**Zero-field splitting of Kondo resonances in a carbon nanotube quantum dot.**
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**condmat/0410467**

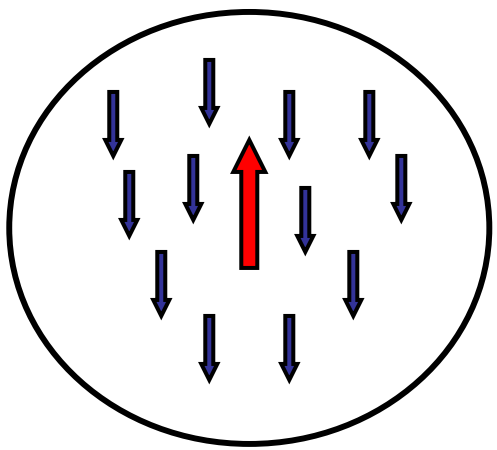
- Low-temperature (mK) electron transport measurements on CVD-grown SWCNTs (d~1-3 nm) on $SiO_2$ substrate; Au electrodes thermally evaporated
- Kondo resonance
- Splitting of Kondo peaks at zero magnetic field

# Kondo Effect in QDs

Screening of a single-spin by conduction electrons

Formation of a singlet state (S=0) induced by spin fluctuations

Narrow (order of $k_B T_K$) resonance at $E_F$ leads to conductance increase, opening of a new transport channel (at T=0, $G=e^2/h$, unitary limit)



Energy scales:

$\Gamma$ = level broadening

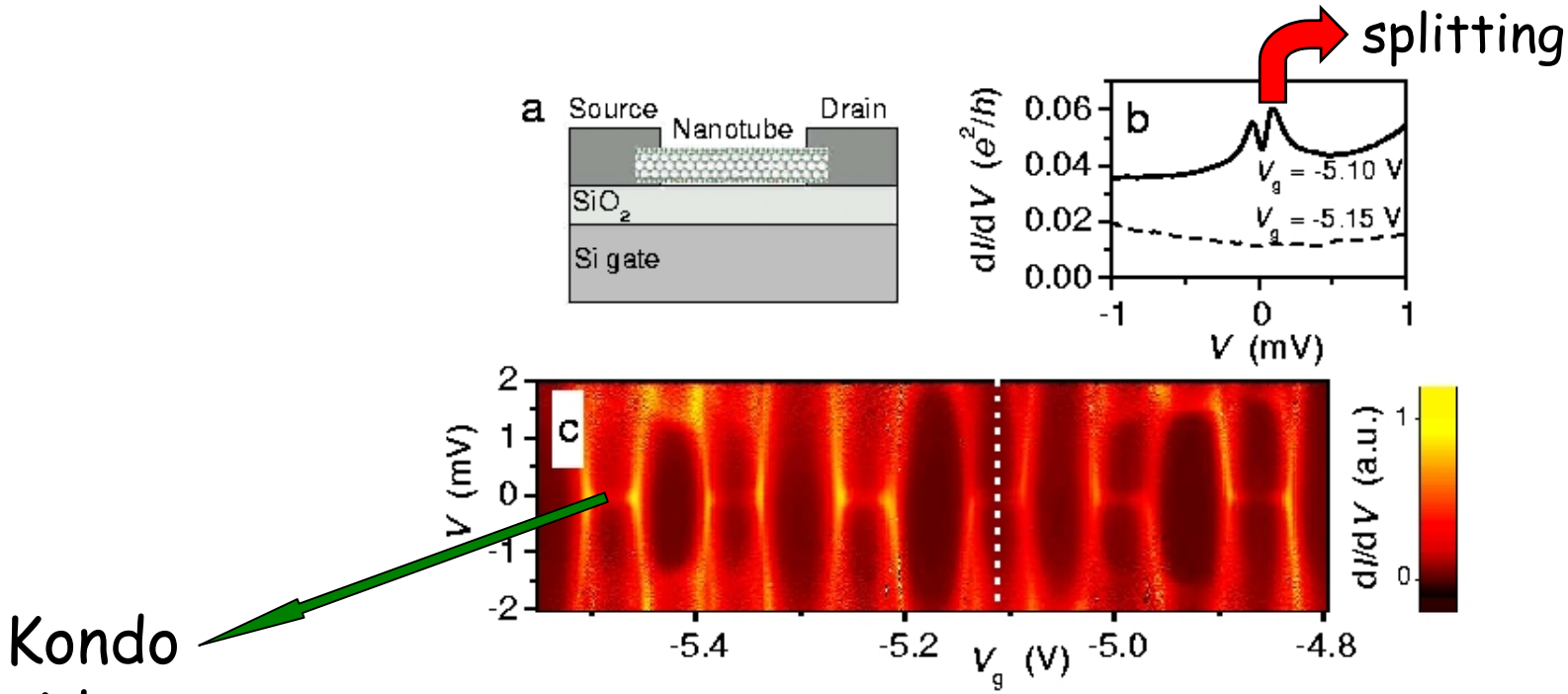
$\Delta\varepsilon$ = level spacing

U = charging energy

$k_B T$ = temperature

$G(T\sim300\ K, V_G) \sim 1.8\ e^2/h$ → metallic tubes

splitting




Kondo ridges S=1/2

FIG. 1: (a) Schematic of nanotube device, comprising a single-wall carbon nanotube, two Cr/Au electrodes (source and drain), and a doped Si gate underneath the $SiO_2$ cap layer. (b) Differential conductance $dI/dV$ as a function of source-drain voltage $V$ for gate voltages $V_g = -5.10$ V (solid) and $V_g = -5.15$ V (dashed) at temperature $T_{el} = 80$ mK. (c) Plot of $dI/dV$ as a function of $V$ and $V_g$ (color online). The dashed line corresponds to the solid trace in (b).

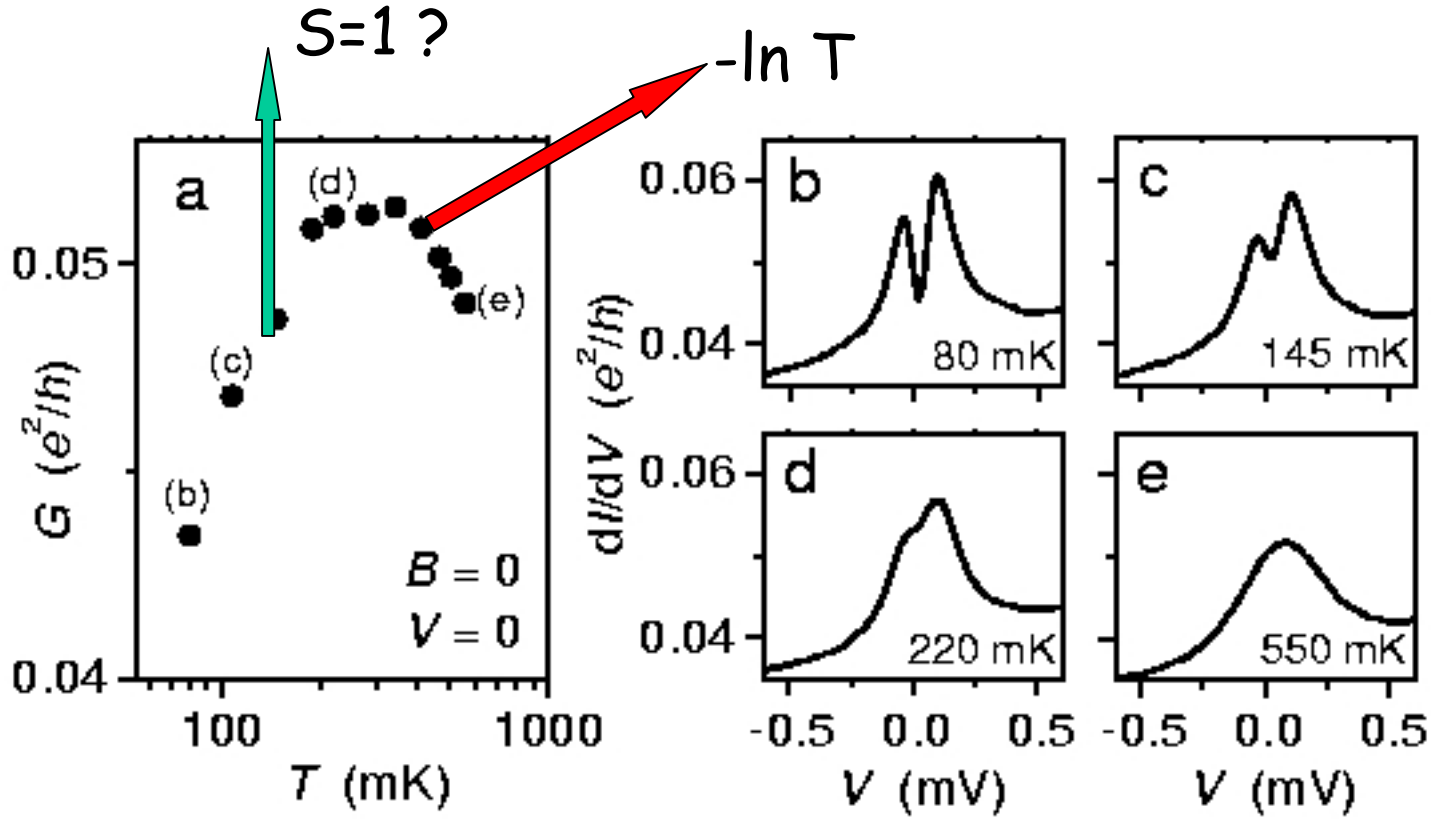



FIG. 2: (a) Temperature dependence of the zero-bias conductance $G$ for the resonance shown in Fig. 1b ($V_g = -5.10$ V). (b)-(e) $dI/dV$ as a function of $V$ for the same resonance, at temperatures 80 (b), 145 (c), 220 (d), and 550 mK (e).

# Splitting at all fields !

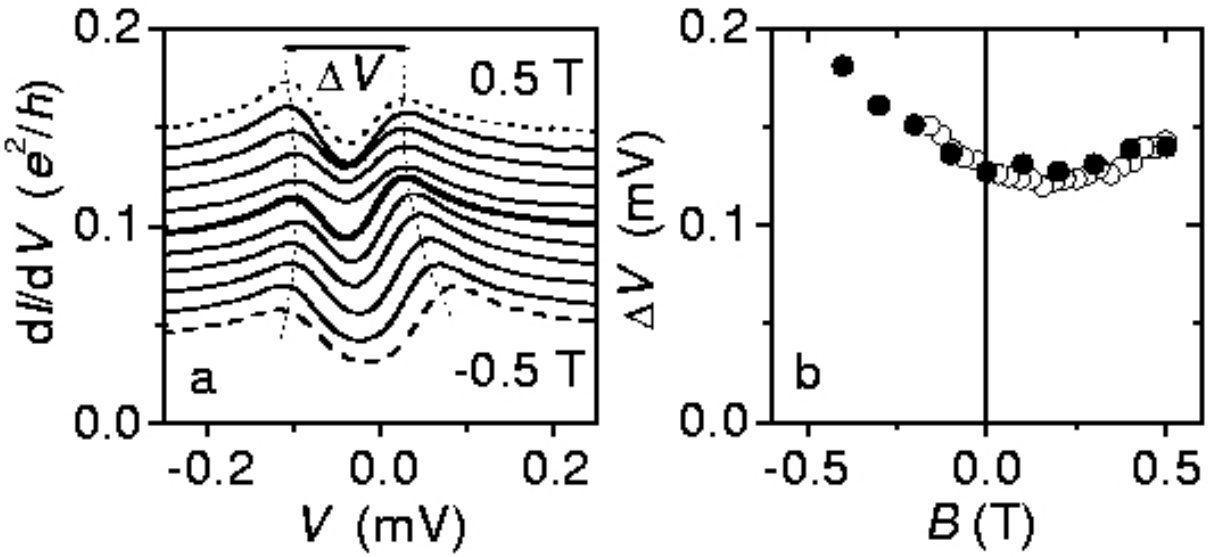



FIG. 3: (a) Magnetic field dependence of $\mathrm{d}I/\mathrm{d}V$ as a function of source-drain voltage $V$ for the peak in Fig. 2(b) at base $T_{\mathrm{el}} = 80$ mK. The applied magnetic field $B$ was increased from $-0.5$ T (dashed) over 0 T (thick) to 0.5 T (dotted) in steps of 0.1 T. Subsequent curves are offset by 0.01 $e^2/h$ for clarity. (b) Peak splitting $\Delta V$ as a function of applied magnetic field $B$ for the data in (a) (solid) and another series where $B$ was swept from 0.5 T to $-0.3$ T (open).

....the Kondo resonances in this study has probed
the effect of a magnetic impurity
(iron-containing catalyst material used to grow the CNT)
on electron transport in a carbon nanotube device.....

Possible consequences for spin-dependent transport (GMR) ?

Difficult to see Kondo effect in CNTs contacted by FM electrodes because of bad contacts (low transmission),
see e.g. K. Tsukagoshi et al. Nature 401, 573 (1999)