Entanglement Generation in Parallel NV Centers for Enhanced Quantum Sensing

arXiv:2501.18244

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ICE - 10
València, 21st October, 2025

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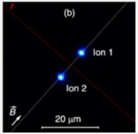
CNS2023-144994

The Quantum Technologies (QuTe) Group

Trapped Ions

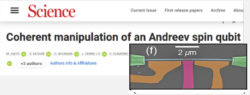
- Quantum clocks
- Quantum computers
- Quantum mass spectrometry



J. Cerrillo, A. Retzker and M. B. Plenio, *Phys. Rev. Lett.* **104**, 043004 (2010).

Superconducting Circuits

- Quantum computation
- Quantum simulation

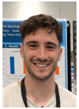


M. Hays, V. Fatemi, D. Bouman, J. Cerrillo, [...] and M. H. Devoret *Science* **373**, 430 (2021)

NV Centers

- nano NMR
- Quantum sensing

López-García, A., Cerrillo, J. *EPJ Quantum Technol.* **12**, 52 (2025)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Funding

Massachusetts Institute of Technology

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CNS2023-144994
Diseño de dispositivos cuánticos nanoelectrónicos autónomos basado en tensores de transferencia

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Capacitation of Quantum-Entangled NV-Center Sensing

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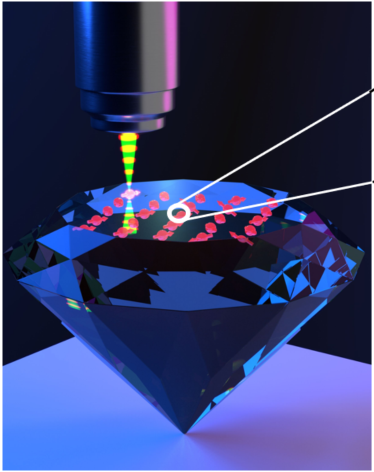
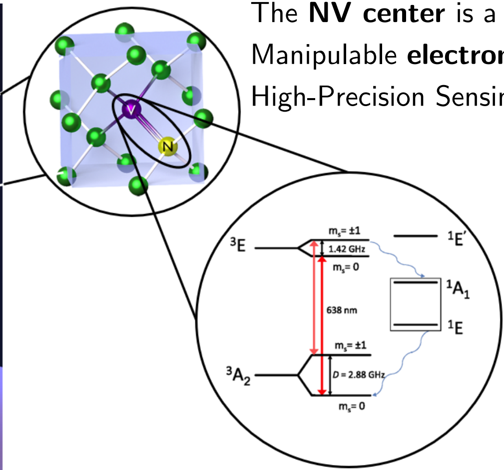
Overview

1. Introduction
2. The two NV center system
3. Entangled state generation
4. Summary

What is an NV center?





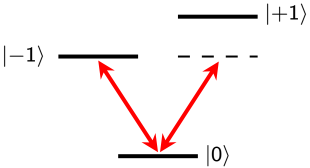
The **NV center** is a point defect in diamond

Manipulable **electronic spin** $S = 1$

High-Precision Sensing

What is an NV center?

- Conventionally treated as a 2 level system
- Population Leakage at low μB
- Population Leakage at High Frequency Signals



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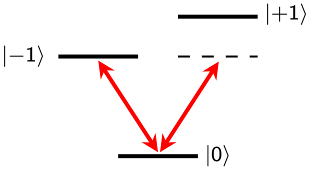
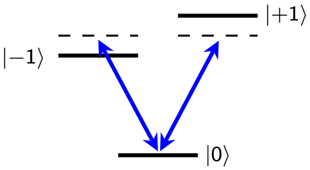
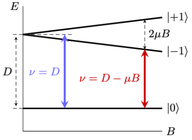


- Solved by working with three levels
  - J. Cerrillo, S. Oviedo Casado, J. Prior, Phys. Rev. Lett. **126**, 220402 (2021)
  - P J. Vetter, [...] and F. Jelezko, *Phys. Rev. Appl.*, **17**, 044028 (2022)

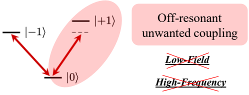


- Spin-1 Control of NV Centers via Pulses of Fixed Frequency and Amplitude

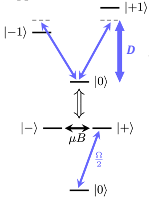
Poster Session 1: Alberto López-García

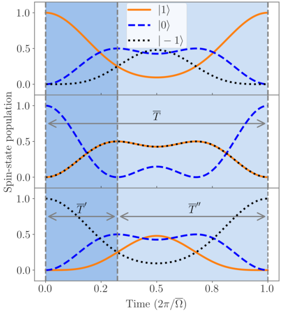


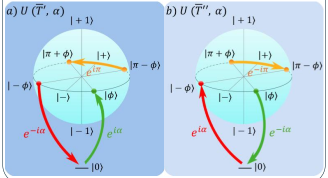
Conventional Approach



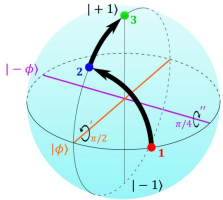
NV-ERC Approach



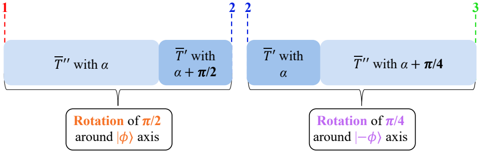




Arbitrary Qubit Qates



Schedule:



NV-ERC → *Arbitrary Gates:* ***Qubit*** *and* ***Qutrit***

Sensitivity in Sensing

- The precision in a measurement is limited by the standard quantum limit (SQL)

$$\Delta v \propto \frac{1}{\sqrt{n}}$$

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$$\Delta v \propto \frac{1}{\sqrt{n}}$$

- Use of entangled states (GHZ, NOON, etc.) allows to push this limit down to the Heisenberg limit

$$\Delta v_{\mathrm{H}} \propto \frac{1}{n}$$

Sensitivity in Sensing

- If we let the system evolve under an external magnetic field for a time t, the state $|\pm 1\rangle$ will collect a phase $\pm\omega t$

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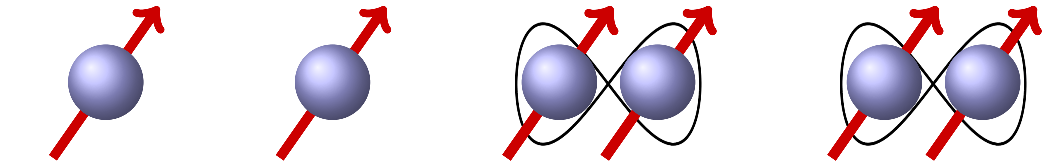
2 Level System	3 Level System	GHZ state 2 LS	GHZ state 3LS



$\frac{1}{\sqrt{2}}\,|0\rangle + \frac{e^{-i\omega t}}{\sqrt{2}}\,|-1\rangle$	$\frac{e^{i\omega t}}{\sqrt{2}}\,|+1\rangle + \frac{e^{-i\omega t}}{\sqrt{2}}\,|-1\rangle$	$\frac{1}{\sqrt{2}}\,|00\rangle + \frac{e^{-2i\omega t}}{\sqrt{2}}\,|-1-1\rangle$	$\frac{e^{2i\omega t}}{\sqrt{2}}\,|+1+1\rangle + \frac{e^{-2i\omega t}}{\sqrt{2}}\,|-1-1\rangle$
$\Delta\phi = \omega t$	$\Delta\phi = 2\omega t$	$\Delta\phi = 2\omega t$	$\Delta\phi = 4\omega t$

Heisenberg Limit

- Heisenberg limit can only be reached when the NV centers have parallel axes

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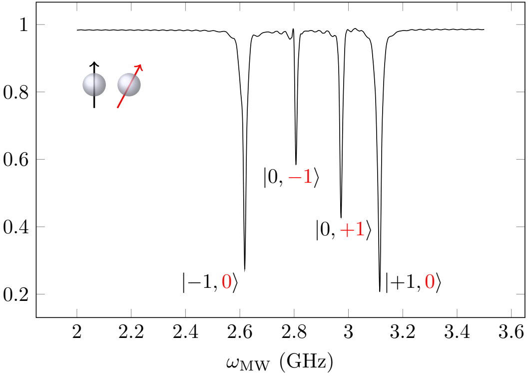

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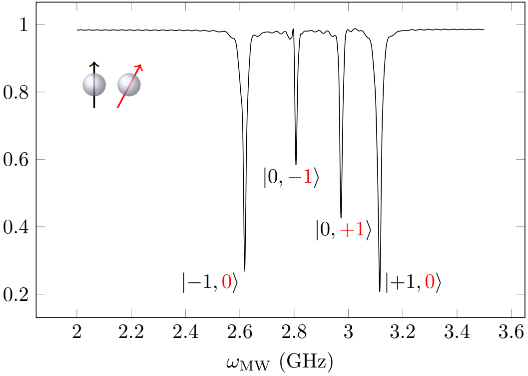
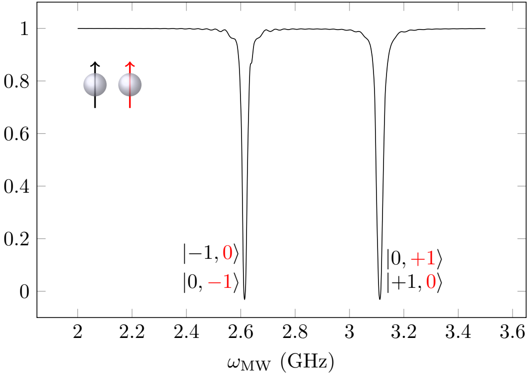
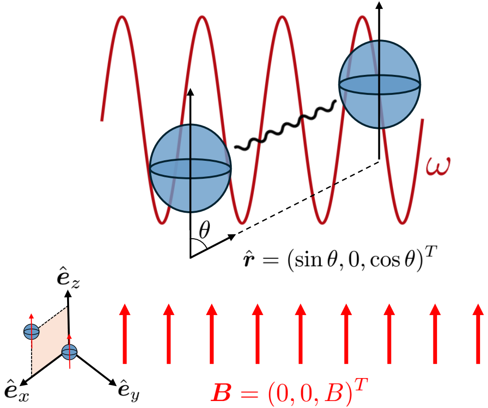




- Two **parallel** NV centers
- **Dipole-dipole interactions**
- Globally addressed by a **single MW pulse**
- Uniform external magnetic field $\boldsymbol{B} = (0, 0, B)^T$.

In an appropriate rotating frame:

$$
\begin{aligned}
\hat{H}_{\text{RWA}} =& \mu B(\hat{S}_{1,z} + \hat{S}_{2,z}) \\
& - \Delta(\hat{S}_{1,z}^2 + \hat{S}_{2,z}^2) + \frac{\Omega}{2}(\hat{S}_{1,x} + \hat{S}_{2,x}) \\
& + (A_{xx} |0+\rangle\langle +0| + A_{yy} |0-\rangle\langle -0| + \text{H.c}) \\
& + A_{zz}\hat{S}_{1,z}\hat{S}_{2,z}
\end{aligned}
$$

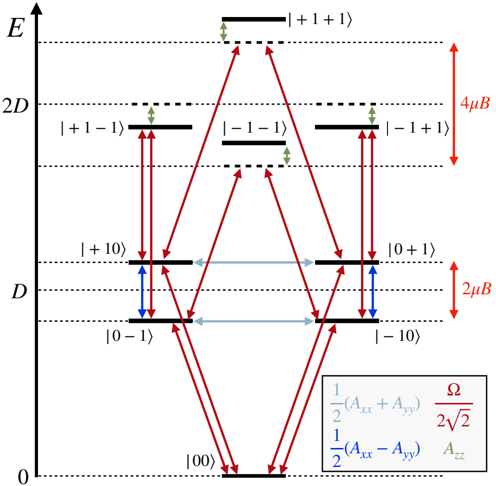


The two dipolarly interacting NV center system

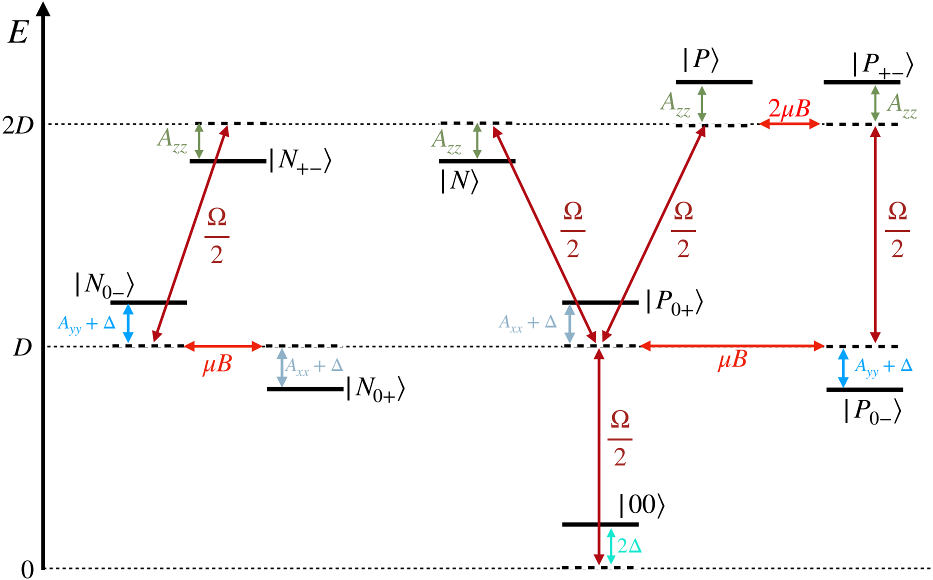
- Two **parallel** NV centers
- **Dipole-dipole interactions**
- Globally addressed by a **single MW pulse**
- Uniform external magnetic field $\boldsymbol{B} = (0, 0, B)^T$.

In an appropriate rotating frame:

$$\begin{aligned}\hat{H}_{\mathrm{RWA}} =& \mu B(\hat{S}_{1,z} + \hat{S}_{2,z}) \\ &- \Delta(\hat{S}_{1,z}^2 + \hat{S}_{2,z}^2) + \frac{\Omega}{2}(\hat{S}_{1,x} + \hat{S}_{2,x}) \\ &+ (A_{xx} |0+\rangle\langle+0| + A_{yy} |0-\rangle\langle-0| + \mathrm{H.c}) \\ &+ A_{zz}\hat{S}_{1,z}\hat{S}_{2,z}\end{aligned}$$



States of interest



$$|P\rangle = \frac{1}{\sqrt{2}}(|{+}{+}\rangle + |{-}{-}\rangle),$$

$$|N\rangle = \frac{1}{\sqrt{2}}(|{+}{+}\rangle - |{-}{-}\rangle),$$

$$|P_{ij}\rangle = \frac{1}{\sqrt{2}}(|ij\rangle + |ji\rangle),$$

$$|N_{ij}\rangle = \frac{1}{\sqrt{2}}(|ij\rangle - |ji\rangle), \quad i \neq j$$

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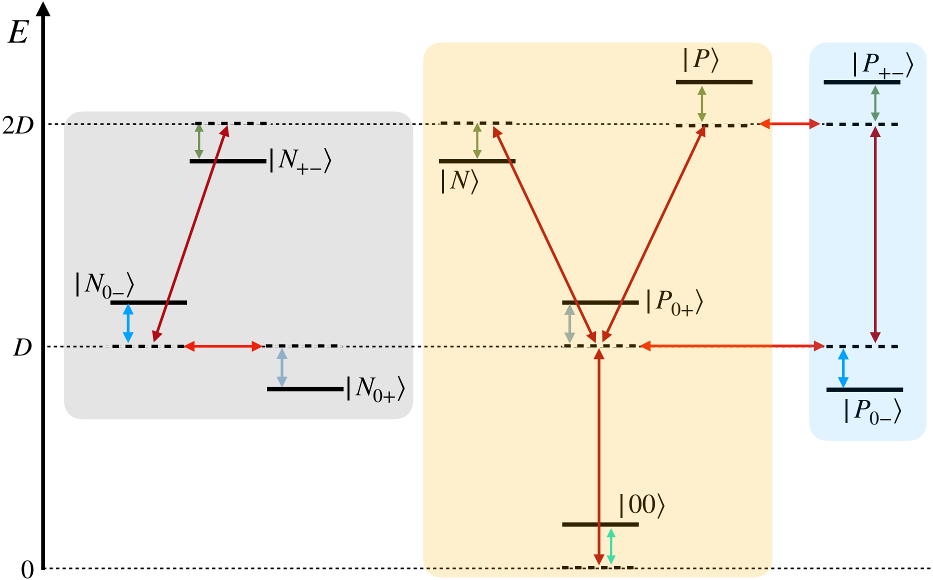

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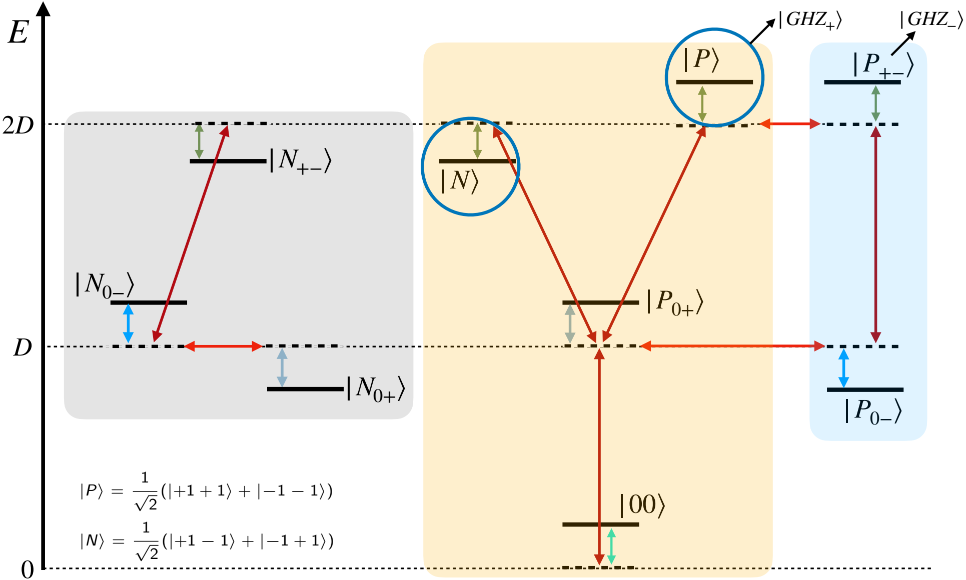
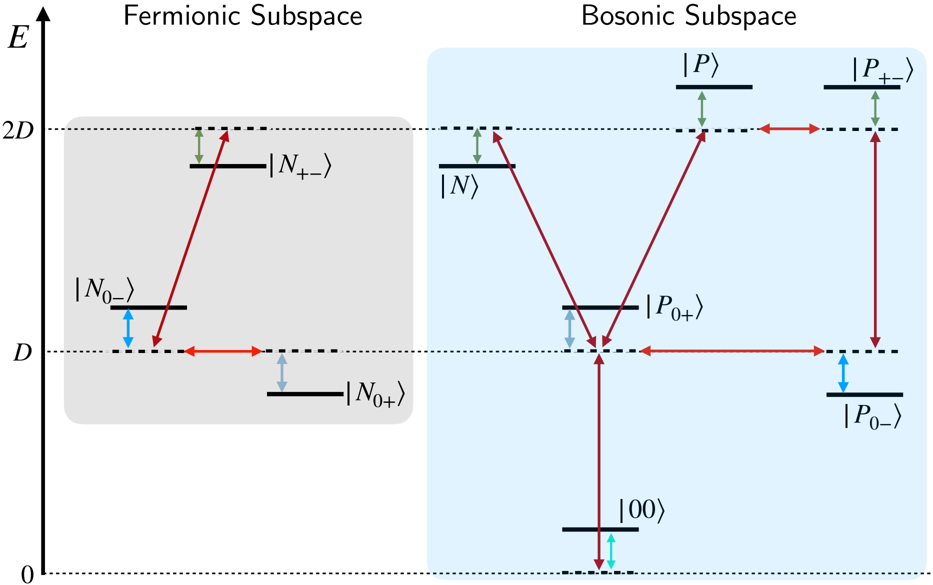


$$|P\rangle = \frac{1}{\sqrt{2}}(|+1+1\rangle + |-1-1\rangle)$$

$$|N\rangle = \frac{1}{\sqrt{2}}(|+1-1\rangle + |-1+1\rangle)$$

States of interest



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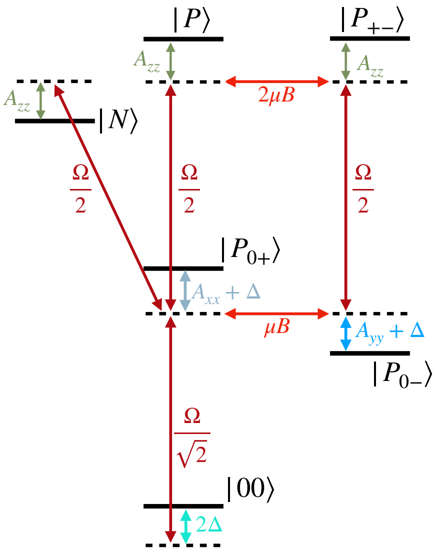
$|N\rangle$ state generation



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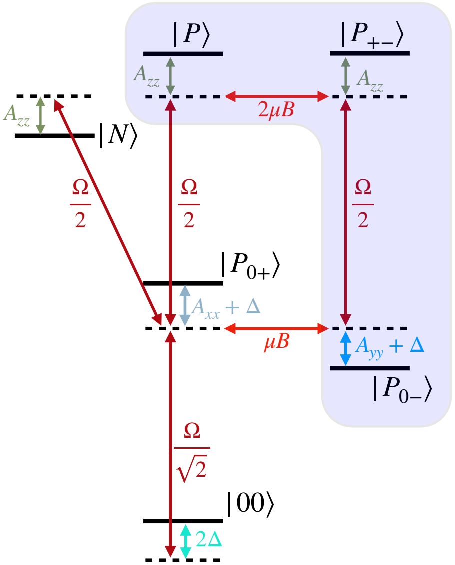

- We aim to eliminate $|P\rangle$, $|P_{+-}\rangle$ and $|P_{0-}\rangle$

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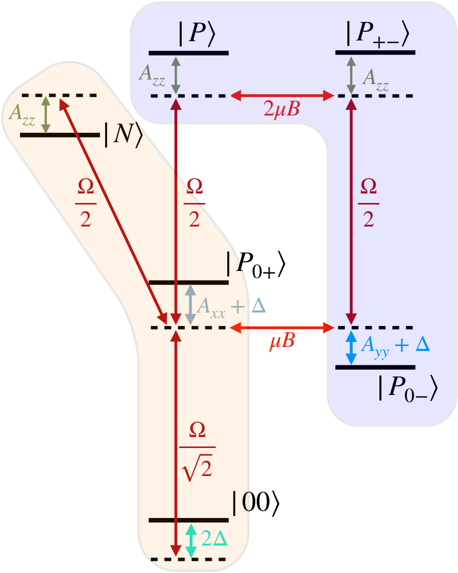

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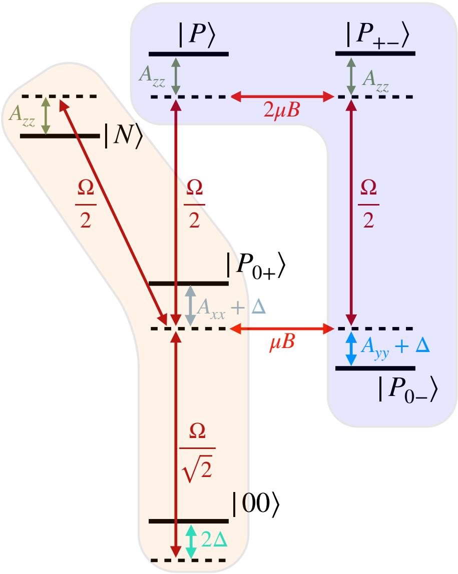
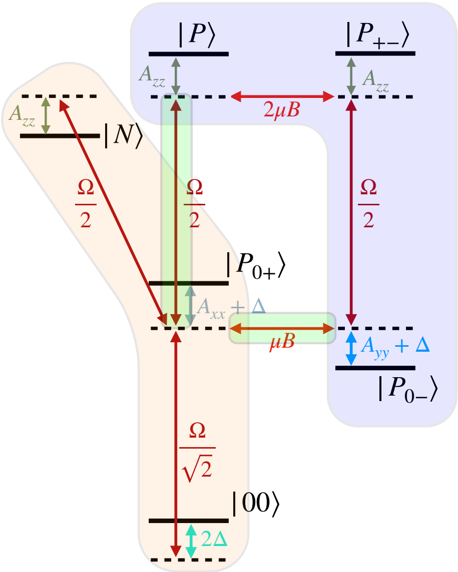


- We aim to eliminate $|P\rangle$, $|P_{+-}\rangle$ and $|P_{0-}\rangle$

$$\hat{H}_1 = \begin{pmatrix} 2\Delta & 0 & \Omega/\sqrt{2} \\ 0 & -A_{zz} & \Omega/2 \\ \Omega/\sqrt{2} & \Omega/2 & A_{xx}+\Delta \end{pmatrix}, \quad \hat{H}_3 = \begin{pmatrix} A_{zz} & 2\mu B & 0 \\ 2\mu B & A_{zz} & \Omega/2 \\ 0 & \Omega/2 & A_{yy}+\Delta \end{pmatrix}$$

$|N\rangle$ state generation



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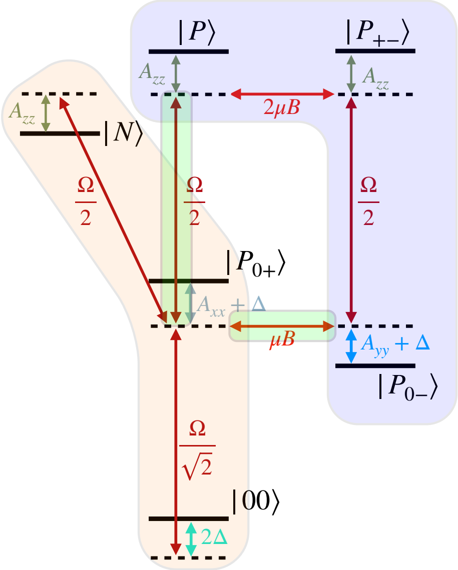
$$\hat{H}_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \Omega/2 & 0 & \mu B \end{pmatrix}$$

$|N\rangle$ state generation



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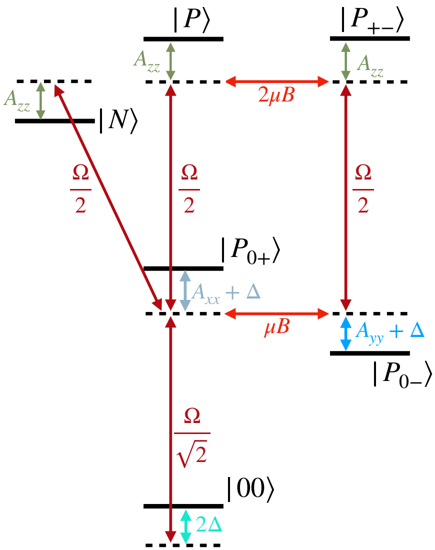
$$\hat{H}_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \Omega/2 & 0 & \mu B \end{pmatrix}$$

$$\hat{H}_{\text{eff}} = \hat{H}_1 - \hat{H}_2 \hat{H}_3{}^{-1} \hat{H}_2{}^{\dagger} = \begin{pmatrix} 2\Delta & 0 & \Omega/\sqrt{2} \\ 0 & -A_{zz} & \Omega/2 \\ \Omega/\sqrt{2} & \Omega/2 & A_{xx}+\Delta+\delta \end{pmatrix}$$

with

$$\delta = -\frac{(\mu B \Omega)^2[2(A_{yy}+\Delta)-A_{zz}]}{4(A_{yy}+\Delta)(A_{zz}-4(\mu B)^2)-A_{zz}\Omega^2}\left[\frac{2}{A_{zz}}+\frac{1}{A_{yy}+\Delta}\right]-\frac{\Omega^2}{4A_{zz}}-\frac{(\mu B)^2}{A_{yy}+\Delta}$$

$|N\rangle$ state generation



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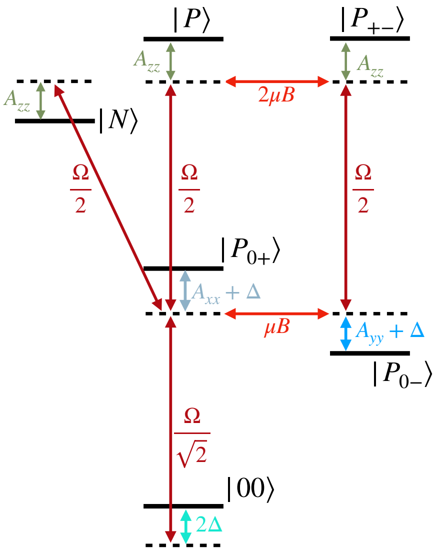
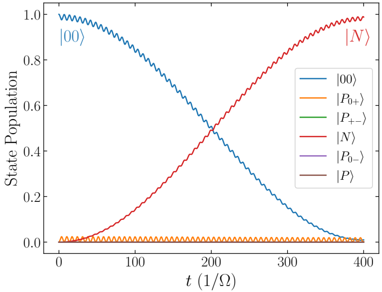
- In general, we will have a good Raman transfer for $\Omega/2 < A_{xx} + \Delta + \delta$ and $\Omega < A_{zz}, A_{xx}$

$|N\rangle$ state generation



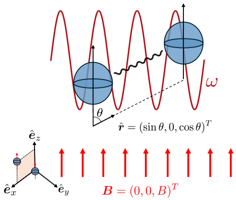
$$\hat{H}_{\text{eff}} = \begin{pmatrix} 2\Delta & 0 & \Omega/\sqrt{2} \\ 0 & -A_{zz} & \Omega/2 \\ \Omega/\sqrt{2} & \Omega/2 & A_{xx}+\Delta+\delta \end{pmatrix}$$

- In general, we will have a good Raman transfer for $\Omega/2 < A_{xx} + \Delta + \delta$ and $\Omega < A_{zz}, A_{xx}$
- $\Delta \approx -A_{zz}/2$ is a good first guess, but has to be finely tuned using δ

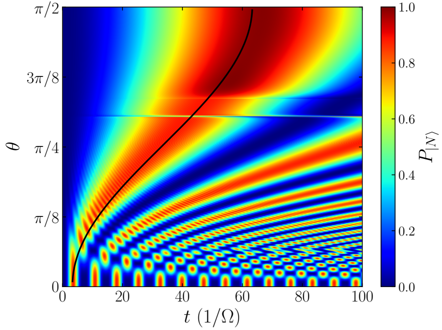


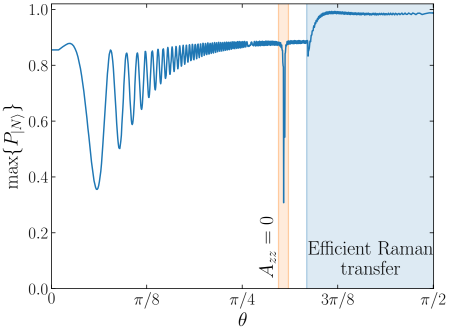
M. Morillas-Rozas, A. López-García, J. Cerrillo, arXiv:2501.18244

$|N\rangle$ state generation as a function of θ



- $A_{xx} \propto (1 - 3\sin^2\theta)$
- $A_{zz} \propto (1 - 3\cos^2\theta)$





Summary

- We propose a novel mechanism that uses globally addressing MW pulses on two dipole-coupled parallel NV centers to prepare maximally entangled states of the double quantum transition of the NV ground state, which can be used for several sensing purposes.

- After identifying the states of interest, we generate them using an approach based on Raman transfer and adiabatic elimination.