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Exploring Spin Mixing with Fluorescence Microscopy

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Abstract

Point defects in diamond, also known as color centers, offer unique possibilities for solid-state quantum magnetometry. Here, we demonstrate and explore quantum spin mixing and optical readout of nitrogen vacancy diamond quantum states with a portable, educational toolkit from Quantum Education Initiative. Visible light photons electronically excite NV centers, upon which their integrated photoluminescence is measured through a free-space photodetector. With household magnets, changes in photoluminescence are correlated with changes in the NV electrons magnetic spin state to intuitively understand optical initialization and readout of an NV ensemble. As a continuous wave laser is used for excitation, we do not demonstrate the trivial procedure for optical readout for quantum gates. Rather, we employ a magnet with a non-zero transverse field component to induce steady-state spin mixing, allowing us to observe decreases in photoluminescence due to occupation of the $m_s = \pm 1$ sublevels.

Keywords

Spin Mixing, Fluorescence, Quantum Magnetometry, Be Filled by the Editorial

1. Introduction

In recent years, quantum technologies have begun to move beyond theoretical and industrial settings into educational environments, where hands-on experimentation is increasingly seen as essential for developing intuition around complex quantum phenomena [1]. Among the most accessible platforms for such learning is the nitrogen-vacancy (NV) center in diamond—a point defect that offers optical

control and readout of electron spin states at room temperature [1]. Unlike traditional atomic systems, NV centers do not require ultra-cold environments or vacuum chambers, making them ideal for classroom-friendly demonstrations of quantum mechanics [1]. Here, we investigate how spin mixing and optical readout of NV spin states can be explored using simple tools: a continuous-wave laser, a photodetector, and household magnets. By linking changes in photoluminescence to the magnetic spin states of NV centers under varying magnetic field orientations, we aim to observe a clear, intuitive understanding of quantum state preparation and measurement in solid-state systems.

Nitrogen-vacancy (NV) centers in diamond are point defects that consist of a substitutional nitrogen atom adjacent to a vacancy in the carbon lattice [2]. In their negatively charged state (NV^-), these defects form an electronic spin-1 system that retains quantum coherence at room temperature—making them uniquely valuable for solid-state quantum sensing [2]. The ground state of the NV^- center is a spin triplet with a zero-field splitting of 2.87 GHz between the $m_s = 0$ and $m_s = \pm 1$ sublevels, primarily due to spin-spin interactions within the electron system [3] (**Figure 1**). This energy structure can be optically manipulated and read out using green laser excitation (532 nm), enabling a mechanism known as optically detected magnetic resonance (ODMR) [4]. Unlike traditional magnetometry techniques that require cryogenic temperatures or complex vacuum systems, NV-based magnetometry can operate under ambient conditions [1]. In the absence of microwave driving, NV centers can still be used for magnetometry [5]. This relies on the fact that transverse magnetic fields —those perpendicular to the NV axis—cause mixing between the spin sublevels [5]. As a result, the quantum state of the NV is no longer a pure ms eigenstate but becomes a superposition that includes components of the $m_s = \pm 1$ states [5]. Because these mixed states decay less efficiently via radiative transitions, an overall reduction in PL intensity is observed as the transverse field strength increases, even for small field magnitudes [5].

When exposed to an external magnetic field, the spin sublevels of the NV center experience Zeeman splitting, which alters their energy levels and, consequently, the photoluminescence (PL) emitted upon optical excitation [2]. This results in a measurable decrease in PL intensity even without microwave driving, enabling detection of magnetic field perturbations through purely optical control [5]. Since the NV^- electron's Hamiltonian is sensitive to magnetic fields, applying transverse magnetic fields with simple permanent magnets allowed us to explore spin polarization, optical readout and spin mixing. Even modest fields (on the order of a few millitesla) are sufficient to observe steady-state spin mixing effects in an NV ensemble, demonstrating the fundamental coupling between magnetic fields and quantum spin populations in a compact, room temperature setup. This phenomenon provides a simple yet powerful means to optically probe magnetic field perturbations using only a laser and a photodetector—with no microwave excitation required. In ensemble measurements, where NV centers are oriented along four

crystallographic directions, even a fixed-direction magnet can generate transverse components for some subpopulations. This makes all-optical NV magnetometry ideal for educational use, where intuitive demonstrations of quantum state readout and spin-magnetic field interactions are the primary goal.

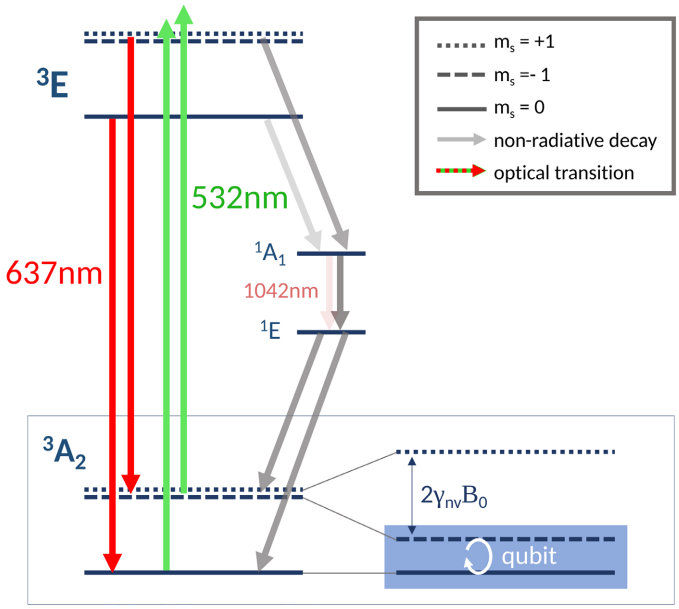

Figure 1. Electronic structure of NV^- electrons.

2. Methodology

QEI's kit and associated manual were used for the methodology. The fluorescence microscope was assembled as depicted below.

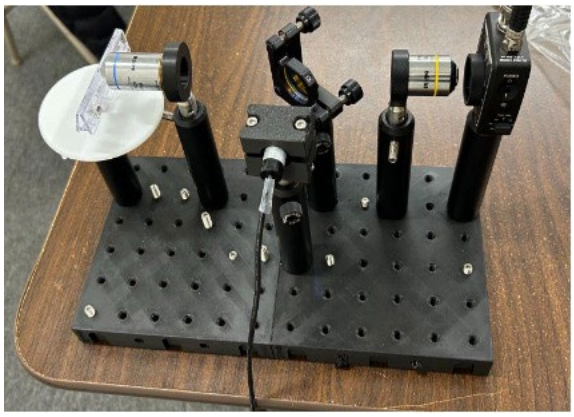

Figure 2. Detection setup.

First, we observed safety protocols using laser safety glasses of optical density (OD) 5 (for 532 nm light). The glasses transmitted a negligible amount of green light, while still allowing enough room light to align and conduct the experiment. For convenience, we used only collinear or orthogonal sets of screw holes to de-

cide where to mount the optics. The following instructions were followed to align optical elements.

Alignment Setup (Figure 2)

1) Mount the laser diode

2) Mount the dichroic mirror at 45 degrees with respect to the laser and the microscope objective

3) Mount and adjust the objective such that the laser passes through the center of the microscope objective

(a) Observe the light reflected on the wall—by allowing the light to propagate far, we can clearly observe any skewness or misalignment of the laser.

4) Place the diamond at the focal point (2 mm)

(a) The fluorescent, red beam will have the greatest intensity when the surface of the diamond is at the focal point of the microscope objective.

5) Align the second objective such that a small, bright red spot is visible near the focal point item Mount the photodetector

(a) Ensure detector is at focal point of second objective.

(b) Estimate the position of the detector with a notecard.

(c) Ensure the photodetector is relaying a voltage to the multimeter that is greater than the background counts at the given gain value.

(d) Adjust the height of the photodetector to maximize the signal.

(e) Adjust the angle of the photodetector to maximize the signal.

A 532 nm diode laser was first affixed to an optical breadboard and aligned with a dichroic mirror at a 45 degree angle. A microscope objective (magnification 40x, numerical aperture 0.65) was then placed between the dichroic mirror and the diamond plate, allowing the laser to reflect light from the mirror and through the center of the objective into the diamond. The diamond plate was then adjusted to the focal point (2 mm), and a second objective (magnification 10x, numerical aperture 0.25) was placed such that the red diamond fluorescence was visible. Finally, an amplified photodetector was mounted such that the fluorescence detected was maximized. Two banana wires were plugged into a multimeter and connected to an alligator wire which was plugged into the photo-detector. After connecting the photo-detector with a battery, the multimeter was able to relay the fluorescence intensity as a voltage. In this setup, the sampling frequency of photoluminescence measurements off the photodetector are limited by the sampling frequency of the multimeter. As the multimeter already limits downstream analysis to steady state effects rather than photoluminescence changes on the nanosecond scale, the use of a pulsed wave light source would have had limited benefit due to the inability to resolve signal changes on smaller timescales. Furthermore, a pulsed wave light source with controllable frequency would typically not be available in an educational setting. With that in mind, the use of a pulsed wave light source would have helped to reduce noise in the measured signals as the initial change in photoluminescence observed on the nanosecond scale is typically greater in magnitude than the steady state differential.

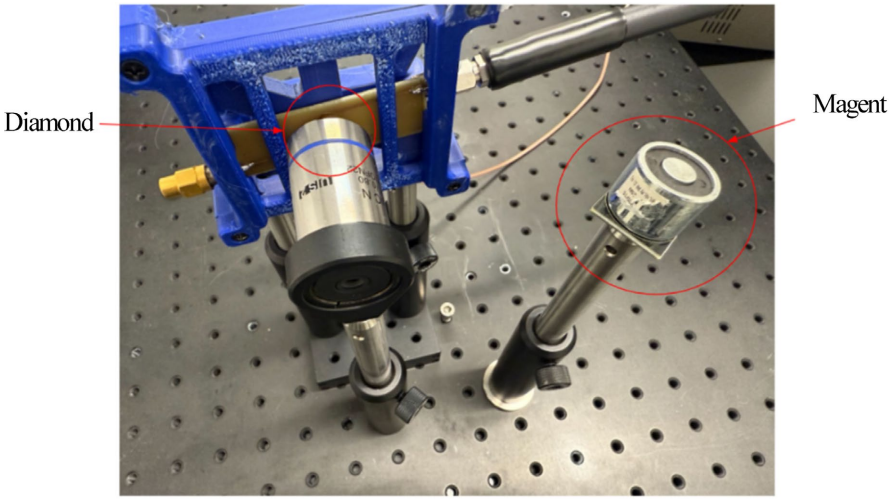

Figure 3. Magnet and diamond orientation.

The magnet utilized was a P20/15 electromagnet with 25 N holding force (approximately 7.8 Teslas of magnetic field strength at the edge of the cylindrical face) to generate the magnetic field. The magnet was positioned in the same horizontal plane as the NV center with the two circular faces also parallel to the horizontal plane (**Figure 3**).

3. Results

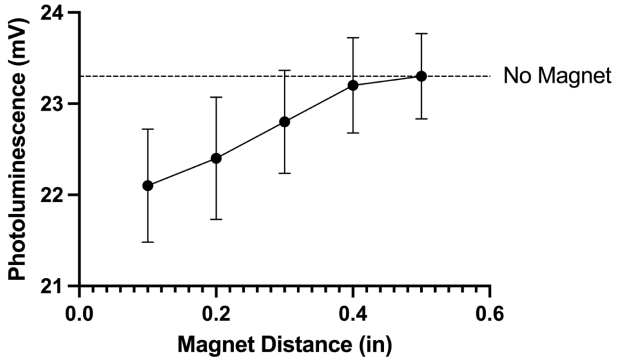

Figure 4. Photoluminescence response to magnet distance.

As expected, the electrons experienced the largest transverse field component when the was placed closest to the diamond plate (**Figure 4**). In this setup, the optical cycling induced by the continuous laser excitation reduces the observed steady state photoluminescence on the photodetector. The presence of the magnet resulted in larger levels of spin mixing, decreasing fluorescence and the resulting photoluminescence detected on the photodetector. While not thoroughly explored, the optical initialization and polarization of NV electrons were indirectly observed. As sub-ms time resolution was not a capability of the presented system, we only observed the steady state response of the NV electrons to photons and the transverse field. If the photons did not polarize the electrons into the $m_s = 0$

spin state, the distribution of electrons would be in a thermal distribution across the spin states, diminishing the effect of transverse field-induced spin mixing.

4. Conclusion

By constructing a fluorescence microscope with NV diamond as the emitter, we were able to observe spin mixing of quantum magnetic spin states via a magnet with a non-zero transverse field component. The different levels of fluorescence emitted by the electrons correspond with the density of electrons in the zero and non-zero spin states. Optical readout of quantum gates requires measuring the first 200 ns of the fluorescence response. As such, this high bandwidth measurement was not included in the scope of this exploration. Ultimately, spin mixing and optical readout of quantum states was achieved through a portable fluorescence microscopy kit.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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