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Rigid discrete time crystal on a diamond quantum simulator under a zero magnetic field

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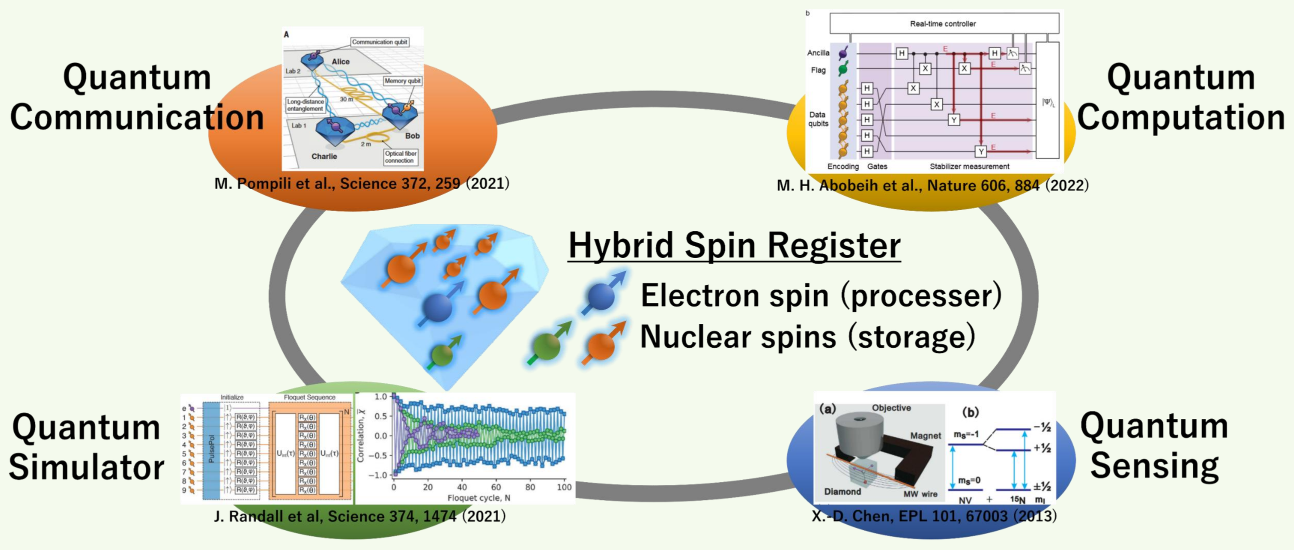
Background and motivation

Hybrid spin register in diamond

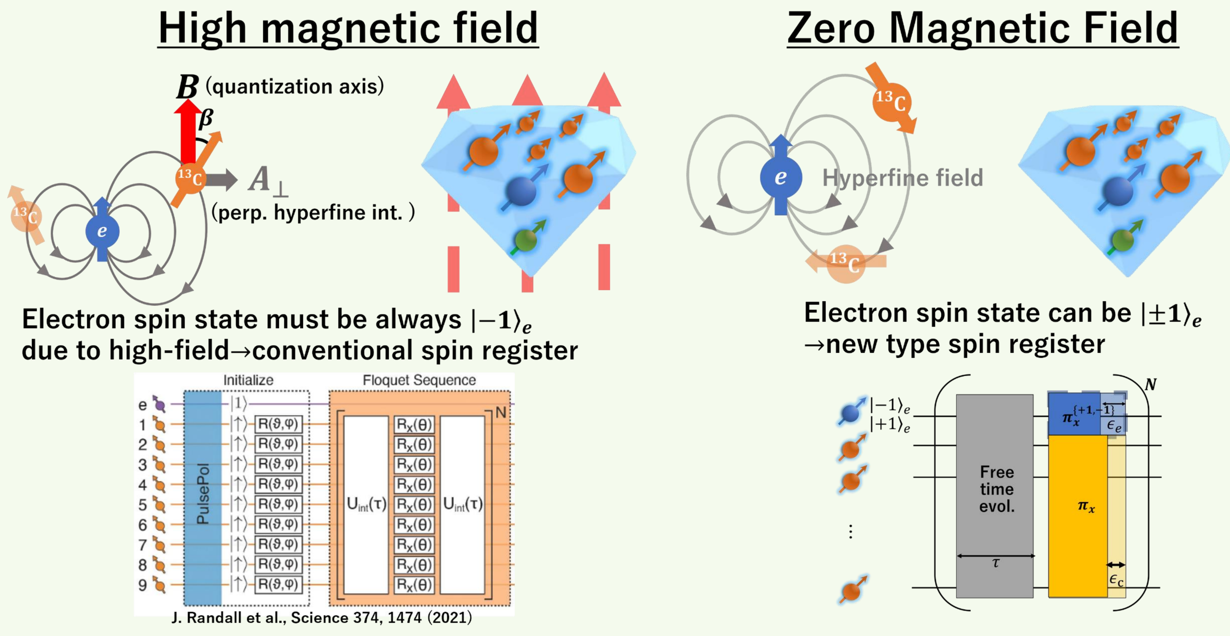
A nitrogen-vacancy (NV) center with surrounding nuclear spins provides a promising platform for quantum information technology



Our motivation

Conventional method under high magnetic field ($\sim 100-1000$ Gauss) is awkward for nuclear spin operation and constrains the degrees of freedom as a quantum simulator

However, the zero-field method enables to fully utilize the degrees of freedom and opens the way to find new nonequilibrium phenomena

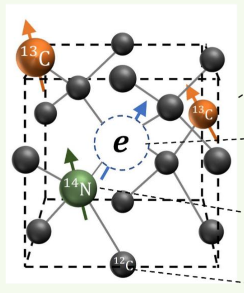


Our research

We propose a new type of discrete time crystal, consisting of a spin-1 central electron system coupled with spin-1/2 nuclear spins, operating under a zero magnetic field

NV center under a zero magnetic field

Model: zero-field NV center



$$H=\underbrace{D_0S_z^2}_{\text{zero-field splitting}}+\underbrace{\sum_i A_{zz}^{(i)}S_z\otimes I_z^{(i)}}_{\text{e-n hyperfine int.}}+\underbrace{\sum_{i,j} C_{zz}^{(ij)}I_z^{(i)}\otimes I_z^{(j)}}_{\text{n-n hyperfine int.}}$$

S: electron spin, I: nuclear spin, $D_0\sim 2.8$ GHz, $A_{zz}\sim O(\mathrm{kHz}-\mathrm{MHz})$, $C_{zz}\sim O(\mathrm{Hz})$

Electron Spin: microwave control (~ns), T_2^* (~μs), optically readout

Nuclear Spin: quantum memory (T_2^* (~ms), indirect readout

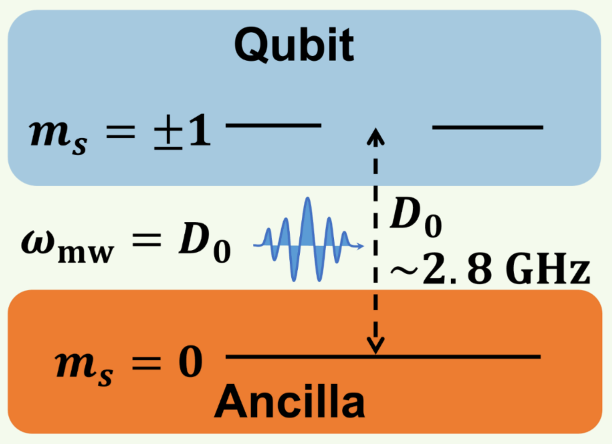
C. E. Bradley et al., Phys. Rev. X 9, 031045 (2019)

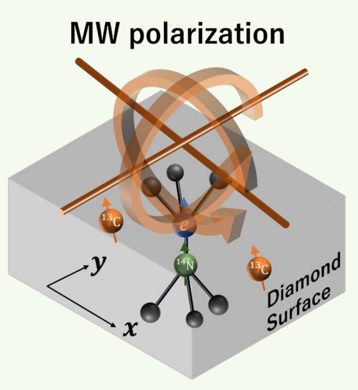
Electron spin control

Y. Sekiguchi et al., Nat Commun 7, 11668 (2016)

Degenerate levels can behave as a qubit by introducing an ancillary level

$$H=\underbrace{D_0S_z^2}_{\text{ZFS}}+\underbrace{\sum_{\gamma=x,y}\Omega_\gamma\cos(\omega_{\mathrm{mw}}t+\phi_{\mathrm{mw}})S_\gamma}_{\text{Microwave driving}}$$





Zero-field MW echo

When we set

$\omega_{\mathrm{mw}}=D_0, \phi=0, \Omega_y=0$

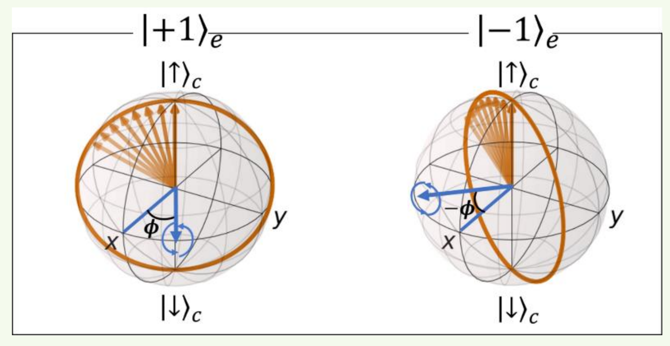
$U_{x,e}^{\{+1,-1\}}(\pi)$

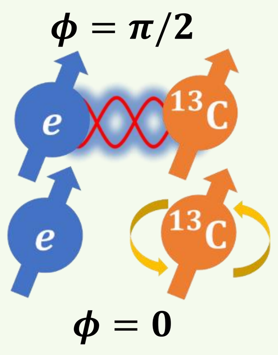
$=|+1\rangle_e\langle -1|+|-1\rangle_e\langle +1|s$

$+|0\rangle_e\langle 0|$

Nuclear spin control

$$H=\underbrace{A_{zz}S_z\otimes I_z}_{\text{Hyperfine int.}}+\underbrace{\sum_{\gamma=x,y}\Omega_\gamma\cos(\omega_{\mathrm{rf}}t+\phi)I_\gamma}_{\text{Radiofrequency driving}}$$





Zero-field RF echo

When we set

$\omega_{\mathrm{rf}}=A_{zz}, \phi=0, \Omega_y=0$

$U_{\mathrm{RF},C}(\pi)$

$=(|+1\rangle_e\langle +1|+|-1\rangle_e\langle -1|)\otimes R_x(\pi)+|0\rangle_e\langle 0|\otimes \hat{1}$

Discrete time crystals

Discrete time crystal (DTC)

D. V. Else et al., Phys. Rev. Lett. 117, 090402 (2016)
N. Y. Yao et al., Phys. Rev. Lett. 118, 030401 (2017)

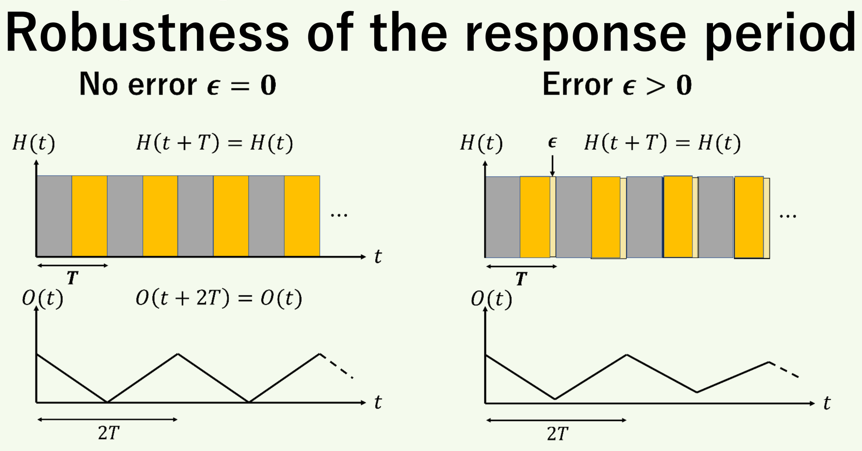
DTC is a nonequilibrium phase of matter with a Floquet Hamiltonian $H(t)=H(t+T)$ which satisfies

1. Time translation symmetry breaking

Existence of a local observable that respond at nT (for integer n>1)

2. Rigidity*

Robustness of the response period against perturbations



*The second condition is required for eliminating trivial cases ex. spin echo (trivially satisfies condition1)

$|\uparrow\uparrow\uparrow\cdots\uparrow\rangle\rightarrow|\downarrow\downarrow\downarrow\cdots\downarrow\rangle\rightarrow|\uparrow\uparrow\uparrow\cdots\uparrow\rangle$

Recent works and challenge

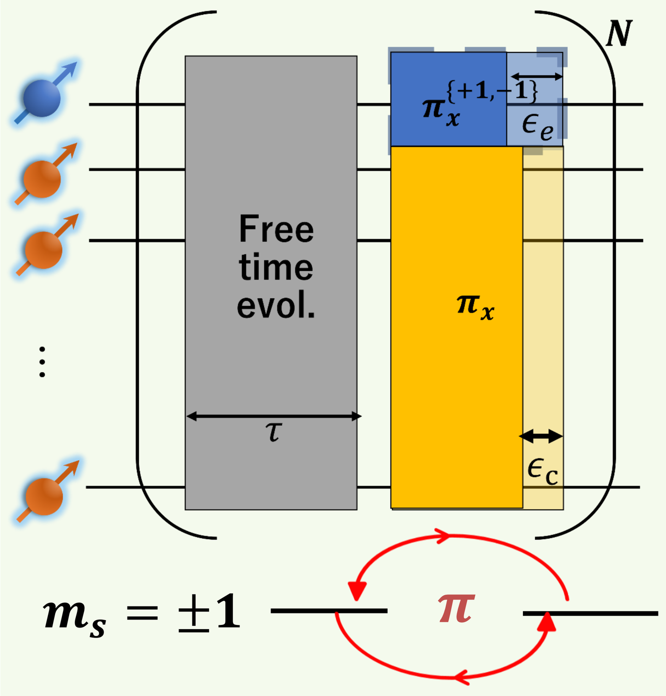
Central spin model DTC

S. Pal, Phys. Rev. Lett. 120, 180602 (2018), R. Frantzeskakis, Phys. Rev. B 108, 075302 (2023)

→ using spin-1/2 as a central spin→ hard to implement in NV center

Zero-field discrete time crystal

2T-DTC



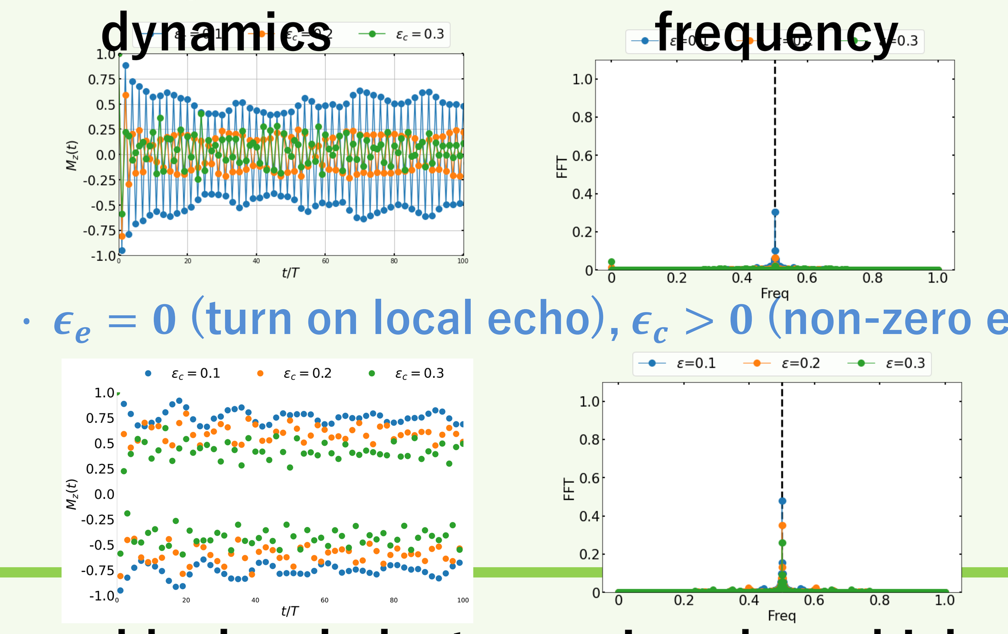
Floquet unitary

$$U_{\mathrm{F}}=U_x^{\{+,0\}}(2(\pi-\epsilon_e))U_{\mathrm{RF},C}(\pi-\epsilon_c)U_{\mathrm{free}}(\tau)$$

· $\epsilon_e=1$ (turn off local echo), $\epsilon_c>0$ (non-zero error)

Magnetization dynamics　Oscillation frequency

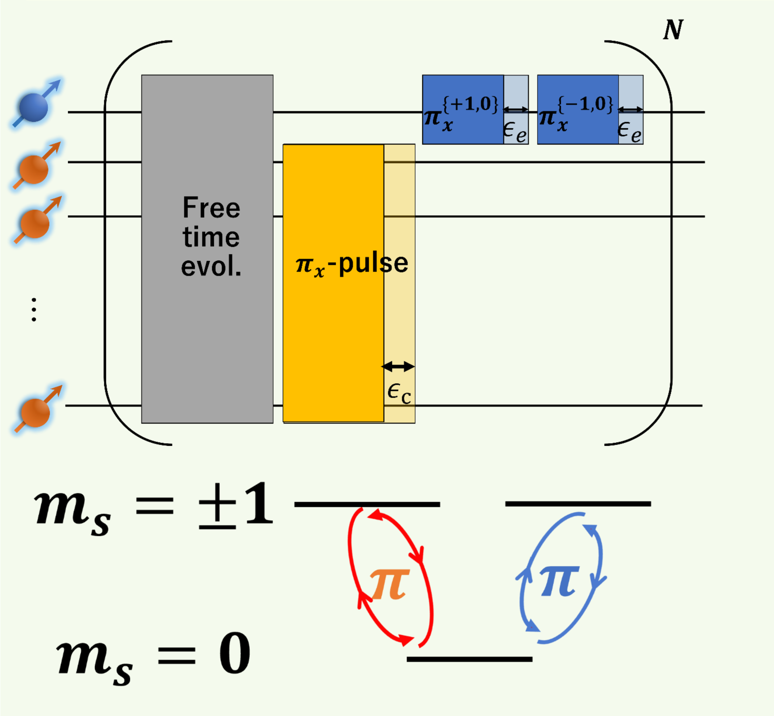
· $\epsilon_e=0$ (turn on local echo), $\epsilon_c>0$ (non-zero error)



Property

Rigidity is significantly enhanced by local electron spin echo, which influences the macroscopic behavior by strong A_{zz}

3T-DTC and 3T→2T DTC

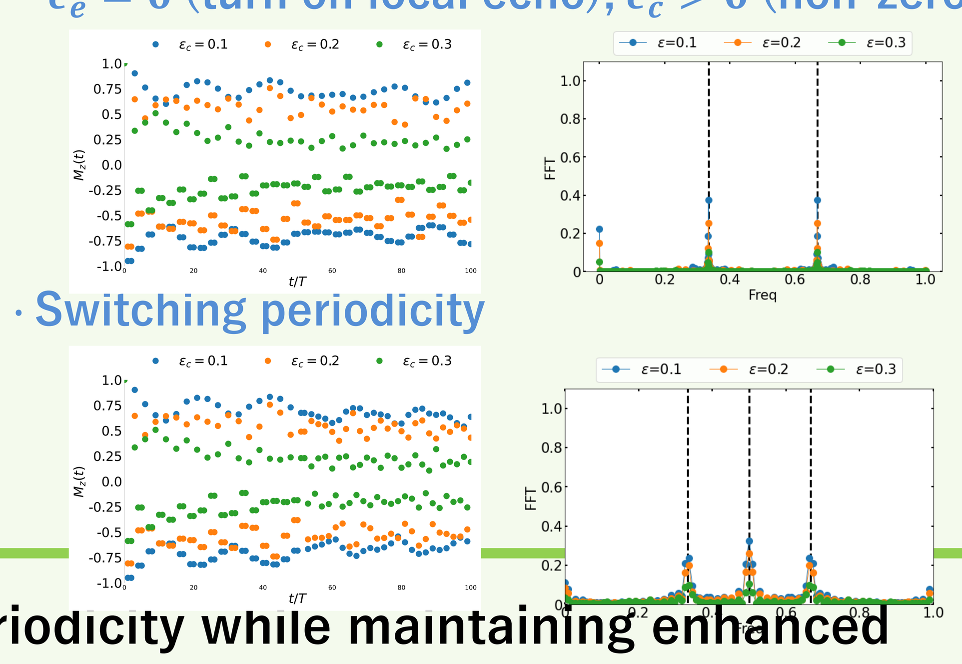


Floquet unitary

$$U_{\mathrm{F}}=U_x^{\{+1,0\}}(\pi-\epsilon_e)U_x^{\{-1,0\}}(\pi-\epsilon_e)\times U_{\mathrm{RF},C}(\pi-\epsilon_c)U_{\mathrm{free}}(\tau)$$

· $\epsilon_e=0$ (turn on local echo), $\epsilon_c>0$ (non-zero error)

· Switching periodicity



Property

Zero-field DTC can switch periodicity while maintaining enhanced rigidity

Origin of the enhanced rigidity

· Floquet effective Hamiltonian($2T$, ordinal)

$$H_{\mathrm{eff},2T}=\sum_{i,j}C_{zz}^{(ij)}I_z^{(i)}\otimes I_z^{(j)}+\sum_i\frac{\epsilon_c}{\tau}\left(\cos A_{zz}^{(i)}\tau+\sin A_{zz}^{(i)}\tau\right)I_x^{(i)}$$

The error term is suppressed by nuc-nuc hyperfine interactions

· Floquet effective Hamiltonian($2T$, enhanced form)

$$\sum_i A_{zz}^{(i)}S_z\otimes I_z^{(i)}-\sum_i\epsilon_cA_{zz}^{(i)}S_z\otimes I_y^{(i)}-\sum_i\epsilon_cA_{zz}^{(i)}\cot(A_{zz}\tau)I_x^{(i)}+\sum_{i,j}C_{zz}^{(ij)}I_z^{(i)}\otimes I_z^{(j)}$$

The error term is significantly suppressed by cot when A_{zz} is large value

Summary

We have established a novel method of realizing DTC on a zero-field diamond quantum simulator

Zero-field DTC rapidly influences macroscopic observable changes in nuclear spins with just a single electron spin acting as a switch