PRINCETON UNIVERSITY
Physics Department
Advanced Laboratory

THE MÖSSBAUER EFFECT

Introduction

The optical radiation from atoms making a transition from an excited state to the ground state is readily absorbed by other atoms of the same kind in their ground states. This is the principle of the optical pumping experiment, for example. This resonant absorption is possible because the energy width of the resonance is larger than the energy carried away by the atoms as they recoil to conserve momentum, and thus the emission and absorption peaks still overlap.

For nuclear gamma rays, however, this condition is no longer true. The lifetime of many nuclear states is such that the natural line width is much smaller than the recoil energy For this reason, resonant absorption would not be expected to occur. Nevertheless, Mössbauer discovered that if a γ-emitting atom is embedded in a crystal lattice, there is a finite probability that a photon will be emitted with negligible energy loss. The basic idea is that when a nucleus bound in a crystal lattice emits a low energy γ-ray, it is not free to recoil arbitrarily. Instead, its momentum is used to excite normal modes of the lattice, called phonons. One of these modes is the rigid translation of the entire crystal, and in this case the energy loss due to recoil is very small indeed.

The same considerations apply to the absorption of the γ-ray by a nucleus in its ground state. In order for the photon emitted by one nucleus to raise an identical nucleus to its excited state, both emission and absorption processes must take place without recoil. The interesting thing is the relatively high probability for this to occur. This process of "recoilless" emission and resonant absorption is known as the Mössbauer effect.

The Mössbauer effect can be detected fairly easily because the cross section for absorption varies strongly in the vicinity of resonance. Measurements are typically carried out by moving an absorber relative to a source, thus Doppler shifting the γ-rays around the resonance peak, while measuring the transmitted intensity as a function of velocity. The Mössbauer effect is important because it allows the measurement of extremely small energy perturbations, since the line width is so small. The "Q" of the resonance can be as high as $Q = E/\Delta E = \nu/\Delta\nu \approx 10^{12}$.

Overview of the Experiment

The apparatus used in the Advanced Lab (see Figures 1 and 2) uses a radioactive source containing cobalt diffused into a palladium foil. The Co^{57} nuclei decay by electron capture to Fe^{57}, leaving the Fe^{57} in an excited nuclear state. The iron nuclei then relax by emitting a 136 keV γ-ray (with 7% probability) or a 122 keV γ-ray (with 93% probability). The resulting 14.4 keV state decays by photon emission 11% of the time, and the remaining decays occur by atomic electron ejection. The transition with the highest Mössbauer probability is from the 14.4 keV excited state to the ground state.

In preparing for this lab, you should calculate the energy with which the iron nucleus would recoil if it were free to move. Contrast this with the uncertainty in the photon energy due to the lifetime of the excited state, which is about 9.8×10^{-8} seconds.

In order to detect photons that pass through the absorber, thereby measuring the absorption effect indirectly, we use a proportional counter. Some details about this type of detector are discussed by Melissinos (1969). The detector used in this experiment contains a mixture of xenon and methane. Since xenon is a heavy element, the probability that a photon in the energy range of interest will ionize it is quite large compared with, for instance, argon. This detector, therefore, has good efficiency for detecting the 14.4 keV photons. Over a limited range of incident photon energies, the amplitude of the detector's output pulses is proportional to energy. Because there are many other photons present besides the 14.4 keV ones (such as the 136 and 122 keV γ's already mentioned and a 6.5 keV X-ray emitted by the newly created Fe^{57} atoms), you will have to use a single channel analyzer to select the interesting pulses.

The radioactive cobalt source is housed in a brass vacuum vessel mounted on a table attached to a screw drive. The screw drive, in turn, is attached to a heavy iron plate mounted on springs. This arrangement is used to reduce possible vibrations of the source with respect to the absorber. You should calculate the vibrational amplitude that would smear out the energy and make the resonance unobservable—and decide whether you think this arrangement should be effective.

The velocity of the absorber is controlled by a variable speed DC motor connected to the screw drive by a rubber belt. The range of velocities can be changed by moving the belt to different positions on the pulleys. A small computer controls a power supply driving the motor, and also takes charge of the data taking. In order for the computer to determine the absorber velocity, you need to measure the distance that the carriage travels between the two positions at which a microswitch sensor turns on and off. Be careful to measure the actual distance between the closing of the microswitch and its opening—and to check for possible asymmetry between the "forward" (absorber moving toward the detector) and "backward" directions of travel.

Procedure for Taking Data

A student version of this list can be found at the end of this document. It holds your hand a bit more.

1. Turn on the various power supplies, the monitor oscilloscope, the computer, etc. Set the high voltage for the proportional counter to 3300 V.

2. Use the scope to inspect detected pulses at the output of the second amplifier stage. Set the controls on this amplifier so that the strongest pulses saturate the amplifier and there are two clear groups of pulses with amplitudes ~ 5 V. (Why does this make sense?)

3. Adjust the window setting on the single channel analyzer to 0.5 V, and invoke the Labview program Spectral Scanner on the PC to record counting rates as the baseline setting is stepped from 0 to 8 V in steps of 0.25. (Think about why these numbers may be appropriate, and choose better ones if you wish.) With the slot for holding absorbers empty, it should be possible to see two spectral lines clearly in the displayed histogram of count rates as a function of baseline voltage.

4. Measure the counting rate spectrum again, this time using a chromium absorber between the source and counter. The chromium will absorb most of the 6.5 keV x-rays (which are more numerous that the desired 14.4 keV line) and will make it clear which line is corresponds to the 14.4 keV nuclear γ-rays.

5. Once you have identified the 14.4 keV peak, adjust the amplifier gain until the peak occurs at a baseline of about 5 V.

6. When you are happy with the displayed spectrum, use its shape to select a window width and baseline that will maximize the signal-to-noise ratio for the rest of the experiment. You want to accept most of the 14.4 Kev photons, while rejecting as much as possible of everything else.

Objectives

There are three interesting sets of data that you should obtain. For your first run, use the stainless steel absorber. Stainless steel is non-magnetic, so the absorption line will be unsplit; it also has enough chromium in it to eliminate most of the 6.5 keV photons. Use the full range of motor speeds and the lowest speed range of the pulley system. With the stainless steel absorber in the slide holder, invoke the program MOSS and use it to determine the counting rate as a function of velocity.

In addition to counting the number of γ-rays detected while the microswitch is depressed, the computer also keeps track of the time interval. The quotient of these two numbers is the desired count rate, and is recorded in a disk file. The program knows that it should go through an integral number of forward-backward counting cycles (because the solid angle coverage of the detector varies with the absorber's location). If you are careful in setting up the experiment, the dominant errors in your data will be the statistical fluctuations in the number of counts. In order to keep this source of error roughly constant as a function of velocity, MOSS will proportionally increase the number of forward-backward passes when the motor is running at higher speeds.

You will discover that with the stainless steel absorber, the minimum counting rate does not occur at zero velocity. This is because the Fe^{57} nuclei in the stainless steel absorber have a different chemical environment from those in the source, which are surrounded by cobalt and palladium atoms.

After you have obtained a good absorption profile with the stainless steel absorber, repeat the process with the source cooled to liquid nitrogen temperature. First pump out the vacuum chamber to a pressure of 50 microns or lower. This will take 30 minutes or more. Then, while continuing to pump, fill the nitrogen flask to start cooling the source. Because the source is mounted in plastic, a poor conductor of heat(see Figure 2), about 30 minutes is required to fully cool it. Keep pumping, and keep the flask full of LN_2. When you are ready to take a new velocity spectrum, close the valve and disconnect the pump hose to avoid transmission of vibration along it. You should observe a shift in the velocity of the absorption minimum, due to the second-order Doppler effect (or equivalently, a change in relativistic time dilation) at atomic speeds comparable to those of a jet airplane!

Finally, you should obtain a spectrum using a magnetic iron absorber: either the "natural iron" or the isotopically enriched Fe^{57} foil. (The latter has the advantage of having proportionally more of the nuclei that you want—but the disadvantage that it is small so that the counting rate will be low.) To avoid

excessive interference from the 6.5 keV x-rays, you should also use the chromium foil. Look at the data in Wertheim (1961), page 57, for guidance on the speed range that your spectrum should cover. There are 6 levels into which the line is split, and you can find them all and measure their energy shifts.

Data Analysis

Use Kaleidagraph to fit your curves. You should create a fit function that is the appropriate form and be able to interpret physically the fitting parameters as discussed below.

- Using your data from the stainless steel absorber at room temperature, determine a lower limit for the lifetime of the Fe^{57} excited state. Why is this a lower limit? What effects would broaden your absorption curve?

- Process your low-temperature data in the same way, and compare the differential shift of the absorption minimum (relative to the room-temperature data) with an upper limit that you calculate by ignoring quantum effects on the atomic vibrations. (The exact calculation of the shift, taking into account quantum effects, is difficult because the iron atoms in the source are so much lighter than the palladium atoms in the lattice.) Compare your measurements of the fraction of 14.4 keV photons emitted without recoil, at the two temperatures, with the data given by Nussbaum et al. (1968). Remember that our source has the Co^{57} diffused into a palladium foil. Why does this make a difference? What would be required to measure the recoilless fraction with more accuracy?

- Using your data obtained with the natural iron absorber (or the enriched Fe^{57} absorber), calculate the magnitude of the "hyperfine" magnetic field at the nucleus. The relevant energy level diagram, with allowed transitions shown, is given on page 10 of Lustig (1961). [Why does your spectrum look qualitatively different from Figure 3 of Wertheim (1961)?] The ground state energy splitting is given by $\alpha = 2\mu H$, while the splitting between adjacent levels of the excited state is $\beta = \frac{2}{3}\mu^* H$ (why?). In these expressions H is the magnetic field at the nucleus, $\mu = 0.0902$ nuclear magnetons is the magnetic moment of the ground state of Fe^{57}, and $\mu^* = -0.1546$ nuclear magnetons is the magnetic moment of the 14.4 keV excited state.

References
1. Frauenfelder, H. 1960, *The Mössbauer Effect*, (New York: Benjamin). (This is an excellent source of articles and reviews about what Mössbauer spectroscopy is, and how it is applied.)
2. Lustig, 1961, *American J. Phys.*, **29**, 1.
3. Melissinos, A. C. 1969, *Experiments in Modern Physics* (New York: Academic Press), pp. 181, 265. (Here are some details on the use of proportional counters in a Mössbauer experiment.)
4. Nussbaum et al. 1968, *Phys. Rev.* **173,** 653.
5. Schumacher, 1970. *Introduction to Magnetic Resonance,* (New York: Benjamin). (An interesting book on the subject of resonances as a whole. The section on the Mössbauer effect, pp. 84-87, contains novel comparisons with other types of resonance phenomena.)
6. Wertheim, 1961, *Nucleonics*, **19**, 152.

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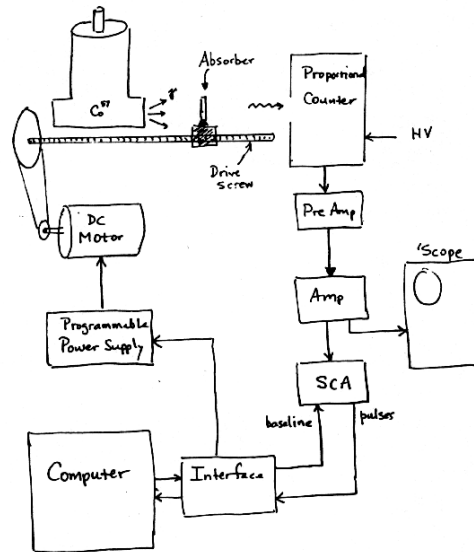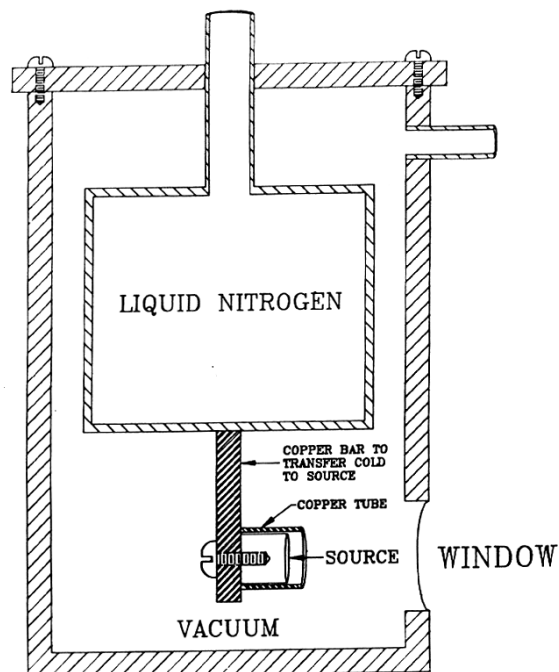J. H. Taylor
Revised January, 2002
R. H. Austin

Figure 1:

Figure 2:

How to get started with the Mössbauer Effect Lab

1. Turn everything on. All the power supplies, the oscilloscope, the computer, etc.

2. Set the high voltage power supply to 3300 V, by turning the kV knob to 3.0, the volt knob to 300.

3. Check that the counter (PL-6043) is counting. If it is not, turn it on and then press the start button. If you reset the counter, you must press start to begin counting again.

4. Connect an oscilloscope to "B out" on the single channel analyzer (1430). If there is a wire shortage, you may temporarily disconnect "A out" and use it for this purpose. Don't forget to plug it back in when you're done!

5. Set "V/div" on the oscilloscope channel you are using to 5 V. Most oscilloscopes have measurement buttons which enable you to toggle display of the voltage and time divisions.

6. Adjust "sec/div" on the same channel to about 1-2 μs.

7. Turn on triggering, if it is set on the oscilloscope.

8. Set the amplifier (1416B) to a gain of about 8 with the coarse gain knob, and then adjust the fine gain knob until you see two types of pulses on the oscilloscope with amplitudes under 5 V. The pulses should just saturate the amplifier. You probably do not want a gain outside the range 8-12.

9. If you disconnected "A out" on the single channel analyzer, you should now reconnect the amp lifer and the single channel analyzer.

10. Turn the "window width" knob on the single channel analyzer to 0.5 V (the slot should read 0 and the dial 5.

11. Make sure the absorber holder is empty, and execute the Spectral Scanner program on the computer (there should be a shortcut to it on the Windows desktop).

12. In the Spectral Scanner program, set the minimum scan voltage to 0 V, the maximum voltage to about 8 V, the voltage scan increment to somewhere between 0.10 V and 0.25 V, and the number of scans high enough so that you get several thousand counts at most of the voltages scanned. The amount of time this takes will depend on the strength of the source. The source was replaced in 2001.

13. When the Spectral Scanner program has finished what you asked it to do, print, the output for your records. There should be two large peaks, one corresponding to 6.5 keV radiation and the other to 14.4 keV radiation.

14. To help identify the peaks, repeat the above procedure after placing the chromium absorber in the absorber holder. Again, it might be a good idea to make a record of the shape of the peaks you observe.

15. When you are confident that you have identified the 14.4 keV peak, adjust the amplifier gain and repeat the spectral scan until you make the 14.4 keV peak as strong as possible without it significantly overlapping with the 6.5 keV peak. The lab manual suggests that this will happen when the 14.4 keV peak is at a baseline voltage of about 5 V, however, you may be able to move it farther or not as far depending on the strength of the source.

16. Select a window width for the single channel analyzer which gives as high a signal- to-noise ratio as possible (your signal is 14.4 keV radiation, and everything else is noise).

17. Exit from the Spectral Scanner program and execute the Mössbauer program which resides in the same place. Initially, you will use a stainless steel absorber. Insert it into the absorber holder. Depending on how well you have separated the 6.5 keV and 14.4 keV peaks above, you may wish to keep the chromium absorber, too. Enter the baseline voltage and window width you selected in the designated

place in the program. Specify the acquisition time you desire. Since the length over which data acquisition occurs is discretized, the actual acquisition time will differ from this, depending on the motor speed. Also, keep in mind that data acquisition time usually accounts for only about half of the experimental time. Choose minimum, maximum, and incremental motor speed percentages to cover the range of Doppler shifts of interest. You can specify non-integer values for each of these, which may be useful in resolving your absorption spectrum. If you choose a very low motor speed, you may notice that the motor's rotation is not smooth. You should avoid such a situation. Remember that you can adjust the speed of the drive screw to which the absorber is mounted by adjusting the rubber belts connecting the motor shaft to the drive screw. Finally, input the distances in millimeters that the absorber travels while counting occurs when it is moving towards and away from the source.

18. Press run and you will be reminded to position the absorber as far away from the source as possible. You will have to do this by manually turning the wheels connected to the drive screw. (This task will go faster if you adjust the belt position accordingly.)

Be careful not to force the absorber outside the region where counting takes place and closer to the detector. You should hear the slight click of the microswitch when you move the absorber to the desired location. There is also a louder noise which is made by a toggle near the motor's power supply; if you hear that, you have moved the absorber too far. Click on OK in the reminder pop-up window, specify a file name for your data, and let the counting begin!

19. After you have recorded all the room-temperature data by a procedure similar to that described above, you may need to speak to the lab TA about obtaining some LN_2, which is kept in the stock room on A level. If you retrieve the LN_2 yourself, make sure you bring gloves, goggles, and the large white dewar. You will definitely need to wear the gloves when dispensing the LN_2, and there may not always be a pair nearby. LN_2 evaporates quickly (esp. with our crappy dewars), so you should fill the dewar almost to capacity.

20. Before actually getting the LN_2, power up the vacuum pump and attach it to the nozzle on the source enclosure. Make sure it is firmly attached by tightening the clamps. In a short amount of time, you should achieve a pressure of around 10-15 microns vacuum, which is sufficient for the experiment.

21. With the pump still running, transfer some LN_2 to the small thermos and pour it slowly through a funnel into the top of the source enclosure. If a lot of spray starts coming out the top as you pour, you are either pouring too quickly or you have filled the coolant vessel completely. Keep the vessel full for about 30 minutes, until it has had sufficient time to cool the source. Then, disconnect the pump from the source enclosure, cover the top of the source enclosure to prevent evaporation of the coolant, and perform your data run.

22. When it comes time to analyze your data, you will notice that it is stored as a tab- delineated table of text. Each line contains three entries, the first of which is the absorber velocity, the second is the number of counts recorded at that velocity, and the third is the time spent counting at that velocity (this is often close to but not equal to the acquisition time you specified in the Mössbauer program).

23. Use Kaleidagraph to fit your data.

Written by:

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