The Mössbauer Effect

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Goals

The main goal of this experiment is to exploit the Mössbauer effect to measure the linewidth of the ^{57}Fe 14.4 keV gamma ray. This measurement is one of the most precise in physics: the relative width of the line, $\Delta\nu/\nu$ is only about one part in 10^{13}!

Background

The photons emitted by nuclei making a transition from an excited state to the ground state are not monoenergetic, but have a distribution of energies because of the energy width of the excited state. The natural width of the energy distribution of photons, Γ, is related to the mean lifetime, τ, of the excited state by

$$\Gamma = \hbar/\tau\,, \tag{1}$$

consistent with the uncertainty principle. The width and thus the lifetime can, in principle, be determined from a measurement of the resonance fluorescence, the absorption and reemission of a photon emitted by a nucleus of the same type.

If the excited state has energy centered at E_0 with width Γ, the cross section for the absorption of photons has a sharp maximum at the excitation energy E_0 and drops to half the maximum at $E_0 \pm \Gamma/2$. The integral of the cross section over energy is proportional to Γ, so a measurement of the absorption cross section versus energy can be used to determine Γ and therefore the lifetime τ.

Resonance fluorescence is observed for atomic transitions, but generally not for nuclear transitions because of the nuclear recoil. This recoil is negligible for atomic transitions because of their low energy ($\sim$1 eV), whereas for nuclear transitions of energy of the order of 1 MeV, the recoil shifts the energy of the emitted photon completely off resonance. A nucleus or atom emitting a photon of energy E will recoil with momentum approximately equal to E/c. The energy of the photon will be reduced by the nuclear recoil energy $E_r = p^2/2M \approx E^2/2Mc^2$. If the energy of the excited state is E_0, the energy of the emitted photon will then be $E_0 - E_r$ with $E_r \approx E_0^2/2Mc^2$. Similarly, if the nucleus is to absorb a photon and make a transition of energy E_0, the photon must have energy $E_0 + E_r$. The center of the distribution of energies of the emitted photons is therefore displaced from that of the distribution of absorbed photons by $2E_r = E_0^2/2Mc^2$. (See Figure 1.) If the width of the excited state is less than this amount, no photons will be absorbed by another nucleus of the same kind, and resonance fluorescence cannot take place. For a typical mean lifetime

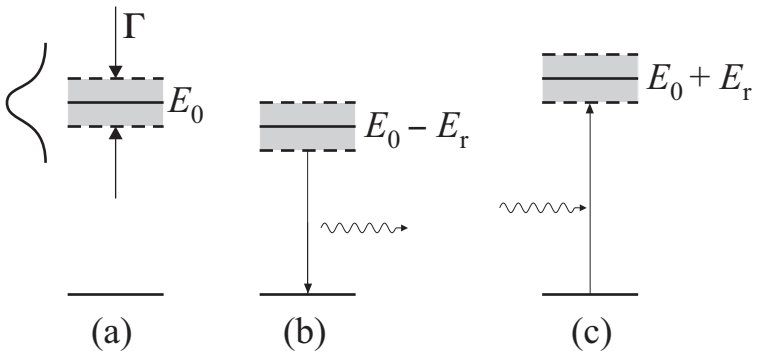


Figure 1: (a) Nuclear energy level has a half width Γ. (b) Shift in energy of emitted photon due to recoil of nucleus. (c) Shift in energy of absorptive transition because of the need of the absorbing nucleus to recoil. If the shifted levels (b) and (c) overlap, resonance fluorescence can occur.

of 10^{-8} sec, the width is about $\Gamma = \hbar/\tau = 10^{-7}$ eV. For a typical atom of atomic number $A = 100$, the nuclear recoil energy is about 10^{-11} eV for $E_0 = 1$ eV and about 10^{-1} eV for $E_0 = 1$ MeV. For atomic transitions, therefore, the recoil energy is negligible compared with the natural width Γ, but for most nuclear transitions, it is much greater than Γ, and there is, in general, no overlap of the emission and absorption lines.

However, the above discussion refers to the case of the emission and absorption of a gamma ray by a free nucleus. In the case of a nucleus in a crystal lattice, the situation is somewhat different, as was shown by R. Mössbauer in 1958. For atoms bound in a crystal lattice, a nucleus does not recoil individually, but the momentum of the nuclear gamma ray is shared by the whole crystal, in the form of vibrational energy, or *phonons*. (This can be understood if we consider that the binding energies of the atoms in a lattice site are of the order of 10 eV, whereas the recoil energies are always less than 1 eV.) However, since phonons are a quantized process, if the recoil energy of the transition is less than the lowest energy phonon that can be excited for a given crystal, then all the energy of the transition is, in fact, taken by the gamma ray, leading to the so-called ***recoilless emission*** or ***absorption*** of the photon; in such a case, resonance fluorescence can, in fact, occur.

Consider now a crystalline source of nuclear gamma rays, for which the Mössbauer conditions for recoilless emission and absorption are met, and resonance fluorescence occurs. We now observe that the resonance fluorescence can be destroyed if we simply move the source at a small velocity relative to an absorber, since the overlap of the emission and absorption lines varies with the velocity of the source, as a result of the Doppler shift. That is, if the emitting nucleus is moving in the laboratory with velocity v in the direction of the gamma ray, which has energy $E_\gamma = h\nu_0$ in the rest frame of the nucleus, then the laboratory energy of the gamma ray E'_γ is given through a Lorentz transformation as

$$E'_\gamma = \frac{1}{\sqrt{1-\beta^2}}(E_\gamma - vp_\gamma) = E_\gamma \frac{1-\beta}{\sqrt{1-\beta^2}} \tag{2}$$

where $\beta = v/c$. For $\beta \ll 1$ we obtain to first order

$$\Delta E = E'_\gamma - E_\gamma = \beta E_\gamma \ , \tag{3}$$

or

$$\Delta E/E = \beta = v/c\,, \tag{4}$$

which, when written as $\Delta\nu/\nu = v/c$, is the first order Doppler shift of a wave emitted (absorbed) by a moving observer. The degree of overlap between the emission and absorption lines, and hence the amount of radiation absorbed, will thus depend on the value of v.

In this experiment, we will consider the 14.4 keV gamma ray of ^{57}Fe, which follows the decay, by electron capture, of ^{57}Co, as shown in Figure 2. The Mössbauer conditions for

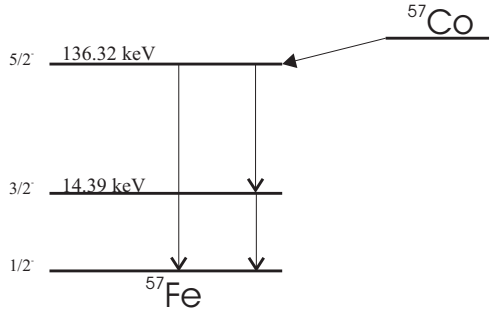


Figure 2: The energy-level diagram of the 57Fe nucleus.

recoilless emission and absorption are met for this material (due to the particular details of the crystal lattice) and so there is considerable overlap between the emission and absorption lines. By varying the velocity of the source, the condition of resonance fluorescence will be destroyed. The 14.4 keV line has a lifetime $t \approx 10^{-7}$ sec, and hence $\Delta\nu/\nu = 4.5\times10^{-13}$. Thus, velocities of order $v = c(\Delta\nu/\nu) = 1.4$ mm/sec will be sufficient to destroy the resonance fluorescence. Such velocities are easy to achieve and control in the laboratory, and we measure the transmission of the 14.4 keV gamma ray through an Fe absorber (either stainless steel or enriched ^{57}Fe) as a function of the velocity of the source.

Apparatus

The apparatus used in this experiment is shown in Figure 3. A ^{57}Co source is mounted on a speaker cone, and a thin absorber of either stainless steel or enriched ^{57}Fe is placed between the source and the detector. Counting electronics consist of a pre-amp, amplifier, discriminator, and scaler/timer. The speaker-source unit is driven at constant velocity by means of a sawtooth wave form from an oscilloscope, after appropriate amplification and bias.

Detector/Pre-amp:

The detector in this experiment is a thin crystal of sodium iodide doped with thallium, NaI(Tl). The use of NaI as a γ ray detector was pioneered by Hartmut Kallman who was a faculty member in the NYU physics department. A γ ray photon produces a pulse of light (scintillation) in the NaI whose amplitude is proportional to the γ ray's energy. The light is

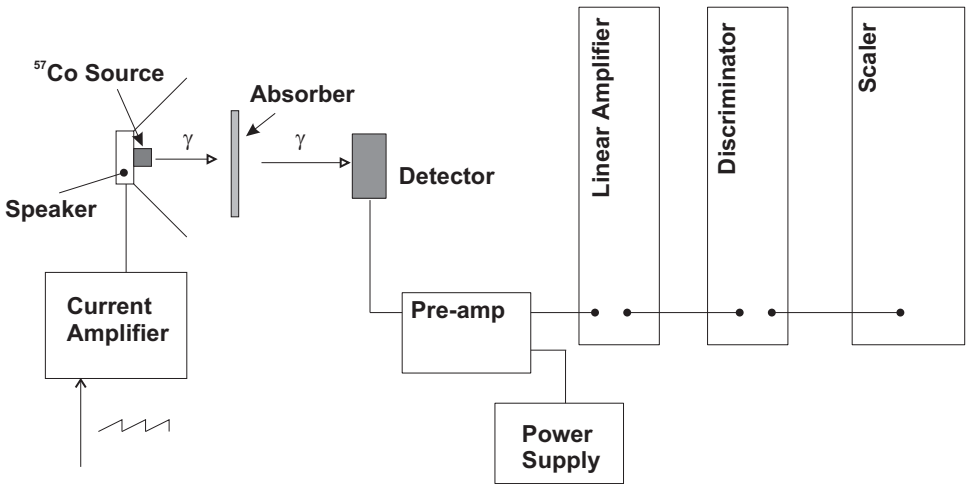


Figure 3: Schematic diagram of the apparatus.

detected by a photomultiplier that views the NaI crystal. The output of the photomultiplier is an electronic pulse consisting of roughly a million electrons.

Electronics:

The typical electronics associated with nuclear radiation detectors has the basic function of (a) transforming low level pulses issuing from the detector, through amplification and pulse shaping, into a pulse more suitable for measurement and analysis; (b) analyzing the pulse height distribution; and (c) counting the pulses. The requirements for different detectors are sufficiently similar so that standard 'NIM' modules in different combinations can be used.

1. Linear Amplifier
   This unit amplifies and shapes the pulses from the detector. A linear relationship between the input pulse amplitude and the output amplitude exists as long as the gain is set lower than what is needed to produce an output of ~ 12 Volts. The gain should be sufficient to spread out the pulse height distribution over the operating range of the discriminator (0-10 volts).

2 Pulse Height Analyzer
To detect and count the 14.4 keV γ rays you will use a Pulse Height Analyzer, PHA. The PHA sorts incoming pulses according to their amplitudes and places each pulse in an energy bin along the horizontal axis. It thus produces a histogram or distribution of all the γ ray energies detected by the NaI-photomultiplier combination. This is viewed using the "EASY-MCA" program on the computer. Right clicking on the display will give an option for MCB Properties, where you can select coincidence counts if desired. This will find coincidences from the "Input" and "Gate" BNC connectors on the PHA.

3 PASCO Interface
The speed of the source is controlled using an oscillator connected to the PASCO interface. Start the PASCO Capstone software on the computer and set up the oscillator

as an output. You can use the output menu to control the frequency and amplitude of oscillations.

There is also a laser that connects to the computer. This is a recent addition to the experiment and allows for precise determination of the speed of oscillations of the radioactive source. The laser is connected to a USB converter, which connects to the computer via USB adapter cable, and there should also be a power cable connected to a nearby outlet extender with an orange switch. When you leave for the day, flip the switch off to turn off the laser until you return.

The graphical output data from this laser is viewed via a program on the computer called "ILD1320 Tool". The laser is on a board that is clamped and mounted to a stand, and can be adjusted fairly easily. The range of the laser is no more than a few inches, so it must be close to the source. There is a red/green LED on the laser, which turns green when the source is in range and the speed is being measured, and turns red when there is an error (out of range). The laser does not have to measure the speed while using the detector to collect data from the source. Instead, you can move the laser in front of the source (blocking the detector), and measure the speed. Once this data is obtained, you can move the laser out of the way and continue with the experiment. Of course, if you change the speed of the source, you will need to measure it again.

When adjusting the laser, wear rubber gloves and the lead lined visor to protect your head from the source.

Procedure:

1. **Check the operation of the detector.**

   The power supply has two toggle switches, one for AC power, and one for high voltage. Turn on the AC power switch, make sure the dials for voltage control read zero, and that the dial for polarity is turned to "positive" (you should not have to change this dial for the length of the experiment, and should never change it while high voltage is on). Turn on the high voltage, and slowly increase to +600 V.

   The linear amplifier (which receives signals from the pre-amp, and outputs to the oscilloscope/PHA) is located on a rack above the power supply with other modules. Flip the toggle switch at the right side of the rack to "On". Observe the output of the amplifier with an oscilloscope. Place the source directly in front of the detector during the test to get a high count rate. Note that the polarity switch on the amplifier (not the power supply) may need to be inverted to get positive output pulses. Trigger the oscilloscope *internally* so that the pulse height distribution can be observed.

   The gain of the amplifier can now be adjusted according to the considerations discussed above.

2. **Check the operation of the discriminator.**

   To maximize the change in the counting rate due to the Mössbauer effect, it is necessary to select only the 14.4 keV transition and to reject the large background of higher energy gamma rays also emitted by the ^{57}Co source. Acquire a PHA spectrum by

collecting 3 minutes worth of pulses. You can preset the data acquisition interval on the PHA. Identify the peaks. What is the origin of the peak at the lowest energies (in the lowest channels)? It may help to roughly calibrate the energy scale with the help of an Americium source available from the instructor. This source produces Neptunium L x-rays at 14 and 18 KeV, as well as a 59 keV γ ray.

Now set a region of interest (ROI) that includes the 14.4 keV peak. You will be monitoring the number of γ rays in this ROI as a function of the velocity of the cobalt source.

3. **Measuring the speed of the source.**

   Open the ILD1320 Tool Shortcut on the desktop. A small window should appear, detecting sensors; the laser should be detected on COM5. Close the window and click "Connect", and data acquisition will begin. You can select "Stop daq" and "Start daq" as needed to collect data. Note that the graph is not displaying the exact position from the sensor to the object.

4. **Check for the Mössbauer effect.**

   Using the stainless steel absorber, check that the apparatus is working properly by comparing the count rate measured with the source stationary to that obtained with the source moving at high velocity ($\sim$ 2 mm/sec). The count rate obviously varies as the source to detector distance changes, and so the 'stationary' count rate should be measured not with the speaker cone in its zero-current equilibrium position, but with the speaker cone moving very slowly such that its average position is the same as when it's moving rapidly.

Questions

Using the stainless steel absorber, determine the absorption line profile, and thus the lifetime of the 3/2− excited state in ^{57}Fe, by measuring the count rate as a function of source velocity. Keep in mind that the absorption line is not necessarily symmetric about zero velocity, and so data must be taken for both positive and negative velocities. In your report, be sure to provide an estimate of the experimental uncertainty in your determination of the lifetime, and discuss the sources of error and how they might be minimized or eliminated.

Now replace the stainless steel foil with the enriched ^{57}Fe absorber, and again measure the absorption line profile. You should now be able to observe the 'Zeeman effect' for the nucleus, due to the strong magnetic fields present at the site of the Fe nucleus; as a result of the magnetic field, both the 3/2− and the 1/2− states are split, and consequently the 14.4 keV line has six hyperfine structure components. See the appendix (Figure 4) for an energy level diagram and its associated spectrum.

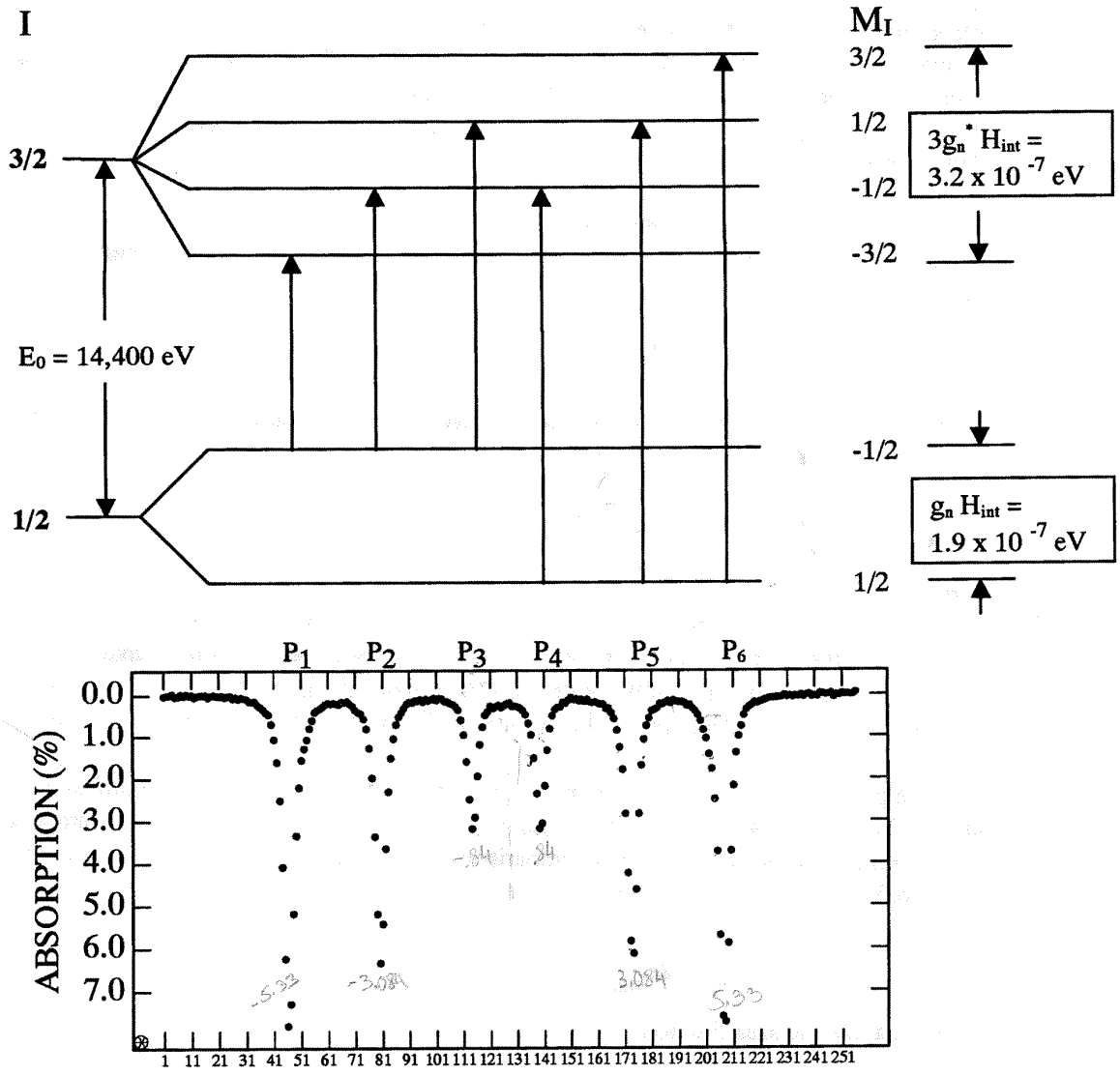
References

[1] A. Melissinos, *Experiments in Modern Physics*, Academic Press, San Diego, 1966.

[2] H. Frauenenfelder, *The Mössbauer Effect*, W. A. Benjamin, Inc., New York, 1962.

[3] E. Segre, *Nuclei and Particles*, W. A. Benjamin, Inc., New York, 1987.

Appendix



$$P_6 - P_1 = (3g_n^* + g_n)\,\beta_n H^{int} = 10.66 \text{ mm/s}$$
$$P_5 - P_2 = (g_n^* + g_n)\,\beta_n H^{int} = 6.17 \text{ mm/s}$$
$$P_4 - P_3 = (-g_n^* + g_n)\,\beta_n H^{int} = 1.68 \text{ mm/s}$$

$$1 \text{ mm/s} = h\nu(1 \text{ mm/s})/c = 14.4 \text{ keV} / 3\text{x}10^{11} = 4.8 \text{ x}10^{-8} \text{ eV}$$

Figure 4. Iron Metal ^{57}Fe hyperfine splitting and Mössbauer spectrum