

From Yu-Shiba-Rusinov states to Qubits

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Introduction to Yu-Shiba-Rusinov state

Anderson Theorem: Superconductivity in conventional superconductor is robust with respect to disorder in the host material preserving time reversal symmetry.

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What happens when the impurity is magnetic?

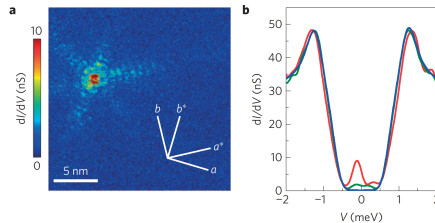
Introduction to Yu-Shiba-Rusinov state

Anderson Theorem: Superconductivity in conventional superconductor is robust with respect to disorder in the host material preserving time reversal symmetry.



What happens when the impurity is magnetic?

Proposed by Yu (1965), Shiba (1968), and Rusinov (1969).
Observed by A. Yazdani et. al. in *Science* **275**, 1767 (1997)



G. Menard et. al., *Nature Physics* (2015)

Single static magnetic impurity

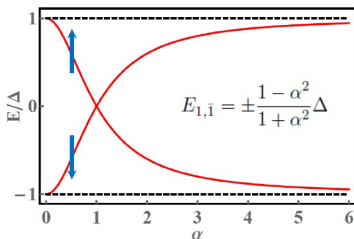
$$H_{\text{tot}} = H_0 + H_{\text{imp}}$$

$$H_0 = \epsilon_k \tau_z + \Delta \tau_x$$

$$H_{\text{imp}} = -JS \cdot \sigma \delta(\mathbf{r})$$

Localized spin polarized in-gap states emerging as a result of the exchange coupling:

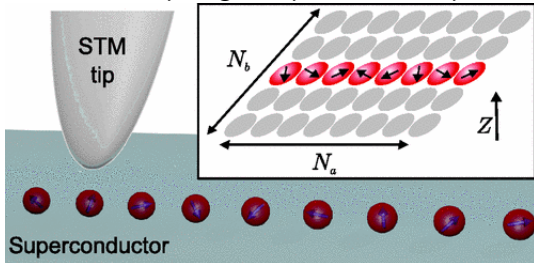
$$\alpha = \pi \nu_0 JS$$



YSR states

Why YSR state is interesting

Array of magnetic impurities on SC $\rightarrow$ setup to realize TS hosting Majorana Fermion $\rightarrow$ Topological quantum computation

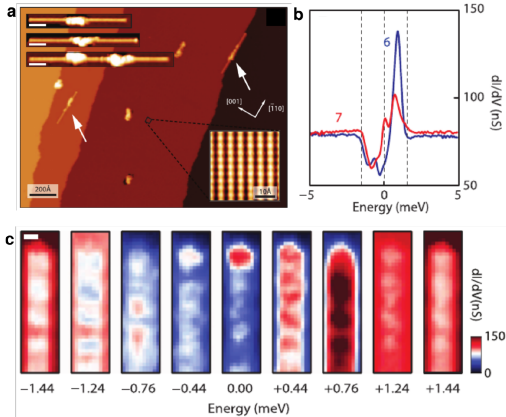


Nadj-Perge et al, PRB (2013)

Vazifeh et al, PRL (2013)

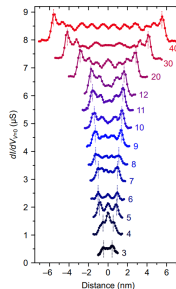
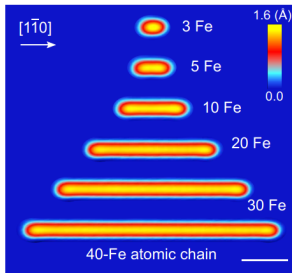
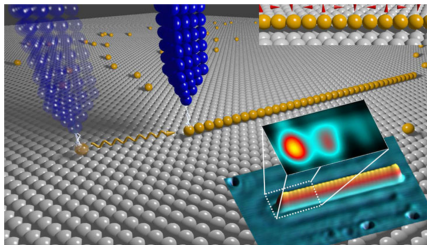
Klinovaja et al, PRL (2013)

Braunecker et al, PRL (2013)



Majorana zero modes at the end of the chain

S. Nadj-Perge et. al., Science (2014)



Atom by atom fabrication of magnetic chain on SC

Kim et. al. Science Advances (2018)

The challenges for YSR based qubit

- No coherent quantum degree of freedom yet identified
- Need for methods to scrutinize Majorana Fermions apart from conductance

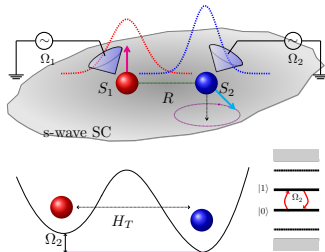
An intermediate (conventional) qubit:



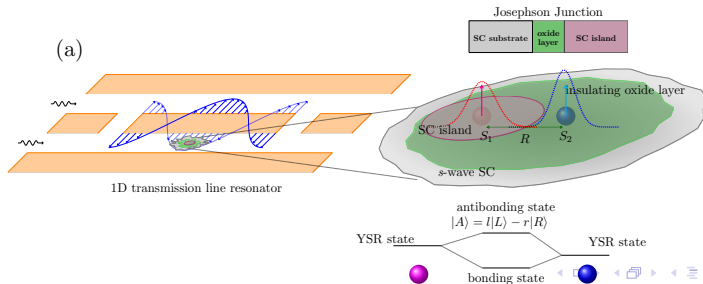
Single YSR state $\rightarrow$ YSR qubit ----- $\rightarrow$ TQC

Building Yu-Shiba-Rusinov Qubit

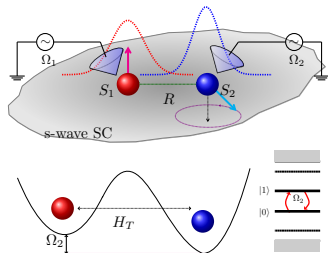
Precessing magnetic impurity



cQED



Dynamics proposal



Crux of YSR qubit proposal:

- Dynamics of the spin biases the double well potential
- Frequency shift (back action on the spin): occupation of in-gap states

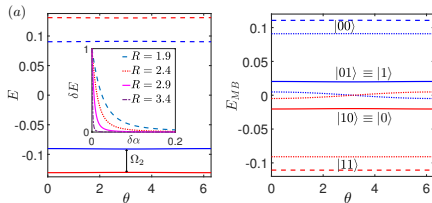
$$H_{\text{BdG}}(t) = H_0 + H_{\text{imp}}(t),$$

$$H_0 = \epsilon_p \tau_z + \Delta \tau_x,$$

$$H_{\text{imp}}(t) = J_1 \mathbf{S}_1(t) \cdot \boldsymbol{\sigma} \delta(\mathbf{r}) + J_2 \mathbf{S}_2(t) \cdot \boldsymbol{\sigma} \delta(\mathbf{r} - \mathbf{R})$$

Qubit Hamiltonian

Energy Spectrum

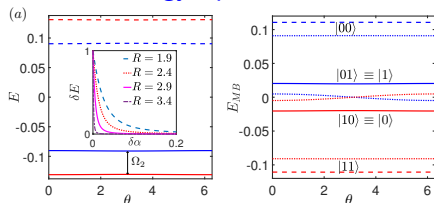


$$H_Q = \frac{E_q}{2} \Sigma_z$$

YSR qubit Hamiltonian in the odd parity sector

Qubit Hamiltonian

Energy Spectrum



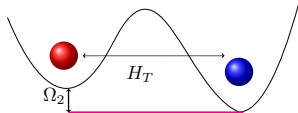
$$H_Q = \frac{E_q}{2} \Sigma_z$$

YSR qubit Hamiltonian in the odd parity sector

$$E_q = \Delta \alpha_1 \alpha_2$$

$$(\alpha_1 - \alpha_2)^2$$

$$+ \left(t_h \sin(k_F R + \pi/4) \cos \frac{\theta}{2} \right)^2$$



$$t_h = \frac{4\alpha_1\alpha_2 e^{-R}}{\sqrt{2\pi k_F R}}, \quad \delta\alpha = \alpha_1 - \alpha_2$$

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

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

Read Out of YSR Qubit via impurity dynamics

Single circularly precessing impurity

$$\mathbf{S}(t) = S(\sin \theta \cos \Omega t, \sin \theta \sin \Omega t, \cos \theta):$$

$$H_{\text{imp}} = -J\mathbf{S}(t) \cdot \boldsymbol{\sigma}\delta(\mathbf{r})$$

$$\text{Dynamic reactive torque } \boldsymbol{\tau}_R(t) = JS\mathbf{n} \times \langle \boldsymbol{\sigma} \rangle = \left(n_s - \frac{1}{2}\right) \frac{\Omega}{2} \mathbf{n} \times \mathbf{z}$$

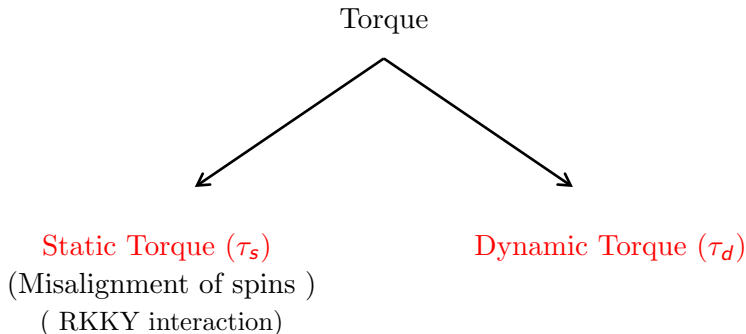
Resonance frequency shift due to the Shiba state:

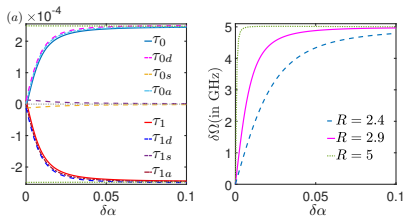
$$\Omega_R = \frac{\Omega_0}{1 + \left(n_s - \frac{1}{2}\right) \frac{1}{2S}}$$

Mishra et. al., PRB 103, L121401 (2021)

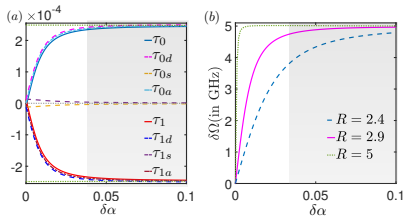
Qubit Read out via impurity dynamics

- Read out at the target spin
- Key player: Torque acting on the target spin





$$\Omega_{Ri} = \frac{\Omega_0 - \frac{\tau_{is}}{S}}{1 + \frac{\tau_{id}}{S}}, \quad \delta\Omega = \Omega_{R0} - \Omega_{R1}$$



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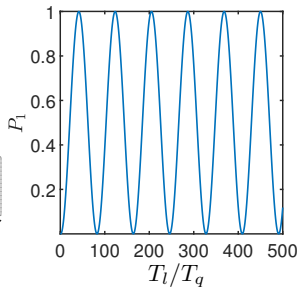
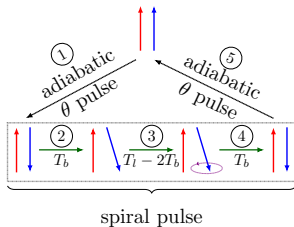
“Good” qubit regime:

- insensitive to fluctuations
- resolving the resonant frequencies, $\delta\Omega \geq 0.1\text{GHz}$ (Yang et. al., Science (2019))
- measurement via STM-ESR technique

Coherent Manipulation: Igniting the dynamics

- Time Evolution operator: $U(t, t_0) = \mathcal{T} e^{-\frac{i}{\hbar} \int_{t_0}^t dt' H_Q(t')}$
- $\psi(t) = U(t, 0)|0\rangle$

(a)



YSR Qubit

$$\theta = \pi$$

- Qubit splitting, $\approx 9.5\text{GHz}$,
- Rabi time period: $\approx 8.55\text{ns}$
- Relaxation time $\approx 7\mu\text{s}$.

Andreev Qubit

$$\delta = \pi$$

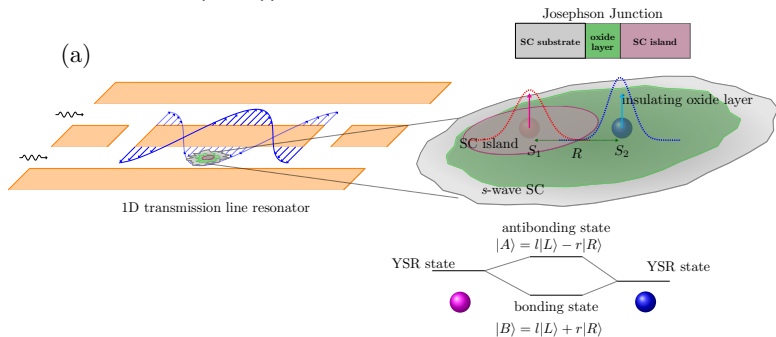
- Qubit splitting, $\approx 8\text{GHz}$
- Rabi time period: $\approx 20\text{ns}$
- Relaxation time $\approx 4\mu\text{s}$

Janvier et.al. Science 349,1199 (2015)

Issue: Building multiqubit gates

cQED proposal

Experimentally feasible: Already implemented in Andreev qubits
(Ref: Zazunov et. al. PRL **90**, 087003 (2003), Chtchelkatchev et. al. PRL **90**, 226806 (2003))



$$\begin{array}{ccccc} H = & H_{SC} & + & H_I & + & H_T \\ & \downarrow & & \downarrow & & \downarrow \\ & \text{SC} & & \text{Island} & & \text{tunneling} \end{array}$$

$$\mathcal{H}_{SC} = \epsilon_k \tau_z + \Delta \tau_x + \sum_{R'=0, R} J_j S \sigma_z \delta(\mathbf{r} - \mathbf{R}'),$$

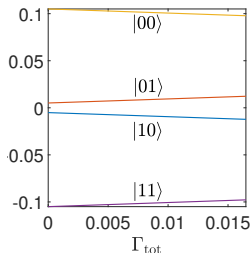
$$\mathcal{H}_I = \epsilon_k \tau_z + \Delta (\tau_x \cos \Phi + \tau_y \sin \Phi), \quad \mathcal{H}_T = t_c \tau_z,$$

Low energy Hamiltonian

$$H_{\text{dim}} = \sum_i \epsilon_i d_i^\dagger d_i + t_{12} d_1^\dagger d_2 + h_{12} d_1^\dagger d_2^\dagger + \text{h.c.}$$

$$\epsilon_1 = \Delta (1 - \alpha_1 + \Gamma_0 + \Gamma_p \cos \Phi), \quad \epsilon_2 = \Delta (1 - \alpha_2),$$

$$t_{12} = -4\Delta e^{-R/\xi} \sin \left(k_F R + \frac{\pi}{4} \right) / \sqrt{2\pi k_F R},$$



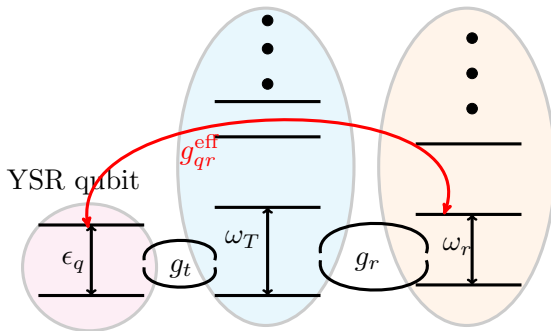
$$H_O = \epsilon_p(\Phi) M_z + \Delta t_h M_x,$$
$$\epsilon_p(\Phi) = \Delta (\alpha_1 - \alpha_2 + \Gamma_0 + \Gamma_p \cos \Phi)$$

Manipulation

Driving the microwave resonator: $H_{\text{tot}} + \mathcal{E}(ae^{i\omega t} + a^\dagger e^{-i\omega t})$

Transmon

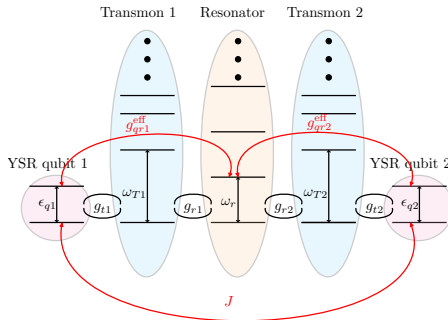
Resonator



$$H_{\text{eff}} = \frac{\epsilon_q}{2} \Sigma_z - (g_q \gamma^2 + g_{qr}^{\text{eff}} (a + a^\dagger)) \beta \cdot \Sigma + \delta'_r a^\dagger a$$

Rabi time period 4 ns

Two qubit gates

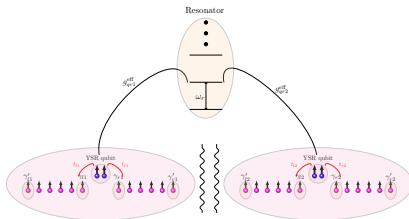
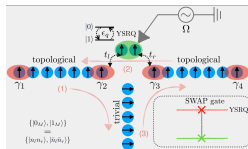


$$H_{qq} = \sum_{i \in 1,2} \frac{\epsilon_{qi}}{2} \Sigma_{zi} + \chi a^\dagger a \Sigma_{zi} + \delta'_r a^\dagger a + J(\Sigma_{1+} \Sigma_{2-} + \Sigma_{1-} \Sigma_{2+})$$

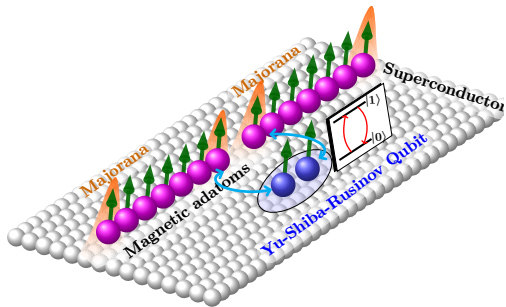
- $J \approx 40\text{ns}$, less than both decoherence time ($4 \mu\text{s}$) and linewidth ($50 \mu\text{s}$)
- $\sqrt{\text{SWAP}}$ gate

- Novel YSR qubits encoded in Shiba dimers
- Read out and control of qubit via dynamics of the impurities or cQED
- Good coherence times, robust for a wide range of experimental parameters.

Future Prospects



- Microscopics of the hybrid qubit: coupling of YSR qubit to Majorana qubit.
- Including SOC and scalar scattering
- Manipulation and detection of Majorana edge modes via magnetization dynamics $\rightarrow$ fingerprint in the STM-ESR signals.
- Similar framework for manipulating Majorana qubits using cQED



THANK YOU!