Quantum computing with magnetic impurities in superconductors

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Aim & Motivation

- Chain of magnetic impurities on $s-$ wave superconductor (SC) $\rightarrow$ viable routes to realize topological SC hosting Majorana bound states that holds promise for TQC.
- Majorana bound states based TQC: distant goal$\rightarrow$ no quantum coherent degrees of freedom yet identified in these systems.
- First step in this roadmap: we propose a minimal system to demonstrate the quantumness of these systems: **YSR qubit** arising from two nearby impurities on $s-$ wave SC.

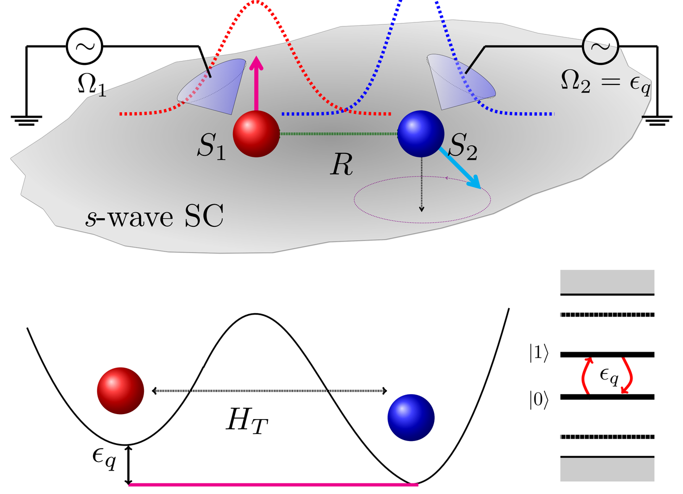
Single YSR state $\rightarrow$YSR qubit - - - -› TQC

- Manipulation and read out of the YSR qubit:
  (a) via dynamics of the impurity spins that engenders it.
  (b) via supercurrents originating from the SC STM tip.

Method I: Magnetization dynamics

In collaboration with **Pascal Simon**, (Laboratoire de Physique des Solides, CNRS, France)

Shiba dimer on $s-$ wave SC:



$$H_{\rm BdG}(t) = \epsilon_p\tau_z + \Delta\tau_x + \textstyle\sum_{j=1,2} V_j(t)\delta(\boldsymbol{r}-\boldsymbol{R}_j)$$

$V_j(t) = J_j\boldsymbol{S}_j(t)\cdot\boldsymbol{\sigma}$

$\boldsymbol{S}_j(t) = (\sin\theta_j(t)\cos\phi_j(t), \sin\theta_j(t)\sin\phi_j(t), \cos\theta_j(t))$

$S_1 \rightarrow$ target spin $\rightarrow$ read out (off-resonant with ϵ_q)

$S_2 \rightarrow$ test spin $\rightarrow$ manipulation (resonant with ϵ_q)

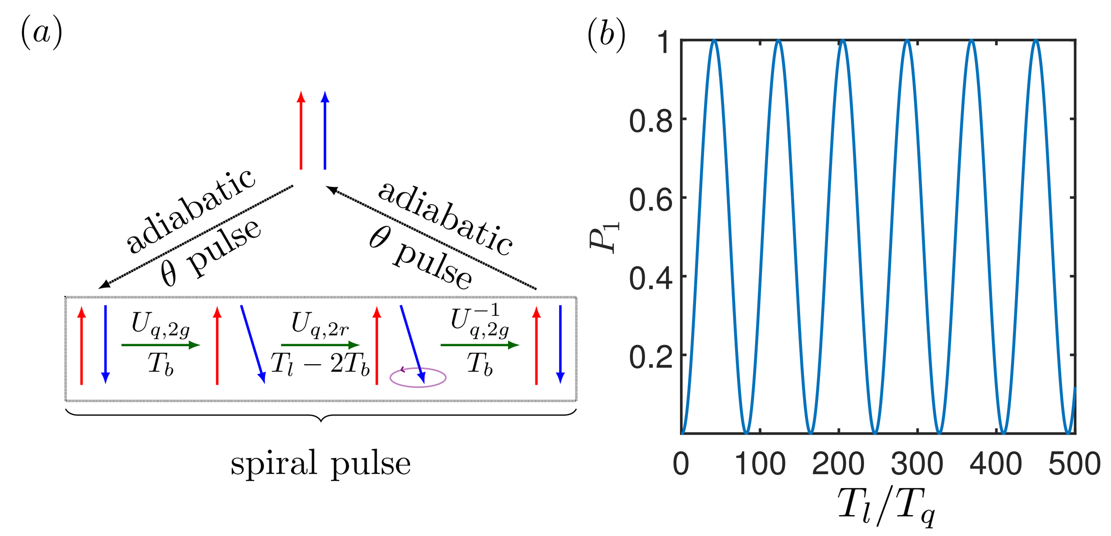
Qubit Manipulation and Read out

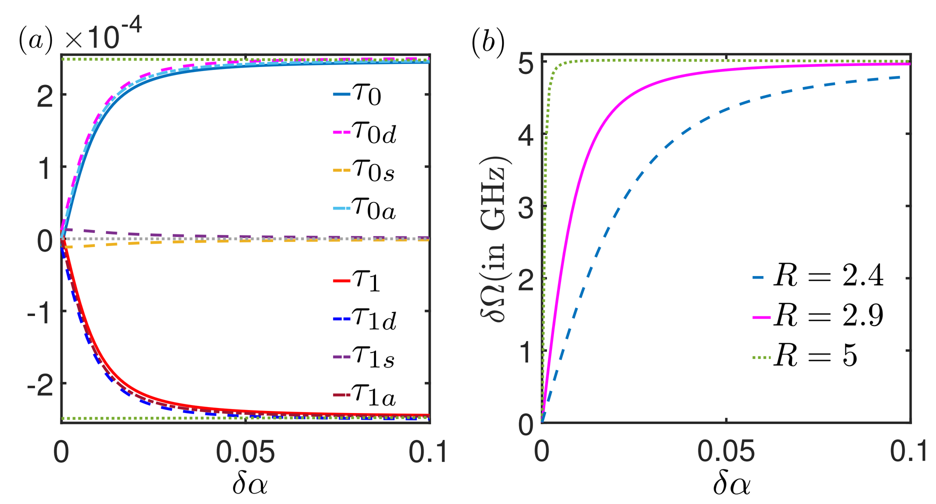
Qubit Hamiltonian: $H_q(t) = \frac{\epsilon_q}{2}\Sigma_z + \boldsymbol{\beta}(t)\cdot\boldsymbol{\Sigma}$

$$\epsilon_q = \Delta\alpha_1\alpha_2\sqrt{\delta\alpha^2 + \left(t_h\sin(k_FR+\pi/4)\cos\tfrac{\theta}{2}\right)^2}$$

$\delta\alpha \gg t_h$, qubit basis $\rightarrow$ left, right states **suitable for qubit operation**

$\delta\alpha \ll t_h$, qubit basis $\rightarrow$ symmetric and antisymmetric superposition





Via feedback torque: $\boldsymbol{\tau} = -J_1S\boldsymbol{n}_1\times\langle\boldsymbol{\sigma}(0)\rangle$

$$\Omega_{r,\sigma} = \frac{\Omega_0 - \frac{\tau'_{\sigma s}}{S}}{1+\frac{\tau_{\sigma d}}{S}}.$$

$\rightarrow \delta\Omega = \Omega_{r,1} - \Omega_{r,0}$ discriminates qubit states in STM-ESR measurements

Rabi time period $T_R = 8.55$ns.

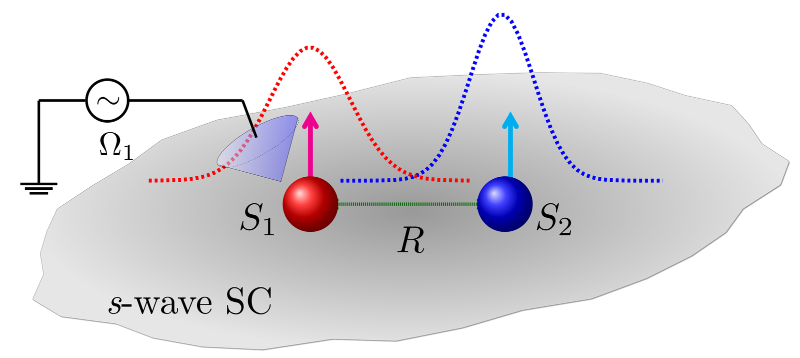
Decoherence: Prime Source: Spin dynamics

Decoherence time $T_2 = 7\mu$s

$\beta_z(t) \approx \sin^2(\theta/2)\dot{\phi}/2 \rightarrow$ shifts the potential well.

$\beta_{x(y)}(t) \propto t_h/\delta\alpha \rightarrow$ Coherent control of qubit.

Method II: Supercurrents



$$H_{\rm BdG}(t) = \epsilon_p\tau_z + \Delta\tau_x + \textstyle\sum_{j=1,2} V_j\delta(\boldsymbol{r}-\boldsymbol{R}_j) + t_c e^{i\phi(t)\tau_z/2}\tau_z\delta(\boldsymbol{r})$$

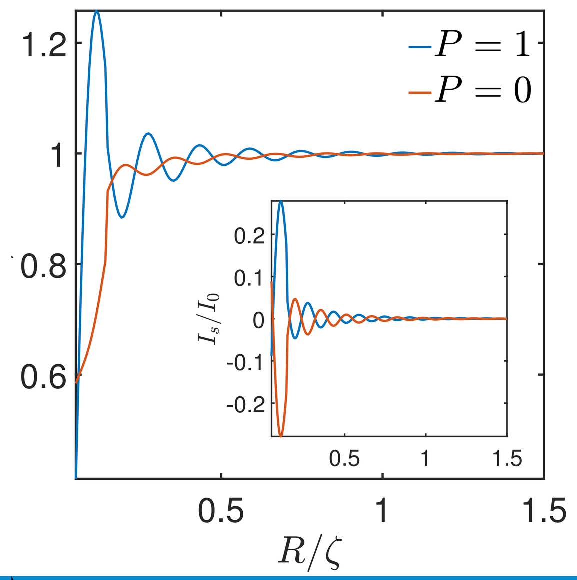
Jospehson spectrscopy of single YSR state

$$I = I_b + (-1)^P I_s$$

$P \rightarrow$ Parity of the YSR state, $I_s \rightarrow$ Shiba current,

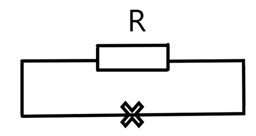
$I_b = I_{b0} + \delta I_b \rightarrow$ Bulk current

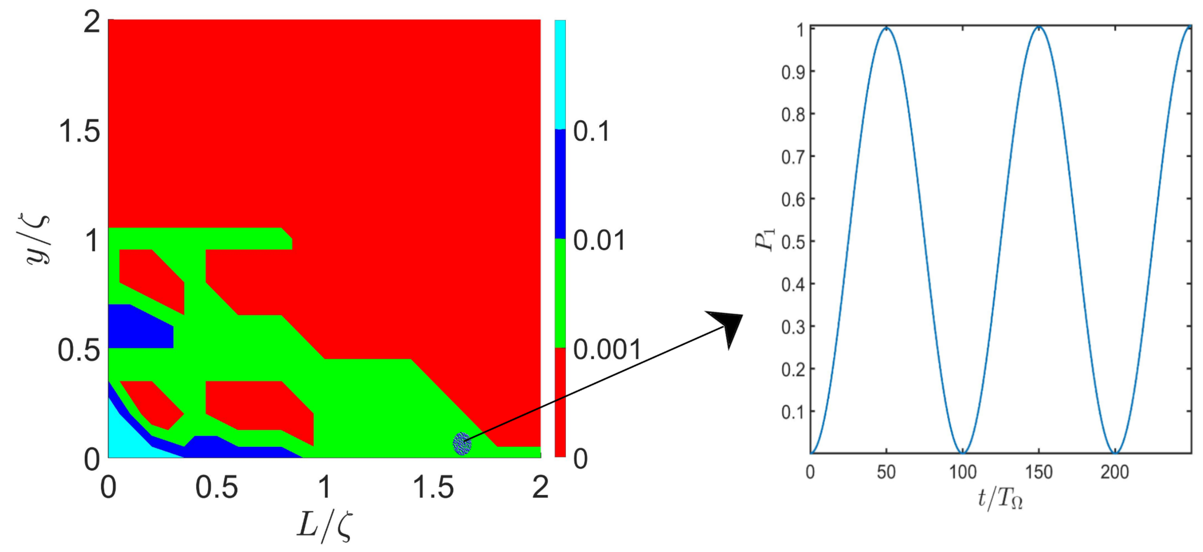
$I_{b0} \rightarrow$ Bare current, $\delta I_b \rightarrow$ Bulk current contribution from YSR state



Using JSTS for qubit manipulation

$\rightarrow$ Current bias applied over the junction in presence of a resistor





Rabi time period, $T_R = 9.2$ns

Read Out:

Electron-Photon coupling $\rightarrow$ Dispersive read out

Controlling hybridization of Majorana zero modes via YSR state

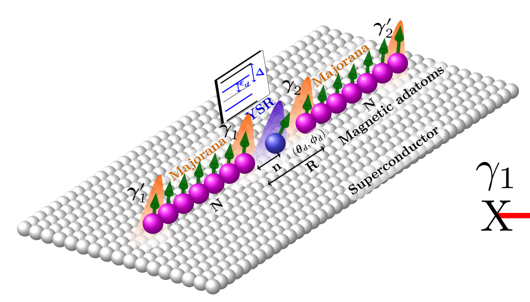
In collaboration with **Ioannis Ioannis, Thore Posske** (University of Hamburg, Germany), **Oladunjoye A. Awoga, Martin Leijnse** (Lund Unviersity, Sweden)

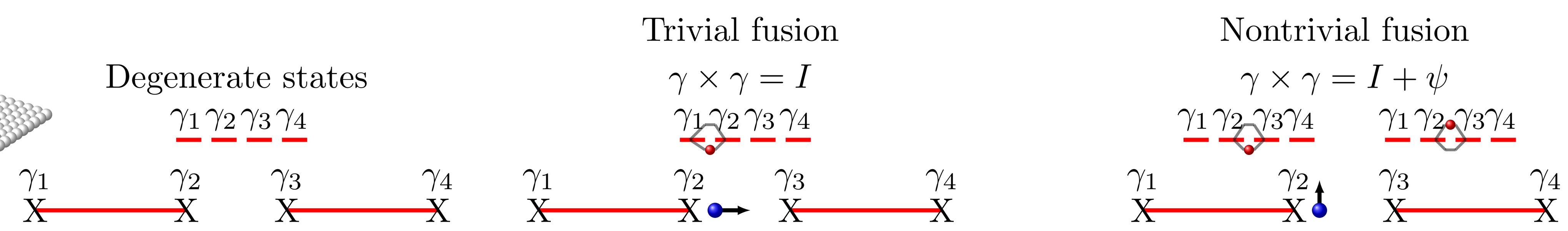
AIM: To control the hybridiation of Majorana zero modes for braiding and fusion for future application in quantum computation $\rightarrow$ Our proposal is to achieve that using YSR states

Popular setups for realizing MZMs:

(i) helically ordered magnetic chains on a conventional s-wave SC,

(ii) ferromagnetically ordered magnetic chains on a spin-orbit coupled SC.



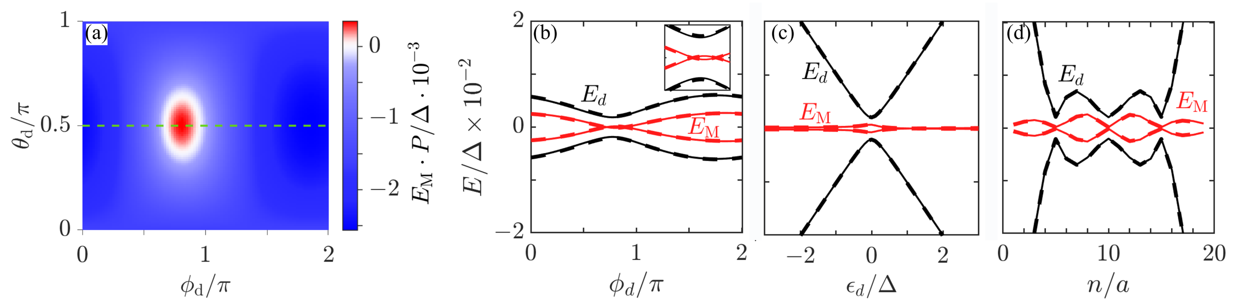


Control Parameters:

(a) Orientation of the impurity (θ, ϕ)

(b) Coupling strength to the SC (ϵ_d)

(c) Distance of the impurity from the magnetic chain (n)



Conclusion and Outlook

$\rightarrow$ YSRQ: spin dimers on s-wave SC. Manipulation and read out via dynamics and supercurrents.

$\rightarrow$ Control of MZMs hybridization via YSR state

$\rightarrow$YSRQ+ MZMs $\rightarrow$ Universal Quantum Computation

Ref: A. Mishra et.al. PRX Quantum 2, 040347 (2021)