Discrete time crystal on a diamond quantum simulator under a zero magnetic field

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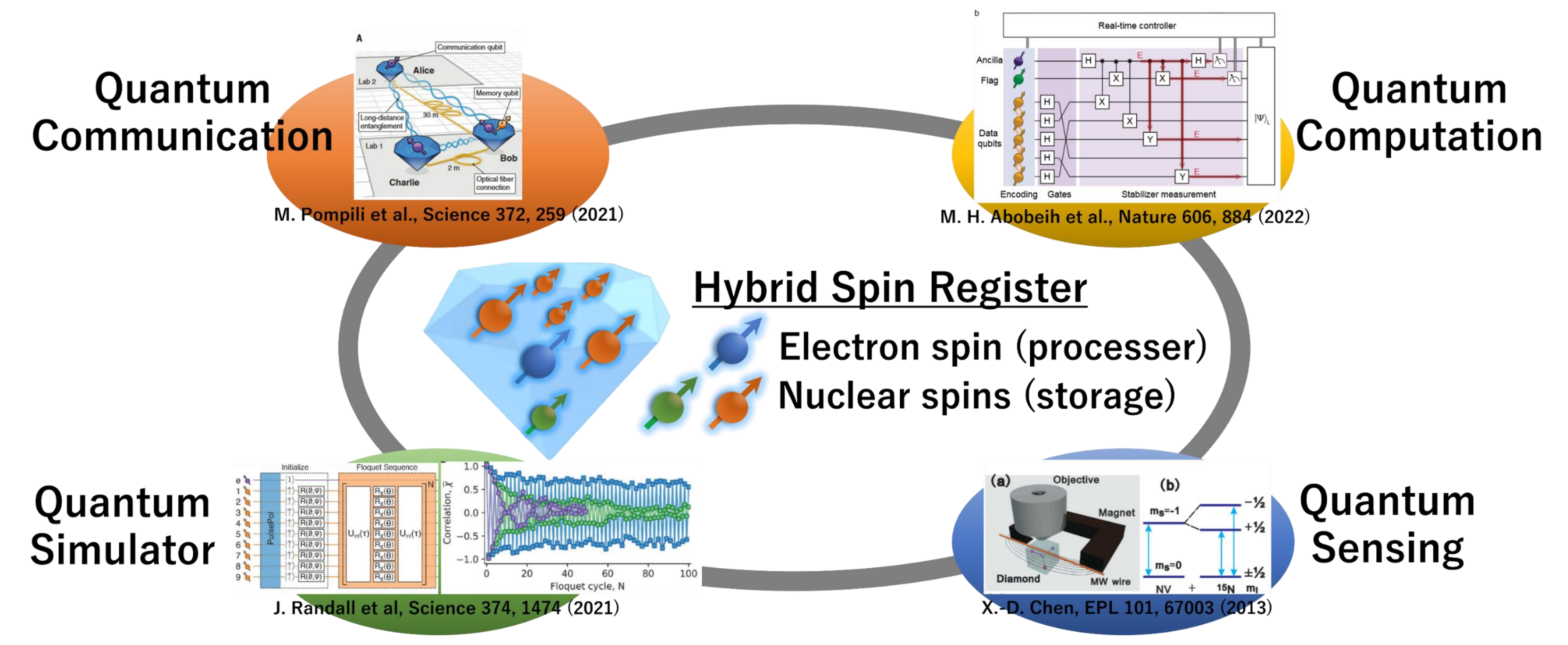
Poster PDF

Background and motivation

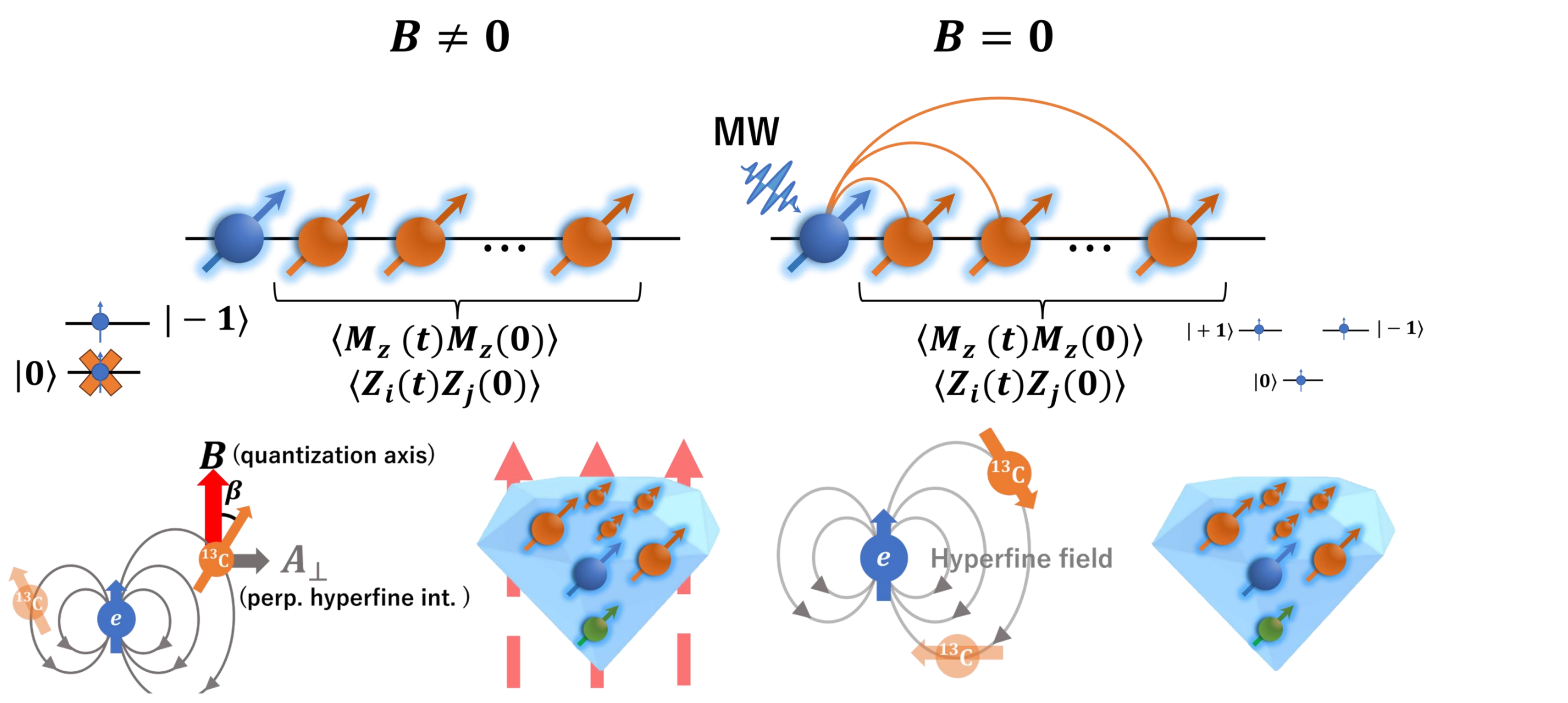
Hybrid spin register in diamond

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



Motivation

Diamond quantum simulators are possible both under high field and under zero field
The zero-field register becomes a simulator with extended degrees of freedom due to the electron spin level structure



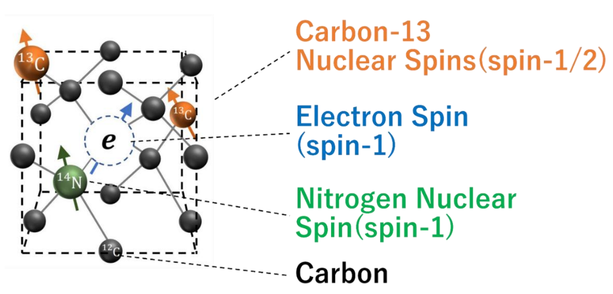
Our research

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

NV center under a zero magnetic field

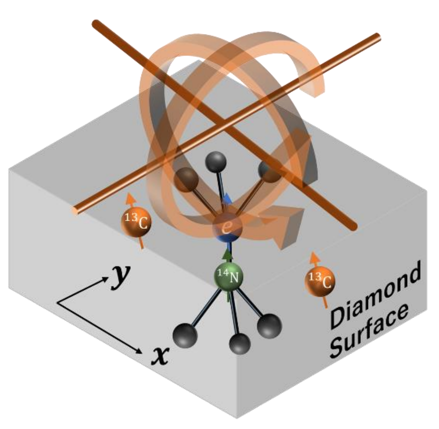
Model: zero-field NV center

$$H = \underbrace{D_0 S_z^2}_{\text{zero-field splitting}} + \underbrace{\sum_i A_{zz}^{(i)} S_z \otimes I_z^{(i)}}_{\text{e-c hyperfine int.}} + \underbrace{\sum_{i,j} C_{zz}^{(ij)} I_z^{(i)} \otimes I_z^{(j)}}_{\text{c-c hyperfine int.}}$$



*we neglected nitrogen nuclear spin terms
S: electron spin, I: nuclear spin, $D_0 \sim 2.8$ GHz, $A_{zz} = O(\text{kHz})$, $C_{zz} = O(\text{Hz})$

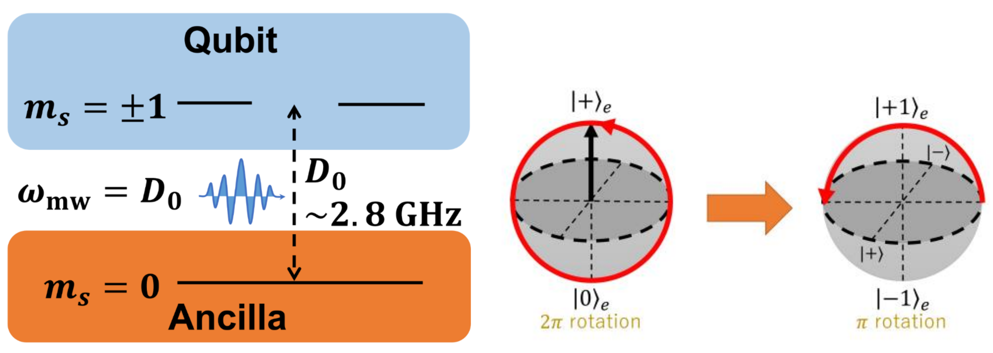
Electron Spin: microwave control ~ ns, T_2^{DD} ~ 1 sec, optical init. & readout
Nuclear Spin: quantum memory T_2^{DD} ~ 1min, init. & readout via electron spin
C. E. Bradley et al., Phys. Rev. X 9, 031045 (2019)



Electron spin control

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

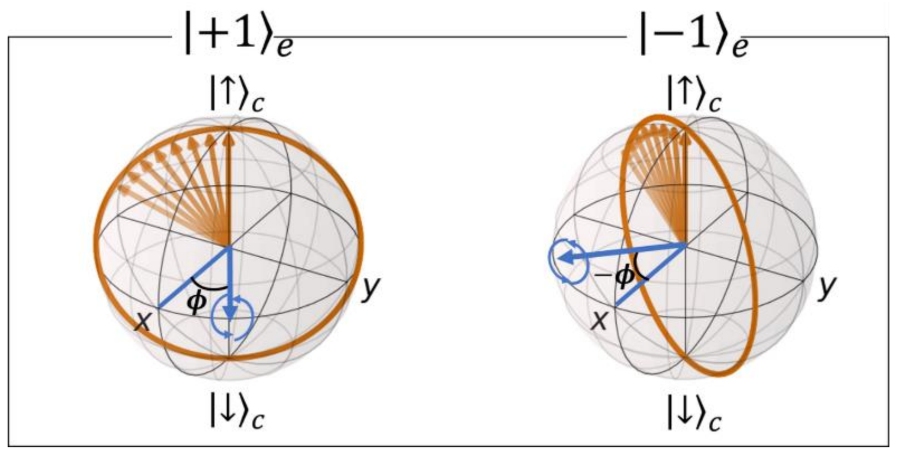
Degenerate levels behave as a qubit by introducing an ancillary level



Zero-field MW echo (switch)

$$\pi_x^{\{+1,-1\}} = \hat{\sigma}_{x,e}^{\{+1,-1\}} + |0\rangle_e\langle 0|$$

Nuclear spin control



Zero-field RF echo

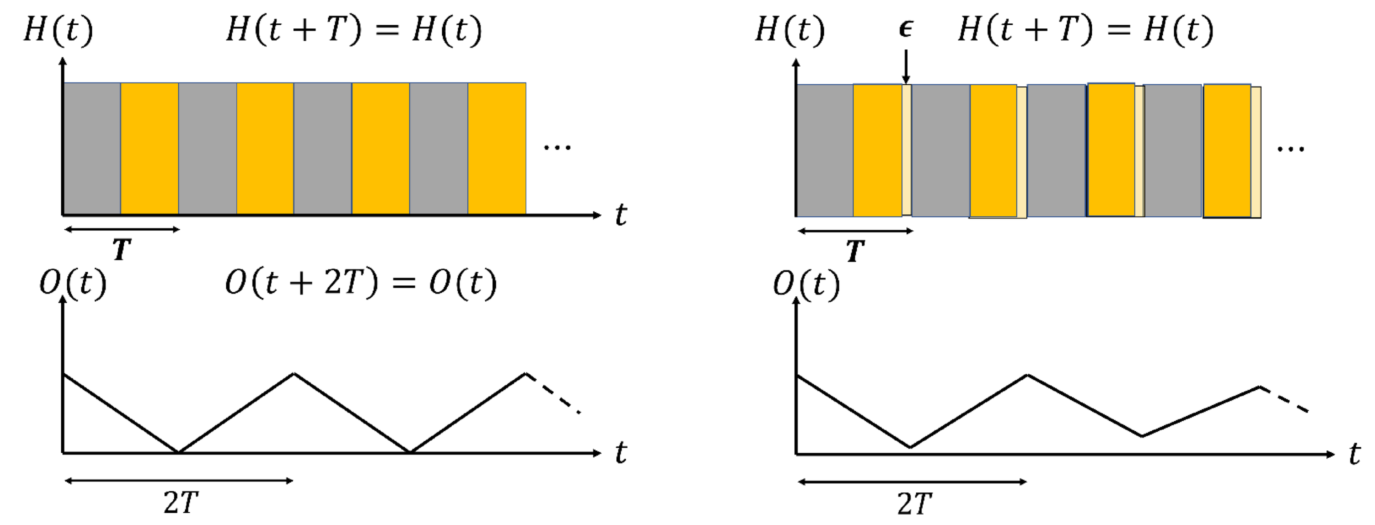
$$\pi_x = \hat{1}_e^{\{+1,-1\}} \otimes \hat{\sigma}_{x,c} + |0\rangle_e\langle 0| \otimes \hat{1}_c$$

Floquet Hamiltonian engineering

Discrete time crystal (DTC)

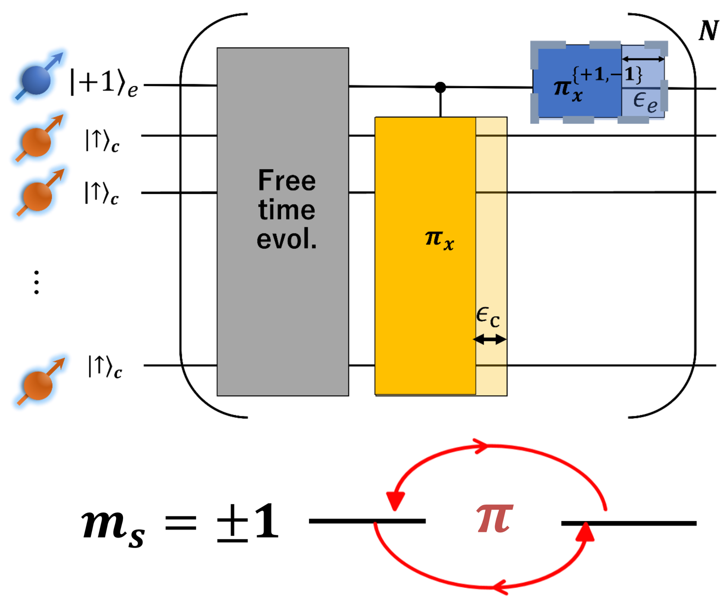
D. V. Else et al., Phys. Rev. Lett. 117, 090402 (2016)
N. Y. Yao et al., Phys. Rev. Lett. 118, 030401 (2017)

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

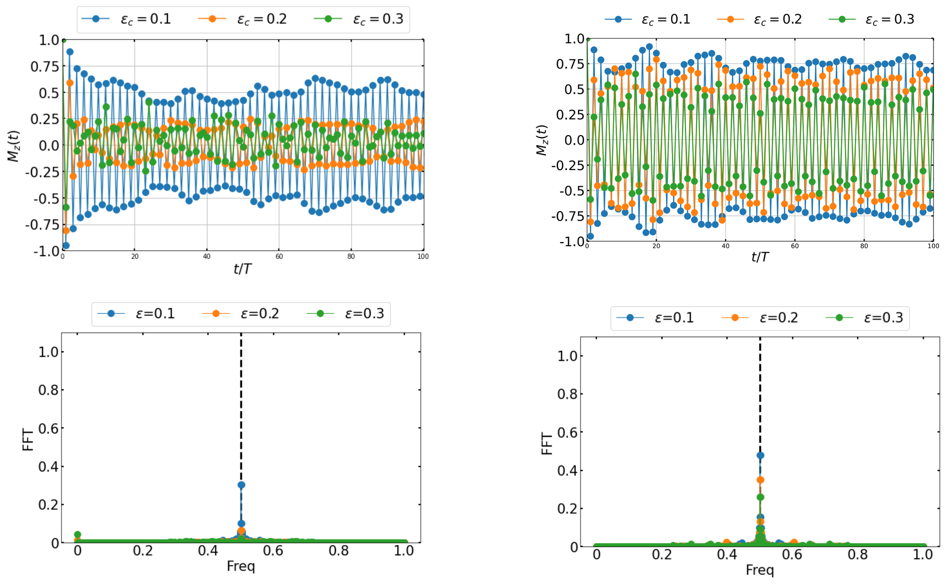


Zero-field discrete time crystal

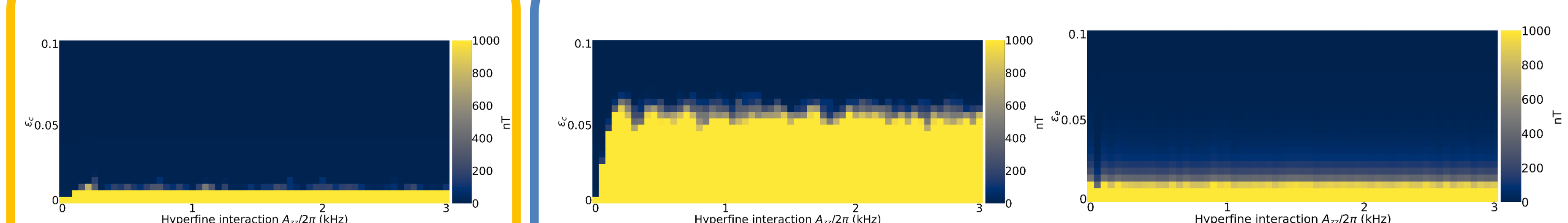
2T-DTC



Nuclear spin magnetization dynamics
・$\epsilon_e = 1$ (switch off)
・$\epsilon_e = 0$ (switch on)



Off　**On**



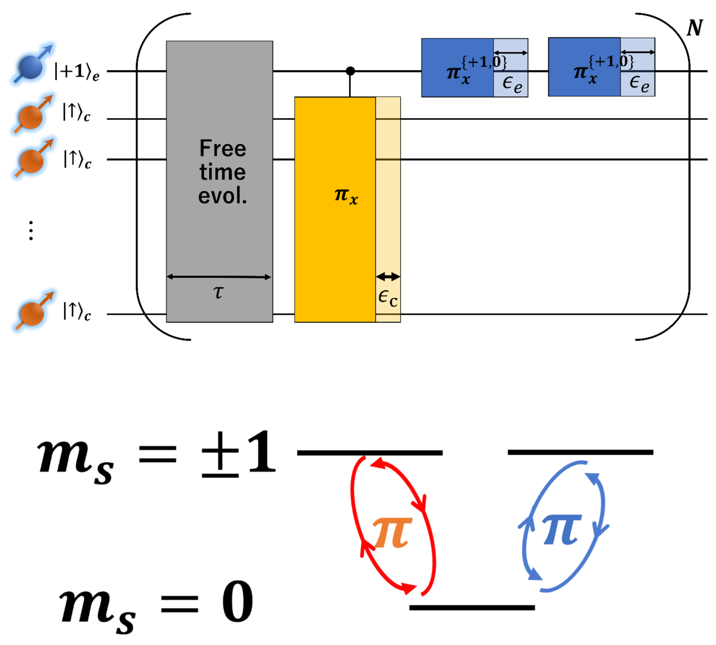
$\epsilon_e = 1, \epsilon_c > 0$　$\epsilon_e = 0, \epsilon_c > 0$　$\epsilon_e > 0, \epsilon_c = 0$

Color bar: The number of Floquet cycles which $|\langle \psi_{\mathrm{init}}|\psi(nT)\rangle|^2 > 0.95$
$A_{zz}^{(i)} \sim [0, 2A_{zz}]$ (uniform)

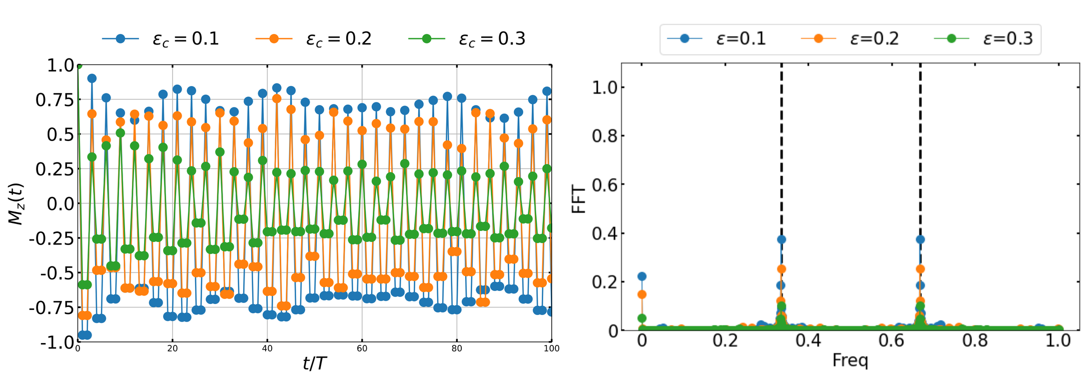
Property 1

Rigidity and fidelity are significantly enhanced by local electron spin echo, which influences the macroscopic behavior by strong $A_{zz} = O(\text{kHz})$

3T-DTC



・$\epsilon_e = 0$ (switch on), $\epsilon_c > 0$



Property 2

Zero-field DTC makes possible to switch the periodicity by the local spin operation

Origin of the enhanced rigidity

・$2T$ DTC, switch off

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

・$2T$ DTC, switch on
The error term is significantly suppressed when A_{zz} takes sufficiently large value

$$H_{\mathrm{eff},2T} = \sum_i A_{zz}^{(i)} S_z \otimes I_z^{(i)} - \sum_i \epsilon_c A_{zz}^{(i)} S_z \otimes I_y^{(i)} - \sum_i \epsilon_c A_{zz}^{(i)} \cot(A_{zz}\tau) I_x^{(i)}$$

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