Detection and Control of Weakly Coupled Nuclear Spins under a Zero Magnetic Field

Naoya Egawa[1*], Shiro Tamiya[2], Kansei Watanabe[3], Joji Nasu[1], Hideo Kosaka[3]

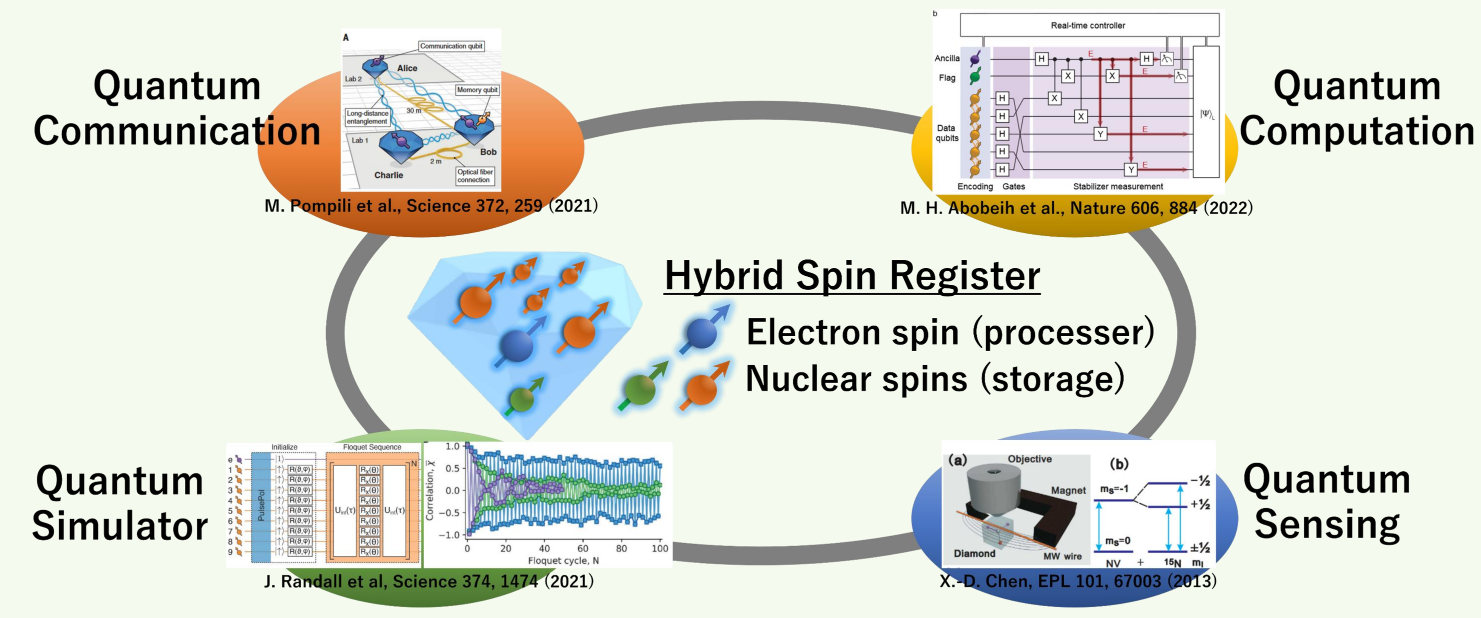
Tohoku Univ. [1], The Univ. of Tokyo[2], Yokohama Natl. Univ. [3]

Poster PDF

Background and Motivation

Hybrid spin register in diamond

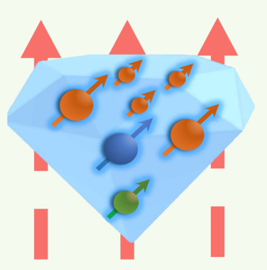
A nitrogen-vacancy (NV) center with surrounding nuclear spins offers a promising platform for quantum information technology



A key challenge in realizing a hybrid spin register is to individually detect and selectively control multiple nuclear spins while keeping coherence

Current standard and challenges

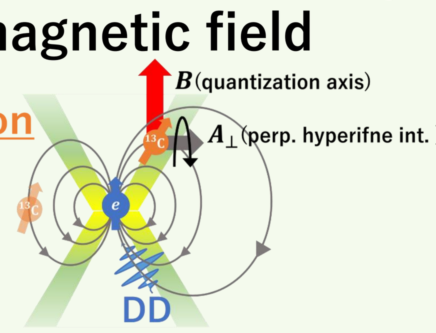
Several strategies of hybrid spin registers have been demonstrated; they come with constraints due to the application of a high magnetic field



Dynamical Decoupling (DD) + Hyperfine Interaction

T. H. Taminiau et al., Phys. Rev. Lett. 109, 137602 (2012)
T. van der Sar et al., Nature 484, 7392 (2012)
S. Kolkowitz et al., Phys. Rev. Lett. 109, 137601 (2012)

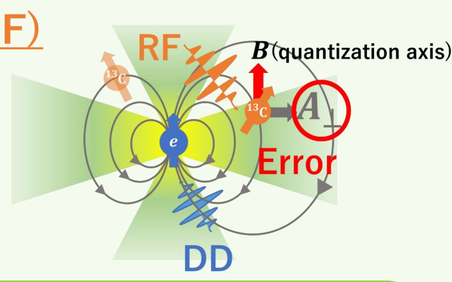
→ π-pulse interval cannot be freely adjusted
→ Multiqubit control is challenging



Dynamical Decoupling (DD) + Radio Frequency (RF)

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

→ π-pulse interval can be adjusted by RF power
→ Nuclear spins with large $A_\perp$ cannot be detected and controlled



Our research

We derive conditions for detecting and controlling nuclear spins without a bias magnetic field, with ideal assumptions

Electron and Nuclear Spin Control

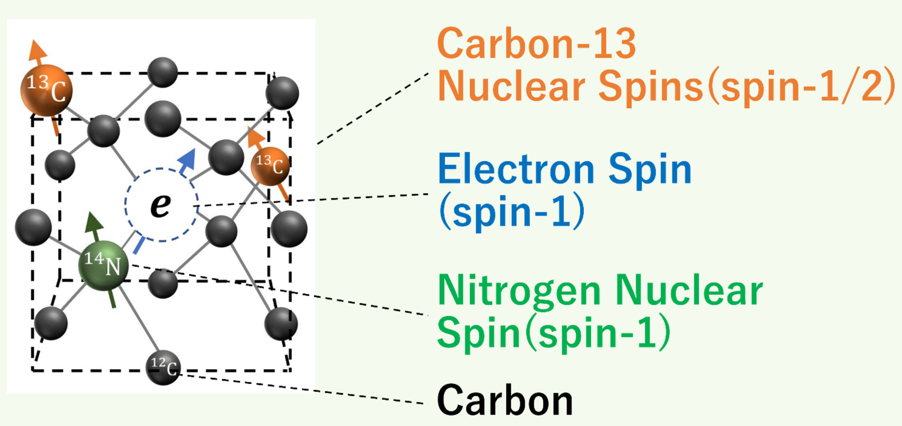
Nitrogen-Vacancy (NV) center

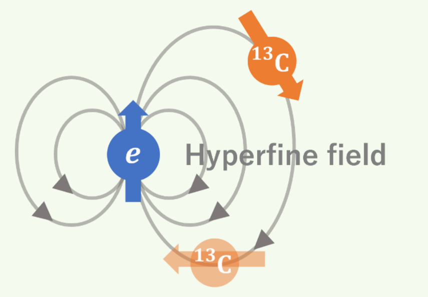
The system comprises the central electron spin and nearby nuclear spins

$$H = \underbrace{D_0 S_z^2}_{\text{ZFS}} + \underbrace{\sum_i A_{zz}^{(i)} S_z \otimes I_z^{(i)}}_{\text{Hyperfine int.}}$$

S: electron spin, I: nuclear spin

$D_0 \sim 2.8\ \text{GHz}$, $A_{zz} \sim O(\text{kHz} - \text{MHz})$





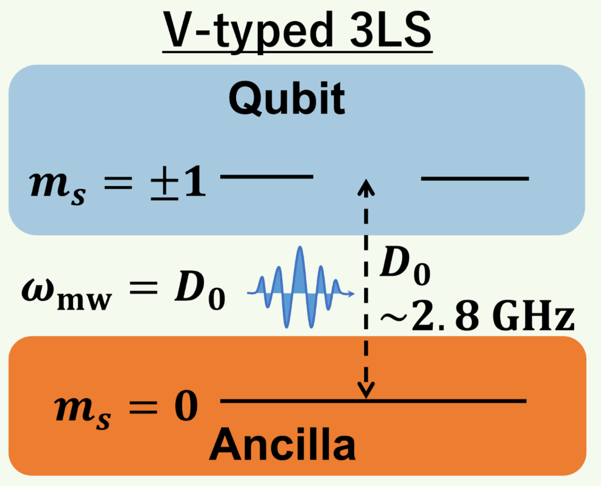
Electron Spin: microwave control (~ns), T_2^* (~μs), optically readout
Nuclear Spin: quantum memory (T_2^* (~ms), indirect readout

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

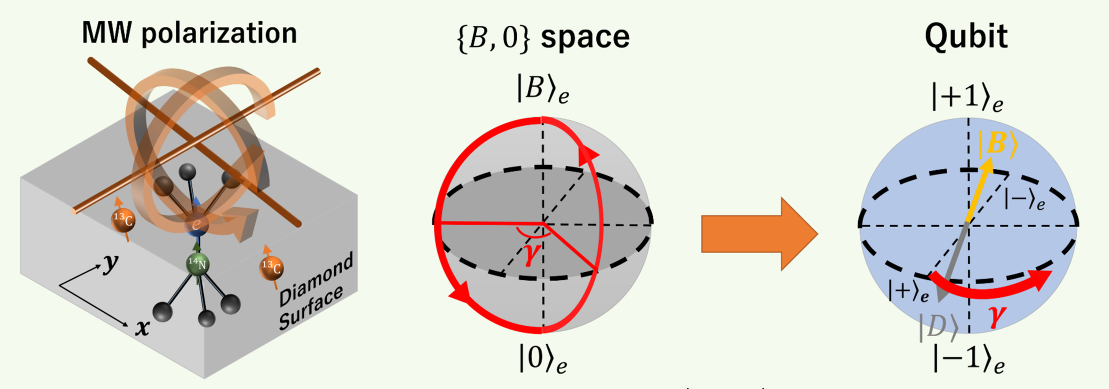
Zero-Field electron spin control

While degenerate levels cannot be employed as a qubit by themselves, introducing an ancillary level enables control

Zero-Field V-typed 3LS



$$H = \underbrace{D_0 S_z^2}_{\text{ZFS}} + \underbrace{\sum_{\gamma = x,y} \Omega_\gamma \cos(\omega_{\mathrm{mw}} t + \phi_{\mathrm{mw}}) S_\gamma}_{\text{Microwave driving}}$$

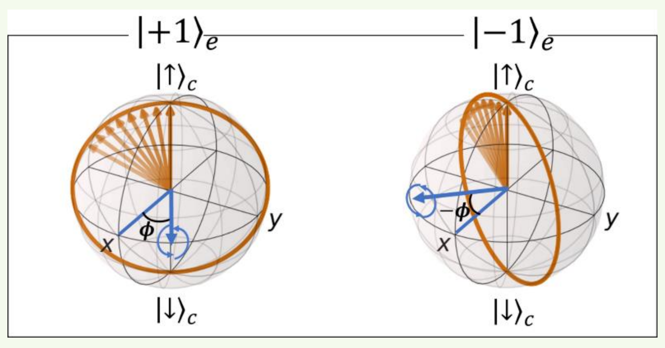


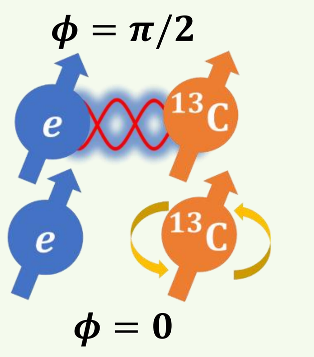
Y. Sekiguchi et al., Nat Commun 7, 11668 (2016)

Zero-Field nuclear spin control

Two-body hybrid spin Hamiltonian

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





Zero-Field RF gate

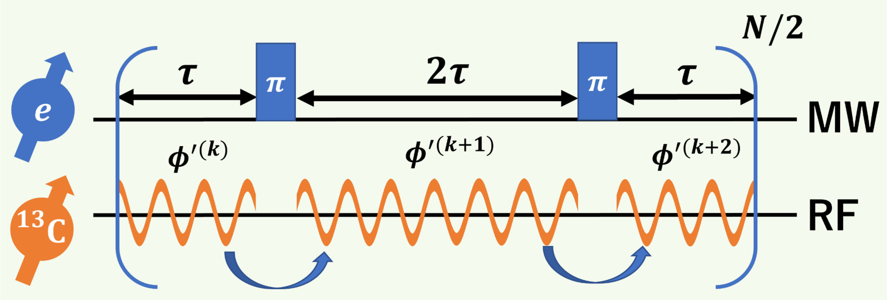
By tuning $\omega_{\mathrm{rf}} = A_{zz}$, $\Omega_y = 0$

$$U_{\mathrm{RF,rot}} = |{+1}\rangle_e\langle{+1}| \otimes R_\phi(\Omega_x t) + |{-1}\rangle_e\langle{-1}| \otimes R_{-\phi}(\Omega_x t)$$

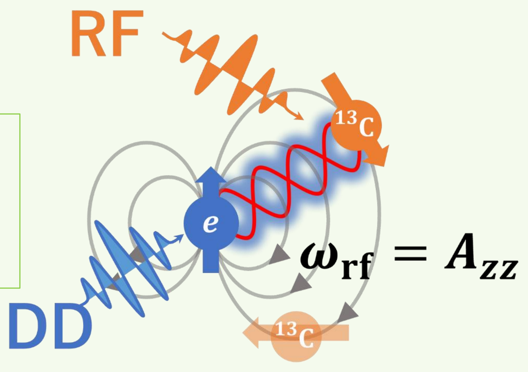
Strategy for Constructing Hybrid Spin Register

Zero-Field hybrid spin control

Dynamical Decoupling (DD): Preserving electron spin coherence
Radio-Frequency (RF): Operation of nuclear spins



N: pulse number
τ: π-pulse interval
$\phi^{(k)}$: RF phase



Postulate

Decoupling π pulses are perfect and instantaneous

RF phase

Time reversal waveform

$$\phi^{(k)} = (-1)^k \phi - k A_{zz}(2\tau)\phi$$

Zero-Field DDRF gate

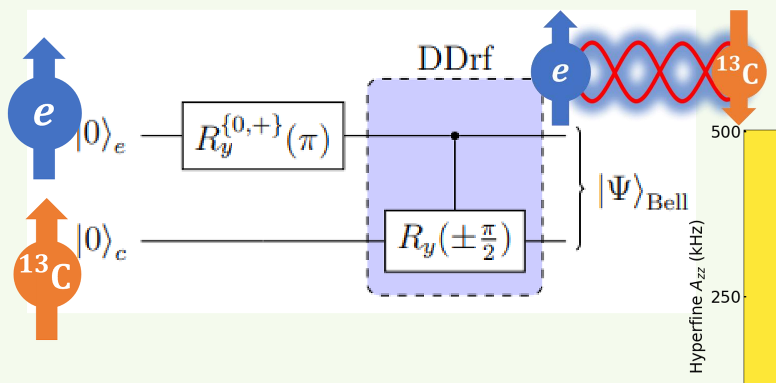
$$\begin{aligned} U_{\mathrm{DDrf}} &= U_{\mathrm{RF}}(\phi^{(N)}) U_\pi U_{\mathrm{RF}}(\phi^{(N-1)}) \cdots U_{\mathrm{RF}}(\phi^{(1)}) U_\pi U_{\mathrm{RF}}(\phi) \\ &= |{+1}\rangle_e\langle{+1}| \otimes R_\phi(\Omega_x \tau) + |{-1}\rangle_e\langle{-1}| \otimes R_{-\phi}(\Omega_x \tau) \end{aligned}$$

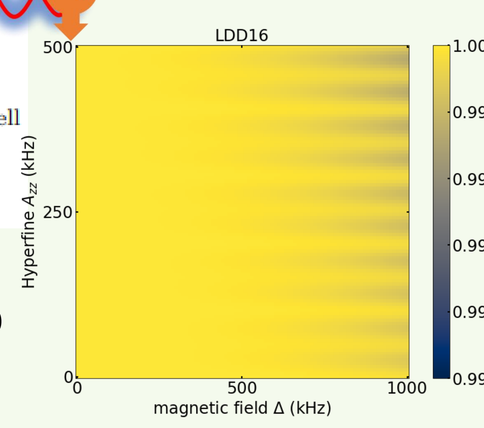
Advantages

- π-pulse interval is adjustable
- Absence of a bias magnetic field allows for the selection of a quantization axis specific to the individual hyperfine interaction
→overcoming high-field limitations

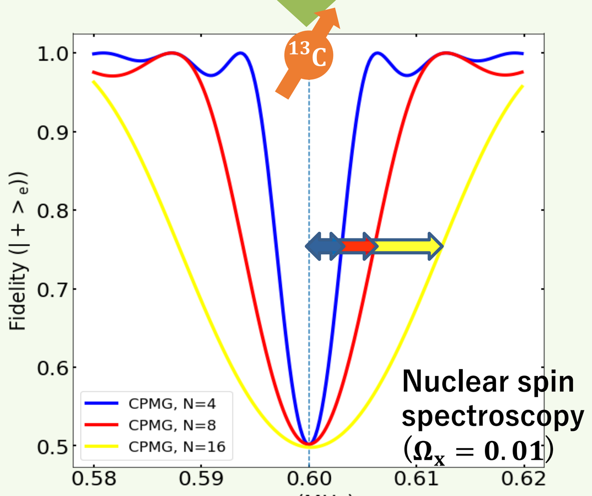
Challenge

Spreading of the width of the nuclear spin detection spectrum as the pulse number increases
→ Selective control is a difficult task





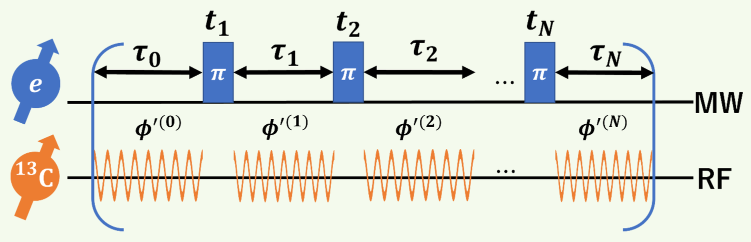
Application of Low-field DD
P. J. Vetter et al., Phys. Rev. Applied 17, 044028 (2022)



Nuclear spin spectroscopy ($\Omega_x = 0.01$)

Improving Frequency Selectivity of Nuclear Spins

Frequency selectivity is improved by optimizing each π-pulse interval



RF phase (General)

$$\phi^{(k)} = (-1)^k \left(\phi + 2A_{zz} \left(\sum_{k=0}^{N-1} (-1)^k t_{k+1} \right) \phi \right)$$

Zero-Field DDRF gate (General)

$$\begin{aligned} U_{\mathrm{DDrf}} = {} & |{+1}\rangle_e\langle{+1}| \otimes R_z\left(A_{zz} \left(T + 2\sum_{k=0}^{N-1} (-1)^k t_{k+1} \right) \right) R_\phi(\Omega_x T/2) \\ & + |{-1}\rangle_e\langle{-1}| \otimes R_z\left(-A_{zz} \left(T + 2\sum_{k=0}^{N-1} (-1)^k t_{k+1} \right) \right) R_{-\phi}(\Omega_x T/2) \end{aligned}$$

optimization

Filter function $\mathcal{F}(\Delta; \{t_j\})$: including information of detection spectrum

Cost function

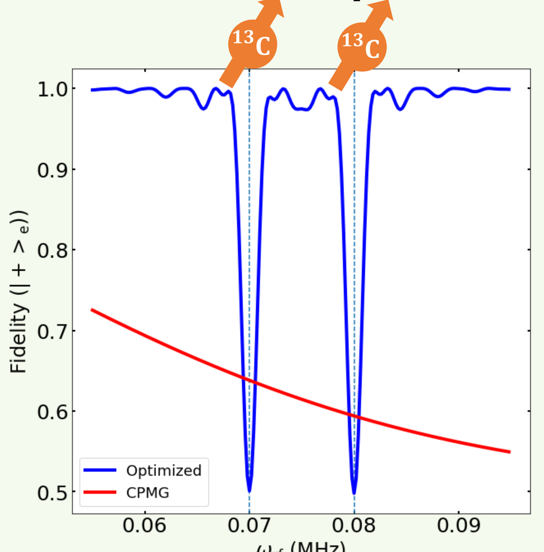
$$D = \sum_\Delta |\mathcal{F}(\Delta; \{t_j\}) - \delta(\Delta)|^2$$

$\Delta = A_{zz} - \omega_{\mathrm{rf}}$: RF detuning
$\delta(\Delta)$: Delta function

minimize D

Constraints for optimization

1. $T + 2\sum_{k=0}^{N-1}(-1)^k t_{k+1} = 0$ (eliminating extra phase rotation)
2. $0.1\ \mu s < \tau_k < 10\ \mu s$ for all k



Nuclear spin spectroscopy (N=126, $\Omega_x = 0.005$, $T = 600\ \mu s$)

Summary

We have established conditions for detecting and controlling nuclear spins assuming that π-pulses are perfect and instantaneous

- Our method addresses the limitations found in the high-field approach
- Low-field DD is not applicable when π-pulse intervals are unequal
→future work

*egawa.naoya.p4@dc.tohoku.ac.jp