The Mössbauer Experiment

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Abstract

This report is an overview of repairing a Mössbauer experiment for an upper level undergraduate modern physics lab. After obtaining a stronger Co^{57} source, measurements were taken with a stainless steel and iron absorber to observe nuclear resonant absorption and radiation. The line width with the stainless steel absorber is $\Gamma = (0.084 \pm 0.006) \times 10^{-13}\ mm/s$, and the fractional line width is $(1.407 \pm 0.101) \times 10^{-13}$. This is in good agreement with the known value of fractional width from the excited state of Co^{57} to its ground state. It is also found that a piece of equipment is malfunctioning, namely the drive module, but a solution for "calibration on the fly" is proposed.

The first observation of nuclear resonance absorption was made in 1951 by British nuclear physicist Philip B. Moon. In 1957, under the guidance of H. Leibnitz, while at the Max Plank Institute, R. Mössbauer discovered recoilless nuclear resonance absorption. This discovery was awarded with the 1961 nobel in Physics, and is often referred to as the Mössbauer effect.[1] Because the Mössbauer effect enables high precision measurements of energy it has a wide range of modern applications in nuclear physics, solid state physics, chemistry, and industry. Also, NASA has sent a Mössbauer spectrometer to Mars mounted on a rover to study the iron minerals of the Martian surface.[2]

In order for nuclear resonant radiation to occur, the transition energy of the emitted radiation must match the energy level separation of the absorber. Typically one will not observe resonant absorption from a nuclei emitting a photon. Due to conservation of momentum, the recoil momentum from the nuclei produces a displacement in the emission and absorption lines, denoted ΔE in figure (1). This displacement of energy produces an emitted gamma ray with less energy than its transition level. Thus, resonant absorption for nuclear gamma rays are not observed.

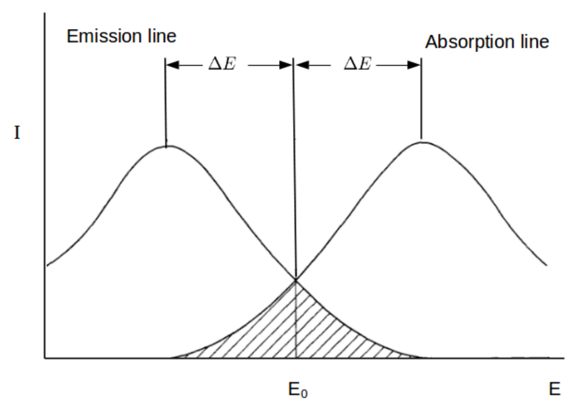

Figure 1: Intensity vs. energy, showing the displacement of emission and absorption line by ΔE. [1]

To make up for the recoil energy loss, Moon succeeded in doing so by moving the radioactive gamma ray source at certain velocities, which

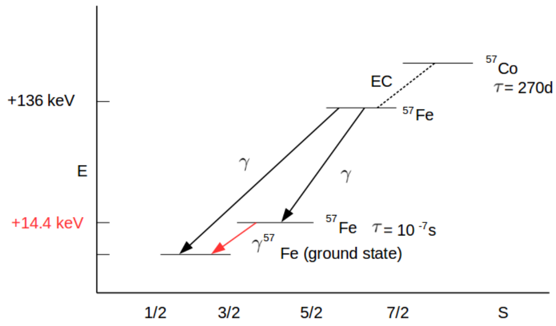

Figure 2: Energy level diagram of Co^{57} decay from excited to ground state by emitting gamma rays. Lifetime is denoted by τ, E is energy, and S is the spin quantum number. [3][4]

Doppler shifted the emission line toward higher energies and produced measurable resonance absorption. Mössbauer then showed that if the nuclei were embedded in a crystal lattice, the recoil momentum would be taken up by the entire solid, thereby producing "recoilless" emission of the photon.

The energy levels of Co^{57} as it decays from the excited to the ground state is shown in figure (2) with respective lifetimes. When the source emitter, in our case Co^{57}, is placed near a stainless steel absorber, energy levels are not split. But when the source is next to the resonant iron absorber, hyperfine splitting takes place with six components. This is the so called Zeeman effect, which is the result of the strong magnetic field interaction within the vicinity of the iron nuclei. In figure (3), the splitting of the nuclear energy levels that we are considering is represented.

An absorber of Fe^{57} is most suitable to study the Mössbauer effect since the energy level matches the energy emitted, which produces a narrow natural line width of the 14.4 keV transition. To quantify the natural line width we may apply the uncertainty principle and the width of the spectra distribution at half-maximum, denoted Γ, with equation (1).

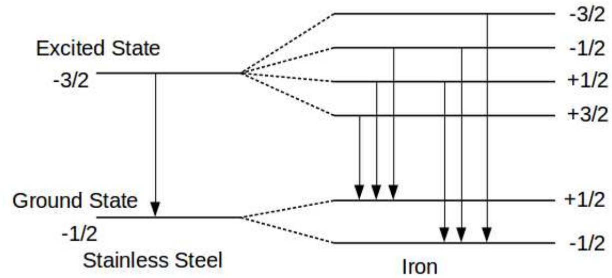

Figure 3: Hyperfine structure splitting of nuclear energy levels of stainless steel and iron.[3]

$$\Delta E = \frac{\Gamma}{2} = \frac{\hbar}{2\tau} \tag{1}$$

Where E is energy and τ is Δt, the lifetime.

The goal of this experiment is to observe the Mössbauer effect, with stainless steel and iron foil absorbers. The experiment at hand needed repair without a clear diagnosis of the malfunction. First, it was found that the Co^{57} source being used in the lab was too weak to provide the necessary data. Therefore, a student grade source was purchased from Science Engineering and Education Company that would be sufficient to provide meaningful data. The radiation source contains Co^{57} on rhodium foil at a strength of 0.14mCi. [5] As well as the strength of the source, this experiment requires that the 14.4 keV line of interest be isolated, and that

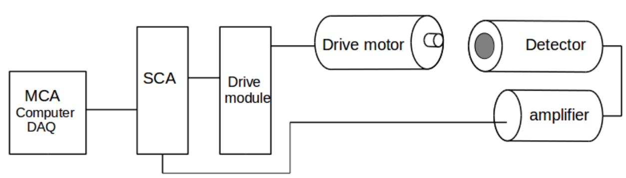

Figure 4: Diagram of experimental set-up. The source is attached to the drive motor, and controlled by the drive module. The detector sends the signal to an amplifier and a single channel analyzer (SCA), and then to a multi-channel analyzer and computer for data acquisition.

constant velocity is provided to the source motion.

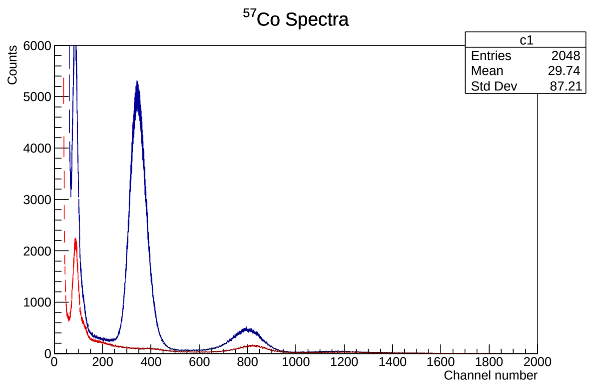

Figure 5: Counts vs. channel number of Co^{57} spectra, blue plot is with no absorber in place, and red plot is with plastic absorber in place. The 14.4 keV line of interest is isolated from channel 700 to 920.

The experimental set up is shown in figure 4, and the equipment used is manufactured by Austin Science Associates. The source is attached to the K-4 drive motor, which is controlled by the S-700A drive module. The drive motor should provide constant velocity to the source, thereby Doppler shifting the emitted gamma rays, which will allow the determination of a clear energy line. The detector is a proportional tube that uses krypton gas to detect the low energy gamma rays and is powered at a positive high voltage of 1800V. The detector signal is sent to an amplifier and then to the S-700S single channel analyzer (SCA). From the SCA the signal is sent to the multi channel analyzer (MCA) and a computer for data acquisition with the Maestro software.

In order to isolate the 14.4keV line, the spectra of Co^{57} is first observed with no absorber, and then with a plastic absorber which blocks the background photons of 6.4keV. Figure 5 shows the energy spectra, where the blue plot is obtained with no absorber, and the red plot with the plastic absorber in place. The 6.4keV peak extinguished by the absorber is apparent as the

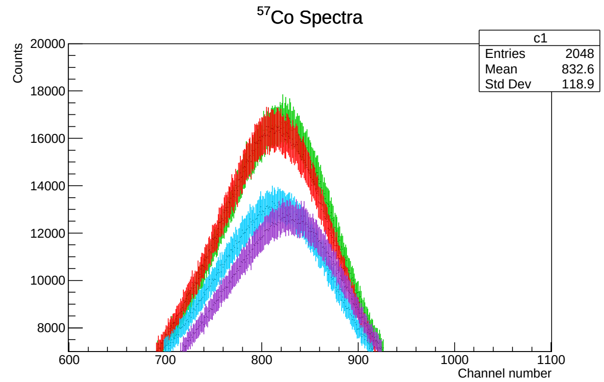

Figure 6: Histogram of counts vs. channel number of Co^{57} spectra in data taking window (channel 700 to 920), at the velocities of -1.00 mm/s (green), -0.5 mm/s (red), -0.20 mm/s (blue), and 0.00 mm/s (violet).

second peak. The window for data taking with Maestro is set to channel 700 to 920. As an inspection of various velocities, figure 6 shows the data taking window containing the line of interest, measured at various velocities: the green plot at -1.00 mm/s, red at -0.50 mm/s, blue at -0.20 mm/s, and violet at 0.00 mm/s. There is a clear shift in intensity from -0.50 mm/s to -1.00 mm/s.

As a calibration of velocity to ensure that the source is moving at a constant rate, displacement of the drive motor is measured with a ruler, counts of displacements are taken in increments of 1 minute for five minutes per data point. The average and their respective errors is plotted in figure 6 and 7, with the equation for errors provided in equations 2 and 3.

$$x = x_{avg} \pm \Delta x_{avg} \tag{2}$$

Where avg denotes average, x represents the counts, and Δx_{avg} is calculated by

$$\Delta x_{avg} = \frac{\Delta x}{\sqrt{N}} = \frac{(x_{max} - x_{min})/2}{\sqrt{N}}. \tag{3}$$

N is the number of data sets taken per point, which in our case is 5.

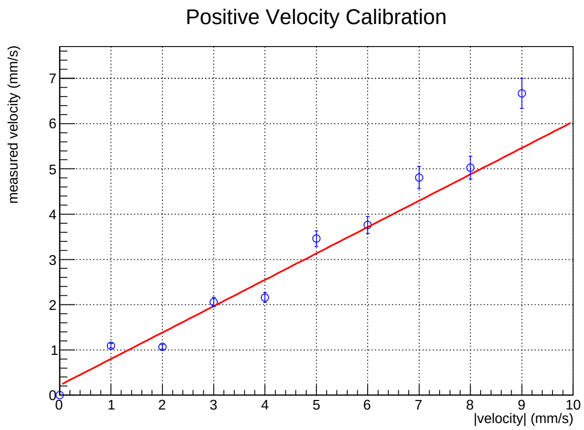

Figure 7: Positive velocity calibration: measured velocity vs. supplied velocity by drive module. There is only good agreement in the range from 0 to 1 mm/s.

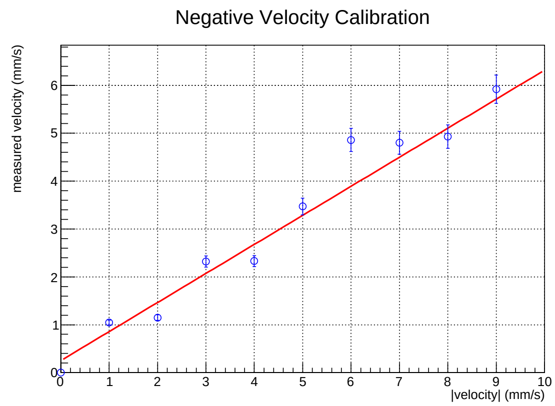

Figure 8: Negative Velocity Calibration: measured velocity vs. supplied velocity by drive module. There is only good agreement in the range from 0 to -1 mm/s.

In this way the velocity may be measured directly and compared with what velocity the drive module says is being supplied to the motor. As one can see in the plots, between the velocities of $0.00mm/s$ to $\pm 1.00mm/s$, there is good agreement with supplied and measured velocity. But after $\pm 1.000mm/s$ the measured velocity deviates greatly from that which is supplied to the motor as stated by the drive module. Therefore, we may obtain meaningful data in the range of $0.00mm/s$ to $\pm 1.00mm/s$, but beyond that, not so much. An idea to solve this problem quickly is to calibrate the velocity "on the fly" per data point. After observing the waveform of the drive motor on the oscilloscope it is determined that the frequency is constant, and is $4.38Hz$. The change then comes from the displacement produced by the drive motor. Since frequency is constant, one can simply hold a ruler to measure the displacement per data point, and adjust the drive module accordingly so that an accurate velocity is obtained per data point. Also, the fidelity was held constant in this calibration, and it may be that fidelity needs to be set at a certain point with the respective velocity.

Although velocity deviations occur after $\pm 1.00mm/s$, we may proceed to observe meaningful data within the noted range. Measurements of counts vs. velocity of the Co^{57} source with the stainless steel absorber is shown in figure 9 with an Lorentzian fit and a constant background. Poisson errors are applied. From plotting the data, we obtain the full width half maximum (FWHM), which represents the apparent width to be $\Gamma_{app} = (0.084 \pm 0.006)mm/s$. Applying the second term from equation (1), we determine the line width to be $\Gamma = (0.042 \pm 0.003)mm/s$. To first order, the Doppler shift of the transmitted wave is found with the following equation, where v denotes velocity and c is the speed of light.

$$\frac{\Delta v}{v} = \frac{\Gamma}{c} \tag{4}$$

The measured value of this shift is $(1.407 \pm 0.101) \times 10^{-13}$, where the error is unchanged since we have only altered the measurement by constants. Since we are considering the stainless steel absorber here, we may see from figure 3 that there is only one transition from excited to ground state. Thus we may calculate the fractional width with the last term in equation 1,

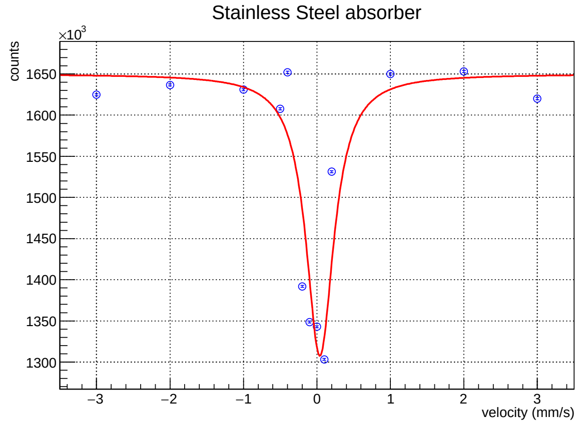

Figure 9: Counts vs. velocity of Co^{57} with stainless steel absorber in place. In the considered range, we may observe a slight shift from the zero peak in the positive direction.

and the following relation.

$$\frac{\Gamma}{E} = \frac{\hbar/\tau}{E} \tag{5}$$

Where E is the 14.4 keV energy, $\hbar$ is Plank's constant divided by 2π, and τ is the lifetime of 1.4×10^{-7}. The calculated fractional width is approximately 3×10^{-13}. Thus we see good agreement with calculation from known values and measurement of fractional width.

There was a great deal of trouble shooting in this experiment since it was not clear from the outset what malfunction was taking place. Overall, the "repair" is successful. Much to the fact that we were able to obtain a stronger Co^{57} source and quantitatively observe how the constant velocity setting is behaving inaccurately. As proposed, "on the fly" velocity calibration should remedy deviations in measurements and provide one to observe the Mössbauer effect in Fe. This method should also be easily reproducible by future students.

Acknowledgement

Don Williamson from Colorado School of Mines in referral to SEEC.

References

[1] Rudolf L. Mössbauer, "Recoilless nuclear resonance absorption of gamma radiation". Nobel Lecture, December 11, 1961.

[2] mars.nasa.govmermissionspacecraft _instru_mossbr.html

[3] Adrian C. Melissinos, and Jim Napolitano. Experiments in Modern Physics, 2nd Edition, Academic Press. pp.385-399.

[4] hyperphysics.phy-ast.gsu.eduhbase nuclearmossfe.html

[5] Specs paperwok that came with new source purchase.

1 Supplements

Source activity study : The source purchased should provide meaningful data for about a couple of years.

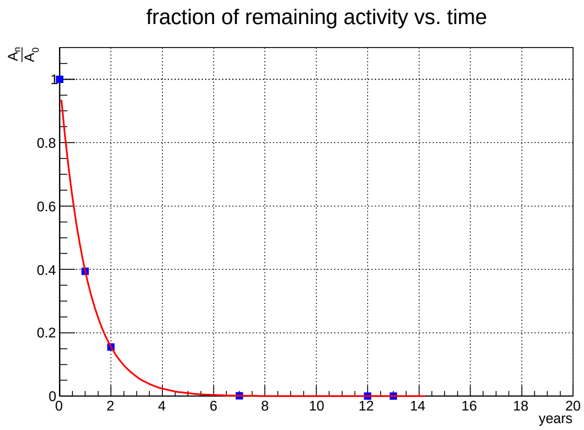

Figure 10: Source activity of Co57

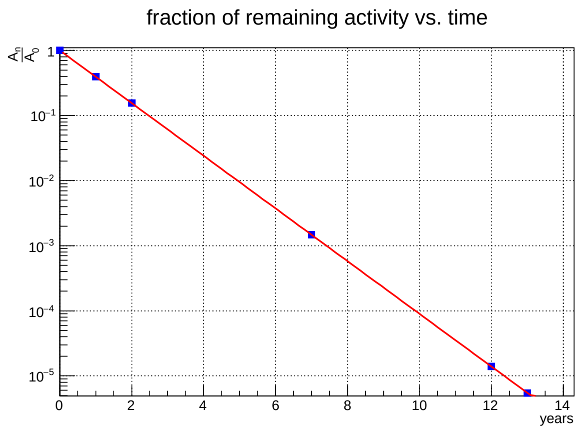

Figure 11: Log scale source activity of Co57

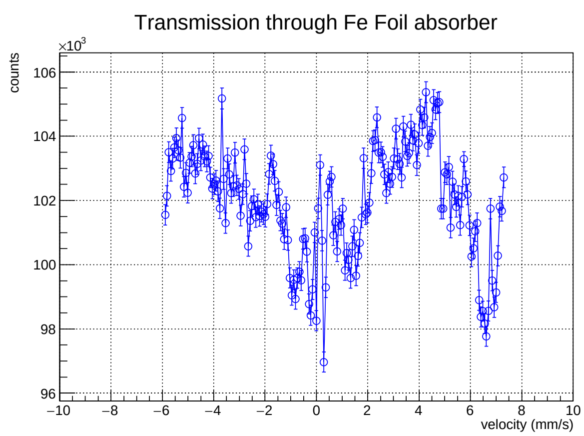

Figure 12: Counts vs. velocity with Fe Foil absorber. Focusing on the range of velocity which is accurate, $\pm 1.00 mm/s$, there appears to be a clear dip at approximately $0.1 mm/s$ and two symmetric dips on each side