A Yu-Shiba-Rusinov Qubit

Archana Mishra[1] (mishra@magtop.ifpan.edu.pl), Pascal Simon[2], Timo Hyart[1,3] and Mircea Trif[1]

[1]International Research Centre MagTop, Institute of Physics, Polish Academy of Sciences, Warsaw, Poland

[2]Laboratoire de Physique des Solides, CNRS, Univ. Paris-Sud, France, [3]Department of Applied Physics, Aalto University, Aalto, Espoo, Finland

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 via dynamics of the impurity spins that engenders it.

Magnetization Dynamics $\rightarrow$ Qubit Dynamics

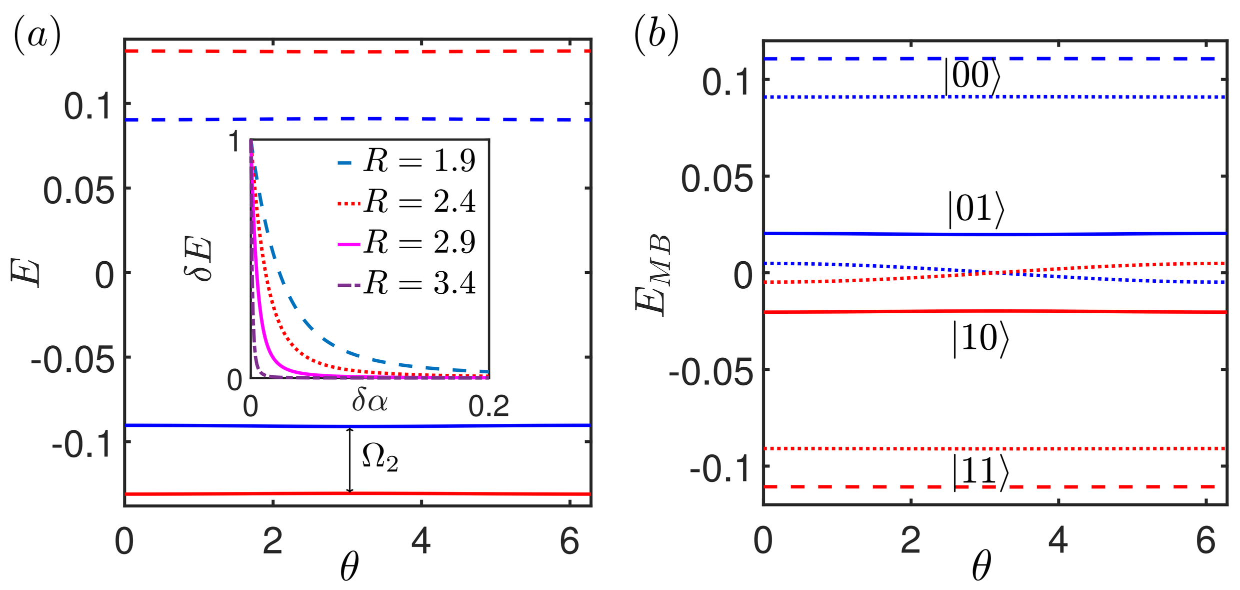
Qubit Hamiltonian

Interaction of individual spins with SC$\rightarrow$ $H_i(t) \approx -\Delta\left(\frac{\boldsymbol{n}_i\cdot\boldsymbol{\sigma}}{\alpha_i} + \tau_x\right) + (\boldsymbol{n}_i \times \dot{\boldsymbol{n}}_i)\cdot\boldsymbol{\sigma}$ $\rightarrow$ Berry phase contribution

Tunneling of YSR states at different impurities$\rightarrow$ $H_T(t) = -\Delta(\boldsymbol{n}_1\cdot\boldsymbol{\sigma})(\boldsymbol{n}_2\cdot\boldsymbol{\sigma})[\tilde{I}_0(R)\tau_x + \tilde{I}_1(R)\tau_z]$

Projection to $\downarrow$ hybrid in-gap states

$$\textbf{Qubit Hamiltonian: } H_q(t) = \frac{\epsilon_q}{2}\Sigma_z$$



$\epsilon_q = \Delta\alpha_1\alpha_2\sqrt{\delta\alpha^2 + (t_h \sin(k_F R + \pi/4)\cos\frac{\theta}{2})^2}$

$\delta\alpha \gg t_h$, qubit basis $\rightarrow$ left, right states

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

Figure: (a) Single particle energy spectrum (b) The many-body energy spectrum. YSR qubit states encoded in $\{|10\rangle, |01\rangle\}$.

$\delta\alpha \gg t_h$ **suitable for qubit operation**

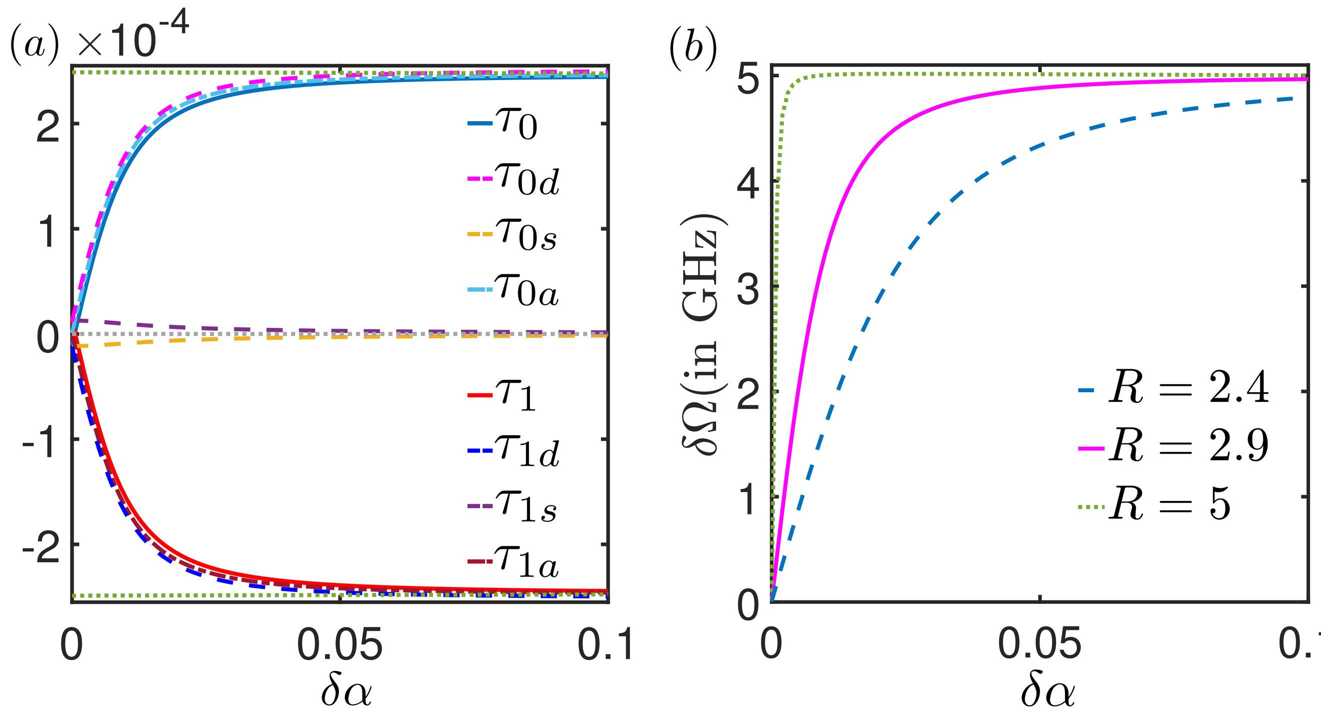
Including the imprints of the classical spin dynamics:

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

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

$\beta_x(y) \propto t_h/\delta\alpha \rightarrow$ Coherent control of qubit.

Qubit Read Out



Via feedback torque: $\boldsymbol{\tau} = -J_1 S\boldsymbol{n}_1 \times \langle\boldsymbol{\sigma}(0)\rangle$

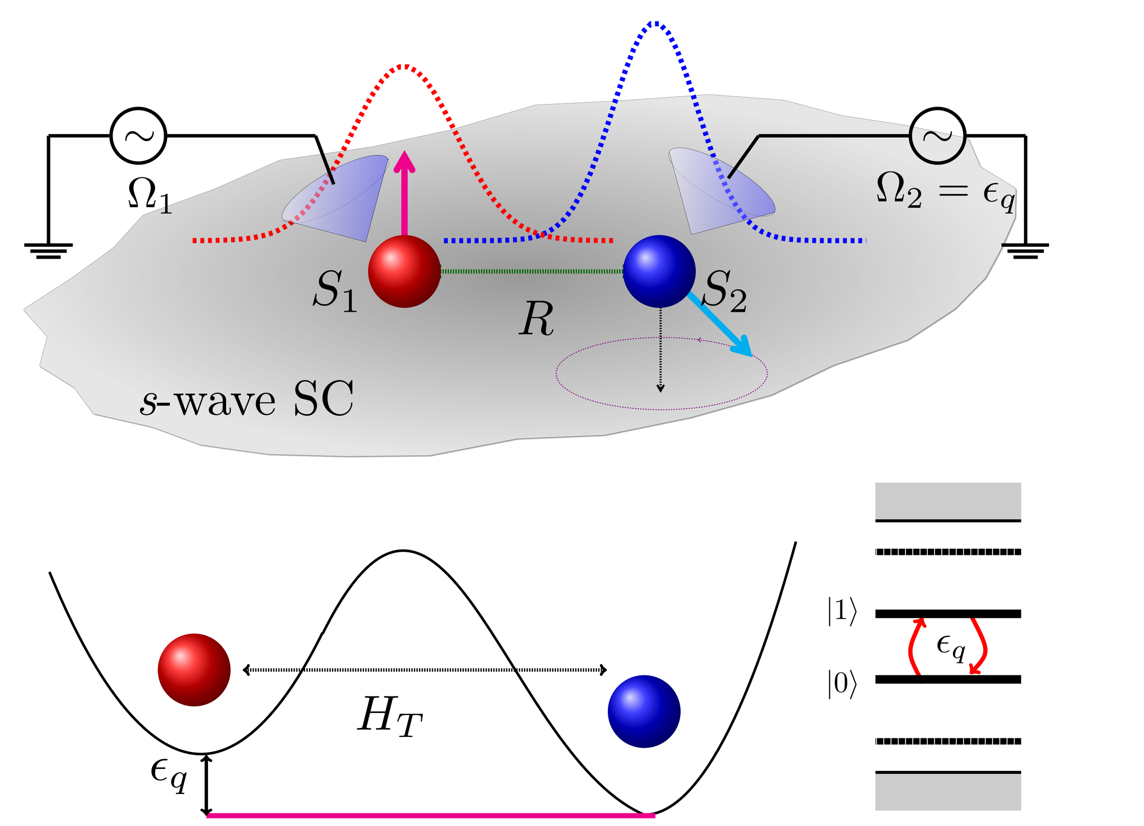
$$\Omega_{r,\sigma} = \frac{\Omega_0 - \frac{\tau'_{\sigma s}}{S}}{1 + \frac{\tau'_{\sigma d}}{S}}.$$

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

$\rightarrow t_h^2 \ll \Omega_1|\delta\alpha|$, dynamic torque dominates, $\tau_d \approx (\Omega_1/4)\sin\theta \rightarrow$ suitable for read out

Basic Idea

Shiba dimer on $s-$ wave SC:



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

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

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

$\boldsymbol{S}_1 \rightarrow$ target spin $\rightarrow$ read out (off-resonant with ϵ_q)

$\boldsymbol{S}_2 \rightarrow$ test spin $\rightarrow$ manipulation (resonant with ϵ_q)

Core of our proposal:

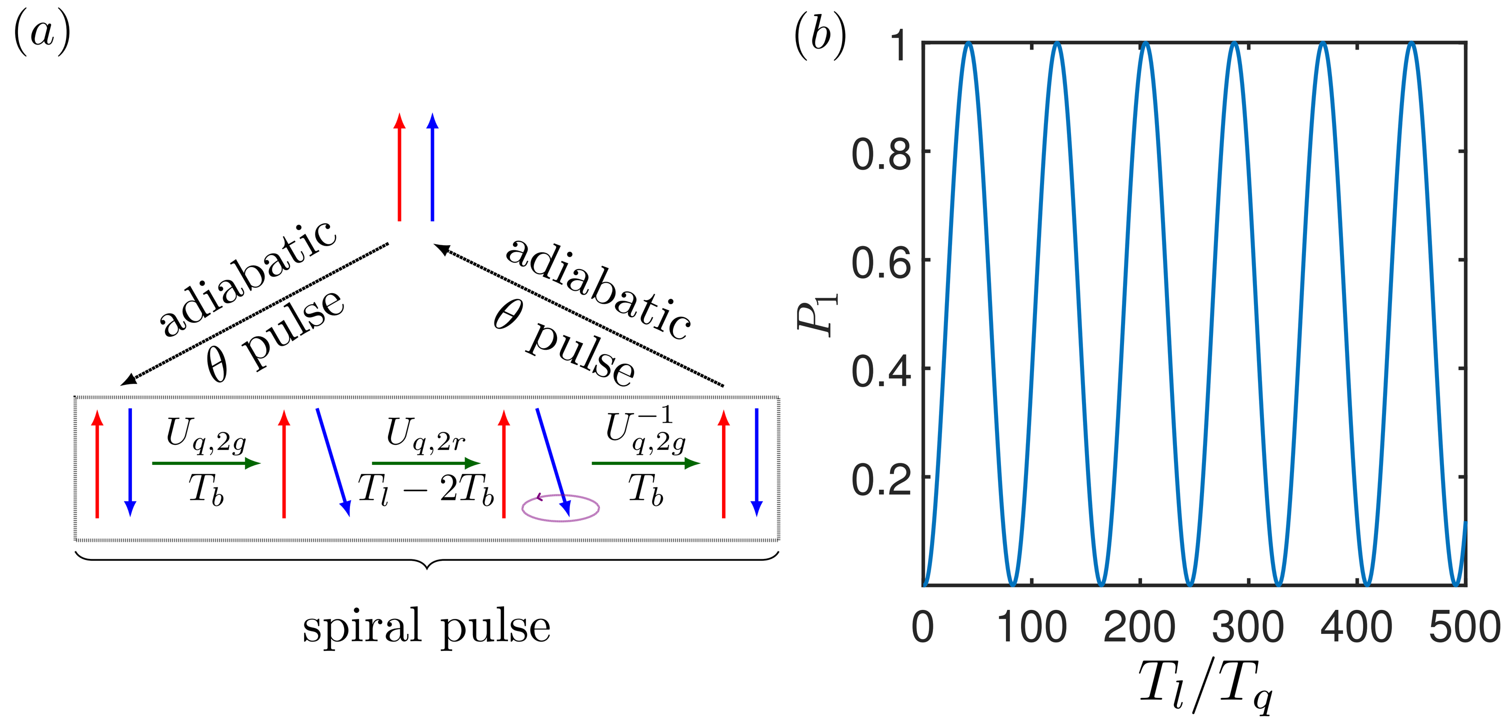
- Dynamics of the spin biases the double well potential
- Frequency shift: feedback *universal* torques acting on classical spin due to its dynamics $\rightarrow$ aids to extract occupation of in-gap states

Single precessing magnetic impurity (Mishra et. al., PRB 103, L121401 (2021)):

$\boldsymbol{\tau}_S(t) = -(n_S - 1/2)F_S\,\dot{\boldsymbol{n}}(t)$$\rightarrow$ **Universal torque with geometric origin**

Qubit Manipulation and Decoherence

Manipulation: via precessing the test spin $\boldsymbol{S}_2 \rightarrow \beta_{x(y)}(t)$ dictate coherent manipulation.



Rabi time period $T_R = 8.55$ns.

Decoherence:

Prime Source: Spin dynamics

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What leads to coherent manipulation also cause decoherence.

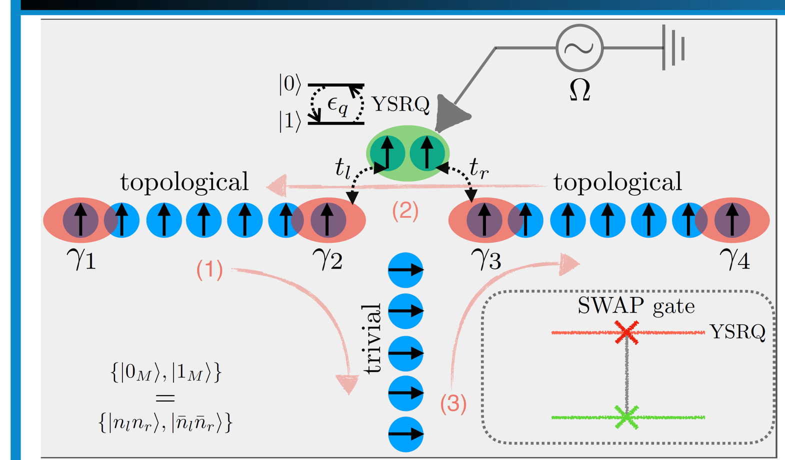
Decoherence time $T_2 = 7\mu$s.

The pulse sequences proposal for coherent manipulation of the YSR qubit.

Adiabatic pulse: $\theta(t) = \pi\tanh(2\pi t/T_a)$, $T_a > T_q$, $T_q = \hbar/\epsilon_q$.

Spiral pulse: $\theta(t) = \pi - \delta\theta\left(\tanh\frac{t}{T_b} - \tanh\frac{t - T_l}{T_b} - 1\right)$ and $\phi(t) = \Omega_2 t \rightarrow U_{q,2} \approx U^{-1}_{q,2g}U_{q,2r}U_{q,2g}$.

YSR-Majorana hybrid qubit



YSR Qubit

+

Majorana Qubit

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Universal Quantum Computation

Initialize and measure MQ via the read out of YSRQ.

Conclusion & Outlook

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

$\rightarrow$ Extend the formalism to include SOC.

$\rightarrow$ Extend the dynamical framework of Shiba dimers to Shiba chains and 2D Shiba islands.

$\rightarrow$ To manipulate & detecte MZM via magnetization dynamics $\rightarrow$ fingerprint in STM+ESR signals.

Reference: A. Mishra et. al. PRX Quantum 2, 040347