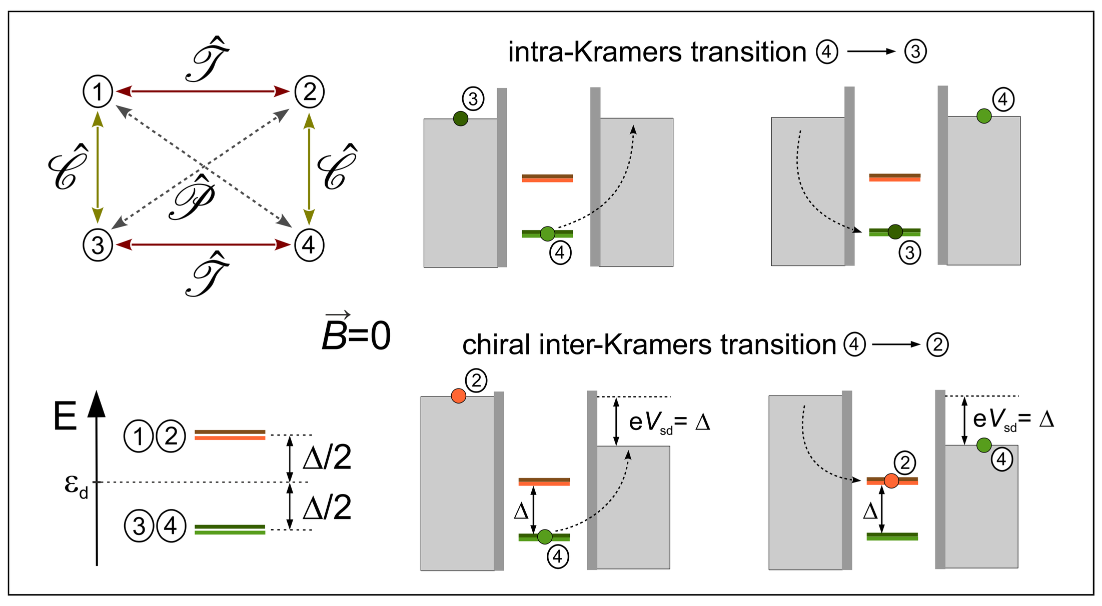


- parallel field ($\Delta_\parallel(B_\parallel) = \sqrt{\Delta_{\mathrm{KK'}}{}^2 + (\Delta_{\mathrm{SO}} + 2 g_{\mathrm{orb}} \mu_{\mathrm{B}} B_\parallel)^2}$):



Conjugation relations

- zero field
  - time-reversal
    $\hat{\mathscr{T}} = -i\hat{\sigma}_y \otimes \hat{\tau}_z \kappa, \quad [\hat{\mathscr{T}}, \hat{H}^{(0)}_{\mathrm{CNT}}] = 0$
  - particle-hole
    $\hat{\mathscr{P}} = \hat{\sigma}_z \otimes (-i\hat{\tau}_y)\kappa, \quad \{\hat{\mathscr{P}}, (\hat{H}^{(0)}_{\mathrm{CNT}} - \varepsilon_d \hat{I}_\sigma \otimes \hat{I}_\tau)\} = 0$
  - chiral
    $\hat{\mathscr{C}} = \hat{\mathscr{P}}\hat{\mathscr{T}}^{-1} = \hat{\sigma}_x \otimes \hat{\tau}_x, \quad \{\hat{\mathscr{C}}, (\hat{H}^{(0)}_{\mathrm{CNT}} - \varepsilon_d \hat{I}_\sigma \otimes \hat{I}_\tau)\} = 0$
- $\hat{\mathscr{T}}$, $\hat{\mathscr{P}}$, $\hat{\mathscr{C}}$ conjugate eigenstates in quadruplet



- perpendicular field ($\hat{H}_\perp(B_\perp) = \frac{1}{2} g_s \mu_{\mathrm{B}} B_\perp \hat{\sigma}_x \otimes \hat{I}_\tau$)
  - time-reversal: broken
  - particle-hole
    $\{\hat{\mathscr{P}}, (\hat{H}_{\mathrm{CNT}} - \varepsilon_d \hat{I}_\sigma \otimes \hat{I}_\tau)\} = 0$
  - chiral: broken
- parallel field ($\hat{H}_\parallel(B_\parallel) = g_{\mathrm{orb}} \mu_{\mathrm{B}} B_\parallel \hat{I}_\sigma \otimes \hat{\tau}_x + \frac{1}{2} g_s \mu_{\mathrm{B}} B_\parallel \hat{\sigma}_z \otimes \hat{I}_\tau$)
  - time-reversal: broken
  - particle-hole
    $\{\hat{\mathscr{P}}, (\hat{H}_{\mathrm{CNT}} - \varepsilon_d \hat{I}_\sigma \otimes \hat{I}_\tau - \frac{1}{2} g_s \mu_{\mathrm{B}} B_\parallel \hat{\sigma}_z \otimes \hat{I}_\tau)\} = 0$
  - chiral: broken

Keldysh effective action theory

- observables expressed as field integral over the Keldysh effective action [10]
- see [11] for the SU(2) case of the theory
- here, (broken) SU(4): construct Keldysh effective action such that conjugation relations are fulfilled
- many-body tunneling density of states $\nu_j(\varepsilon, \vec{B})$ (which leads us to the differential conductance) then follows analogous relations
- example:

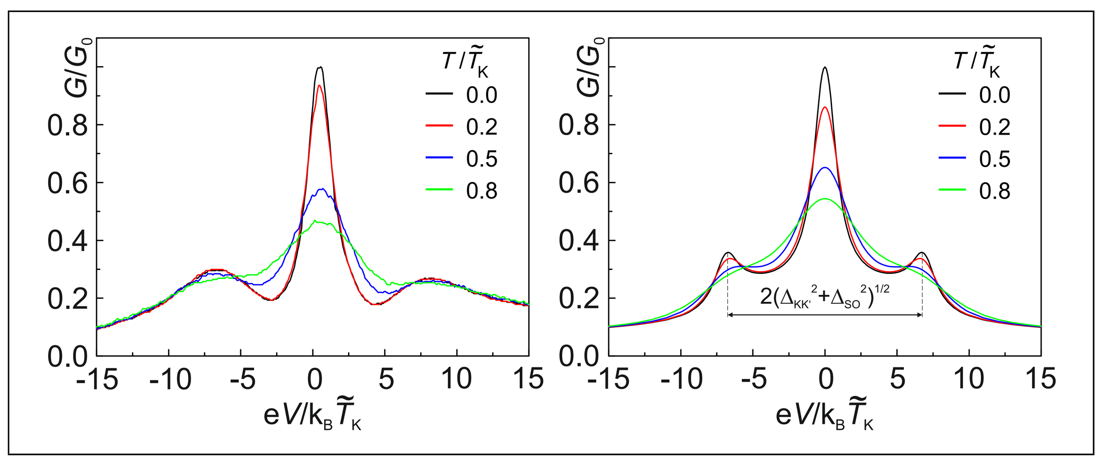
$$\hat{\mathscr{T}}|1, \vec{B}\rangle = |2, -\vec{B}\rangle \quad \longrightarrow \quad \nu_1(\varepsilon, B_\parallel) = \nu_2(\varepsilon, -B_\parallel)$$

- Kondo processes must "flip a spin", always initial $\neq$ final state
- $\hat{\mathscr{P}}$ is preserved $\rightarrow$ no transitions between $\hat{\mathscr{P}}$-conjugated states either

References

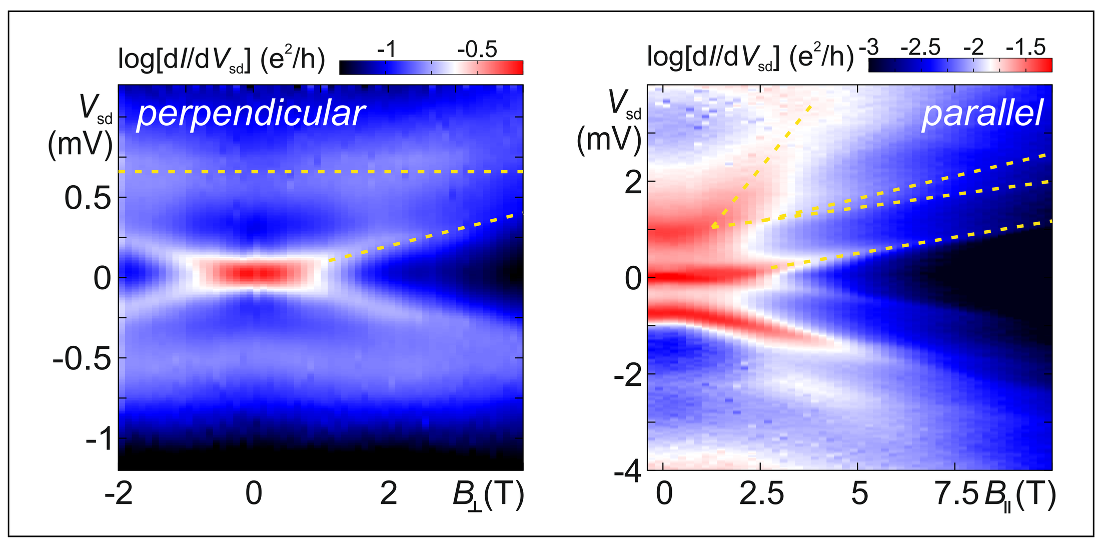
[1] D. Schmid *et al.*, arXiv:1312.6586 (2014).
[2] J. Cao *et al.*, Nature Materials **4**, 745 (2005).
[3] G. A. Steele *et al.*, Nature Nanotechn. **4**, 363 (2009).
[4] A. K. Hüttel *et al.*, Nano Letters **9**, 2547 (2009).
[5] J. Kondo, Progress of Theoretical Physics **32**, 37 (1964).
[6] D. Goldhaber-Gordon *et al.*, Nature **391**, 156 (1998).
[7] D. Goldhaber-Gordon *et al.*, Phys. Rev. Lett. **81**, 5225 (1998).
[8] S. M. Cronenwett *et al.*, Science **281**, 540 (1998).
[9] T. S. Jespersen *et al.*, Nature Physics **7**, 348 (2011).
[10] A. Altland, B. Simons, Condensed Matter Field Theory (Cambridge University Press, 2010), 2nd edn.
[11] S. Smirnov *et al.*, Phys. Rev. B **87**, 121302(R) (2013).

Temperature dependence

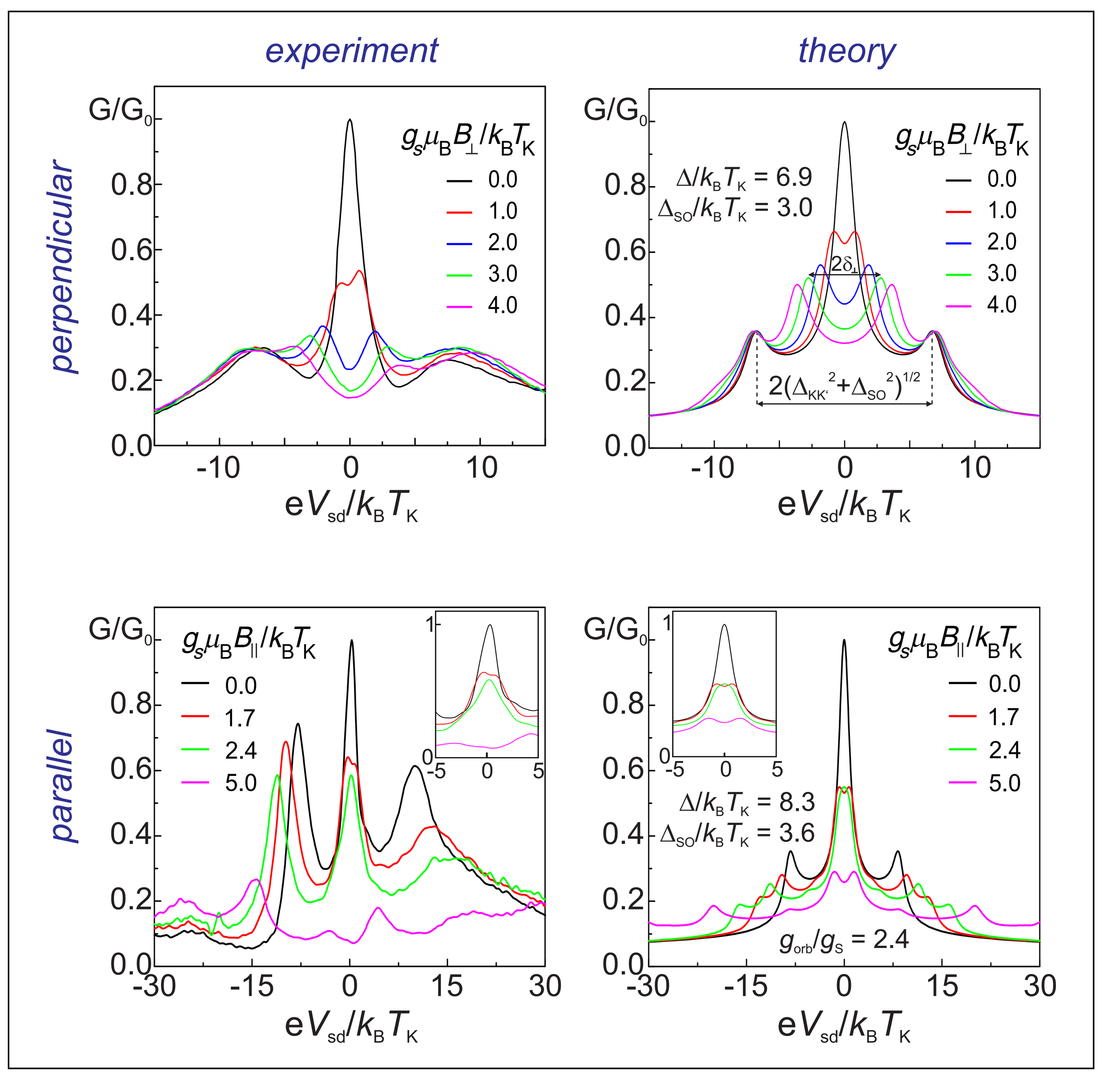


- good qualitative agreement theory - experiment

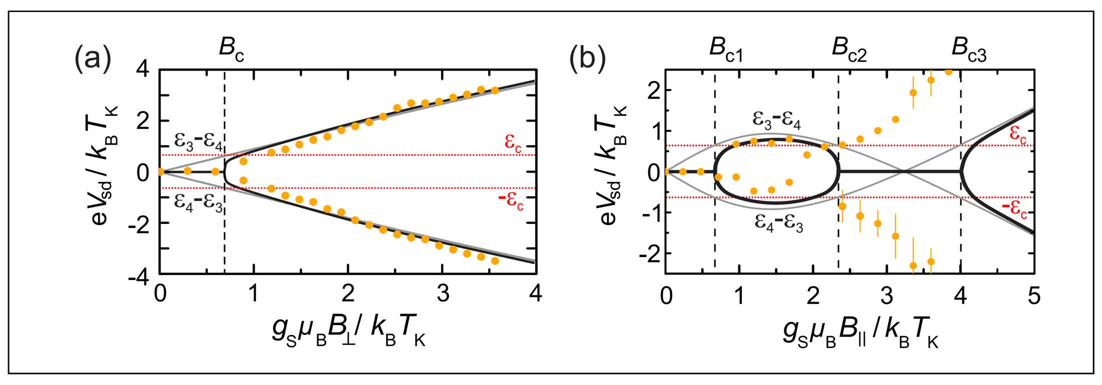
Magnetic field dependence



- field perpendicular to nanotube axis:
  - central peak Zeeman splits with $g = 1.9$
  - satellite peaks are not affected
- field parallel to nanotube axis:
  - much richer peak structure
  - side peaks also move and split
- identification of lines possible from single-particle Hamiltonian
- transitions involving pairs of $\hat{\mathscr{P}}$-conjugated states indeed not visible, consistent with theory



Split in the magnetic field



- threshold behaviour of peak splitting
- consistently modeled by theory
- parallel magnetic field $\longrightarrow$ level crossing, three critical field values

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