This experiment introduces you to the remarkable Mössbauer effect, which is one of several nuclear physics phenomena (along with neutron activation, nuclear magnetic resonance, etc.) that have found widespread application in understanding the physics of materials. This effect is also notable for the tremendous precision it allows in measurements of energy, since it provides energy resolution on the order of the intrinsic line widths of certain transitions associated with metastable nuclear states, and as such it has been used in tests of general relativity and other high-precision experiments.

A. Introduction

When radioactive nuclei decay through the emission of a gamma ray, in order to conserve momentum, something must carry momentum off in a direction opposite to that of the liberated photon. For a free nucleus at rest, the compensating momentum comes in the form of a recoiling nucleus. Consequently, after the decay the nucleus MUST have some kinetic energy which is given by the expression:

$$\Delta E_N = \frac{p_N^2}{2M_N} = \frac{E_{ph}^2}{2M_Nc^2}$$

(1)

where $M_N$, $p_N$, and $\Delta E_N$ are the mass, magnitude of the recoil momentum, and kinetic energy of the nucleus respectively and $E_{ph}$ is the energy of the emitted photon respectively. For a free $^{57}$Fe nucleus emitting a 14.4 keV gamma ray, the kinetic energy of the recoil is on the order of 2 meV). Therefore, from energy conservation, we are tempted to conclude that the energy of the photon must be (slightly) less than the energy difference between the two nuclear states involved in the decay transition. For a free nucleus, this conclusion is valid; however, Rudolf Mössbauer demonstrated in 1958 that for an atom bound in a solid, there is a finite probability that the recoil will be taken up by the entire solid. Since the collective solid is so much more massive than a single nucleus, in this case the energy of the recoil is completely negligible, and the photon’s energy is essentially identical to the energy difference between nuclear states.

This result won Mössbauer the Noble Prize in 1961 [1], and it might seem at first to be a rather esoteric quantum phenomenon of little broader importance. However, when one takes a moment to realize that the energies of the quantum states available to a nucleus depend on the atomic environment in which that nucleus resides, the Mössbauer effect can be exploited to provide a remarkably sensitive LOCAL probe of the atomic, electronic, and magnetic structure of materials. Even though the nucleus involved is unstable (it does, afterall, spontaneously emit a photon), it can be long-enough lived to have very well-defined excitation energies (i.e. the energy width of the transition can be much narrower than the typical differences in nuclear energy levels associated with changes to the local atomic environment). In this lab you will learn about this remarkable quantum mechanical phenomenon, and use it to explore the differences between the local magnetic environment in stainless and “mild” steel. A rather old, but extensive, description of the technique (including useful values of the cross sections involved etc.) may be found in the 1971 book by Greenwood and Gibb[2]. Other useful background information may be found in references[3, 4].

The particular nuclear cascade utilized in this experiment is shown in figure 1. A $^{57}$Co nucleus beta-decays into an excited state of $^{57}$Fe (roughly 136 keV above the ground state). This excited state typically decays into a metastable state with emission of a 122keV photon, and that state subsequently emits a 14.4keV gamma ray. Note that in the presence of a (local) magnetic field, both the ground and 14.4keV excited states of the Fe nucleus will be split into a number of sublevels by the nuclear Zeeman effect (how many each, and what gamma transitions would be allowed, note that the ground and excited states may have different nuclear magnetic moments ($\mu$ for the ground state, and $\mu'$ for the excited state). Thus the Mössbauer effect may be used to measure the local magnetic field if the value for $\mu$ is known. More interestingly, if the Fe atoms in a given material can occupy
more than one environment (with different local magnetic fields), the Mössbauer effect can be used to measure those variations in the local environment. NMR can also be used to determine the magnetic moment of the ground state, and according to Bearden such measurements give a value of $\mu_{\text{Mössbauer}} = -0.0003(7) \mu_N$.

Mössbauer’s second key insight was to realize that a photon emitted by one (excited) $^{57}\text{Fe}$ nucleus could be absorbed by another $^{57}\text{Fe}$ nucleus (initially in its ground state) in an identical atomic environment only if this "macroscopic mass" takes up the recoil (actually, the original experiments were performed with $^{193}\text{Ir}$, but the iron isotope is much more commonly used today due to its importance in studies of magnetic materials). Moreover, he realized that a difference in chemical environment would induce enough of a shift in energy for the nuclear states involved, that a nucleus in a different chemical environment might be unable to absorb the gamma even with this lack of recoil. However, and this is what makes this phenomenon a tool for Materials Research, the photon can be Doppler shifted into resonance with the absorbing nucleus by moving the source (or absorbing) nucleus at relatively low velocity (on the order of mm/s to cm/s). Most of the relevant nuclear information needed to translate Mössbauer spectra into information on the materials involved may be obtained from the Mössbauer Effect Data Center[5].

**Equipment**

In this experiment you will use a relatively strong radioactive source of $^{57}\text{Co}$. This source is regulated under a license to the University from the Nuclear Regulatory Commission (NRC). It should never reside anywhere but inside the apparatus itself or inside the locked radioactive materials cabinet in SW125, and you should not manipulate it yourself except under direct supervision of a faculty member associated with the NRC license. Contact your instructor when you are ready to use the source, and whenever you need to put it back in the cabinet.

The apparatus shown in figure 2 allows you to controlably change the speed at which an absorbing nucleus is moving toward or away from the source, and to record the number of photons that reach the detector. You can use the logger Pro interfaced to simultaneously monitor the voltage applied to the motor and the photons recorded by the detector. Over the course of the experiment, the source strength is essentially constant, so any change in the detector count rate (for a fixed geometry) comes from a change in the absorption by the foil. The motor is driven by a bipolar power supply, and the applied voltage is controlled by a signal generator as shown in figure 3.

An important element of this experiment is controlling backgrounds and understanding the details of your counting chain, since the Mössbauer spectrum shows up as a relatively small (less than 10%) change in the detector count rate as a function of the absorber’s velocity. The detector used in this experiment is a NaI(Tl) scintillator, similar to the one that you used in the gamma spectroscopy lab, however this detector is optimized for detecting the low energy gamma (14.4keV) from the $^{57}\text{Fe}$ nucleus, rather than the higher energy gammas you studied in that lab, so there are differences in the way it behaves. A typical spectrum from this detector for the source you will use is shown in figure 4. Two of the peaks in this spectrum are labeled, the primary 122keV gamma from the initial excited $^{57}\text{Fe}$ state to the metastable Mössbauer state, and the 14.4keV Mössbauer line itself. Take a few minutes to understand the origin of some of the other features in this spectrum. In particular, what is the origin of the large peak near channel 250 (hint, it is not a photopeak)?

In order to maximize your signal to noise, it is important to set up the SCA so that the computer only records counts associated with photons in the 14.4keV peak of this spectrum (this also makes it possible to estimate the recoil free fraction for your sample). You can use the Ortec 926 MCB in combination with the gate and delay modules to set the lower level discriminator and window much more precisely than you have had reason to do in any previous experiment in this lab. The procedure to use is as follows:

- Take the output from the spec. amp and pass it through the 427 delay module and into one channel of a two-channel oscilloscope
- Use a tee to pass the spec. amp output also to the input of the timing SCA.
- Use the 416A module to create a wide gate pulse whenever the SCA produces a TTL output pulse.

![FIG. 2. This figure shows a schematic diagram of the apparatus. The absorbing sample is a round foil of roughly 24 cm diameter which is mounted on a rotating aluminum disk. The axis of rotation can be varied from horizontal to ±60 deg, and the velocity of the absorbing nuclei (relative to the fixed source) may be controlled by changing this angle and/or the rotation rate of the motor. The emitted gamma rays pass through the sample at a position that is roughly 104±4 mm from the axis of rotation.](image-url)
FIG. 3. This figure shows a schematic diagram of how the electronics may be connected. Note that the output of the function generator should be fed into the “Voltage Programming” input of the Kepco power supply, and this supply should be put in voltage control mode with the voltage control switch on and the current control switch off.

Before coming to the lab to start the experiment, take a few minutes to consider and answer the following questions:

- The metastable state in the $^{57}$Fe nucleus has a half-life of roughly 100ns. What would you expect to be the natural line width for this transition?
- What relative velocity between the source and sample would you expect to be sufficient to shift off the absorption resonance for an $^{57}$Fe nucleus?
- What is meant by the recoil-free fraction for a material and would you expect this to be smaller or bigger for a material with a large Debye temperature (say 900K) than for a material with a lower Debye temperature (say 400K).

Experiments

- Read reference [3] and mount the Stainless Steel sample on the apparatus. Adjust the equipment to cover the range $\sim \pm 2\text{mm/s}$. Is the resonant absorption at a velocity of 0.0 mm/s? Would you expect it to be at 0.0 mm/s? How does the width compare to the intrinsic width?
- Comment on the difference between the absorption spectra you see with the non-magnetic (stainless steel) as opposed to a ferromagnetic material like common steel. Note, for the ferromagnetic sample,
you should increase the range of velocities you cover to ±10mm/s.

• Determine the local value of the magnetic field in the ferromagnetic sample (you may assume that in this material all Fe atoms are in equivalent sites), and determine the value of $\mu^*$.

• If you are feeling ambitious, estimate the recoil-free fraction for the non-magnetic sample.

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**Supplemental Technical Notes**

• The motor driving the rotation in this apparatus is a Fingertech “Silver Spark” synchronous motor with an integrated 600:1 gear box. Vibrations from the motor can cause issues for applied voltages greater than ±1.5V so you should work at voltages lower than this whenever possible. The motor lifetime is degraded by operation above 10V.

• When remounting the sample, do not overtighten the belt connection the drive motor to the spindle as this can bend the shaft of the motor, and it may also increase the transmission of vibrations to the sample. Also, be sure to leave the axis free to rotate so that the belt does not slip.

• The detector is a Bicron model 1XM.040/2B NaI(Tl) detector, but the scintillator in this detector is much thinner than the one you used in the $\gamma$-spectroscopy lab. The PMT in this detector is designed to operate at bias voltages of +1300V or less (do not exceed +1500V).

• The bipolar supply used to drive the motor occasionally will not respond to the voltage programming from the function generator. If this happens, simply cycle the power on the supply and it should recover.

• The motor has a tendency to stall at low voltages. To minimize the impact of this on your spectra, use the 95mm diameter drive wheel rather than the 63mm diameter one.