Christian Scheller 17.08.2018

PRL **118,** 137701 (2017) PHYSICAL REVIEW LETTERS week ending 31 MARCH 2017

Transport Signatures of Quasiparticle Poisoning in a Majorana Island

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(Received 17 December 2016; published 27 March 2017)

We investigate effects of quasiparticle poisoning in a Majorana island with strong tunnel coupling to normal-metal leads. In addition to the main Coulomb blockade diamonds, “shadow” diamonds appear, shifted by $1e$ in gate voltage, consistent with transport through an excited (poisoned) state of the island. Comparison to a simple model yields an estimate of parity lifetime for the strongly coupled island ($\sim 1\ \mu$s) and sets a bound for a weakly coupled island ($> 10\ \mu$s). Fluctuations in the gate-voltage spacing of Coulomb peaks at high field, reflecting Majorana hybridization, are enhanced by the reduced lever arm at strong coupling. When converted from gate voltage to energy units, fluctuations are consistent with previous measurements.

LETTER

doi:10.1038/nature17162

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Exponential protection of zero modes in Majorana islands

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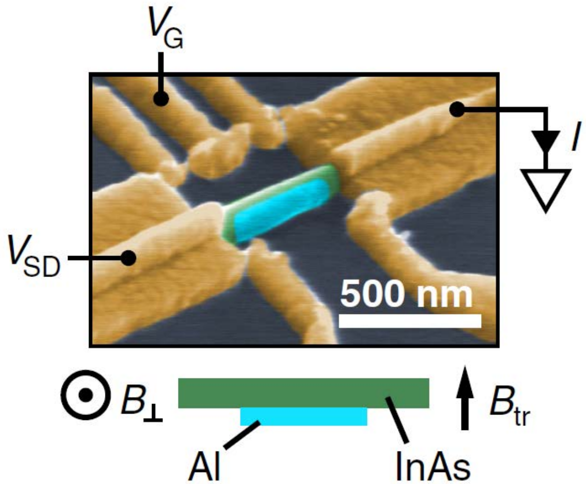
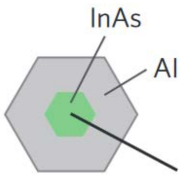
Device Layout

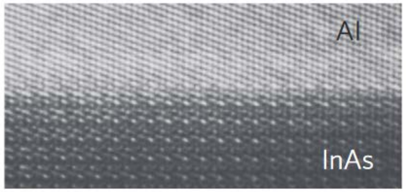
Sample:
- [0001] wurtzite InAs nanowire
- MBE Al on 2 of 6 faces (hard gap)
- Chemical etch to remove Al shell at ends
  $\rightarrow$ L=400nm Al island
- Ti/Au contacts
- Gates near 50nm exposed segment to form dot

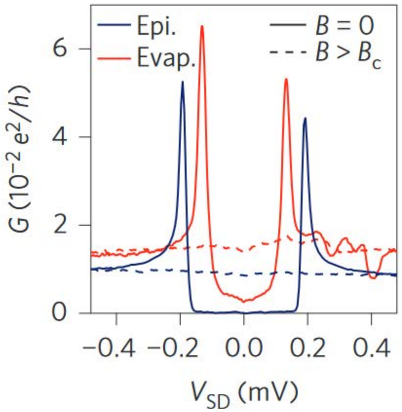


B-field:
- perpendicular to wire
- Thin film Al (10nm) $\rightarrow$ high critical field:
  B_{crit} = 0.7 T (perp. substrate)
  B_{crit} = 0.2 T (in plane)

Measurements: Lockin 5μV, 314Hz, 50mK (fridge)







W. Chang et al., Nat. Nanotech. **10**, 232 (2015)

Charge states of island (no poisoning)

Number of charges on island: $N=2N_{cp}+N_0$

N_{cp}: Cooper pairs on island

N_0: (0/1) occupation of subgap state

State energies $E(N_{cp},N_\Delta,N_0) = E_C/2*(N_G-N)^2+N_0*E_0$

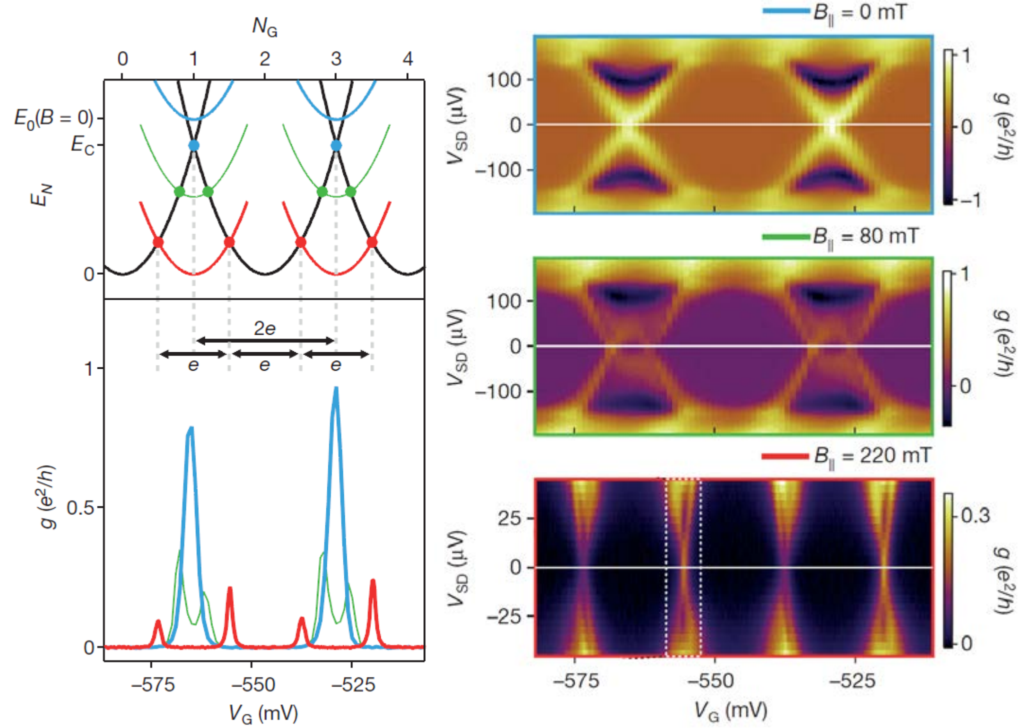
Gate induced charge $N_G=C_GV_G/e$

Capacitance C_G (island – side gate)

Charging energy $E_C=e^2/C_{tot}$

Even N: $(N_{cp},0)$ lowest state: condensate

Odd N: $(N_{cp},1)$ 1 particle in subgap state



S.M. Albrecht et al., Nature **531**, 206 (2016)

Charge transport @degeneracies

- $E_0 > E_C$ Transport through cooper pairs => 2e spacing
- $E_0 < E_C$ Alternating peak spacing S_o, S_e (E_0 lowered by Zeeman energy)
- $E_0 = 0$ Transport through Majorana zero modes => 1e spacing

Charge states of island

Number of charges on island: $N=2N_{cp}+N_{\Delta}+N_0$

N_{cp}: Cooper pairs on island

N_{Δ}: Quasiparticles in BCS continuum

N_0: (0/1) occupation of subgap state

State energies $E(N_{cp},N_{\Delta},N_0) = E_C/2*(N_G-N)^2+N_{\Delta}*\Delta +N_0*E_0$

Gate induced charge $N_G=C_GV_G/e$

Capacitance C_G (island – side gate)

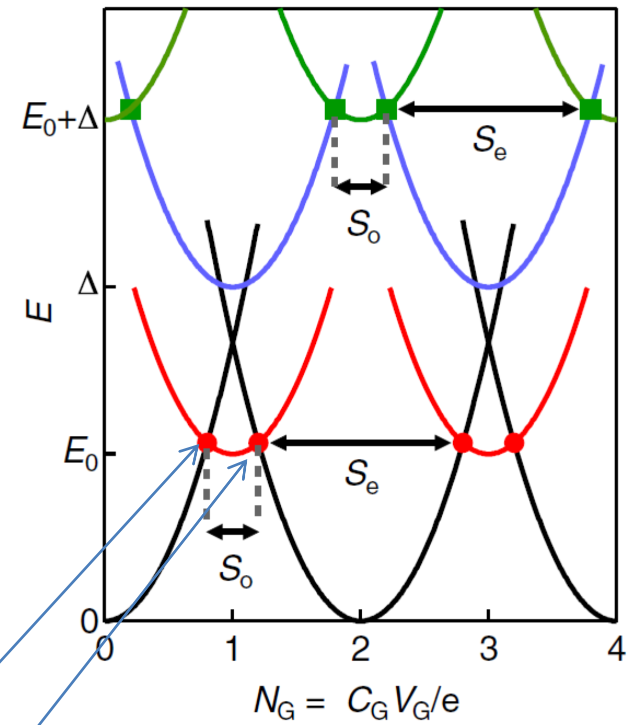
Charging energy $E_C=e^2/C_{tot}$

Even N: $(N_{cp},0,0)$ lowest state is pure condensate, **black**

$(N_{cp},1,1)$ 1st excited state, **green**

Odd N: $(N_{cp},0,1)$ 1 particle in subgap state, **red**

$(N_{cp},1,0)$ 1st excited state, **blue**



Charge transport @T=0 (no poisoning):

- Island in ground state
- Tranport @ degeneracies

$$(N_{cp},0,0) \rightleftarrows (N_{cp},0,1)$$

$$(N_{cp},0,1) \rightleftarrows (N_{cp}+1,0,0)$$

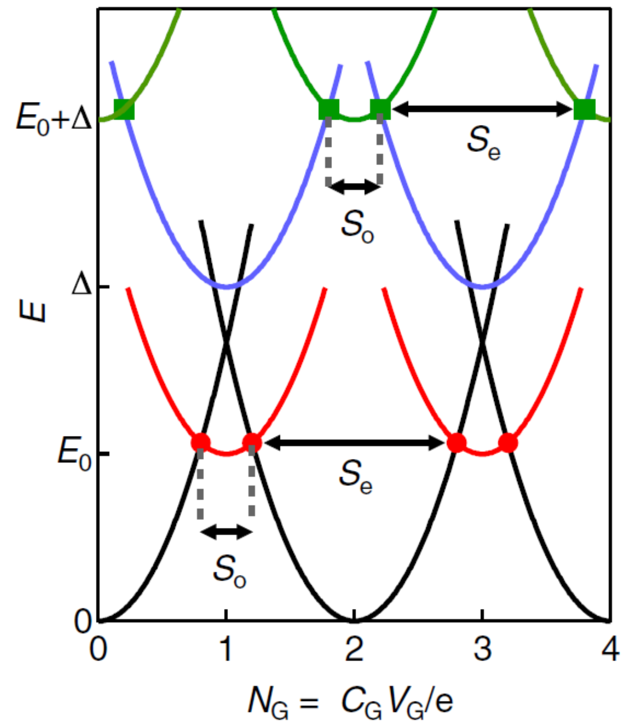
Transport with poisoning

Poisoning: Presence of quasiparticles (relaxe in energy down to BCS peak @ Δ)

Transport at degeneracies with $N_{\Delta}=1$ (green squares)

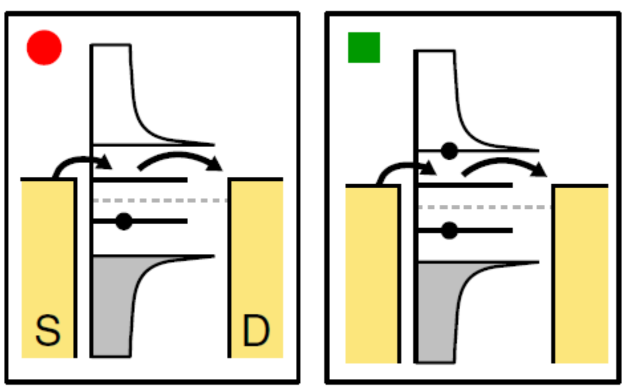
Returning to unpoisoned state:

- Cooper pair recombination $(N_{cp},1,1) \rightarrow (N_{cp}+1,0,0)$
  (possible due to lack of transl. invariance)
- Quasiparticle relaxation to subgap state:
  $(N_{cp},1,0) \rightarrow (N_{cp},0,1)$
- Quasiparticle tunneling to lead
  $(N_{cp},1,N_0) \rightarrow (N_{cp},0,N_0)$



Visibility of “excited state transport”:

- Relaxation rate
- Poisoning rate
- Γ_{SD}



Appearance: Same as ground state, but shifted by 1e in gate voltage

Coulomb blockade diamonds

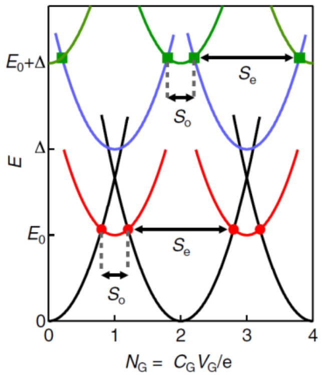
Without subgap state:
1 set of diamonds with 2e peak spacing

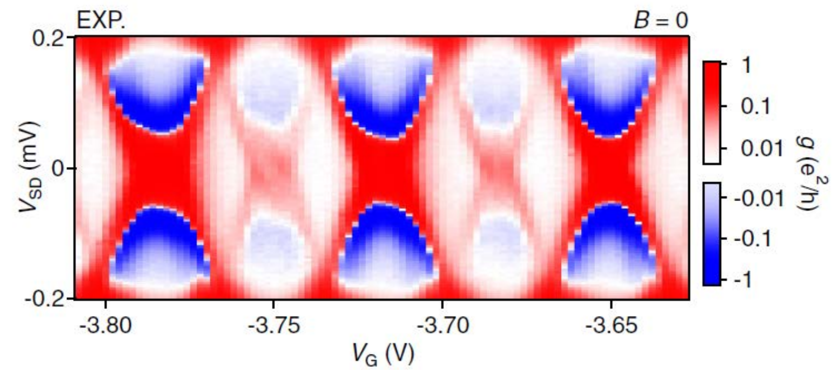
Subgap state:
Alternating peak spacing S_o, S_e

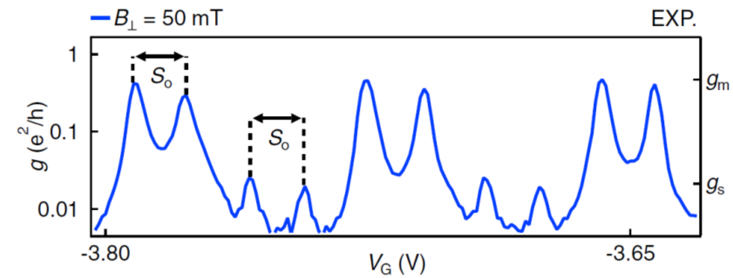
2 sets of diamonds
- Small strong
- Faint large

Nearly vanishing odd diamonds
=> E_0 only slightly smaller than $E_C/2$

- Weak lines within large diamond
  $\rightarrow$ quasiparticle transport

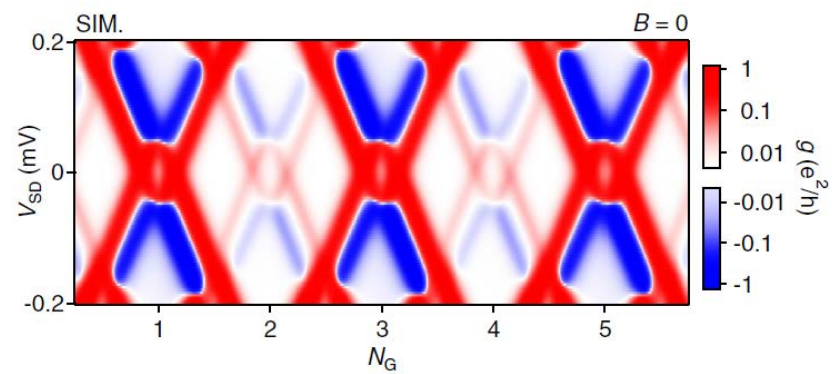






Extracted parameters:
E_C=210μeV, E_0=75μeV, η=6meV/V,
Δ=140μeV (induced gap, onset negative diff. cond.)
Γ_S=1GHz, Γ_D=6GHz (peak height, width), previously ≈ 0.5GHz
τ_{qp}=0.1μs (relaxation quasiparticle to subgap state, previously meas. in similar devices)

Numerical simulations (using above parameters):
Best match using τ_p=1.2μs (poisoning time)
- Electron like $(N_{cp},0,N_0) \rightarrow (N_{cp},1, N_0)$
- Hole like: $(N_{cp},0,N_0) \rightarrow (N_{cp}-1,1, N_0)$

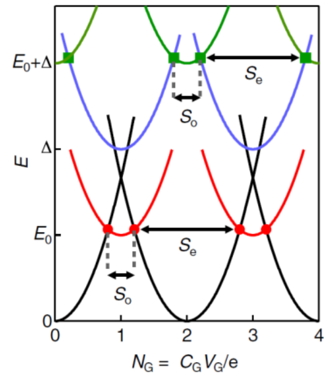


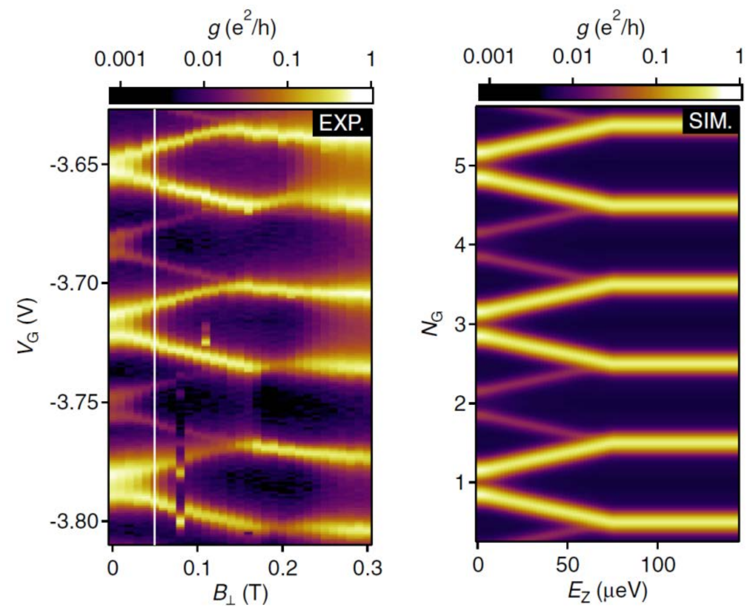
Evolution to Majorana modes

Emergence of zero energy mode:

- Increasing B_{perp} lowers state energy of E_0:
  $E_0 = 75\mu eV - E_Z$
- Uniform spacing $S_o = S_e$ for $B_{perp} > 0.16T$
  => zero energy state
- For B > 0.16 T: state remains at zero
  with small oscillations
  => hybridized Majorana modes

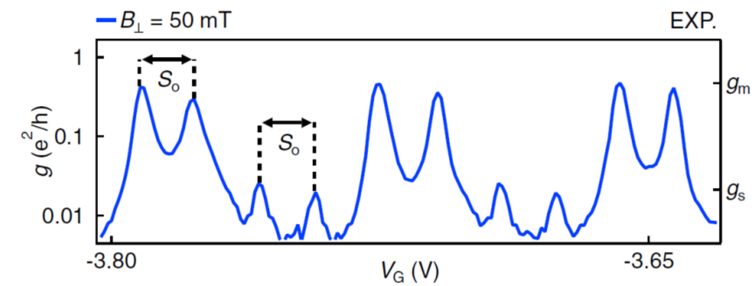
Simulations use same parameters as for CBP





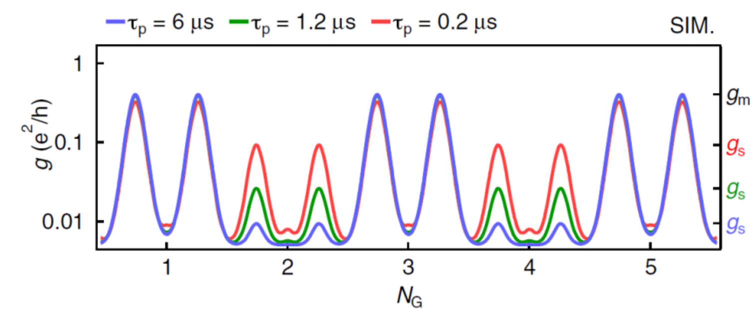
Shadow diamond & poisoning rate:

- Clearly split Coulomb peaks at finite field
- Strongly suppressed shadow peaks
- Peak height depends strongly on τ_p
  => Poisoning rate $\tau_p = 1.2\mu s$



Parity lifetime of $\tau_p = 1.2\mu s$ (obtained from ration gm/gs)

- Here, not ideal tuning for long lifetimes
  (large source drain coupling)
- Estimate g_m/g_s for devices without shadow diamond
  (g_s = noise floor) => conservative estimate **$\tau_p > 10\mu s$**

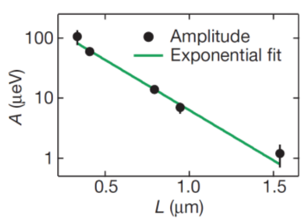


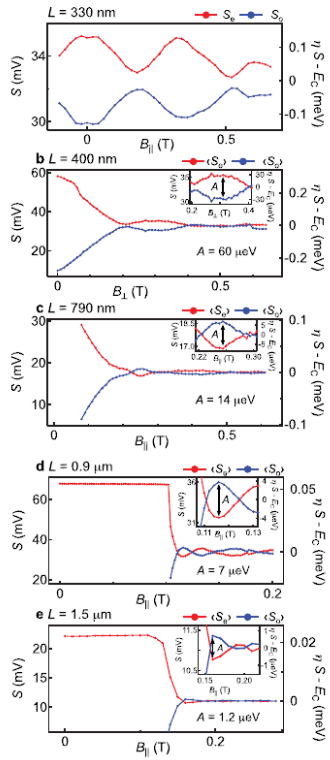
Hybridized Majorana modes

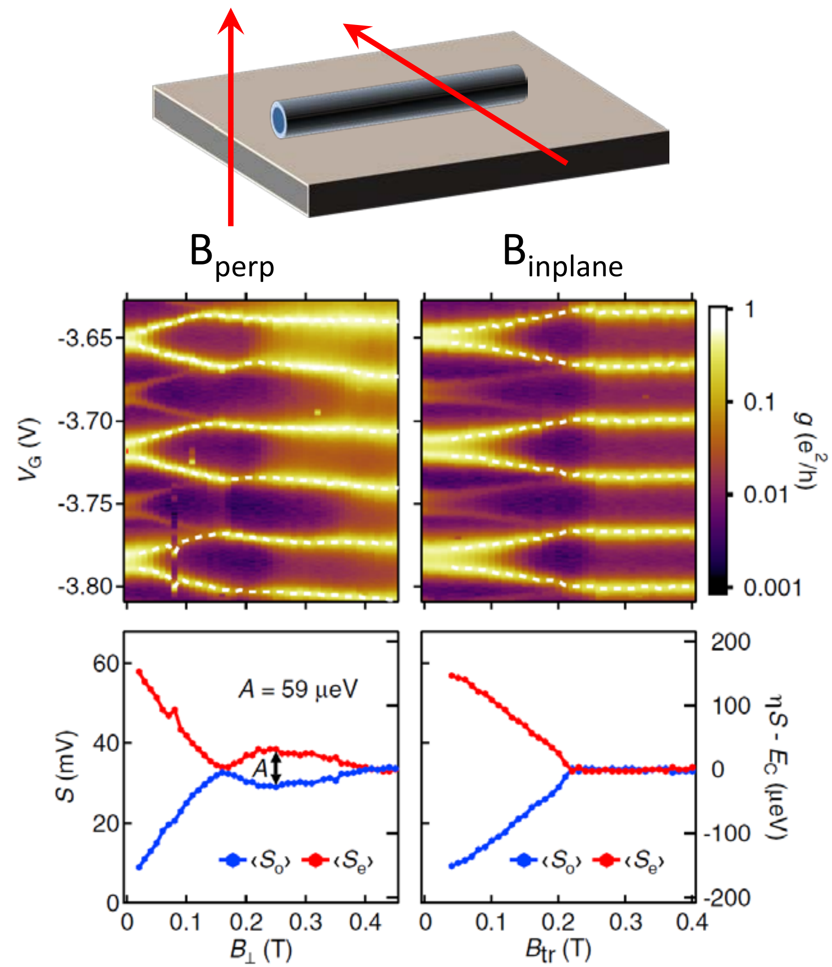
B-field evolution of subgap state:

- spacing $S_o(S_e)$ increases (decreases) with growing field, both B_{perp} , $B_{inplane}$
- Strong and faint peaks merge
  - ⇒ Uniform peak spacing
  - ⇒ zero energy state
- Small oscillations for B_{perp} consistent with hybridizing Majorana modes in finite length device:

$A = A_0 * e^{-L/\xi} = 64\mu eV$
$L = 400nm$
$A_0 = 300\mu eV$
$\xi = 260nm$







No oscillations for $B_{inplane}$?

- Merging happens at higher field, close to gap closing
- => expect “trivial” 1e period, no Majorana modes

Summary

- Observation of merging (oscillating) subgap states
- consistent with hybridizing Majorana modes in finite length samples
- Observation of shadow Coulomb diamond => quasiparticles
- Intensity of shadow diamond => quasiparticle poisoning rates
- Majorana parity lifetime of 10μs (1.2μs) in weakly (strongly) coupled devices