NV Center Lab Report

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March 2024

Introduction

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1 Confocal Image

1.1 Procedure

After manually setting the positioning system to a x, y, z position of around 6 each, we first find the z position to establish the focus on our center by performing a position sweep in the z direction and taking the PL count at each position. We defined our sweep range to be from $z_0 - 0.2$ to $z_0 + 0.2$ moving in steps of 0.005. At each step, we would take the average count from the time tagger over 5 bins. We plot the z position vs the average PL count and fit this data to a Gaussian ($Ae^{-\left(\frac{x-x_0}{\sigma_x}^2\right)}$ where x_0 is our initial center guess and σ_x is the standard deviation of x) to find our focus.

After finding the focus, we must sweep for the x and y positions of our center. To find a particular center, we sweep in a radius of 0.03 in each direction, in steps of 0.003. As a result, we will acquire a two dimensional heatmap where the "heat" is determined by the average PL count we acquire at each x, y position. We spend $0.2s$ on each point to allow for sufficient counting. Moreover, we average over two bins with a binwidth of 10^{11}. From this design, we get a Confocal image of a particular center. To get a zoomed out image of multiple centers, we expand our sweep radius to 0.1 in steps of 0.005. To conclude where our center is, we fit one dimensional Gaussian curves for each position x, y like we did to find our focus, and return those values. Moreover, note for future experiments, we must reimplement this procedure by sweeping in each direction to track our center as it drifts over time and update our center appropriately.

1.2 Results

From sweeping in the z axis, we conclude that our focus is ≈ 6.46 For the x, y axis, the result from our sweep

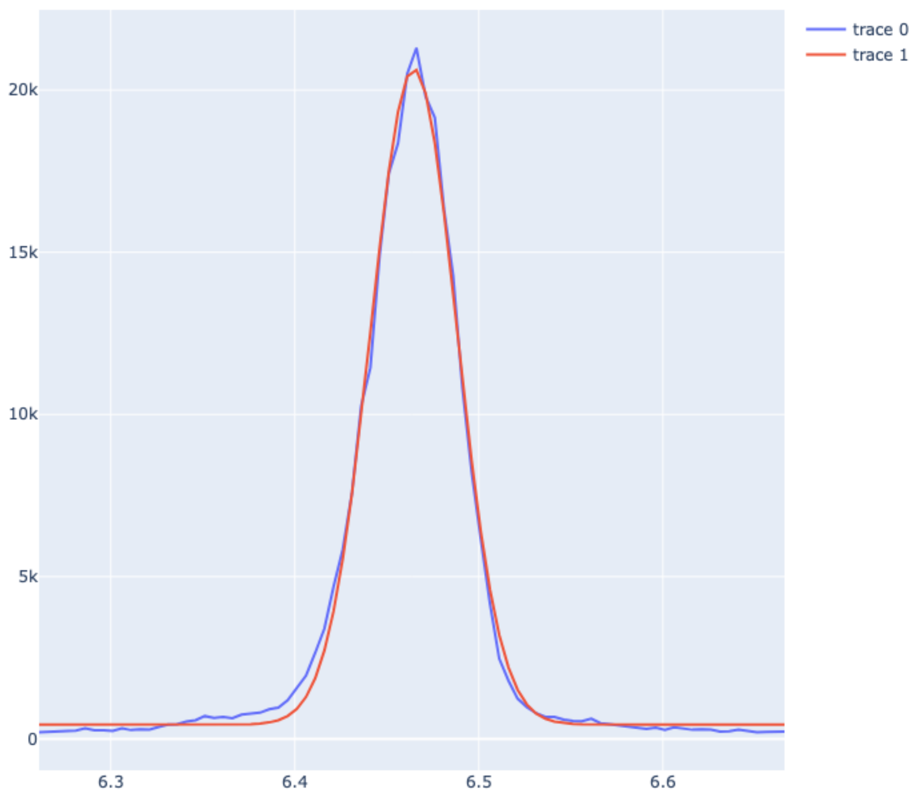

Figure 1: Fitted Gaussian distribution of z-position vs mean counts

is the following Figure 2 containing the heat-map of the counts at each tuple (x, y) We observe that there is a high count rate at $(x, y) \approx (5.98, 6.12)$. We confirm this by plotting the distribution of counts vs each coordinate in Figures $3, 4$. Note that we see the sudden spike in count rates to the right of our center as indicated by the heatmap, meaning another center could be close-by. Finally, we can decrease our resolution and widen our sweep to find a larger picture of what is around our center. With this approach, we get the heatmap in Figure 5. We observe many centers in this picture as there are several heat spots.

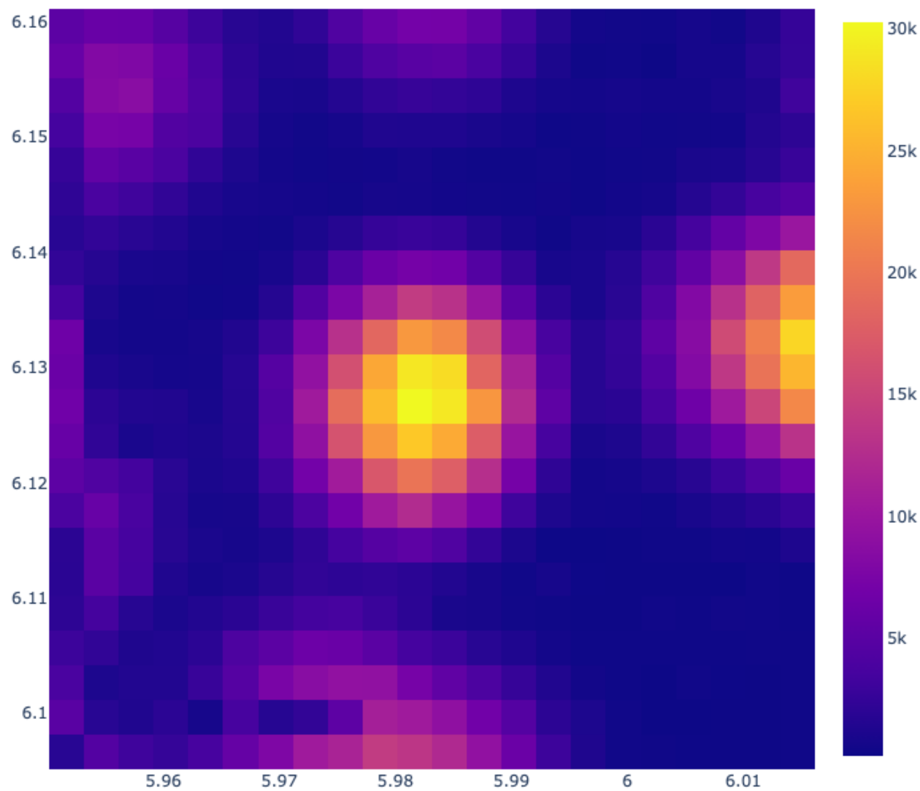

Figure 2: Heatmap displaying mean counts at each (x, y) position within the described range

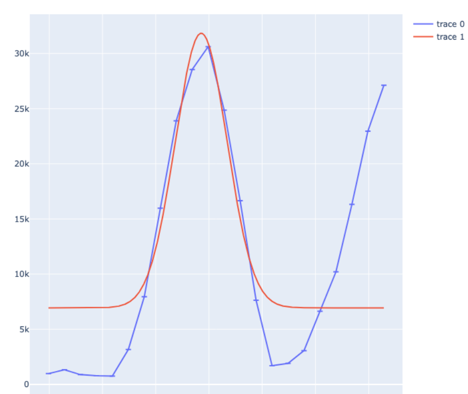

Figure 3: Fitted Gaussian distribution of x-position vs mean counts

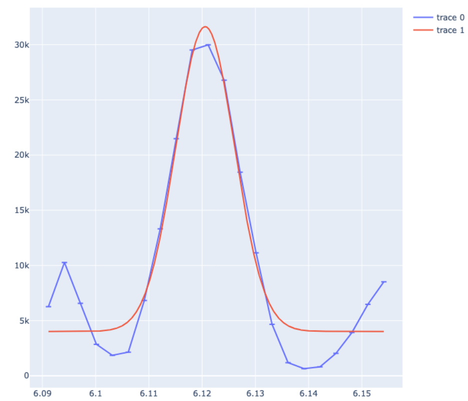

Figure 4: Fitted Gaussian distribution of y-position vs mean counts

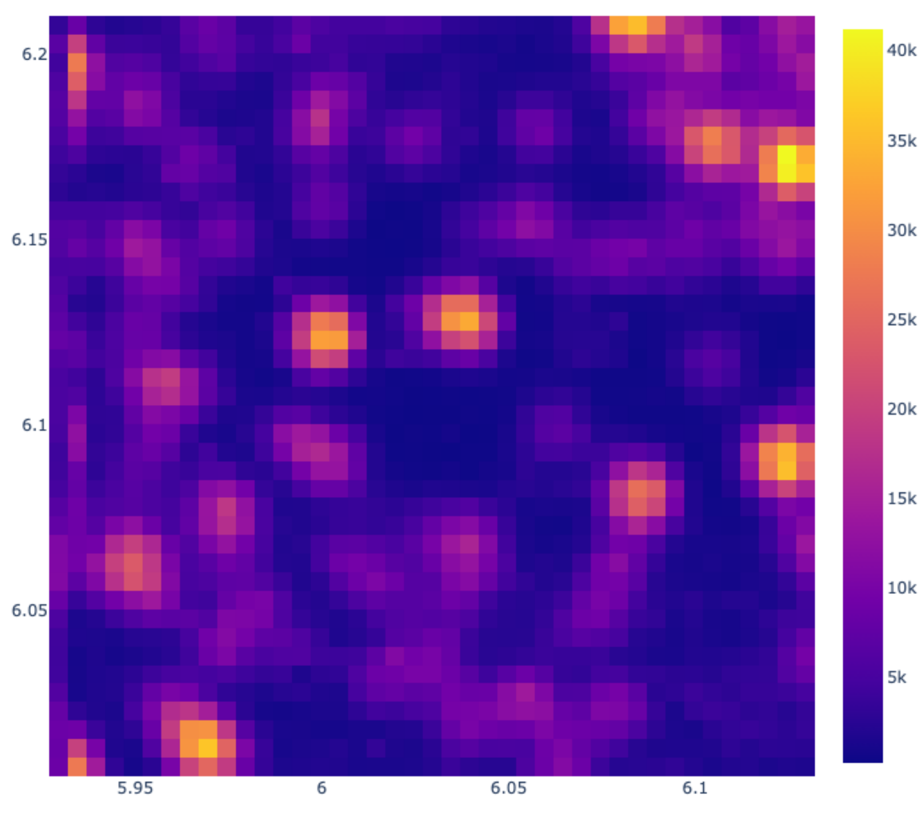

Figure 5: Zoomed out heatmap of multiple NV centers

2 ODMR Spectrum

2.1 Procedure

We do a frequency sweep centered at 2.8GHz with radius 0.05GHz in steps of 0.005GHz while the Green Laser is on and emitting PL for us to count. For each frequency, we're applying frequency pulses over $10\mu s$. Our total duration of the experiment is 5 milliseconds for each frequency.

We apply a reference pulse for the first half of the sequence and the signal pulse for the last half to hopefully cancel out some noise in the experiment. In particular, the purpose of the reference pulse is to acquire some initial count rate data after initialization to $m_s = 0$ by the green laser. This will be extremely accurate as we are not getting as many dark counts. After applying the microwave pulse, the signal pulse gets the count rate after which will inevitably be less than (or equal to) these reference counts.

We define the duration of each pulse as the sum of the bin widths for each counter and multiply this by 10^{-11}. Moreover, we repeat each experiment at each frequency 5 times. Moreover, note that before each pulse sequence, we refocus our center by repeating the procedure in section 1.

Continuing, the average count rate for each signal is the total counts divided by this pulse duration. We then normalize the count rates by dividing the signal rate by the reference rate. Taking the average over these normalized count rates for the five trials, we have our normalized PL count, which is the contrast we wanted.

We plot frequencies vs normalized PL count and fit this data to a Lorentzian curve with equation $-A\frac{((0.5*\Gamma)}{((f-f0)^2+(0.5*\Gamma)^2))} + 1$ where f is a varied frequency, $f0$ is some initial frequency, A is an arbitrary parameter, and Γ is the width of the curve. We note that the optimized $f0$ of this fit will be our transition frequency, and we report the contrast at this frequency.

2.2 Results

We plot the results of the frequency sweep below by plotting the frequency vs the normalized mean PL counts. Note that the normalized mean PL counts corresponds to the signal contrast, and so the lowest normalized mean PL counts will correspond to the transition frequency as this means we observe the highest dark counts, so the ratio of excited spins to ground state spins is largest. We see the results in Figure 6. From the graph, we find the transition frequency to be $\approx 2.799 \pm 0.0004$ GHz since at around 2.8GHz the spin contrast is the largest at around 0.778 ± 0.004.

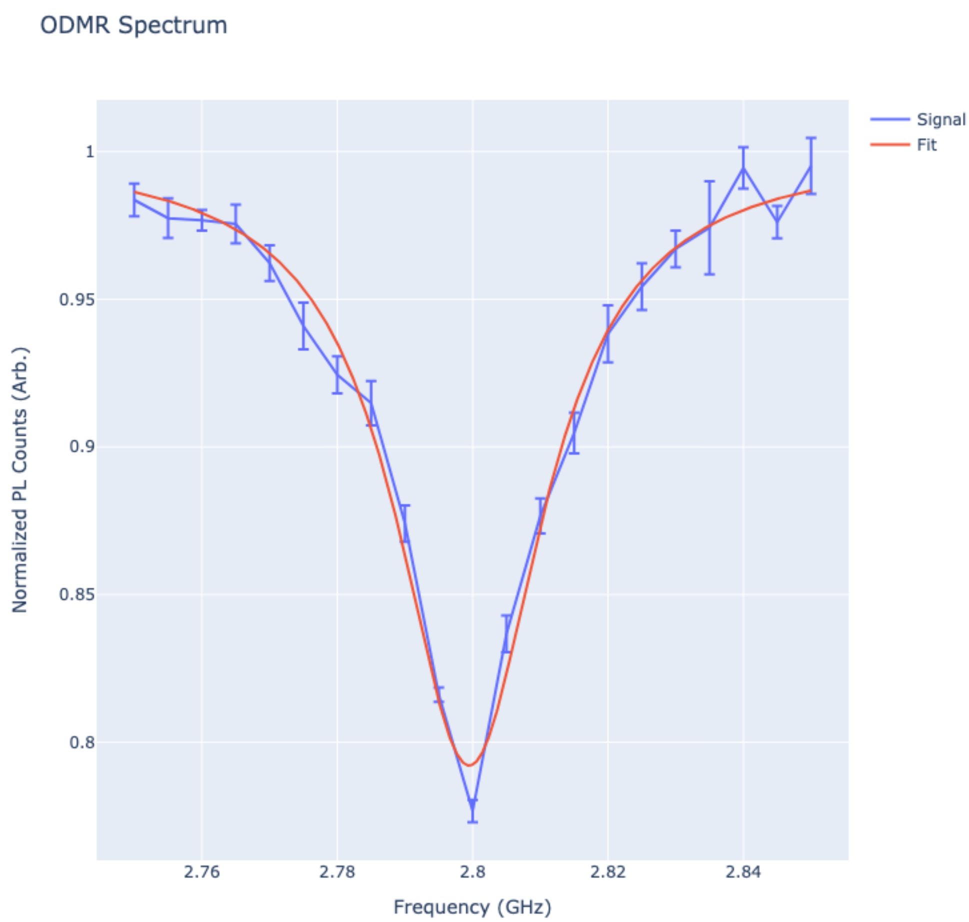

Figure 6: ODMR spectrum graph plotting the frequencies vs signal contrast

3 Rabi Experiment

3.1 Procedure

We first segment our pulse sequence into appropriate microsecond intervals for initialization, measurement, and PL collection. After initialization with the green laser, we apply the reference pulse. Then we apply the microwave pulse which will be pulsed at our transition frequency found from the ODMR, which will be applied over a varied duration τ. This τ ranges from $2ns$ to 205ns in steps of $5ns$. We also turn on the AWG after which we reapply the green laser for measurement and signal pulse to get the counts. At this point, our mathematical calculations are the same (duration of reference, signal, rates, etc), but this time we average our count rate over 13 trials per time τ.

From this data of the Rabi experiment, we now would like to find our π pulse duration and $\pi/2$ pulse duration. We plot a curve with our varied pulse durations τ on the $x-$axis in nanoseconds and our mean normalized counts on the $y-$axis. We fit this to a damped oscillator, which has equation $Ae^{-\frac{\tau}{T}}\cos(\frac{2\pi}{P}\tau - \phi) + C$ where A is the amplitude, T is the decay time, P is the period of the oscillation, ϕ is the phase shift, and C is the offset of the curve. Note that we expect some damping due to $T1$ decay. In fact, the graph of the experiment will illustrate this. We note π duration will be $\frac{\phi+\pi}{2\pi P}$ as this provides a conversion from radians to time. Similarly, $\pi/2$ duration will be $\frac{\phi+\frac{\pi}{2}}{2\pi P}$.

3.2 Results

With the above procedure, we acquire the data presented in Figure 7. From this fit, we find the following

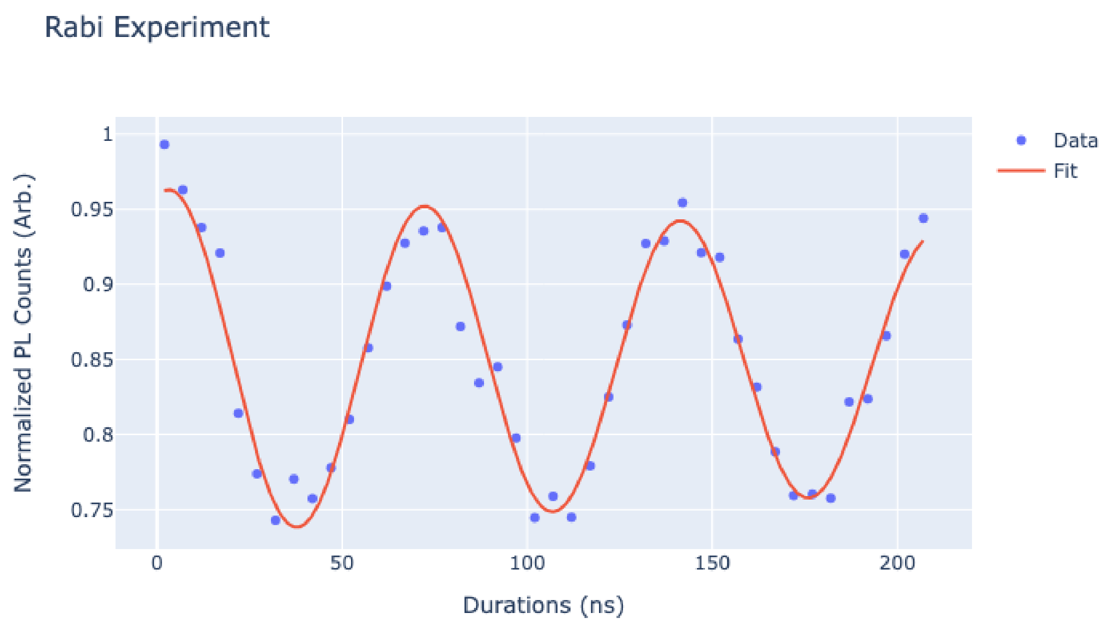

Figure 7: Rabi Oscillation Graph presenting the frequency duration vs normalized mean PL counts

parameters with errors: $T \approx 698.87ns \pm 305.25ns$, $P \approx 69.09ns \pm 0.518ns$, $\phi \approx 0.31 \pm 0.0767rad$. With these values, we calculate the $\pi-$pulse duration as $\tau_\pi \approx 37.92ns \pm -0.839ns$. Moreover, the $\pi/2$ pulse duration is $\tau_{\pi/2} \approx 20.64ns \pm 0.858ns$.

4 Ramsey Experiment

4.1 Procedure

For the Ramsey experiment, we utilize the π and $\pi/2$ durations to apply pulses and acquire the $T2^*$ time. In particular, we utilize similar setup as before, where we apply the green laser for initialization, apply a reference pulse. Now we apply a $\pi/2$ pulse by turning on the microwave pulse for the duration found in the rabi experiment. We then wait a varied delay τ, after which we apply another $\pi/2$ pulse. Then we use the laser and apply a signal pulse for readout and acquire our PL counts. Our varied delay τ ranges from $0ns$ to $2000ns$ in increments of 50 delays. Moreover, for each time τ we average over 13 bins. We plot a curve of our τ vs our normalized mean PL counts and fit this to a damped oscillation curve.

4.2 Results

We plot the results below in Figure 8. We extract the fit parameters and error and acquire a $T2^*$ time of $4129.14ns \pm 720.14ns$.

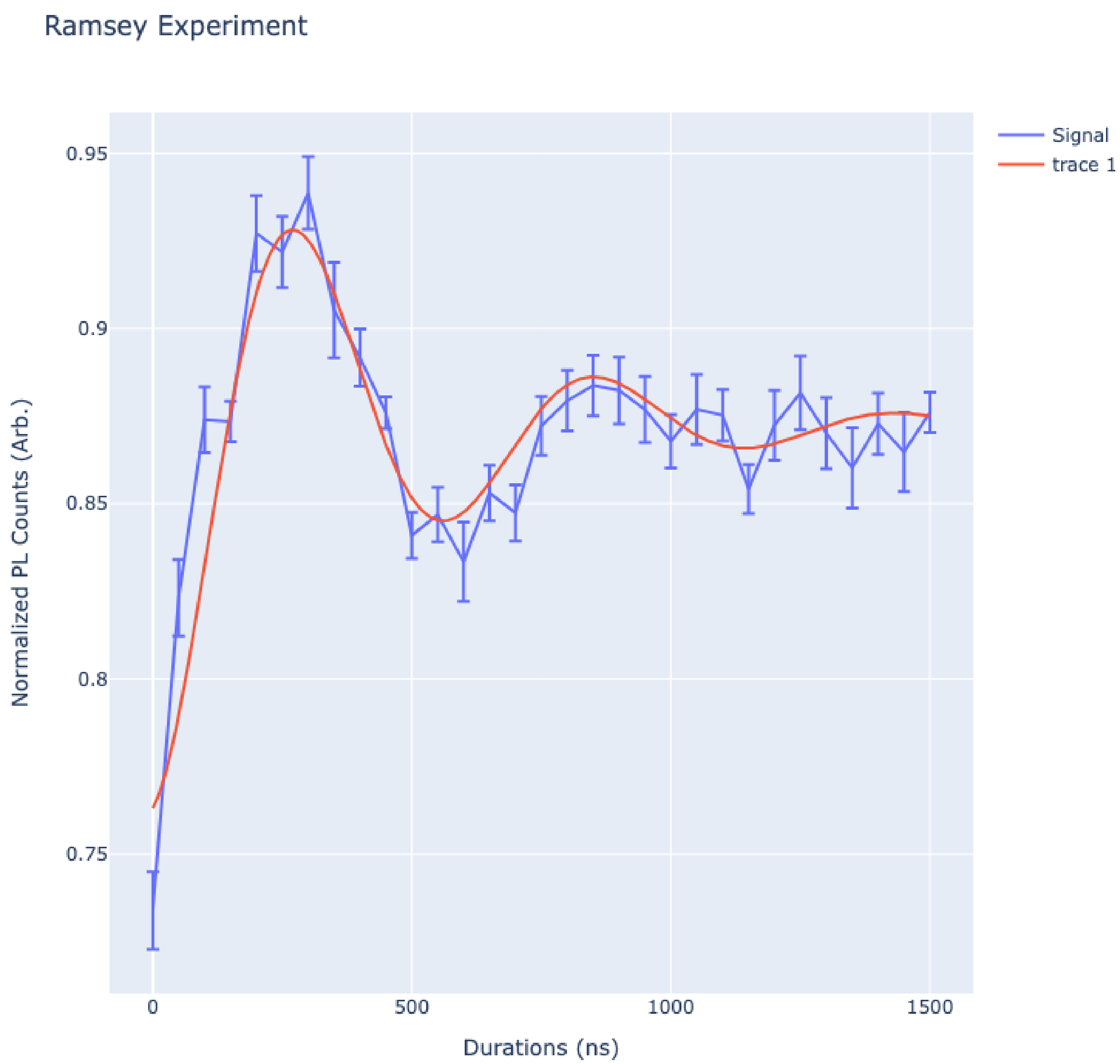

Figure 8: Ramsey Damped Oscillation Graph presenting the varied delay τ vs normalized mean PL counts

5 Hahn Experiment

5.1 Procedure

Much like the ramsey experiment, we apply multiple pulses with delays. This time, we turn on the green laser for initialization and apply the reference pulse. Then we apply a $\pi/2$ pulse, wait a varied delay τ, apply a π pulse, wait another delay τ, and finally, apply a last $\pi/2$ pulse. After this pulse sequence, we use the laser and signal pulse for readout again. This time, our τ ranges from $0ns$ to $2000ns$ in increments of $20ns$. We average the results over 13 bins to determine the normalized mean PL counts. Lastly, since we utilized two delays, we plot of 2τ vs normalized mean PL counts curve and fit to a variety of curves and processes as described below.

While one would hope to discover an exponential decay to determine the $T2$ time, unfortunately we will see that this does not occur, making the decay time indiscernible. Nonetheless, we will report the decay time from two trials of this experiment, while we report a third trial where we take our pulse length out to longer times.

5.2 Results

With the above experimental design, we acquired the following graph of 2τ vs normalized mean PL counts. We plotted the exponential decay fit as well as an exponential decay fit with equation Ae^{-x/T_2}. One notices that there is no observable decay from the second fit. We can try taking this experiment out to longer times as well to see what occurs. We observe this result in figure 10 and 11.

From these curves, we also notice that the peak to peak duration is also the same. One could confirm this by looking at the time from peak to peak or doing a Fourier Transform and observing whether the oscillations in the transform are constant or not. The time from peak to peak in Figure 9 and 10 are roughly $2\tau = 600ns, 2\tau = 300ns$ for the first two curves, and the consistent time from peak to peak indicates a lack of decay.

In Figure 9, the damped oscillator finds the decay time as $5413.81ns \pm 693.56ns$, but the exponential decay fit somehow reports the decay as negative. Nonetheless, we observe from the curve that no sensible decay is detectable. In Figure 10, we observe a decay of $9029.08ns \pm 1008.98ns$ from the damped oscillator fit.

We can explain the oscillations from this experiment with an explanation consisting of a physical explanation of this experiment. Due to interactions between the electron spins from the NV center and the Carbon atoms in the diamond, our readout of the spins is affected. In particular, the hyperfine coupling interactions between $C13$ nuclei and the NV center causes the damped oscillations found in this experiment. An example of this result can be observed in the following paper [YY], which also conducts a Rabi, Ramsey, and Hahn experiment on an NV center. While these oscillations are not as strong, they're a proof of concept that $C13$ dynamics affect results of these experiments.

Figure 9: Hahn experiment data presenting the varied delay 2τ vs normalized mean PL counts. $2\tau = 2000ns$

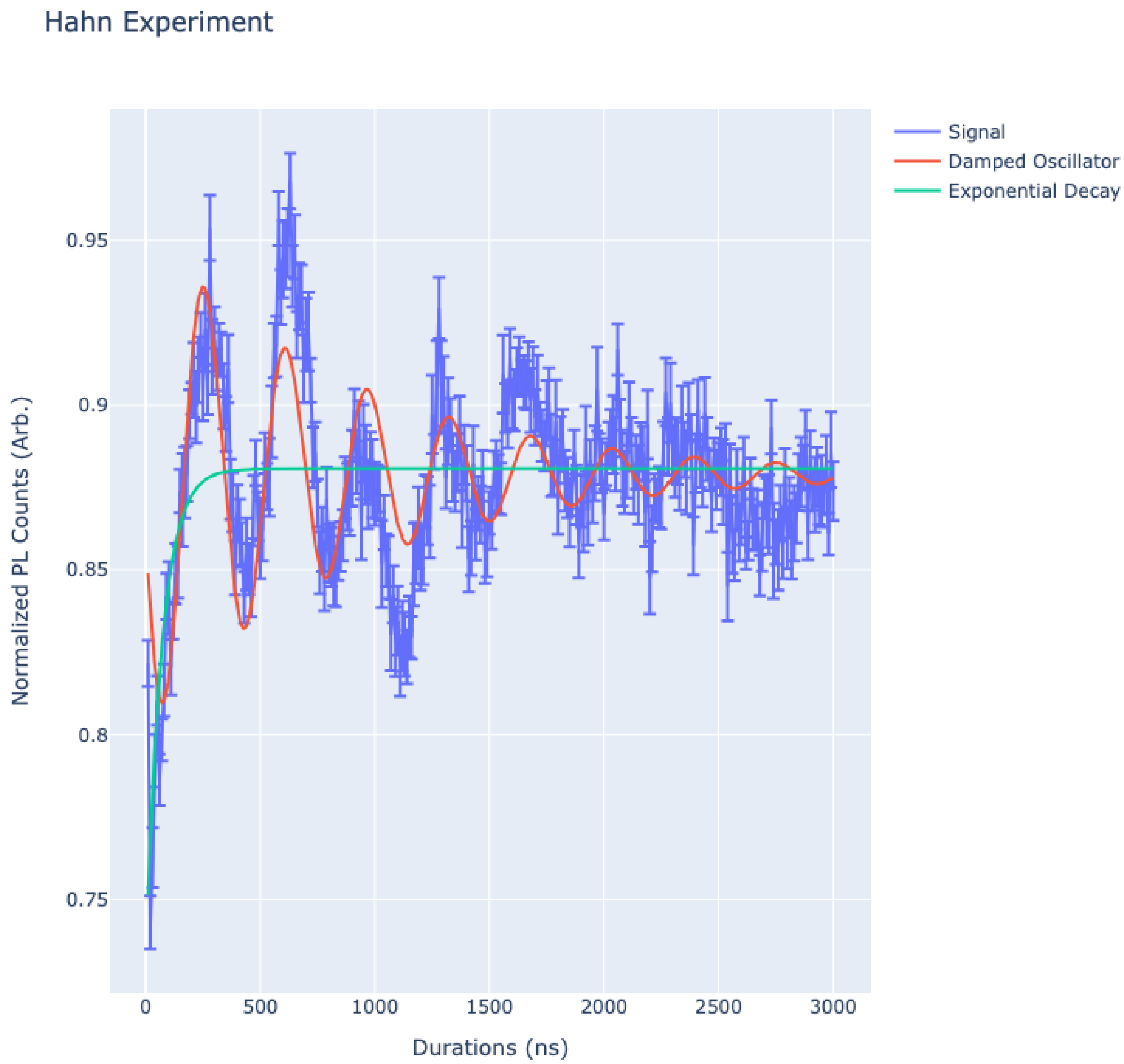

Figure 10: Hahn experiment data for longer times to $2\tau = 3000ns$

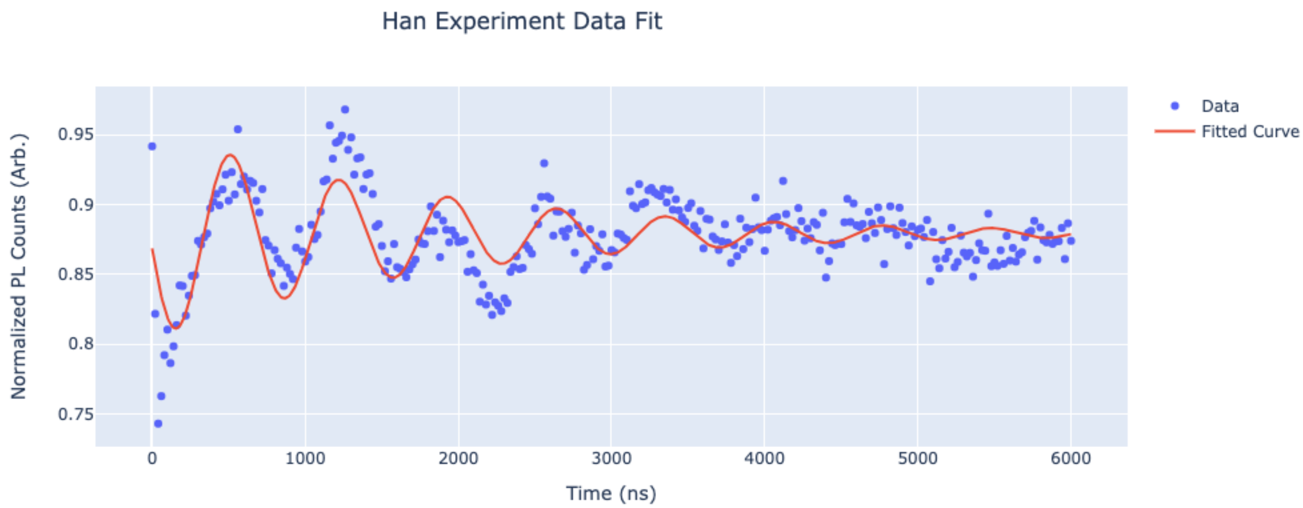

Figure 11: Hahn experiment data for longer times to $2\tau = 6000ns$

References

[YY] Yang Yang, Hyma H. Vallabhapurapu, Vikas K. Sewani, Maya Isarov, Hannes R. Firgau, Chris Adambukulam, Brett C. Johnson, Jarryd J. Pla, Arne Laucht. "Observing hyperfine interactions of NV centers in diamond in an advanced quantum teaching lab." Am. J. Phys. 1 July 2022; 90 (7): 550–560. `https://doi.org/10.1119/5.0075519`