Verification of the Magnetic-Dipole Nature of Our Transition: Fluorescence of a Dipole

Zachary Buckholtz

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Abstract

Between April and September of 2016 we did several variations of a standing wave experiment in an attempt to verify the magnetic-dipole nature of the $^7F_0 \rightarrow {}^5D_1$ transition of Eu^{3+}:Y_2SiO_5. Eventually it became apparent that a different method would be needed. This lead us to explore the anisotropy of our crystal to carry out the verification. This proved to be an effective method.

1 Prologue

As described in [1], our previous attempts to verify the magnetic dipole nature of the $^7F_0 \rightarrow {}^5D_1$ transition (simply referred to as the transition or our transition from now on) of Eu^{3+}:Y_2SiO_5 (YSO). This proved to be a fruitless endevour. The reasons for this and the reasons we want to demonstrate the magnetic-diopole nature of our transition can be found in the writeup on those efforts [1].

2 Introduction

The idea behind this experiment is simple; exploit the anisotropic response of the crystal to determine which field is producing the fluorescence. To get a more intuitive view of this, one can use the classical picture that the europium ions are tiny dipole antennas. The classical radiation pattern of a dipole is a donut shape where the donut is coaxial with the dipole. This donut also represents the directional sensitivity of the dipole. In other words, the dipole is most responsive to electromagnetic waves which are polarized parallel to the dipole.

Due to the crystalline nature of our crystal, these dipoles are all oriented roughly the same way with respect to the crystalographic and optical axes. Now, imagine that we send in light with the electric field polarized along one of the optical axes, let's say the D1 axis. If we were to then rotate the crystal around this axis, the orientation of the electric field in the crystal would not change. Now let's assume, just as an example, that the dipoles are all aligned with the D2 axis. As we rotate the crystal around the D1 axis and electric field, the magnetic field's orientation changes. Since the dipoles are aligned perpendicularly to the axis of rotation, the magnetic field's alignment will alternate between being perpendicular and parallel (or antiparallel) to the dipoles. Thus, if the magnetic field does indeed interact with the europium, we would expect the intensity of the fluorescence to change as we rotate the crystal. The same experiment can be done with the magnetic field aligned with the D1 axis. As we rotate the crystal in this situation and if the electric field does not interact with the europium, we would expect no change to the intensity of the fluorescence, disregarding the effects of reflections and transmissions.

3 Experimental Setup and Procedure

The Experimental setup can be seen in Figure 1. To carry out the measurement described in the introduction, we needed a way to accurately rotate the crystal. To do this we put the crystal in a Gimbal mount. The starting position was such that both of the mount's axes of rotation were parallel to the table. The crystal was arranged such that the starting direction of the axes were normal to four of the crystal's faces. The laser was a 527 nm linearly polarized beam generated by an SHG cavity (not shown in Figure 1. The polarization state of the laser was selected with a half-wave plate. The laser, in eithher the S or P polarization state, was then directed along one of these axes

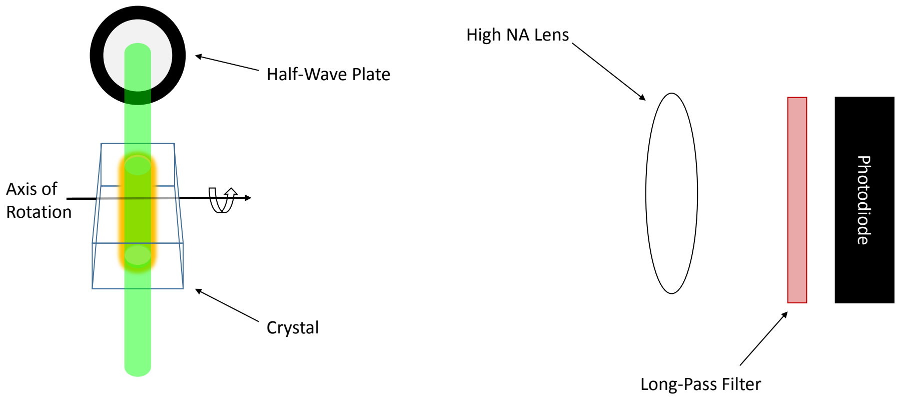

Figure 1: The Experimental setup. The crystal is mounted in a Gimbal mount with an axis of rotation parallel to the page. The Laser beam is coming roughly out of the page. The filter we used was a red transmission filter with a cutoff low enough to transmit the fluorescence. The photodiode was a Thorlabs PDA36A (CHECK THIS).

and perpendicularly to the other. The crystal was then incrementally rotated along the axes that was perpendicular to the beam. The fluorescence was collected with a high NA lens and focused onto our Newport power meter after going through a filter to remove any green light. The power in the fluorescence was measured as the crystal was incrementally rotated around the axis that was perpendicular to the laser. This procedure was repeated for each polarization state incident on each of the three axes of the crystal.

4 Data Analysis and Results

We want to be able to compare the fluorescence between the different polarization states as a function of incidence angle. To do so we need to account for the other factors that could be causing a change in the amount of fluorescence. There are two such factors that influence the amount of fluorescence collected onto the power meter, and they both depend on the angle at which the beam enters the crystal. The first factor is that the beam's pathlength in the crystal will change as the angle of incidence is changed, and it is the same for both polarization states. This can be accounted for by multiplying each measurement by $\cos\theta_i$[1]. The other factor is, which does depend on the polarization state, is the change in laser power in the crystal from reflections and transmissions.

Before we continue, it is important to note that there are two assumptions made in the following analysis. One is that, dispite the anisotropy of the crystal, we assume that the index of refraction is the same in all directions. This is not strictly true, but the small difference in index between the different directions is small and does not have much of an impact here. The other assumption is that the absorption of the green beam in the crystal is negligible. To be more precise, we assume that the main source of attenuation of the beam in the crystal is transmissions through the faces.

The Fresnel coefficients of power reflection and transmission for a beam propagating in a material with index of refraction n_1 and permeability μ_1 towards an interface with a material with index n_2 and permeability μ_2 at an

[1]The actual pathlength is $L/\cos\theta_i$. L is the length the beam travels through the crystal at normal incidence and θ_i is the angle of incidence (measured from the normal of course).

angle of θ with the normal of the interface are given by

$$\begin{aligned} &\text{S wave: } R = \left| \frac{n_1 \cos\theta - \frac{\mu_1}{\mu_2}\sqrt{n_2^2 - (n_1 \sin\theta)^2}}{n_1 \cos\theta + \frac{\mu_1}{\mu_2}\sqrt{n_2^2 - (n_1 \sin\theta)^2}} \right|^2 ; \qquad T = \left| \frac{2 n_1 \cos\theta}{n_1 \cos\theta + \frac{\mu_1}{\mu_2}\sqrt{n_2^2 - (n_1 \sin\theta)^2}} \right|^2 \\ &\text{P wave: } R = \left| \frac{\frac{\mu_1}{\mu_2} n_2^2 \cos\theta - n_1 \sqrt{n_2^2 - (n_1 \sin\theta)^2}}{\frac{\mu_1}{\mu_2} n_2^2 \cos\theta + n_1 \sqrt{n_2^2 - (n_1 \sin\theta)^2}} \right|^2 ; \qquad T = \left| \frac{2 n_1 n_2 \cos\theta}{\frac{\mu_1}{\mu_2} n_2^2 \cos\theta + n_1 \sqrt{n_2^2 - (n_1 \sin\theta)^2}} \right|^2 . \end{aligned} \tag{1}$$

We assume that both materials (air and our crystal in this case) have negligible magnetic susceptiblities so that their permeabilities, μ_1 and μ_2, are equal to the permeability of free space[2].

When the beam initially hits the crystal, it undergoes a power reduction via a transmission. The beam then undergoes numerous reflections in the crystal, bouncing between the two opposing faces, and undergoing a power reduction on each reflection. Since the crystal faces are not high-reflectivity mirrors, the total beam power in the beam is dominated by the first few reflections, which is in compliance with our earlier assumption that the main source of power loss in the crystal is through the interface. Because of this, we can approximate the sum of each reflected beam with a geometric series. Thus the total beam power in the crystal is

$$P_{total} = T(\theta_i)(1 + R(\theta_r) + R^2(\theta_r) + ...)P_{incident} = \frac{T(\theta_i)}{1 - R(\theta_r)} P_{incident} \tag{2}$$

where θ_i is the angle of incidence at the air-crystal interface and θ_r is the angle of incidence at all of the crystal-air interfaces (related to θ_i by Snell's law).

To normalize the data, we make the assumption that the power measured by the powermeter is proportional to the amount of fluorescence which is itself proportional to the power of the beam in the crystal. We then multiply our data by $\cos(\theta_r)$, to acount for the change of pathlength in the crystal, and divide by the coefficient in equation 2. The data is further normalized by dividing each set of data with a given polarization and propagation orientation by the normalized power at normal incidence. The results of this normalization canbe seen inf Figures 2 - 4. Figures 2 and 3 clearly show a response from changing the orientation of the magnetic field but not the orientation of the electric field. Figure 4 was a little more messy. Since the beam was propagating along the long axis there was a much smaller window of angles in which we could send in the beam without hitting the sides of the crystal. Even for those low angles that the incident beam did not hit any sides, some of the reflected beams did. For this reason, these plots are not quite as conclusive as Figures 2 and 3.

References

[1] Z. N. Buckholtz. *Verifcation of the Magnetic-Dipole Nature of Our Transition: Standing Wave Experiment.* Unpublished.

[2] N. R. Brewer, Z. N. Buckholtz, Z. J. Simmons, E. A. Mueller, and D. D. Yavuz. *Coherent Magnetic Response at Optical Frequencies using Atomic Transitions*, Phys. Rev. X **7**, 011005 (2017).

5 Notes

- The detector was the newport power meter, not a photodiode.
- What power did I use?
- What not to do.
- Which axis is which?

[2] Although the main point of our Rabi flopping experiment in [2] was to demonstrate a deviation from the permeability of free space in YSO, the power of the laser in this experiment is much lower. Therefore the deviation is much smaller and, thus, negligible.

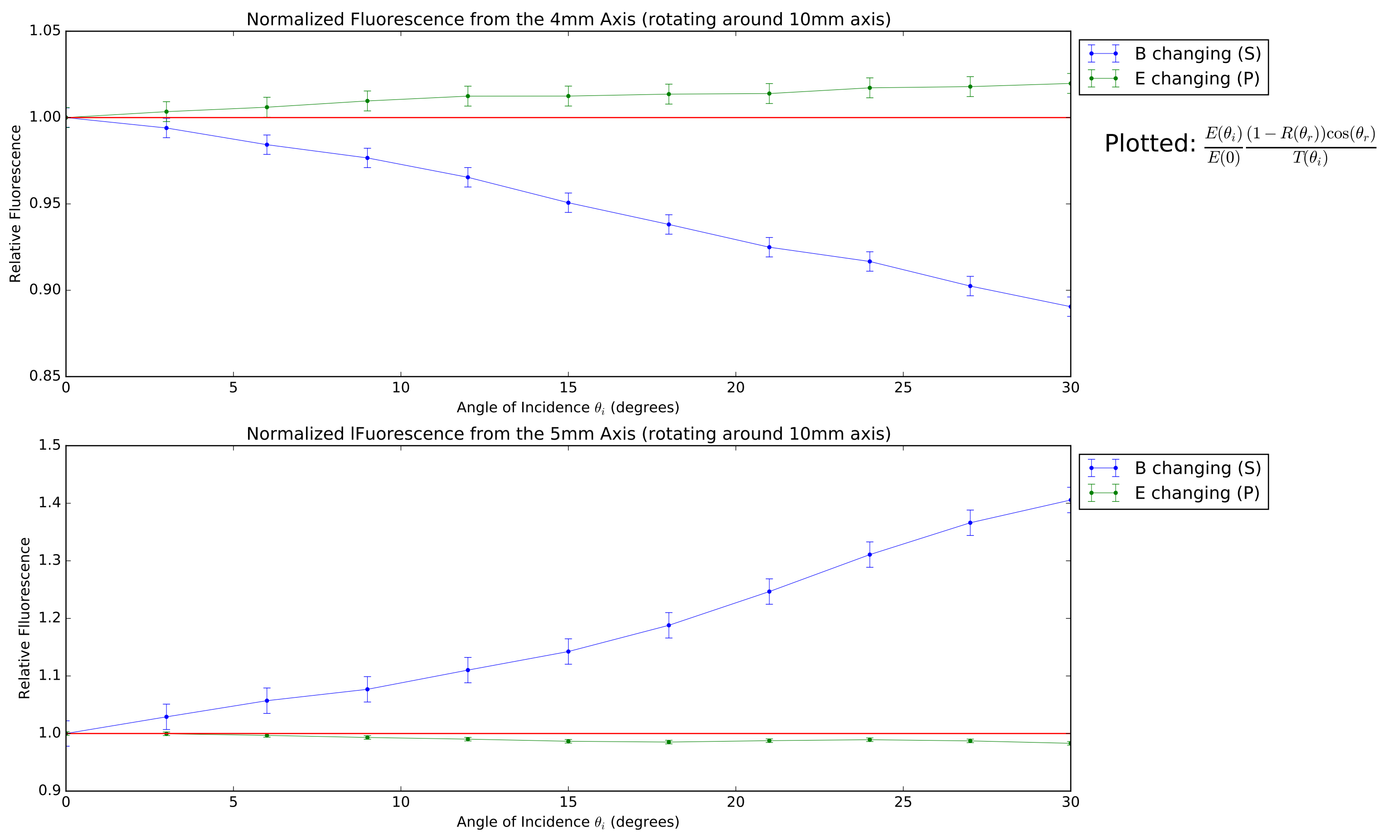

Figure 2: Fluorescence while rotating around the 10 mm axis. In the top plot the beam is propagating along the 4mm axis. In the bottom plot the beam is propagating alog the 5 mm axis. These plots clearly show that the fluorescence responds to the orientation of the magnetic field and not the electric field.

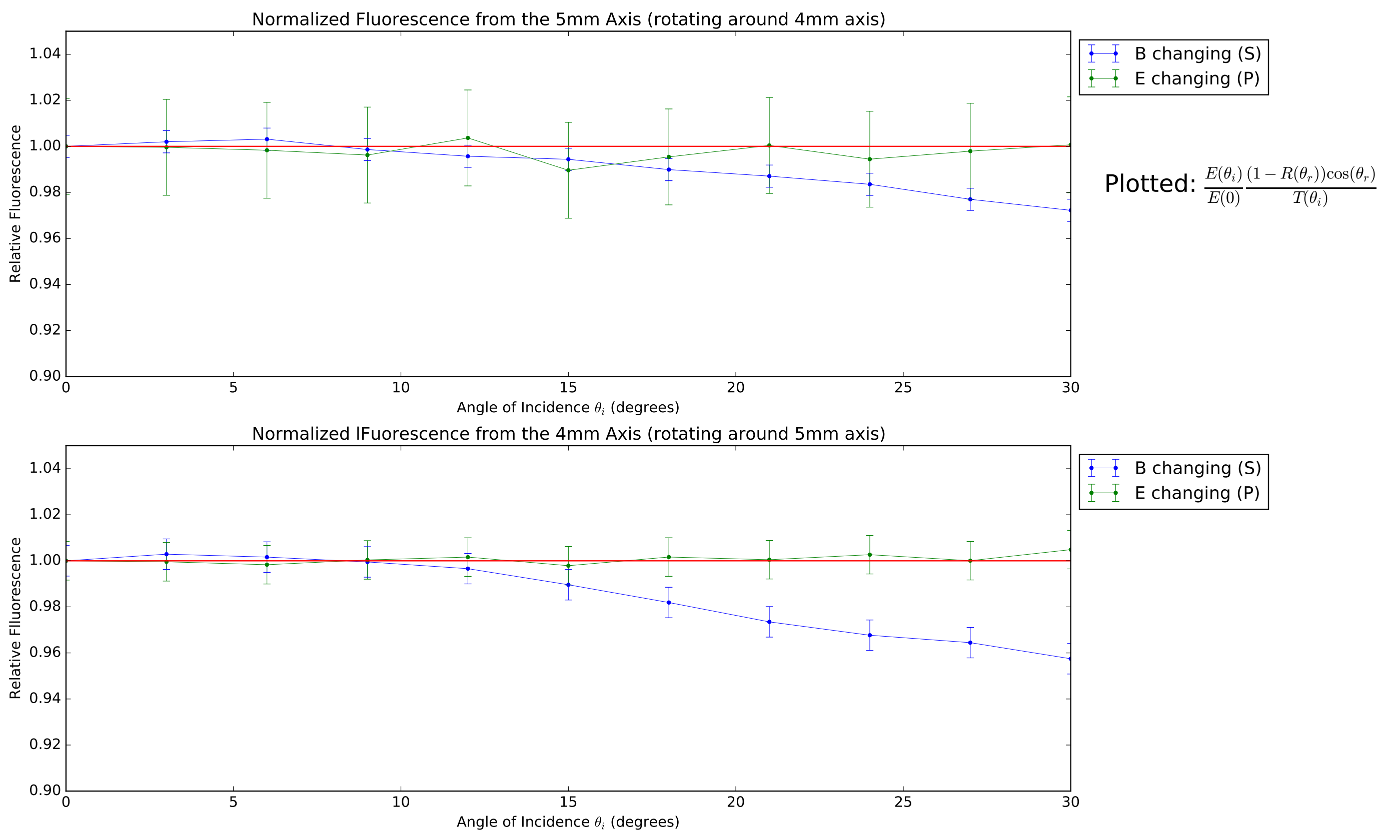

Figure 3: The top plot shows propagation along the 5mm axis and roation around the 4 mm axis. The bottom plot shows propagation along the 4 mm axis and rotation around the 5 mm axis. These plots also clearly show the dependence on the magnetic field.

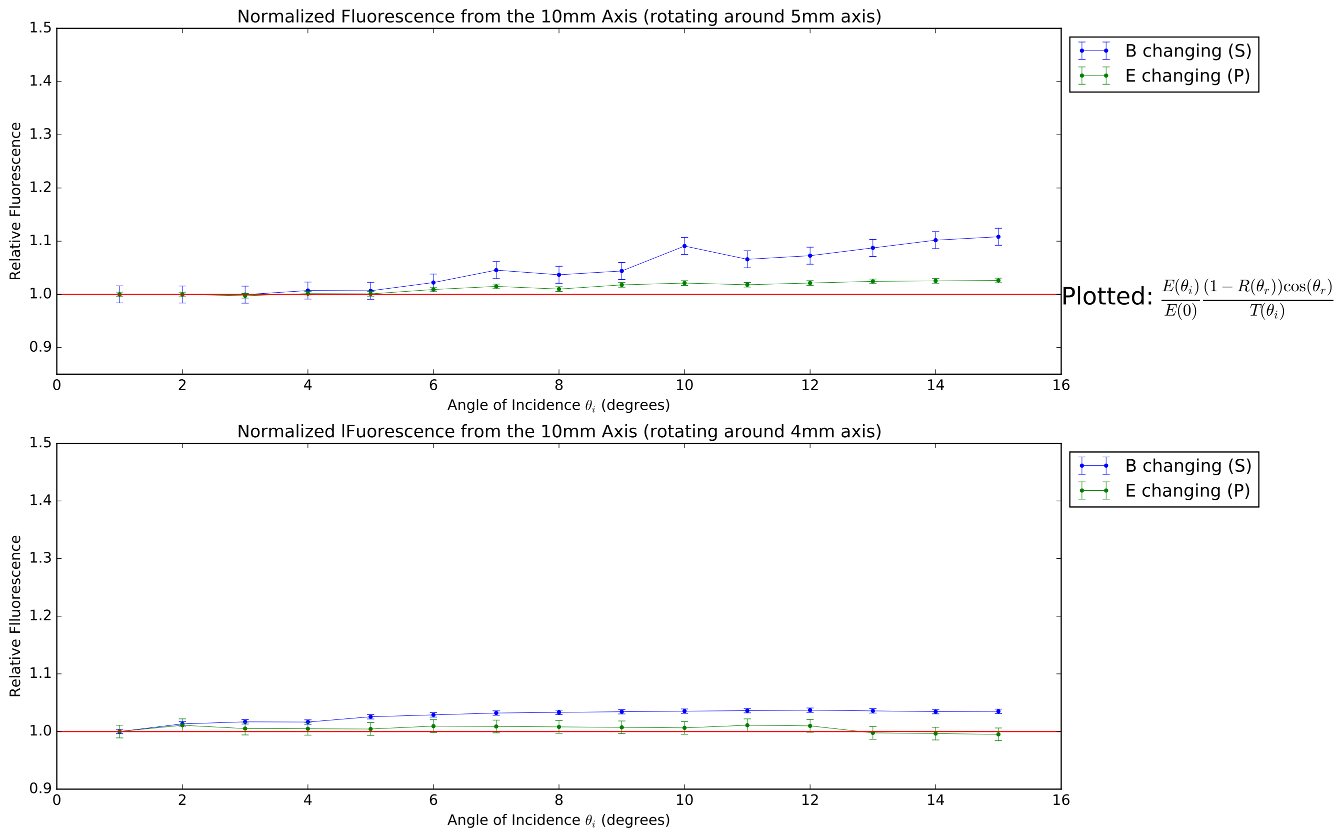

Figure 4: Fuorescence while propagating along the 10 mm axis. In the top plot the crystal is being rotated around the 5 mm axis. In the bottom plot the crystal is being rotated around the 4 mm axis. These plots are less conclusive than Figure 2. This is because of the length of the crystal. Due to propagating along the long axis of the crystal, we could only use smaller angles before the incident beam hit an edge of the crystal. Even though the incident beam was not hitting an edge, reflected beams were more likely to hit an edge as well.