The Transverse Doppler Effect: A Possible Undergraduate Lab to Demonstrate Relativity

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I. ABSTRACT

In the classic Pounds and Rebka General Relativity experiment of 1960, the Mössbauer effect was used to measure the gamma-ray frequency shift due to the gravitational potential energy. According to the equivalence principle, the same effect should occur in an accelerated system. An experiment to measure this effect is being assembled at Houghton College. Initial work has been done to produce a 5 μC ^{57}Co source by electroplating ^{57}Co out of a cobalt solution onto steel foil, and heating the foil in a vacuum to approximately 1000 °C. The source will be placed near the edge of a thin high-speed rotating steel disc enriched in ^{57}Fe. The 14.4 keV gamma rays from the ^{57}Co source will penetrate the disc and be detected by a CdTe x-ray detector on the other side. Varying the radial acceleration of the rotating absorber will change the characteristic energy of the resonance absorption, resulting in a change in the gamma transmission. To reduce background, a NaI detector will detect the 122 keV gamma ray from ^{57}Co in coincidence with the 14.4 keV gamma ray.

II. BACKGROUND

With the discovery of the Mössbauer effect [1] in 1958, a new avenue opened for precision tests of special and general relativity by allowing frequency shifts to be measured to better than one part in 10^{13}. Almost immediately following this discovery a series of experiments were performed measuring the redshift in accelerating systems [2,3,4,5,6] and in gravitational systems [7,8,9,10]. Of the latter, the Pound-Rebka experiment [8] of 1960 is probably one of the most famous experiments of the last century. The best measurement ever made of redshift due to acceleration using this technique, by Kundig [4], had an accuracy of about 1%.

III. MÖSSBAUER EFFECT

The Mössbauer Effect occurs when a recoilless gamma ray is emitted by an nucleus and then reabsorbed by another nucleus. This does not occur when the nuclei are not moving relative to one another as a completely recoilless gamma ray is not possible. Because of the Heisenberg uncertainty relation, nuclei will have an energy distribution as shown in Figure 1a, where E_r is the mean resonance energy. The emitted gamma ray will have energy of E_r-R (Figure 1b) and the required amount of energy for a gamma ray to have in order to be absorbed is E_r+R (Figure 1c) where R is the Doppler energy shift due to recoil. The overlap shown in Figure 1d are gamma rays can be absorbed.

By decreasing the energy difference between the emitted gamma ray and the energy needed for the gamma ray to be absorbed (we will call this R), we can thus increase the overlap and the chances of absorption. There are two ways to do this. First, we could use a Doppler shift by either moving the source toward the absorber, or the absorber towards the source. In Figure 2 we can see the case where the absorber has a velocity component in the direction of the source. Second, we could accelerate the absorber so that time dilation decreases the energy difference. Though we will demonstrate the first, our main goal is to be able to demonstrate the second case.

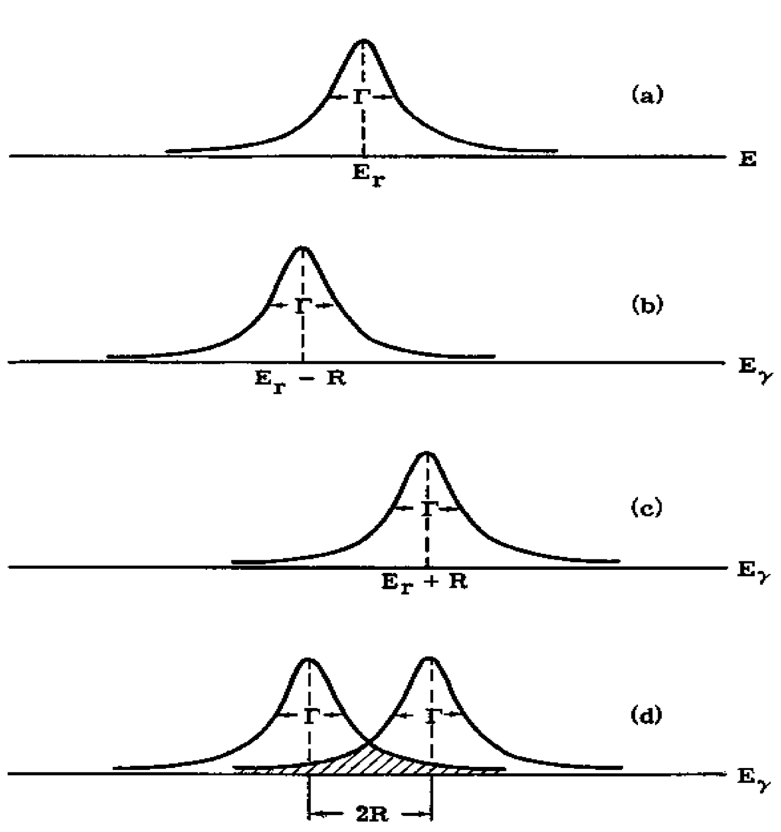

Figure 1. (a) Energy distribution of a nuclear decay. (b) Energy distribution of de-excitation photons. © Energy spectrum required to excite the nucleus. (d) Overlap of (b) and (c). Figure taken from [11].

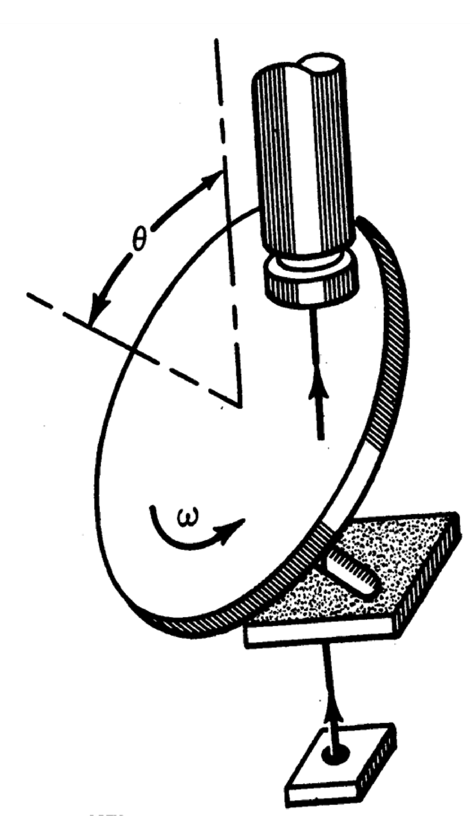

Figure 2. Experimental set-up using a Doppler shift to cause resonance reabsorption of gamma rays. Figure taken from [11].

IV. APPARATUS

The measurement of the redshift due to acceleration we propose for a student experiment is more modest than the one reported by Kundig [4], and is similar to the measurement of Hay et al [2]. The ^{57}Co source will be placed near the edge of a thin high-speed rotating disc containing enriched ^{57}Fe. The 14 keV gamma rays (Figure 8) from the ^{57}Co source will penetrate the disc and be detected by a CdTe x-ray detector on the other side (Figure 9). Because of the acceleration of the absorber, the characteristic energy of the resonance absorption will be reduced, causing fewer gamma rays to be absorbed. This will result in an increase in the measured transmission count rate as the angular velocity, and hence radial acceleration, of the disc is increased. By rotating the disc more slowly and placing it at an angle (Figure 2), the standard Mössbauer experiment may be performed, which will be useful to the students in debugging the apparatus.

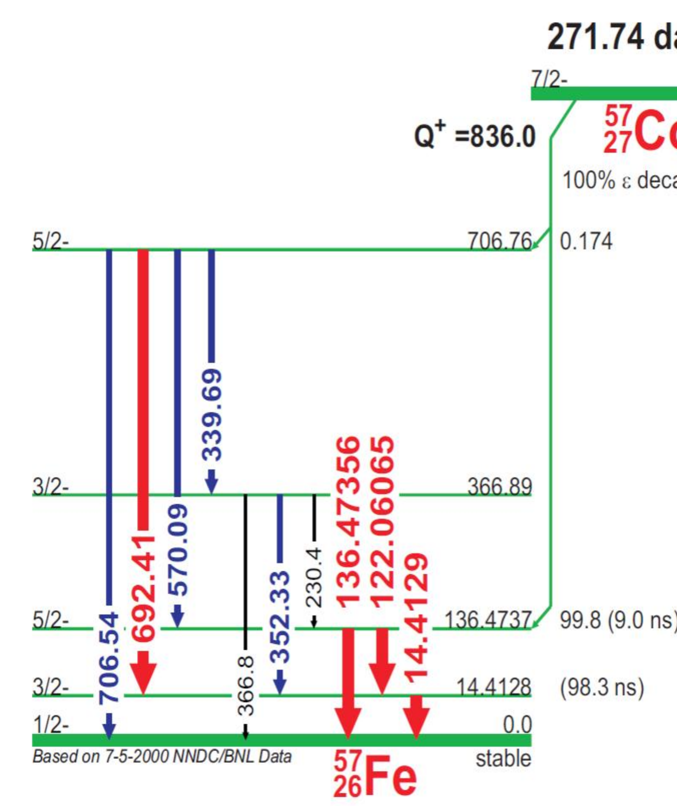

Figure 8. Energy decay scheme for ^{57}Co.

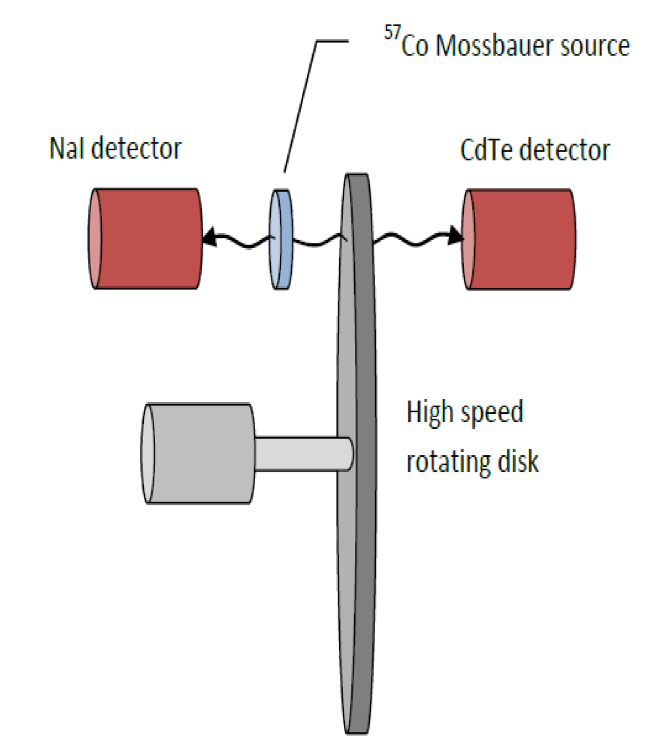

Figure 9. Apparatus to demonstrate the Mössbauer Effect.

Since a relatively weak source will be used, several techniques will be employed to reduce unwanted background. A CdTe x-ray detector has been selected since it will provide excellent energy resolution and efficiency at these low energies. The ^{57}Co decays 99.8% of the time by electron capture to an excited state of ^{57}Fe, which then decays 85% of the time by emitting a 122 keV gamma ray followed by the 14.4 keV gamma ray (Figure 8). A NaI detector will detect the 122 keV in coincidence with the 14.4 keV gamma ray in the CdTe detector. Although this will reduce the total count rate, this should be compensated by the large reduction in background rate.

The rotating disc will be similar in size to a CD-ROM – made of high strength plastic about the same diameter and thickness, with a very thin 0.001 inch steel foil attached to one side with adhesive. On the bare metal side of the disc, enriched ^{57}Fe will be electroplated to about 2 mg/cm² in a ring near the outer radius. It will be driven by a high speed brushless DC motor to speeds of greater than 15,000 rpm. The entire assembly will be housed with a protective enclosure for safety. Neglecting background and with realistic dimensions, the expected count rate for a 5 μCi source would require about 60 minutes per angular speed setting to achieve a statistical uncertainty of a few percent, similar to the experiment of Hay et al. [2].

V. PRODUCTION OF SOURCES

One of the aims of this project is to produce sources using a exempt amounts of radioactive material for schools without licenses to have larger radioactive sources. We will be using 5μCi of ^{57}Co in a solution with 0.1M HCl and added ^{59}Co. The ^{59}Co increases the Co ion current through the solution, otherwise, if the solution only contained the 5μCi of ^{57}Co, most of the current would be due to electrolyzing the HCl. The cobalt is electroplated to steel foil using the set-up shown in Figure 3. The amount of cobalt in the solution is monitored by measuring the current through the solution (Figure 4).

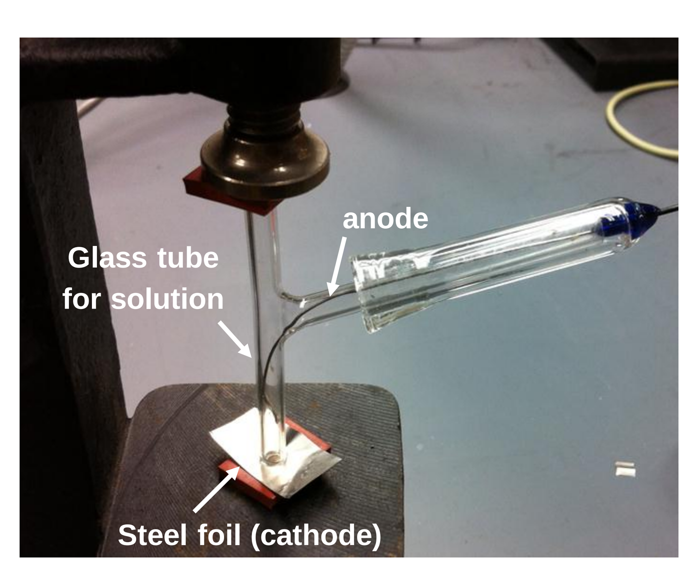

Figure 3. The apparatus used to electroplate the cobalt onto the steel foil.

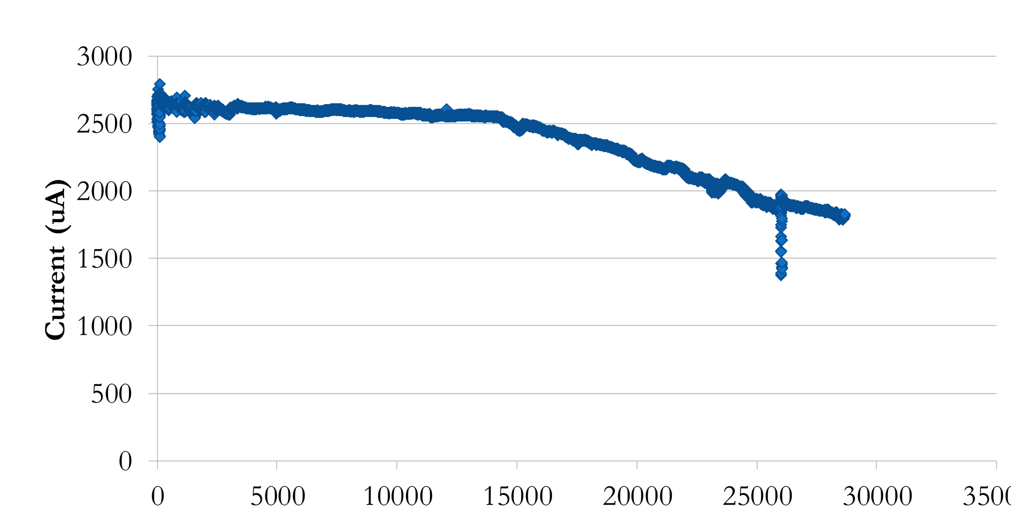

Figure 4. The current as a function of time through the cobalt solution. Note that electrolyzing 0.1M HCl without any cobalt has a current of approximately 1.75 mA at the voltage we electroplate at, 4V.

After the ^{57}Co has been electroplated onto the steel, it will be heated in the furnace so the ^{57}Co can diffuse into the steel lattice structure. The steel will be heated in a vacuum with a pressure of about 10^{-6} torr by flowing current through the foil (Figure 5). The temperature of the foil can be determined by measuring the blackbody spectrum (Figure 6) and the resistivity of the foil (Figure 7).

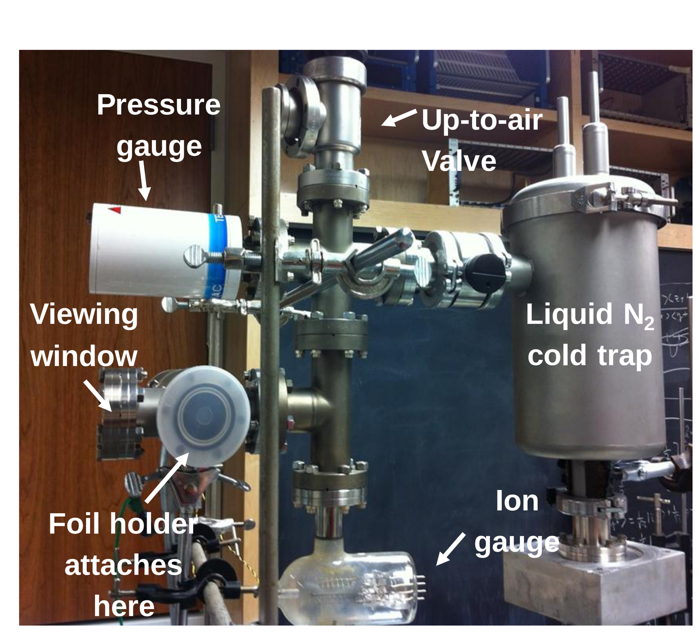

Figure 5. The apparatus heats the foil so that the ^{57}Co can diffuse into the lattice structure of the steel foil.

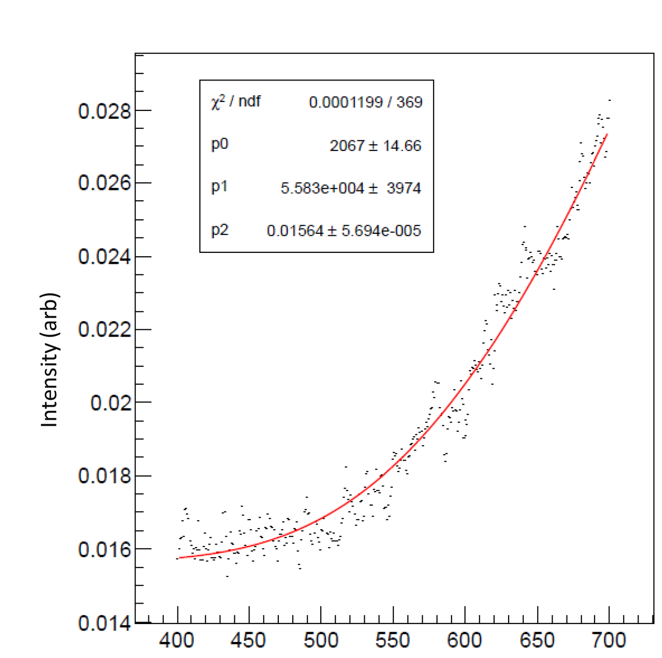

Figure 6. The black body spectrum of the hot steel foil. A fit of Planck's law gives T=2067±15°C.

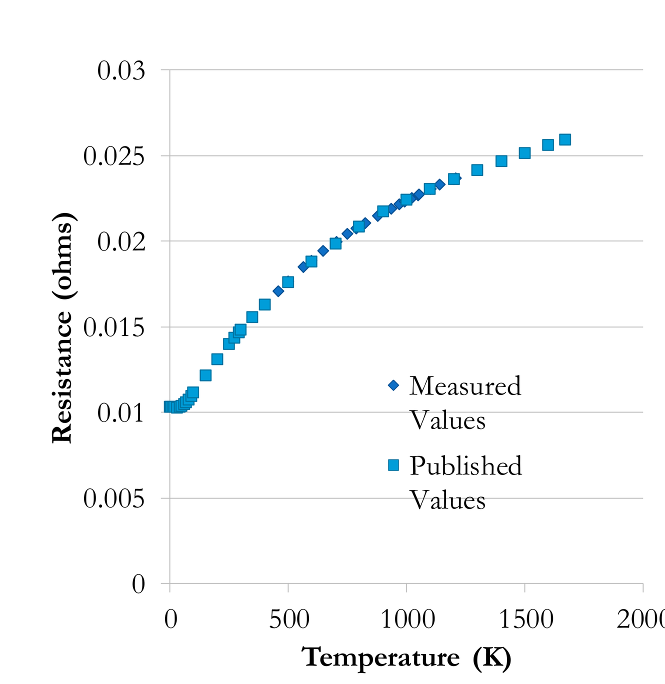

Figure 7. Measuring the resistivity of the foil as it is heated allows the temperature to be determined by comparison to previously measured values.

VI. CONCLUSION

A technique for producing Mossbauer sources by electroplating exempt quantities of ^{57}Co onto steel foils and heating in a vacuum is being developed. The long term goal is to use these sources in undergraduate experiments to demonstrate the transverse Doppler effect.

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