Spin cross-correlation experiments in an electron entangler

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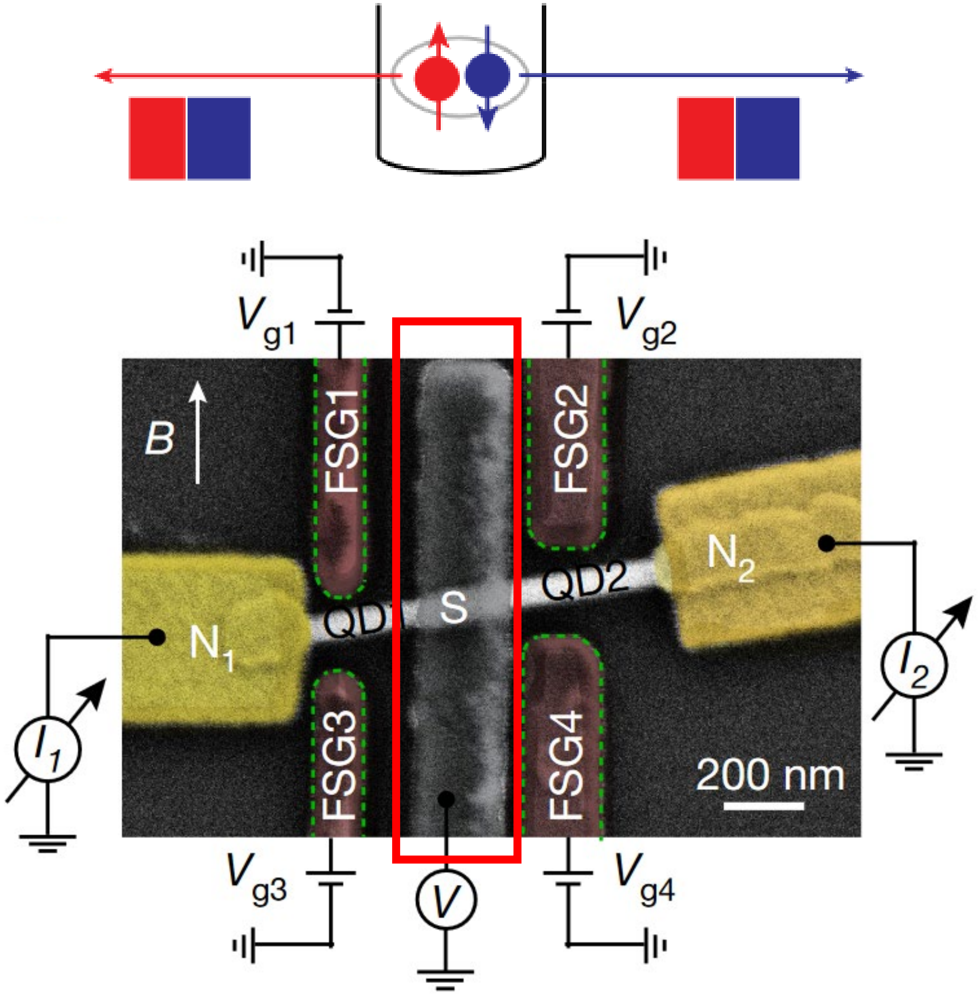
presented by Simon Geyer, 16/12/2022

Motivation

- measure spin correlation of Cooper pairs for the first time

- towards applications with topological superconductors
- towards Bell tests with massive particles

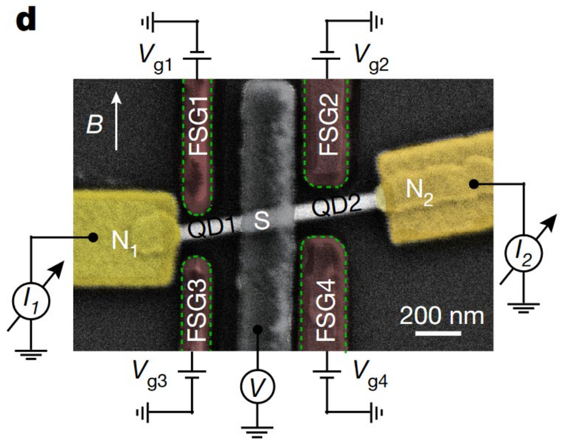
CPS



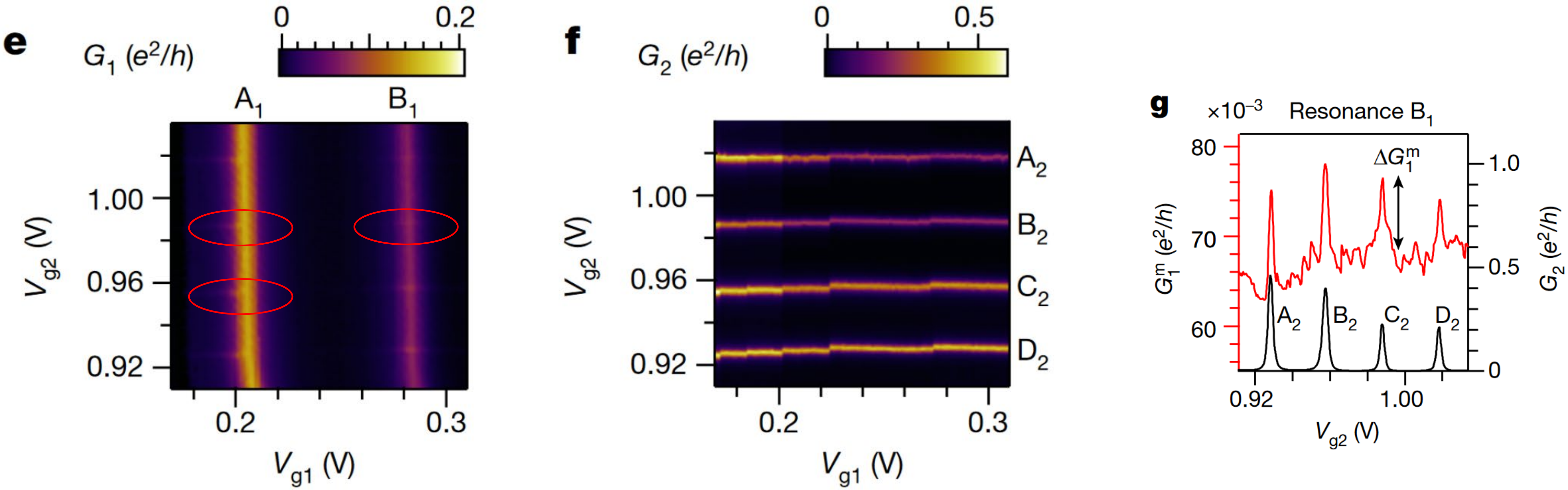
- CPS = Cooper-pair splitter
  → source of correlated electrons
  (charge-correlation AND spin-correlation)

S = titanium/aluminium

Charge correlation



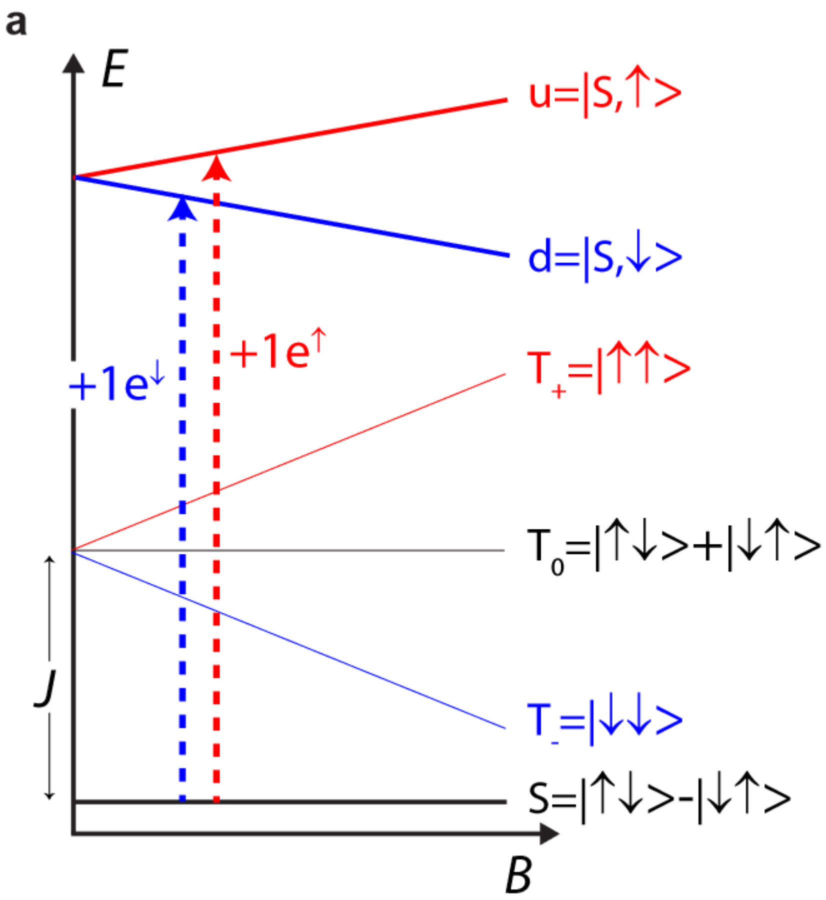
- measure $G_i = dI_i/dV$ at bias voltage V = 0
- „DQD“ diagram -> positive cross-correlation at „crossings“

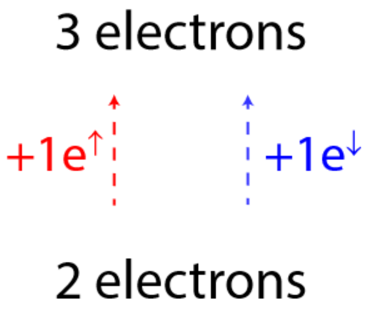


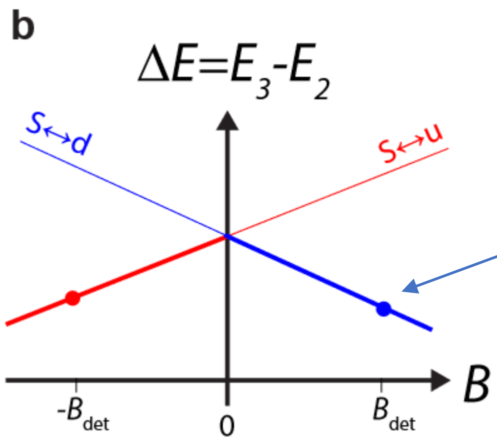
QD as a spin filter

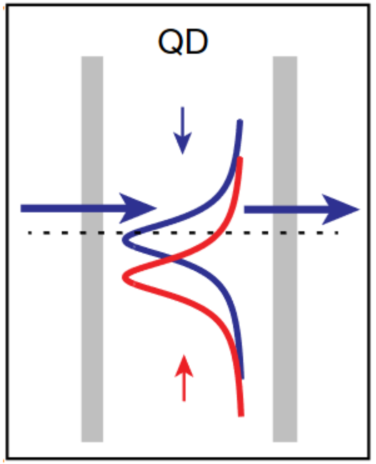
in InAs NW

- at finite B: different dE for spin up vs down electron
- set V_{gate} to select only one transition

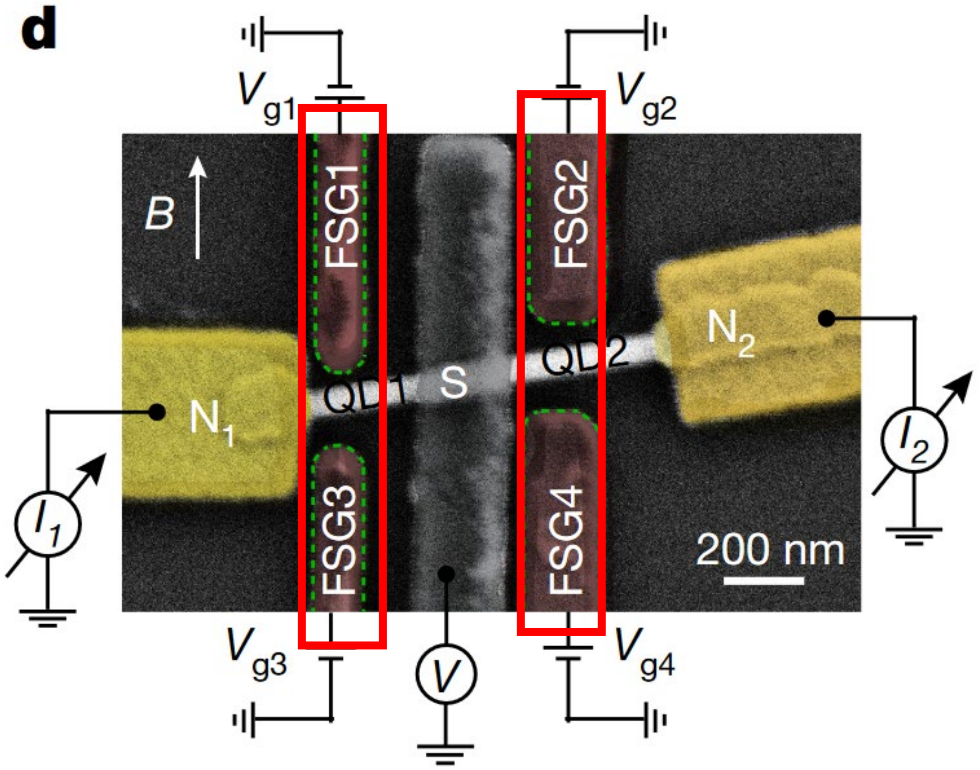






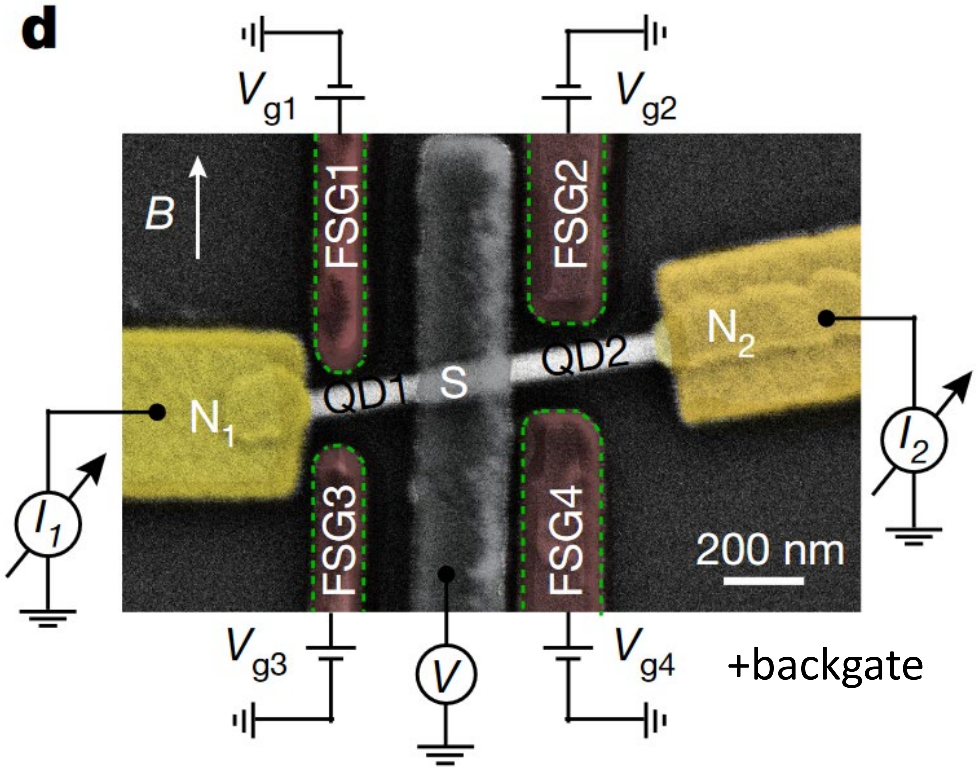


FSG

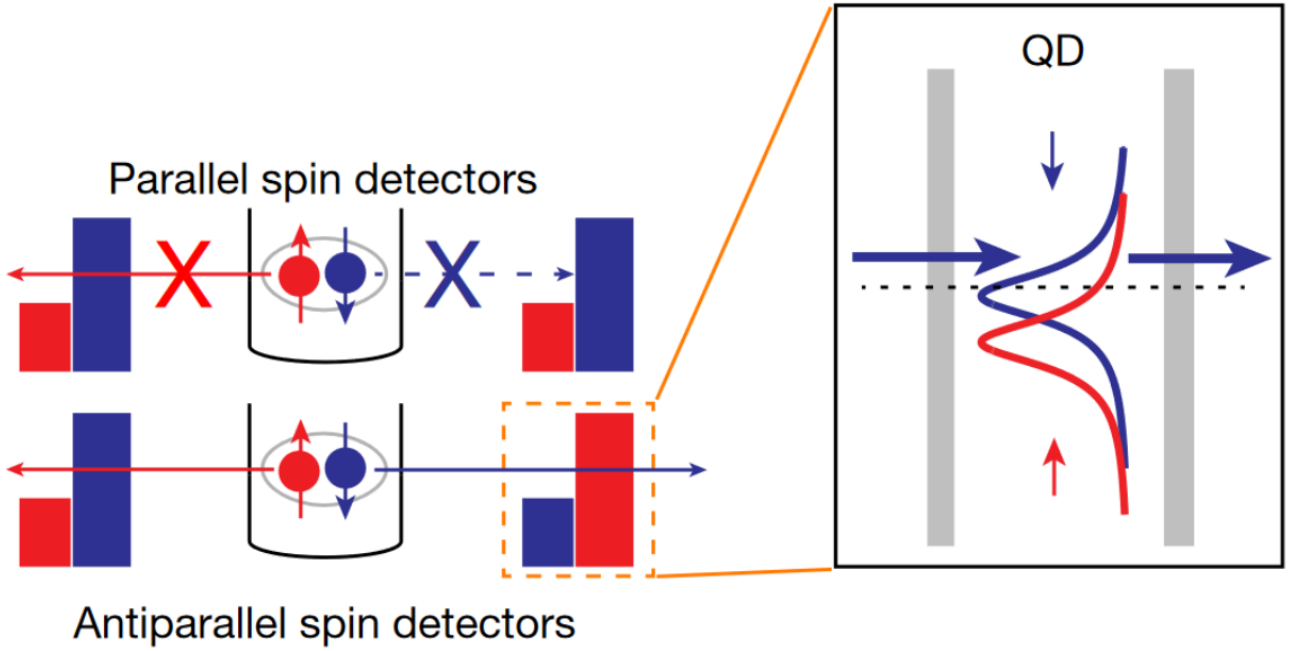


- FSG = ferromagnetic split-gates (Permalloy)
- individual Zeeman splitting for each dot
- four possible states of FSG: (+,+), (+,-), (-,+) and (-,-)
- B_{sw1} ~100mT, B_{sw2}~25mT
  → all four states accessable with B_{ext} sweep sequences

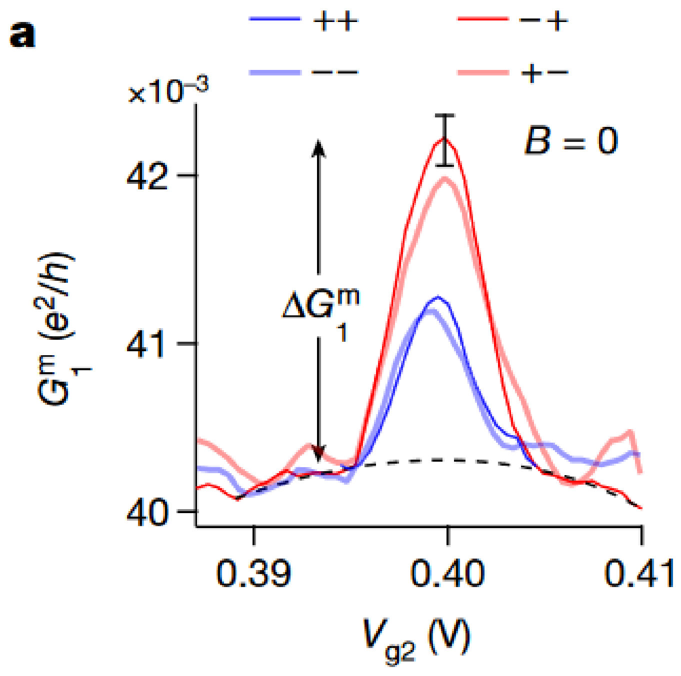
CPS with FSG QD spin filters



+backgate



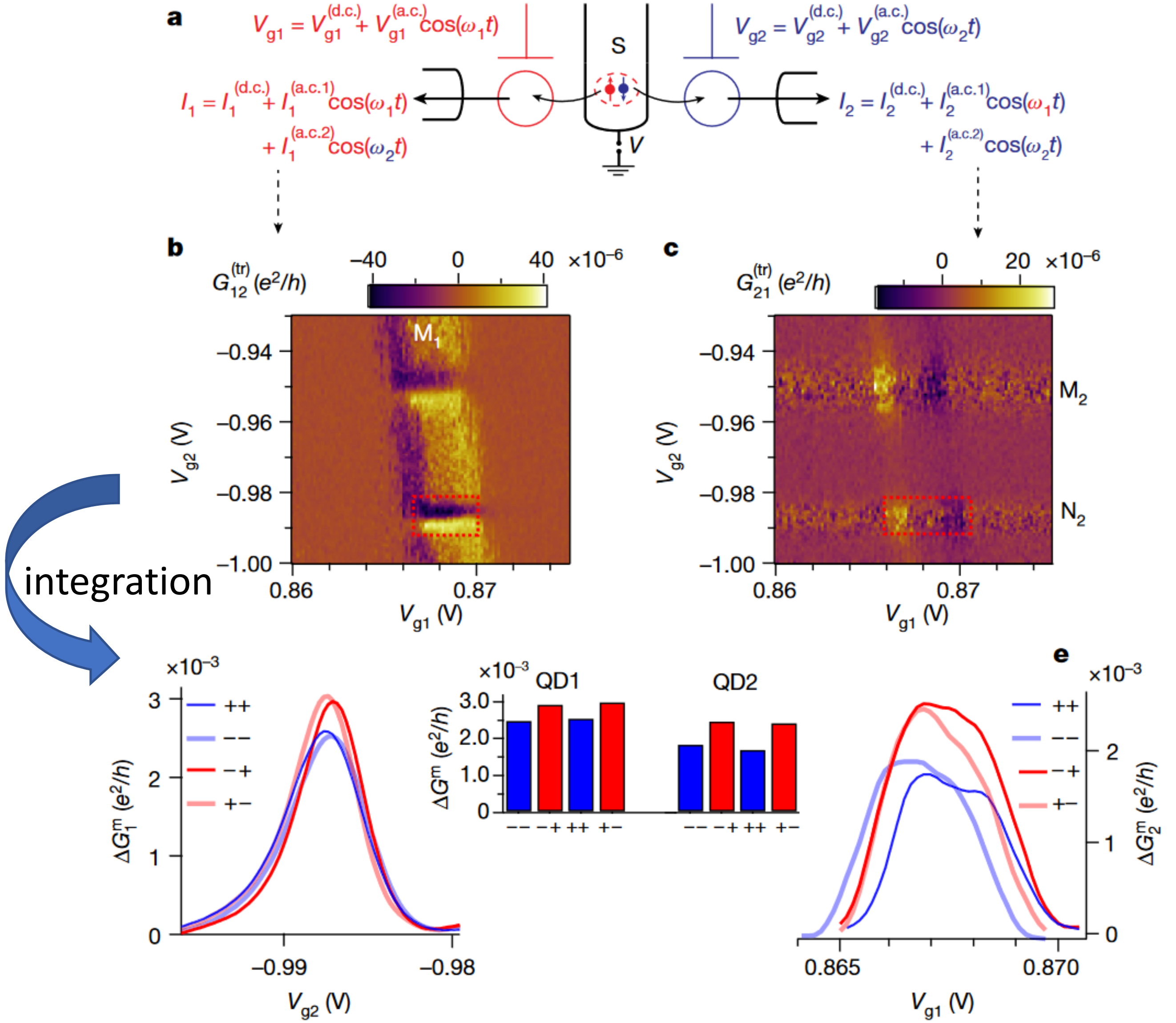
Spin correlation measured in QD1



- negative spin correlation
- suppressed by factor ~ 2

Spin correlation measured in both QDs

- measure transconductance (only sensitive to correlated effects)
- simultaneous suppression of conductance for parallel spins in both QDs → anticorrelation
- CPS fraction:
  - conductance $\eta_{\text{tot}} = \frac{2\Delta G^{\text{cps}}}{G_1^{\text{m}} + G_2^{\text{m}}} \approx 3\%$
  - transcond. $\eta_{\text{2dot}} = \frac{\Delta G^{\text{cps}}}{\Delta G^{\text{cps}} + \Delta G^{\text{other}}} \approx 85\%$



Non-ideal spin-correlation operator

- take into account non-ideal QD polarisation P
- neglect non-CPS contribution to G involving both dots

$$\langle \hat{C} \rangle_{\exp} = \frac{\Delta G_{++}^{\mathrm{cps}} - \Delta G_{+-}^{\mathrm{cps}}}{\Delta G_{++}^{\mathrm{cps}} + \Delta G_{+-}^{\mathrm{cps}}}$$

perfect correlation: +1
perfect anticorrelation: -1

- non-ideal QD spin polarisation is main factor for deviation from Cexp =-1

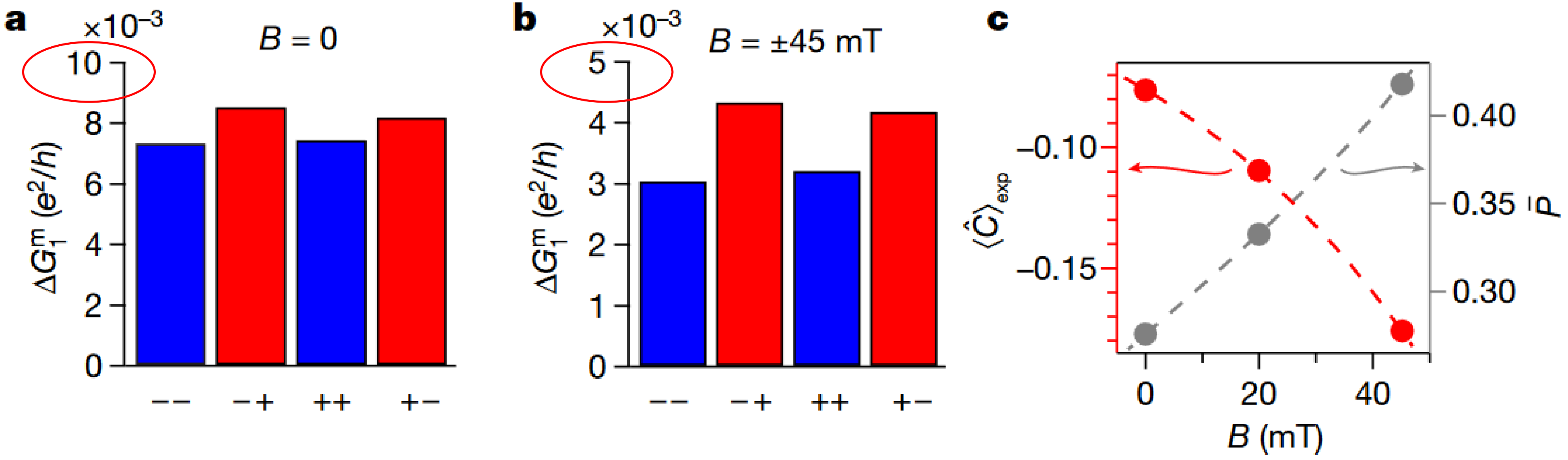
$$\langle \hat{C} \rangle_{\exp} \approx -0.37$$

$$\bar{P} = \sqrt{P_1 P_2} \approx 60\% \text{ at } B = 0$$

clear anticorrelation

Improve QD polarisation

- homogenious $B_{ext} < B_{sw}$ of FSG and B_{crit} of S
- $P \sim B_{ext}$



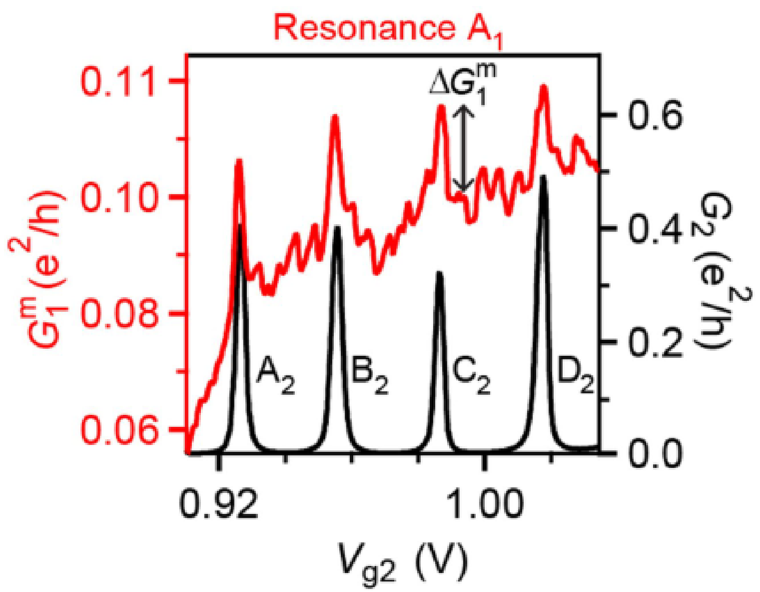
Conclusion

- measured spin-cross correlation of cooper pairs in 2 dots
- improved spin-cross correlation with B_{ext}

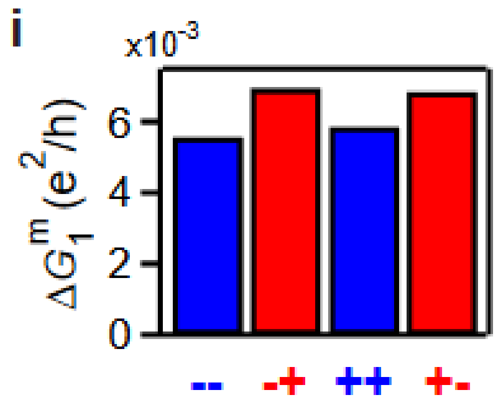
- higher C_{exp} possible with
  - increased QD lifetime
  - higher B_{ext} (needs other FSG)

Appendix

QD1 charge correlation measurement

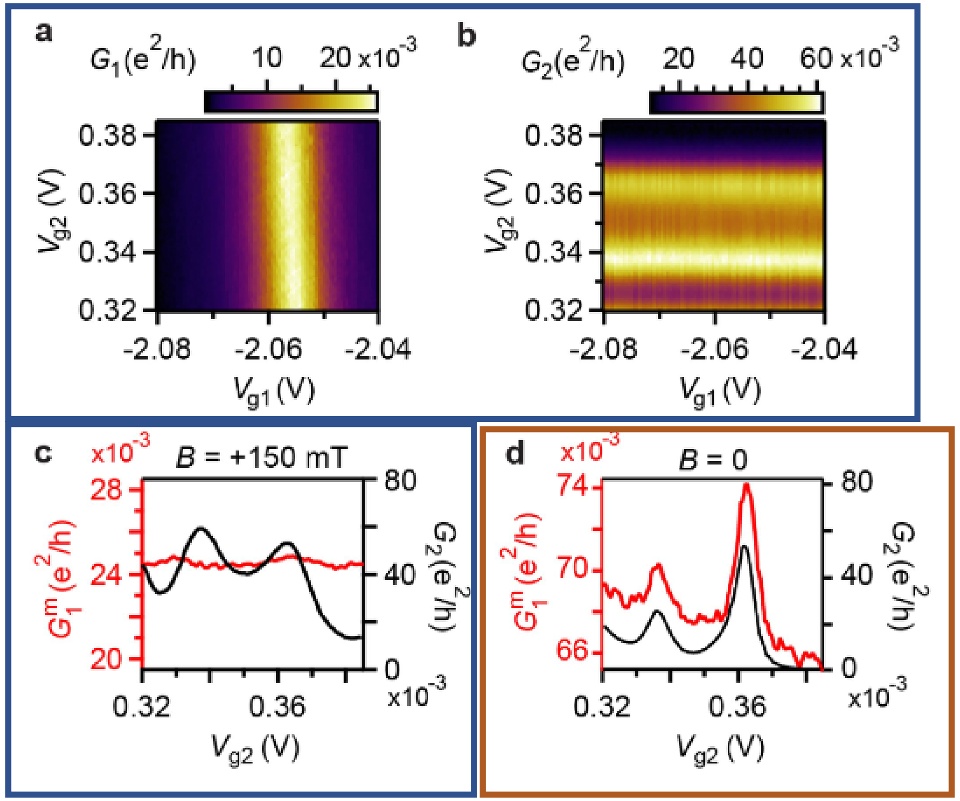


QD1 spin correlation measurement

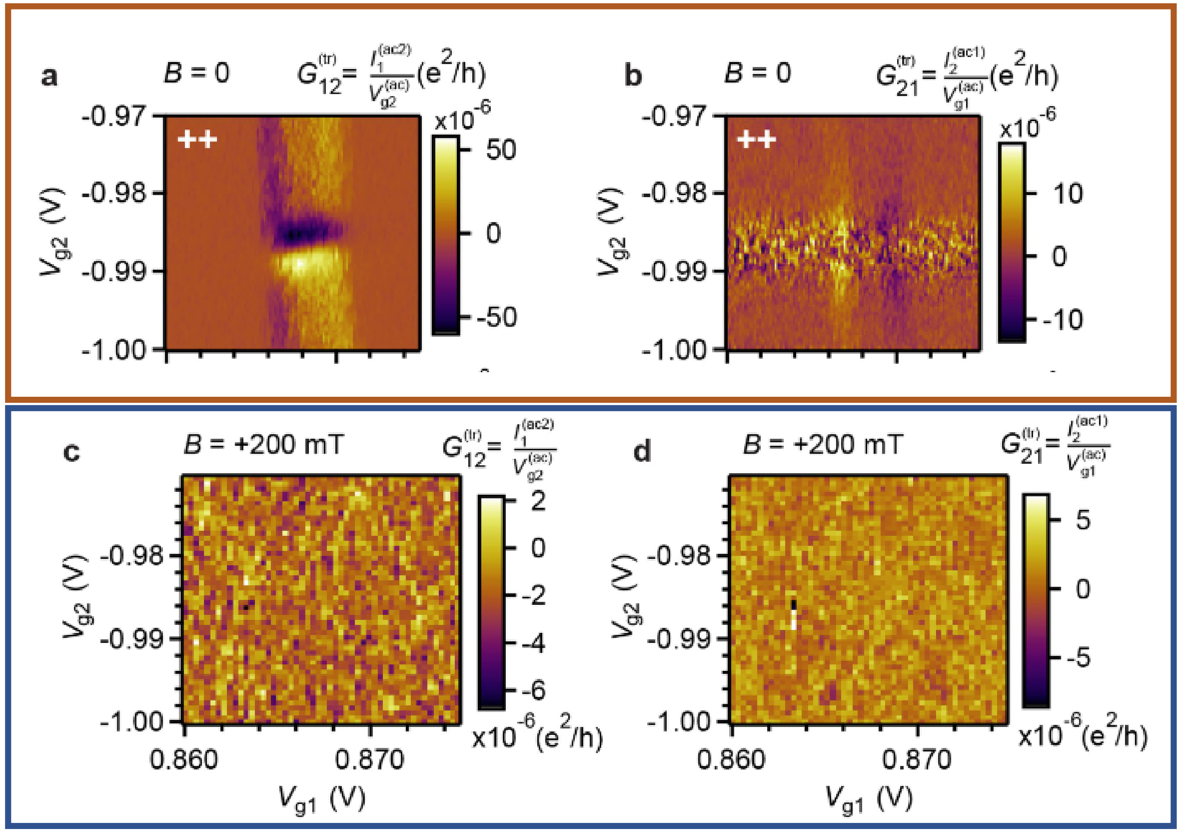


Normal metal vs superconductor

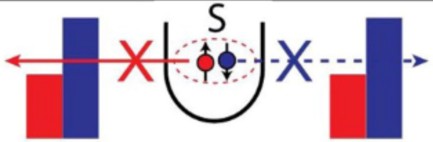
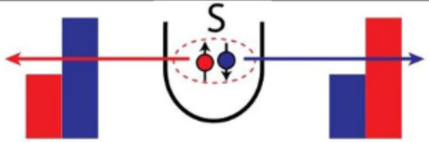
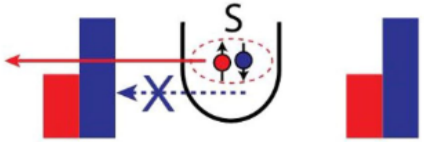
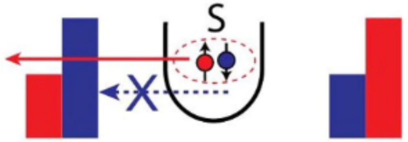
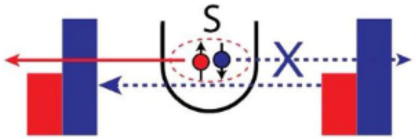
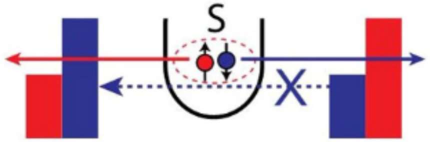
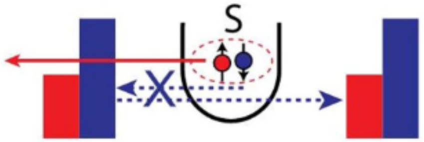
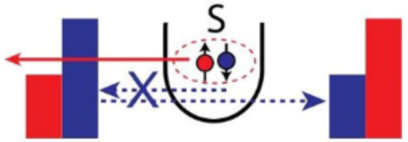
Conductance



Transconductance



Other transport mechanisms

Process	ΔG	Parallel state ($P = 1$)	Antiparallel state ($P = 1$)	ΔG^{++}	ΔG^{+-}
Cooper Pair Splitting (CPS)	$\propto D_1^\uparrow D_2^\downarrow + D_1^\downarrow D_2^\uparrow$			$= 0$	> 0
Local Pair Tunneling (LPT)	$\Delta G_1 \propto D_1^\uparrow D_1^\downarrow$ $\Delta G_2 \propto D_2^\uparrow D_2^\downarrow$			$= 0$	$= 0$
CPS + Single Electron Tunneling (SET)	$\propto D_1^\uparrow D_2^\downarrow D_{12} + D_1^\downarrow D_2^\uparrow D_{12}$			$= 0$	$= 0$
LPT + SET	$\propto D_1^\uparrow D_1^\downarrow D_{12} + D_1^\downarrow D_1^\uparrow D_{12}$ $+ D_2^\uparrow D_2^\downarrow D_{12} + D_2^\downarrow D_2^\uparrow D_{12}$			$= 0$	$= 0$