The Mossbauer Effect: Measuring Internal Magnetic Field Strength and the Nuclear Magnetic Moment in the First Excited State Using Precise Mossbauer Spectroscopy to Interrogate the Zeeman Effect

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When an atom interacts with an energetic particle such as a photon in the gamma range, the momentum of that particle is passed to the atom as atomic recoil. However, when an atomic nucleus is bound to a solid lattice, the momentum from the photon is delivered to the crystal lattice as phononic resonance, minimizing or negating individual atomic recoil and producing strong resonance with a narrow linewidth. This higher precision allows us to measure the strength of the internal magnetic field and the magnetic moment in the first excited state using the Zeeman effect, which describes how magnetic energy levels will subtly split in the presence of a magnetic field. Using the doppler effect to probe this splitting, we were able to find precise values due to the narrow linewidth provided by the recoil-free resonant absorption of the Mossbauer effect. We found the internal magnetic field strength in iron Fe57 to be $3.8047178 \times 10^5 \pm 5.7717570119 \times 10^4$ Gauss. The nuclear magnetic moment in the first excited state had an experimental value of $0.14518019954724576 \pm 0.0179$ nuclear magnetons. These values are consistent with the expected theoretical values of 3.5×10^5 Gauss for the internal magnetic field and 0.1549 ± 0.0001 nuclear magnetons for the nuclear magnetic moment of the first excited state.

I. INTRODUCTION

According to the time-energy uncertainty principle, the minimum uncertainty in energy corresponds to the time taken to measure the energy level. The lower bound of the energy spread, or linewidth of the energy, is determined by the lifetime of the state. However, when a photon hits an atomic nucleus that is loosely held (e.g., gaseous), the nucleus will respond kinetically by recoiling, resulting in a larger measured linewidth for the energy of the resonant absorption/emission. When a nucleus is tightly bound in a lattice, the resonant emission and absorption is recoil-free, resulting in a narrower energy linewidth. This is because the incident particle imparts momentum to the entire lattice rather than an individual atom, causing the entire solid to vibrate. This experiment concerns itself with the recoil-free absorption and emission of gamma rays in an Fe57 lattice, using the Zeeman effect to measure hyperfine splitting. We can measure the splitting due to the Zeeman Effect because the linewidth is smaller in recoil-free absorption/emission.

The Zeeman effect describes the hyperfine splitting of energy levels in the presence of a magnetic field. Depending on the position of the atom within an external magnetic field, the strength of the energy level splitting changes. However, our material has an internal magnetic field, which we can measure by measuring the hyperfine splitting due to the Zeeman effect. Equation 1 describes the relationship between the hyperfine splitting, the internal magnetic field of the material (H), and the magnetic moment of the nucleus (μ) at a particular spin quantum number (m_j).

$$\Delta E = -\frac{\mu H m_j}{I} \tag{1}$$

When we move our gamma ray source back and forth, we can tune the effective energy using the doppler effect. The doppler effect shifts the effective frequency higher when the source moves towards the atom and lower when the source moves away from the atom. This allows us to scan through different energies to determine the respective energies differences of the hyperfine splitting due to the Zeeman effect. By moving the source at low velocities, we can tune the energy levels by extremely slight amounts; this allows us to measure the hyperfine splitting, which is several orders of magnitude smaller than the energy difference between spin state transitions. Equation 2 demonstrates how the doppler effect tunes the effective energy (ΔE), where E_0 is the original, "stationary" energy of the gamma ray, v is the speed of the gamma source, and c is the speed of light.

$$\Delta E = \frac{E_0 v}{c} \tag{2}$$

II. METHODS

A. Experimental Methods

We used a gamma ray source to induce recoil-free resonant absorption in a solid lattice, tuning the source to the hyperfine splitting due to the Zeeman effect using the Doppler effect. We then used the energy differences of the hyperfine splitting to measure the internal magnetic field and the nuclear magnetic moment in the first excited state. Our solid lattice sample consisted of iron foil with 2.2% iron nuclei. The gamma ray source emitted photons at 14.4 keV, which is the energy required to excite a transition in an iron atom unaffected by the Zeeman effect. We used aluminum foil to block lower energy radiation from exciting a different transition. To induce the Doppler effect, we moved the gamma source at velocities ranging from -9.59 mm/s to 10.22 mm/s. We used the constant acceleration drive (CAD) to trigger external software to cycle through these velocities every 208.8 ms. The spectral measurement is characterized by the absorption features which correspond to the altered energy levels due to hyperfine splitting; the absorption features show up on the graph as dips in counts from the detector. These absorption features allowed us to determine the differences in resonance energy due to hyperfine splitting, allowing us to find the strength of the internal magnetic field and the nuclear magnetic moment in the first excited state.

B. Raw Data

Figure 1 corresponds to the number of counts received by the detector as the source traveled at different velocities. These differing velocities adjusted the effective energy incident on the iron lattice, allowing the energy to tune to resonate with the hyperfine splitting due to the Zeeman effect. The lower count numbers correspond to the energy levels at which the iron lattice absorbed the incident light.

Since there are 6 total transitions, we expect 12 absorption dips because each the channels sweep through each velocity twice. Thus, the graph of our raw count data is symmetric. The next table shows the channel and number of counts for each dip in our original graph.

Since the CAD has linear acceleration, we can convert these channel values to velocities.

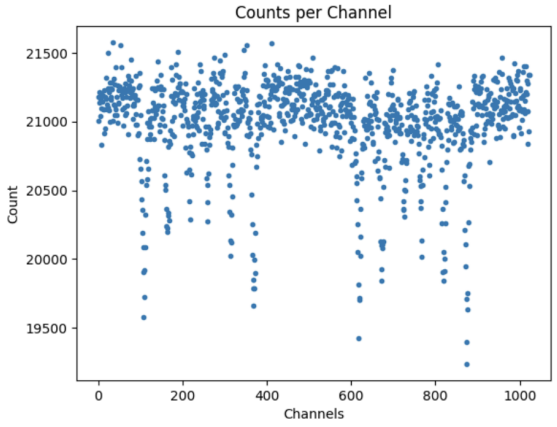

FIG. 1: The above data shows the absorption dips in counts over a velocity scan, retrieved directly from the data collection software.

Minumum Counts Extracted From Data

Channel	Counts
874.0	19237.0
618.0	19426.0
108.0	19575.0
367.0	19663.0
819.0	19839.0
673.0	19844.0
768.0	20018.0
313.0	20024.0
373.0	20193.0
163.0	20200.0
259.0	20272.0
218.0	20289.0

III. RESULTS

Using the effective velocities from each channel, we can find the energy for each transition. Figure 2 shows the six transitions that correspond to the absorption dips.

The energy required for each channel are shown in the "Energy to Induce Transition" table, with error $\frac{1}{\sqrt{2N}}$, where N is the number of counts.

As we saw in figure 2, each of these energies correspond to a different transition. We can use those transition values to find the internal magnetic field strength using the following equation:

$$H = \frac{\Delta EI}{2\mu m_j} \tag{3}$$

Using this equation, we found the strength of the internal magnetic field to be $3.8047178 \times 10^5 \pm 5.7717570119 \times 10^4$ Gauss. In this case, we used the nuclear magnetic moment from the literature to calculate our value.

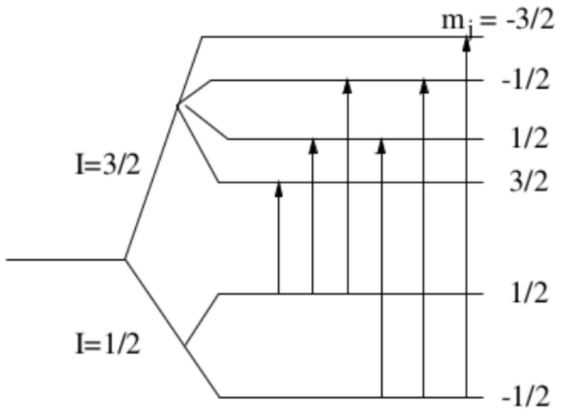

FIG. 2: Each absorption feature in the data corresponds to one of these six transitions.

Energy to Induce Transition

Energy (eV)	Error (eV)
14399.999999744894	0.007147416898918632
14399.99999977915	0.007209934636110368
14399.999999849562	0.007035975447302919
14399.999999883818	0.007099701854280813
14399.999999954232	0.007020526434254538
14399.999999980875	0.007067887977577373
14400.000000032258	0.007023469506928843
14400.000000135024	0.007066828985740603
14400.000000161668	0.007098807358573003
14400.000000237791	0.007131405151117494
14400.000000249209	0.007037194868897662
14400.000000266336	0.007174775356816148

We can also rearrange this equation to find the nuclear magnetic moment in the first excited state using the internal magnetic field strength from the literature.

$$\mu = \frac{\Delta E I}{2 H m_j} \tag{4}$$

We found the nuclear magnetic moment in the first excited state to be $0.14518019954724576 \pm 0.0179$ nuclear magnetons.

In Figure 3, we checked that each channel was distinct by fitting a Lorentz distribution to the data.

IV. DISCUSSION

We found the strength of the internal magnetic field of our iron sample to be $3.8047178 \times 10^5 \pm 5.7717570119 \times 10^4$ Gauss and the the nuclear magnetic moment in the first excited state to be $0.14518019954724576 \pm 0.0179$ nuclear magnetons.

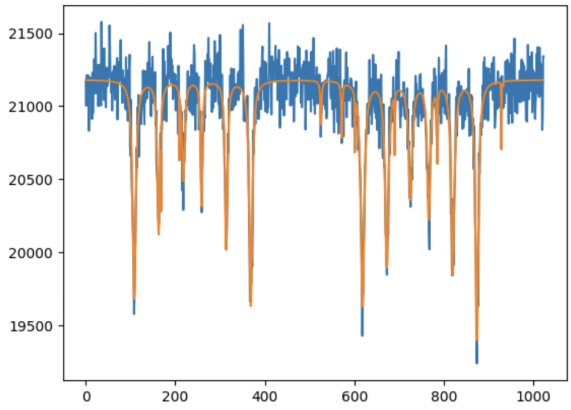

FIG. 3: We used this Lorentz fit to determine that the absorption dips were distinct.

In comparison, the theoretical values from the literature included an internal magnetic field of 3.5×10^5 Gauss and a nuclear magnetic moment in the first excited state of 0.1549 ± 0.0001 nuclear magnetons. Therefore, our experimental values are consistent with the values established by the literature. The Lorentz fit was able to distinguish each energy transition, which is consistent with our theoretical expectation, indicating that our experimental setup provided accurate data. However, we might have improved our results by increasing the interrogation time of the experiment. Alternate transitions may provide a further vector for analysis: we only investigated the $I = 1/2, m_j = 1/2$ transition to find our final values.

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