Initialization and readout of the NV center electronic and nuclear spins at the ESLAC

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Abstract

Nitrogen-vacancy (NV) centers in diamond are a promising platform for quantum technologies that can be operated even at room temperature. Readout of the NV center electronic spin is done by detecting the photoluminescence signal upon laser illumination. Near the excited state level anticrossing (ESLAC), the photoluminescence signal is not only sensitive to the electronic spin state but also to the nitrogen's nuclear spin. This provides a method to measure the spin polarizations of the electronic spin and the nuclear spin simultaneously, which can be advantageous compared to alternative techniques [1]. Laser illumination is used for both multi-shot readout [1] and initialization [2] of the electronic and nuclear spins. In this work, we investigate how both the quality of initialization and the quality of multi-shot readout depend on the magnitude of the external magnetic field. We consider two different *readout* methods and identify the optimal magnetic field value for both. For the second method, which provides the better readout, the optimum is exactly at the ESLAC, which coincides with the optimal point of the initialization. Our results can be used to improve the sensitivity of nitrogen-vacancy based quantum sensors.

Dynamics under laser illumination

Lindblad equation

$$\dot{\rho} = -\frac{i}{\hbar}[H_e + H_N + H_h\rho] + \sum_i \Gamma_i \, D[A_i]\rho,$$

$$D[A]\rho = A\rho A^+ \; -\frac{1}{2}\{A^+A, \rho\}$$

Jump operators:

$$A_i = \; A_e^i \otimes I_N, A_e^i = |k\rangle\langle l|$$

$|k\rangle, |l\rangle \in \{|g,0\rangle, |g,1\rangle, |g,-1\rangle, |e,0\rangle, |e,-1\rangle, |e,1\rangle, |s\rangle\}$

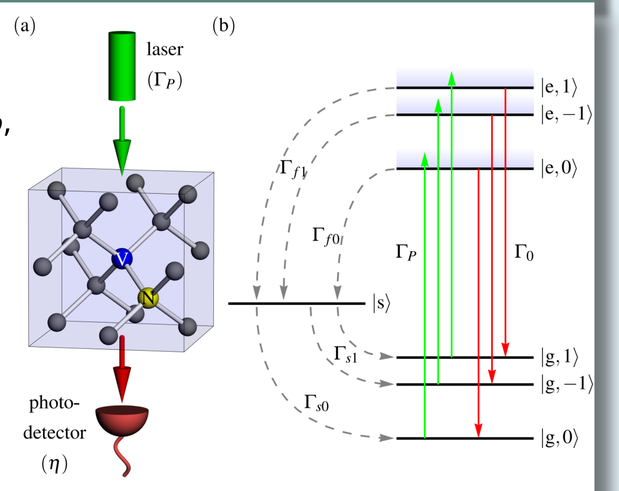
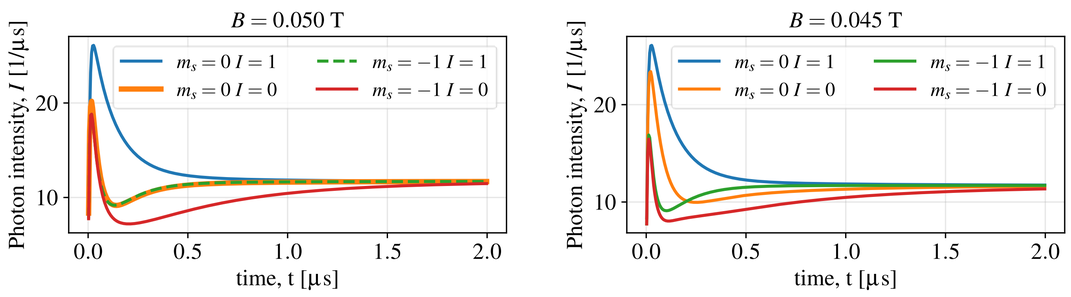


Fig. from Ref. [3]

Photoluminescence intensity for the computational basis states

$I(t) = Tr[P_e\rho(t)]$, where $P_e = |e,0\rangle\langle e,0| + |e,-1\rangle\langle e,-1| + |e,1\rangle\langle e,1|$



Rates for the simulation from Ref. [4].

Initialization

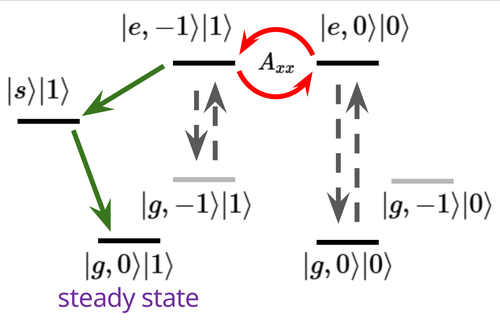
Initialization steps

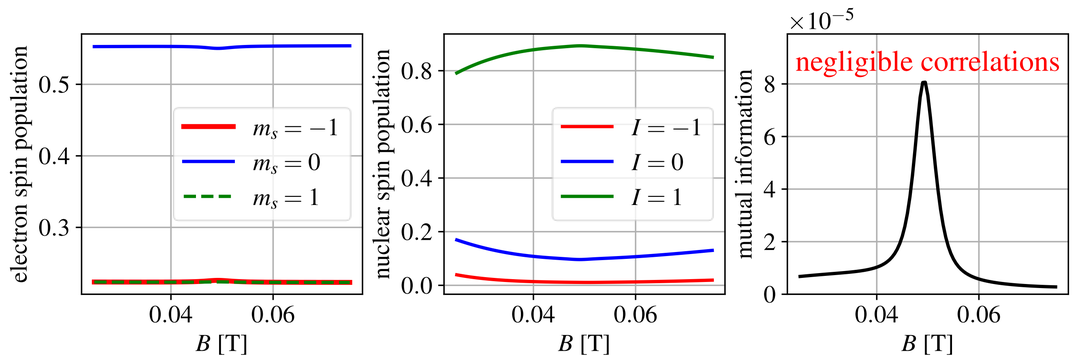
1. Laser pulse
2. Waiting

➢ Steady state: $|g,0\rangle|1\rangle$

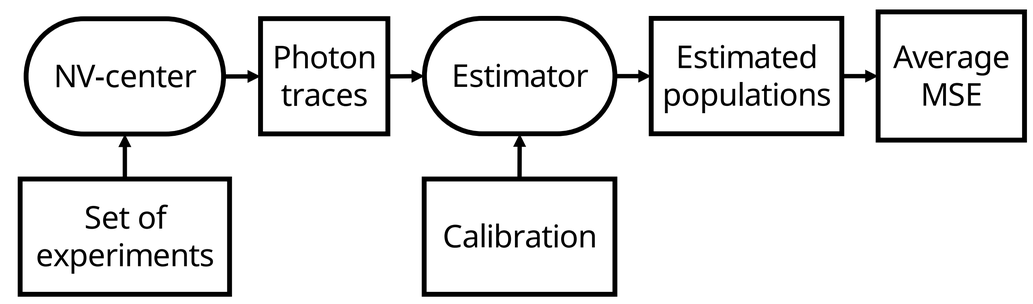
➢ For details, see Ref. [2].

Transitions at the ESLAC near $B = 50$ mT





Multi-shot readout



Set of experiments

1. $S = \{I_eI_N\}$
2. $S = \{I_eI_N,\; X_eI_e\}$

Estimator

See Ref. [1]

estimated occupation probabilities — measured photon counts

$$\hat{\mathbf{p}} = \arg\min_{\mathbf{p}} \|\mathbf{Lp} - \mathbf{m}_{meas}\|_2$$

$$k = n_{bins} \cdot |S| \left\{ \begin{pmatrix} m^1 \\ m^2 \\ \vdots \\ m^k \end{pmatrix} = \begin{pmatrix} l_{00}^1 & l_{01}^1 & l_{10}^1 & l_{11}^1 \\ l_{00}^2 & l_{01}^2 & l_{10}^2 & l_{11}^2 \\ \vdots & \vdots & \vdots & \vdots \\ l_{00}^k & l_{01}^k & l_{10}^k & l_{11}^k \end{pmatrix} \begin{pmatrix} p_{00} \\ p_{01} \\ p_{10} \\ p_{11} \end{pmatrix} \right.$$

$\boldsymbol{m}$ — expected photon counts; $\boldsymbol{L}$ — calibration; $\boldsymbol{p}$ — true occupation probabilities

constraint:
$p_{00} + p_{01} + p_{10} + p_{11} = 1$

bounds:
$0 \le p_i \le 1$

Physical estimator
- Bounds are respected
- Numerical minimization

Unphysical estimator
- Bounds are not respected
- Analytical solution:

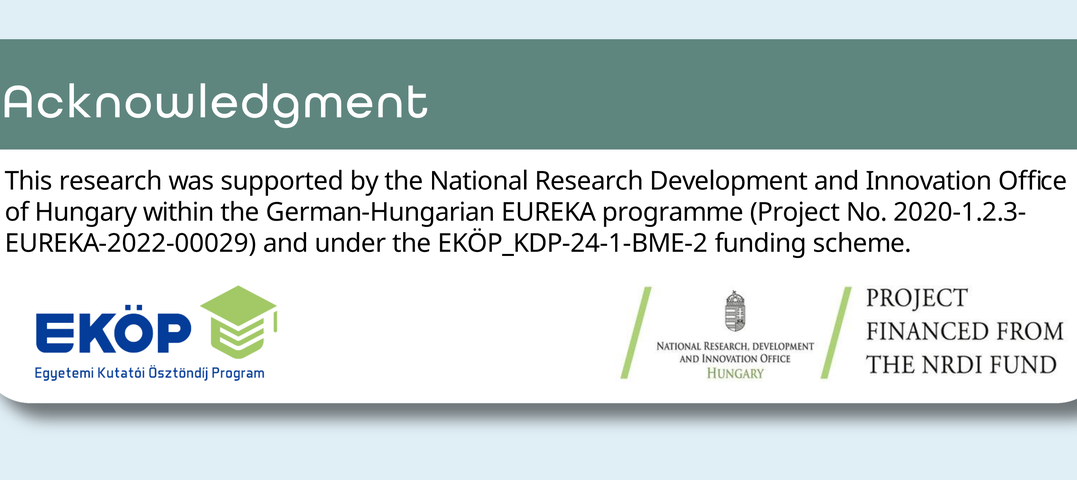
$$\mathbf{p}_u = \left(\mathbf{I} - \frac{\mathbf{W}\mathbf{1}\mathbf{1}^T}{\mathbf{1}^T\mathbf{W}\mathbf{1}}\right)\mathbf{W}\mathbf{L}^T\mathbf{m}_{meas} + \frac{\mathbf{W}\mathbf{1}}{\mathbf{1}^T\mathbf{W}\mathbf{1}}$$

$$\mathbf{W} = (\mathbf{L}^T\mathbf{L})^{-1}$$

$$\mathbf{1}^T = (1,1,1,1)$$

Average MSE (mean squared error)

- $\mathrm{MSE_A} = \mathrm{E}\left[\left(\hat{A} - A\right)^2\right]$
- $\overline{\mathrm{MSE}} = \int d\mu_{Haar}(\psi)[\mathrm{MSE}_{z_1}(\psi) + \mathrm{MSE}_{z_2}(\psi) + \mathrm{MSE}_{z_3}(\psi)]$, where $z_1 = \langle Z_eI_N\rangle, z_2 = \langle I_eZ_N\rangle, z_3 = \langle Z_eZ_N\rangle$.
- For the unphysical estimator: $\overline{\mathrm{MSE}}_{\mathrm{u}} \sim 1/N$, N: shot number



References

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