Mössbauer Spectroscopy

Physics 300

1 Background Information

Mössbauer spectroscopy is a method for measuring small shifts in nuclear energy levels with high precision. This method involves the "recoilless" emission and absorption of gamma rays and utilizes the Doppler effect in order to use these gamma rays as a sensitive probe. Measurements of small shifts in nuclear energy levels provide information about the electromagnetic environment of the nucleus and the structure of the material in which it resides.

1.1 Resonant Absorption

A quantum system can undergo a transition when it absorbs or emits a photon of a specific energy. The energy of the photon is dependent upon the difference in the energy levels of the transition. The energy of the ground state is absolute, but the energy of the excited state is not a precisely defined quantity. Due to the Uncertainty Principle, the natural line width is given by

\[ \Gamma = \frac{\hbar}{2\tau} \]  

(1)

where \( \Gamma \) is the natural line width of the excited state and \( \tau \) is the lifetime of the state.

However, when a photon is emitted by a free system the photon energy is not equal to the transition energy. This is because the system recoils due to conservation of momentum, and takes with it some of the transition energy in the form of kinetic energy. If we call the energy of the transition \( E_T \) and the recoil energy \( E_R \), then the energy of the emitted photon can be expressed as

\[ E_\gamma = E_T - E_R. \]  

(2)

We can rewrite this expression in terms of the recoil momentum \( p_R \) as

\[ E_\gamma = E_T - \frac{p_R^2}{2m}. \]  

(3)

Due to conservation of momentum we see that

\[ p_R = p_\gamma = \frac{E_\gamma}{c} \]  

(4)

where \( p_\gamma \) is the momentum of the photon. By combining Equations 3 and 4 we find that the energy of the emitted photon is
\[ E_{\gamma} = E_T - \frac{E_{\gamma}^2}{2mc^2}. \]  

Likewise, when the photon is absorbed the absorbing system recoils. Therefore, the distributions of the emission and absorption energies are separated by twice the recoil energy. The probability of resonant absorption is proportional to the overlap of these distributions.

In atomic systems this probability is high because the recoil energy is small compared to the natural line widths. In nuclear systems, however, the recoil energy is much larger than the natural line widths, and therefore the probability of resonant absorption is very small.

### 1.2 Recoilless Emission and Absorption

In 1958, Rudolf Mössbauer showed that for atoms bound in a lattice, a nucleus doesn’t recoil individually. The recoil momentum, therefore, is taken up by the entire lattice, which has a very large mass. From equation (5) we see that as \( m \to \infty \), \( E_{\gamma} \to E_T \). Therefore, when the nucleus is embedded in a massive substrate the recoil energy is negligible. This concept applies to absorption of photons as well.

### 1.3 Doppler Shift

When there is relative motion between the emitter and the absorber there is a Doppler shift in photon energy. The energy of the photon is given by the Lorentz transformation

\[ E'_{\gamma} = \frac{1}{\sqrt{1-\beta^2}}(E_{\gamma} + \nu p_{\gamma}) = E_{\gamma} \frac{1+\beta}{\sqrt{1-\beta^2}} \]  

where \( \beta = \frac{\nu}{c} \), \( E_{\gamma} \) and \( p_{\gamma} \) are the energy and momentum of the emitted photon, \( \nu \) is the relative velocity between the emitter and the absorber, and \( E'_{\gamma} \) is the resulting Doppler shifted photon energy. For \( \beta \ll 1 \) we take the first order of the binomial expansion to get

\[ \Delta E = E'_{\gamma} - E_{\gamma} = \beta E_{\gamma} = \frac{\nu}{c} E_{\gamma} \]  

as an expression for the change in photon energy due to the motion.

By varying the relative velocity between the emitter and absorber, a range of photon energies can be scanned. In Mössbauer spectroscopy we measure the absorption rate as a function of velocity, which can be converted to energy shift. Analysis of the absorption spectrum yields information about the electromagnetic environment of the nucleus.
1.4 Use of $^{57}\text{Fe}$ in Mössbauer Spectroscopy

In our Mössbauer spectroscopy experiment we use $^{57}\text{Fe}$. Our $\gamma$-ray source is $^{57}\text{Co}$, which decays to $^{57}\text{Fe}$ via electron capture as seen in Figure 1. When the iron decays from the $I=3/2$ to the $I=1/2$ state a 14.4-keV gamma ray is emitted, which is the photon of interest. For absorbers we use foils of stainless steel and natural iron.

![Diagram of decay scheme](image)

Figure 1: A schematic diagram of the decay scheme of $^{57}\text{Co}$. The cobalt undergoes electron capture, yielding an electron neutrino and an $^{57}\text{Fe}$ atom in an excited state. The iron undergoes a number of nuclear transitions, one of which yields a 14.4-keV gamma ray. This is the gamma ray of interest.

The resolution of the spectrometer is characterized by the ratio $\frac{\Delta E}{E}$. The first excited state of $^{57}\text{Fe}$, has a natural line width $\Gamma = 2.4 \times 10^{-9}$ eV, and the transition produces a photon of 14.4-keV. Thus, the ideal resolution of our apparatus is $1.7 \times 10^{-13}$. The actual resolution of the spectrometer is approximately the width of the absorption peak of stainless steel.

1.5 Isomer Shift

If the chemical environment of the iron nuclei in the source and in the absorber are different, then the electron densities around the nuclei will be different. The electromagnetic interaction between the electrons and the nucleus depends on the electron density, so if the host materials are different there will be a shift in the resonance energy from the source to the absorber, which can be seen in Figure 2.

We see this effect when we take a Mössbauer spectrum of stainless steel. The iron nuclei created in the cobalt have a different host material than the iron nuclei in the stainless steel. This causes a shift in the absorption spectrum of the stainless steel.

1.6 Nuclear Zeeman Effect

The nucleus of an iron atom in natural iron and certain other iron compounds is in a strong magnetic field caused by the electrons of the atom and of neighboring atoms. Since both of the nuclear energy levels of the 14.4-keV transition have spin and associated magnetic moments, they experience hyperfine splitting caused by the interaction of the magnetic moment of the nucleus with the
\[ \Delta E_e \neq \Delta E_g \]

Figure 2: A schematic diagram of the isomer shift due to differences in the chemical environments of the emitter and absorber.

magnetic field, as shown in Figure 3. These new levels are the magnetic substates of the energy levels, which are degenerate in the absence of a magnetic field, and this results in more possible nuclear transitions. The transitions that are allowed are determined by the quantum selection rule, which states that \( \Delta m_I = 0, \pm 1 \).

\[ \Delta E = \mu \cdot B \]  \hspace{2cm} (8)

where \( \mu \) is the magnetic moment of the state and \( B \) is the strength of the magnetic field. This expression holds for any system. When quantum mechanics are applied, this expression can be rewritten as

\[ \Delta E = \mu \cdot B \]  \hspace{2cm} (8)

Figure 3: An illustration of the isomer shift and nuclear Zeeman effect in \(^{57}\text{Fe}\).

The change in energy caused by the interaction of a magnetic moment with a magnetic field can be expressed as
\[ \Delta E = -g\mu_N B_z \left(\frac{m_I}{I}\right), \]  

(9)

where \( g \) is the g-factor or gyromagnetic ratio, \( \mu_N \) is the nuclear magneton, \( B_z \) is the component of the magnetic field in the direction of the magnetic moment, \( m_I \) is the magnetic substate, and \( I \) is the spin of the state. This expression gives us the shift in energy due to the nuclear Zeeman effect.

The energy of the resulting transitions is

\[ E = (E_e + \Delta E_e) - (E_g + \Delta E_g), \]  

(10)

where \( E_e \) and \( E_g \) are the energies of the excited and ground states, and \( \Delta E_e \) and \( \Delta E_g \) are the shifts in the energy levels due to the nuclear Zeeman effect. This expression can be rewritten as

\[ E = E_e - E_g + \Delta E_e - \Delta E_g, \]  

(11)

If we set

\[ E_e - E_g = E_0, \]  

(12)

and

\[ \Delta E_e - \Delta E_g = \Delta E_{\text{transition}}, \]  

(13)

the expression becomes

\[ E = E_0 + \Delta E_{\text{transition}} \]  

(14)

where \( E_0 \) is the energy of the transition if the levels were not split, and \( \Delta E_{\text{transition}} \) is the energy shift caused by the nuclear Zeeman effect.

### 1.7 The Mössbauer Spectrometer

A schematic of the Mössbauer spectrometer is shown in Figure 4. The source is attached to a linear motor that sweeps through a range of velocities at constant acceleration. The motor is controlled with the S-700A Mössbauer drive circuit. The absorber is positioned between the source and a krypton gas proportional counter that counts the photons that are transmitted through the absorber and measures their energy. The pulses from the detector are amplified and analyzed with the MCS-pci card in the computer. A software gate is placed around the 14.4-keV peak in the photon energy spectrum and the number of 14.4-keV photons is plotted as a function of source velocity. When the Doppler shifted gamma rays have energy that corresponds to a nuclear transition energy, the photons will be absorbed and then re-emitted in all directions. At these velocities we will see a decrease in the number of gamma-ray counts in the detector. The correlation between the source velocity and the number of photons is controlled by the MCS-pci card and the velocity and drive signals between the linear motor and the Mössbauer drive circuit are monitored on an oscilloscope.
1.8 References

For more information see the following references:


2 Pre-Lab Exercises

Do the following pre-lab exercises and hand them in separately from your lab report.

Consider the measurement of hyperfine splitting of the first excited and ground states of $^{57}$Fe with a Mössbauer spectrometer.

1. Derive an expression for the measured velocity of a transition, $v_{m_e \rightarrow m_i}$, as a function of $I_e$, $I_g$, $m_{Ie}$, $m_{Ig}$, $g_e$, $g_g$, $\mu_N$, $B_z$, $E_\gamma$, and $c$.
2. Use your general expression for $v_{m_e \rightarrow m_i}$ to write explicit expressions for each of the transition velocities $v_{-\frac{1}{2} \rightarrow -\frac{3}{2}}$, $v_{-\frac{1}{2} \rightarrow -\frac{1}{2}}$, ... .
3. Use the expression for the transition velocities to derive an expression for the gyromagnetic ratio of the excited, $g_e$, in terms of the gyromagnetic ratio of the ground state, $g_g$, and the ratio of differences in transition velocities.
3 Procedure for the Mössbauer Spectroscopy Experiment

This section explains how to perform the experiment. There are important notes at the end of each section, so please read them carefully. A diagram of the experimental setup is shown in Figure 4.

3.1 Setting Up the Experiment

3.1.1 Equipment

Assemble the following equipment:

- NIM bin
- Mössbauer spectrometer track with collimator holder, absorber holder, and detector holder
- ASA K-4 Mössbauer Linear Motor
- ASA S-700A Mössbauer Drive Module
- Mössbauer absorbers (α-iron, natural iron, and stainless steel)
- GE Reuter-Stokes RS-P3-1605-262 X-Ray Proportional Counter
- Ortec 142PC Preamplifier
- Ortec 556 High Voltage Power Supply
- Ortec 572A Amplifier
- PC with Ortec MCS-pci Multi-Channel Scaler and MCS-32 software
- Tektronix TDS 340A Oscilloscope

3.1.2 Connections

Make the following connections using BNC, SHV, and MHV cables (see Fig. 4):

- Linear motor DRIVE BNC → S-700A rear DRIVE BNC → Oscilloscope channel 2
- Linear motor VELOCITY BNC → S-700A rear VELOCITY BNC → Oscilloscope channel 1
- Preamp power connector → Amplifier rear preamp power connector
- Proportional counter MHV → Preamp INPUT MHV
- High voltage power supply SHV → Preamp BIAS SHV
• Preamp ENERGY BNC → Amplifier IN BNC
• Amplifier UNI output BNC → MCS-pci SCA IN BNC
• S-700A rear DATA OUT BNC → MCS-pci START IN BNC
• MCS-pci MIDPASS OUT BNC → S-700A rear BISTABLE BNC → Oscilloscope external trigger

3.1.3 Settings

Turn on the oscilloscope, the NIM bin, and the high voltage power supply (HVPS). Then apply the following settings to the electronics modules:

• High voltage power supply → +1800 V
• Amplifier: Gain → 0.5, Course Gain → 100, Shaping Time → 0.5
• S-700A Drive Module: Velocity thumb wheel → 100 (± 10.0 mm/s), Mode Switch → C.A. ASYM., FIDELITY → ~ 10 o’clock
• Oscilloscope: Ch1 → 2 V, Ch2 → 200 mV, M → 50 ms

3.2 Calibrations

We will use the well-known absorption peaks for α-Fe to calibrate the velocity scale of the spectrometer.

1. Collimate the α-Fe absorber and attach it to the absorber holder.
2. Place the absorber holder on the spectrometer track so that the absorber is directly in front of the hole in the plate in front of the detector.
3. Attach the 57Co source to the linear motor and slide the motor towards the detector so that the source slides into the collimator holder and the collimator holder is against the absorber holder.
4. Build a shielding wall around the spectrometer with the lead bricks.
5. Start the MCS-32 program and select SCA Sweep under the Acquire menu.
6. Stop the data acquisition after you have enough data to see a good 14.4-keV peak. Use the mouse to select the region around the 14.4-keV peak as shown in Figure 5 and click the Set SCA button on the SCA Sweep dialog box.
7. Select Input Control from the Acquire menu and click on the Use SCA Input button on the Input Control dialog box as shown in Figure 6.
8. Select Pass Control from the Acquire menu and set up the dialog box as shown in Figure 7.

9. Select Time Units from the Display menu.

10. Start the data acquisition and then turn the S-700A Drive Module Run switch ON. Monitor the velocity waveform on the oscilloscope (Ch2). After a short time, the velocity waveform should settle down into a regular sawtooth pattern and the LEDs on the drive module should blink alternately. If this condition is not established within a few minutes, adjustments will have to be made to the drive module (see the documentation for the S-700A Mössbauer Drive Module).

11. When you have a good $\alpha$-Fe spectrum with six well-defined absorption peaks like that shown in Figure 8, stop the data acquisition.

12. The well-known absorption peaks for $\alpha$-Fe irradiated with a $^{57}$Co(Rh) source occur at velocities of -5.418, -3.182, -0.946, 0.734, 2.970, and 5.206 mm/s. We will use these values to calibrate the velocity axis of the spectrometer. Position the cursor at the minimum of the left-most absorption peak and select Calibrate from the Calculate menu. The Calibration Worksheet shown in Figure 9 will appear. Type -5.418 into the value window of the Calibration Worksheet and click Enter. Move the cursor to the minimum of the next peak, type the corresponding velocity into the Value window, and click Enter. Repeat this process for the other four absorption peaks. Check the accompanying graph to make sure that the calibration function provides a reasonable fit to the data. If so, click the Apply button to apply the calibration to the current spectrum and then click the Save button to save the calibration function. Close the Calibration Worksheet and unselect Time Units in the Display menu to display the spectrum in velocity units.

![Figure 5: A $\gamma$-ray energy spectrum from the $^{57}$Co source with the 14.4-keV peak of interest highlighted.](image)

### 3.3 Taking Data

Take Mössbauer spectra for both stainless steel and natural iron absorbers.
Figure 6: The Input Control dialog box.

Figure 7: The Pass Control dialog box.

Figure 8: Mössbauer spectrum of $\alpha$-Fe.
3.4 Finishing Up

1. Set the voltage on the HVPS to 0V. When the voltage runs down turn off the HVPS.
2. Turn off the NIM bin and the oscilloscope.
3. Return the $^{57}\text{Co}$ source to its lead capsule and return this to its lead housing.

3.5 Cautionary Notes

1. THE $^{57}\text{Co}$ SOURCE IS RADIOACTIVE. Always be careful when working with or handling it. Keep it away from your body while handling it, and make sure to use the lead bricks to create a wall between the source and yourself while performing the experiment.
2. The window of the detector is very sensitive and will break easily. DO NOT touch it, and be careful when working near it.

4 Data Analysis

- Extract the isomer shift and the width of the absorption peak in energy for the stainless steel absorber.
- From the spectrum on natural iron, extract the isomer shift, the g-factor of the first excited state given the g-factor of the ground state ($0.09044 \pm 0.00007$), and the value of the magnetic field strength at the nucleus.