EXAMINING PARITY VIOLATION IN BETA DECAY USING GAMMA RAY POLARIZATION

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I. ABSTRACT

One of the most revolutionary findings of the twentieth century was discovery that parity is not conserved in weak interactions. This prediction, published in 1956 by Lee and Yang, was confirmed in the classic 1957 experiment by Wu et al. In the original paper, Lee and Yang pointed out that parity violation might also be tested in βγ correlation measurements of the circular polarization of the gamma ray emitted in beta decay. An experiment to measure this effect is being constructed at Houghton College. The transmission of ^{60}Co gamma rays through magnetized iron will be used to measure the circular polarization in coincidence with the electron emitted at 180°. The gamma rays will be detected using a high-purity germanium detector and beta particles by a silicon surface barrier detector. An asymmetry in the coincidence rate when the magnetic field is reversed will indicate parity violation.

II. INTRODUCTION

One of the most revolutionary findings of the twentieth century was discovery that parity is not conserved in weak interactions. Parity is the transformation that inverts each of the coordinate axes, in a sense creating a mirror image. Up until the 1950s, it was assumed that all the fundamental forces were like gravity and electromagnetism, that is, that they were invariant under this transformation so that it should be impossible to tell whether one was observing the system or its "mirror image." In 1956 Lee and Yang [1] made the startling prediction that this seemingly obvious symmetry may be violated by the weak interaction. A few months later, this prediction was confirmed in the classic experiment by Wu et al. [2] Lee and Yang won a Nobel Prize for this pioneering work in 1956.

The experiment of Wu et al. used ^{60}Co as the β source, which has the decay scheme in Figure 1. The ^{60}Co nucleus decays by emitting an electron (β particle) and an antineutrino ($\bar{\nu}$) and in the process drops from angular momentum $J = 5$ to 4. In the experiment, the spins of the ^{60}Co were aligned by an external magnetic field. As shown in Figure 2, if a beta particle is emitted opposite the direction of the nuclear spin, then in the mirror image the beta particle would be emitted in the direction of the spin. If parity is a symmetry for weak interactions like beta decay, then it should not be possible to determine whether one is observing the process or its mirror image. Wu et al. discovered that more beta particles are always detected opposite the nuclear spin, breaking the symmetry.

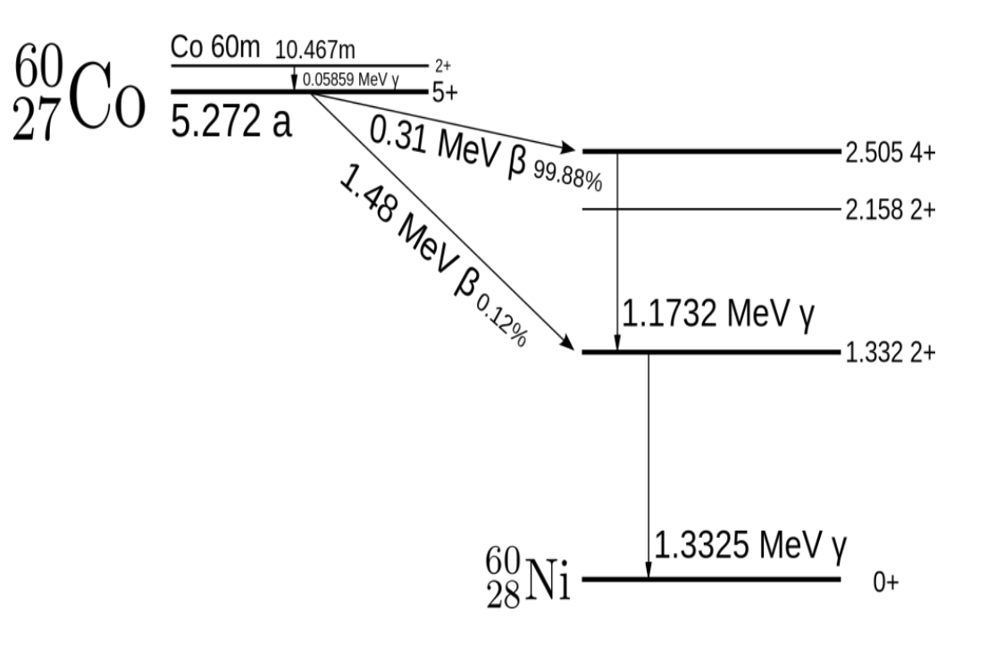


Figure 1. The decay scheme of ^{60}Co. Taken from http://en.wikipedia.org/wiki/Cobalt-60.

In the original paper by Lee and Yang it was pointed out that parity violation could also be tested in βγ correlation measurements of the circular polarization of the gamma ray. This technique was used in several early experiments [3,4,5,6] in the late 1950s, culminating in the famous experiment of Goldhaber et al. [7], which first determined the helicity of the neutrino.

To see how a measurement of the circular polarization of the decay gamma ray works, consider the Wu et al. experiment again, but this time consider the decay of the residual ^{60}Ni nucleus. From Figure 1 the ^{60}Ni nucleus is in a $J = 4$ state which then decays to $J = 2$ by emitting a spin-2 gamma ray. As seen in Figure 3, when the gamma ray is emitted along direction of nuclear spin, its spin must be parallel to the nuclear spin to conserve angular momentum, hence the gamma ray will be right circularly polarized. Conversely, if the gamma ray is emitted opposite the nuclear spin, it will be left circularly polarized. The end result is that a measurement of the circular polarization of the gamma ray emitted opposite the beta particle allows the nuclear polarization to be determined, and hence allows parity symmetry to be tested. For example, in the experiment of Wu et al., it was determined that the beta particles are preferentially emitted opposite the nuclear spin—thus we would expect to see more right circular polarization of the gamma rays emitted at 180°.

Figure 2. If a ^{60}Co nucleus emits a beta particle opposite the direction of its spin (left side), the image in the mirror (right side) would show the beta particle emitted along the nuclear spin direction. This is because the spin of the nucleus is inverted in the mirror.

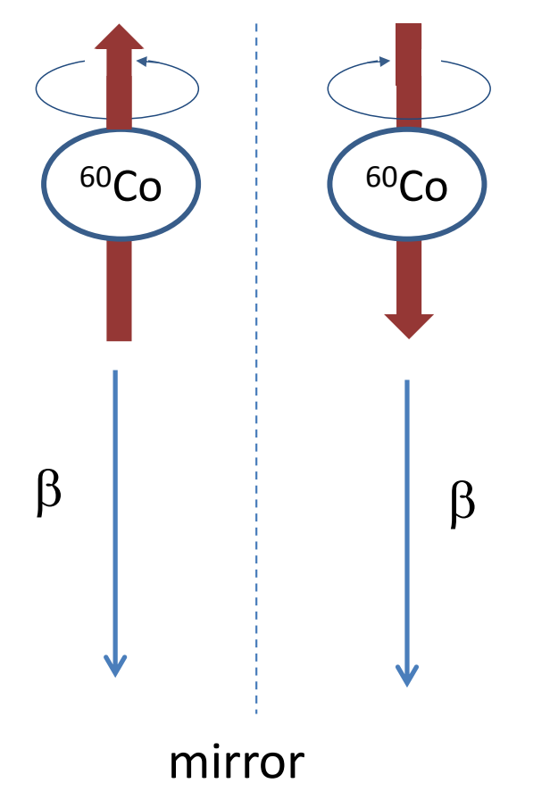
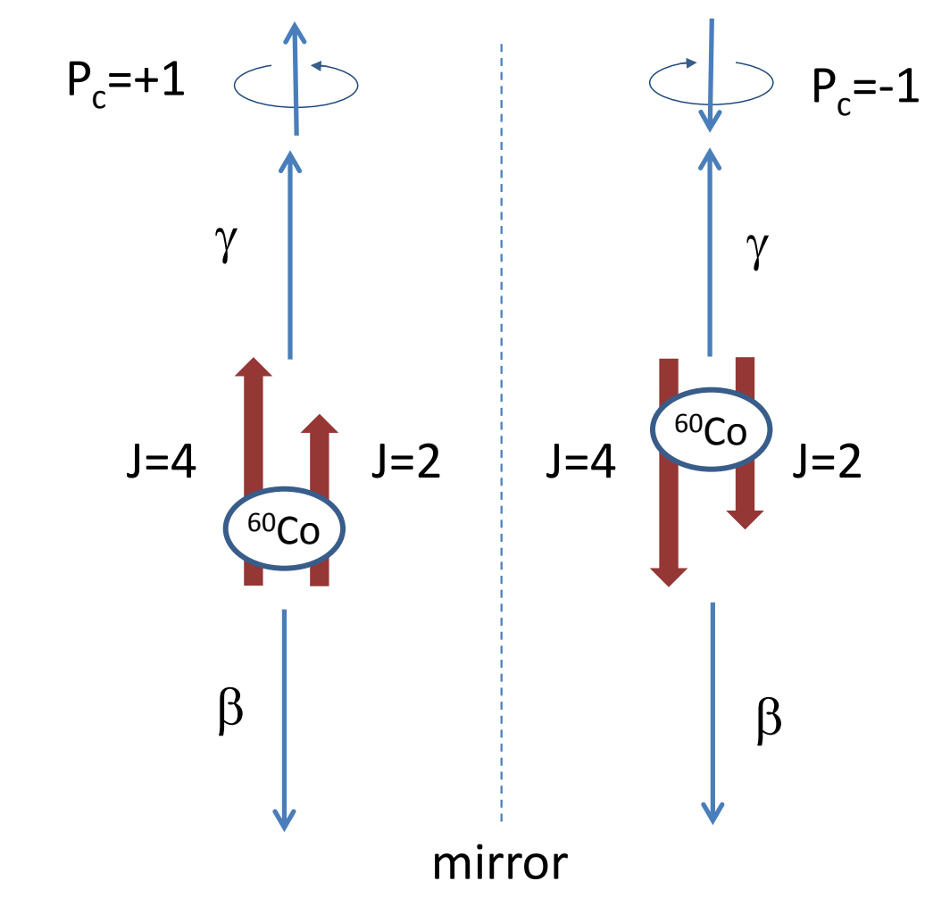


Figure 3. Examine the Wu et al. experiment again, but this time, consider the decay of the ^{60}Ni, which requires the emission of a gamma ray that is circularly polarized to conserve angular momentum. When the gamma ray is emitted along (opposite) the direction of nuclear spin, its spin must be parallel to the nuclear spin, making it right (left) circularly polarized. Thus, determining the circular polarization of the gamma ray emitted opposite the beta particle allows the nuclear polarization to be determined.



III. THEORY

In order to measure the circular polarization of the gamma rays, Compton scattering from polarized electrons in a magnet will be employed. The total Compton cross section [8] is $\boldsymbol{\sigma = \sigma_0 + fP_c\sigma_c}$ where

$$\boldsymbol{\sigma_c = \pm 2\pi {r_0}^2 \left\{ \frac{1+4k+5k^2}{k(1+2k)^2} - \frac{1+k}{2k^2} ln(1+2k) \right\}}$$

is the polarization sensitive part of the cross section, which changes sign (+ for photon spin parallel to electron spin) for aligned and anti-aligned electron and gamma ray polarization. Here, σ_0 is the polarization insensitive part of the cross section, f is the fraction of oriented electrons in the magnet, P_c is the degree of circular polarization of the gamma ray, r_0 is the classical electron radius (2.82 fm), and k is the initial photon momentum.

The number of gammas transmitted through a thickness x is

$$\boldsymbol{N(x) = N_0 e^{-\sigma Z\, N_t x}}$$

where N_0 is the initial number of gamma rays, and Z and N_t are the charge and number density, respectively, for iron atoms in the magnet.

Using this allows the asymmetry to be calculated

$$\boldsymbol{E = \frac{N_+ - N_-}{\frac{1}{2}(N_+ + N_-)} = 2\tanh(-N_t \nu \sigma_c P_c x)}$$

where $N_\pm$ are the number of transmitted gamma rays with photon spin aligned (+) or antialigned (-) with electron spin, ν is the number of oriented electrons per iron atom in the magnet, and P_c is the degree of photon polarization.

Using these formulae and the appropriate quantities for our setup, the expected asymmetry in the count rate between parallel and antiparallel orientations of the magnetic field is approximately 1.1%. A calculation of the expected count rates shows that it will take approximately 25 days to measure the asymmetry to approximately 10%, neglecting background effects, which should be greatly reduced due to the coincidence requirement.

IV. EXPERIMENT

The student experiment we propose will be very similar to the transmission experiment of Lundby et al [3]. The cylindrical iron core of an electromagnet will be placed between a ^{60}Co source and a germanium detector to count the gamma rays passing though the iron. On the opposite side of the source, a 1500 μm depletion depth silicon detector with a surface area of 25 mm² will count beta particles emitted in coincidence, allowing the βγ correlation to be determined. Since the gamma rays are travelling through magnetized iron, however, their attenuation will be affected by the net electron polarization. They will Compton scatter from the polarized electrons, causing attenuation of the gamma rays to depend on whether the electron and photon spins are parallel or antiparallel. Thus, a difference in the count rate when the direction of the magnetic field is switched is an indication of parity violation.

The magnet consists of a cylindrical iron core, approximately 5 cm in diameter and 8 cm long. Copper windings around the core generate the magnetic field that will saturate the core; the field lines return through circular iron endplates and an outer hollow iron cylinder. The direction of the field will be switched at regular intervals, allowing the count rate to be measured for both parallel and antiparallel orientations of the electron and photon spin. Since this experiment will measure a relatively small asymmetry in the count rate, care must be taken to reduce systematic effects. For this reason, the magnet has been constructed with axial symmetry and will be flipped 180° periodically.

A plastic detector and a ^{22}Na source was used in the circuit shown in Figure 6 to calibrate the time-to-amplitude converter.

IV. RESULTS AND CONCLUSIONS

The temporary setup (Figure 7) revealed a timing resolution of 0.28 μs. Obviously, this result will not directly apply for the final setup (Figure 10), which should have a much shorter coincidence resolving time.

Very few physics laboratories at the undergraduate level exist that deal with breakthrough experiments performed after 1950. We are interested in developing this setup into a tabletop laboratory exercise that can be used for undergraduate instruction.

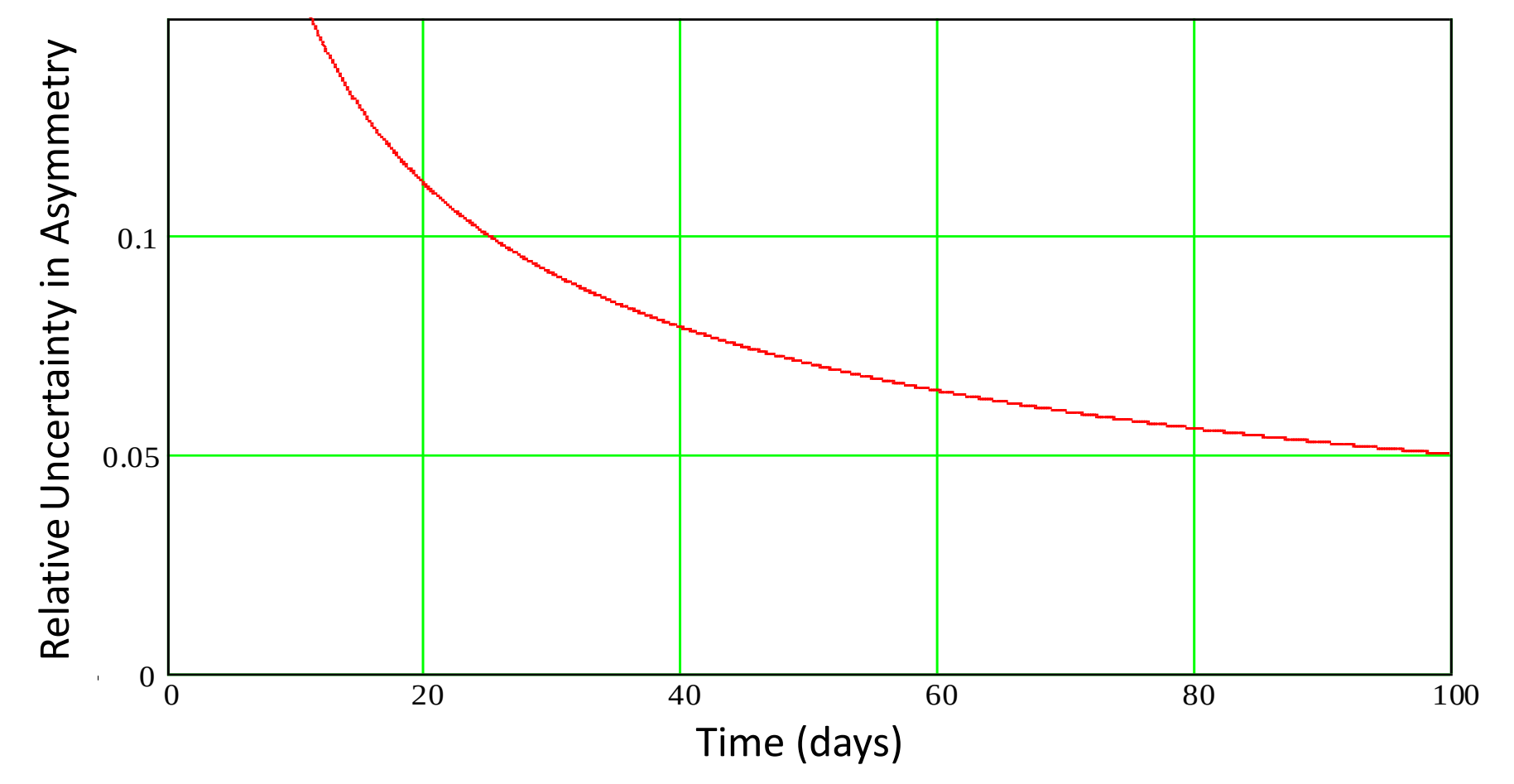


Figure 4. The predicted relative uncertainty in asymmetry as a function of counting time for an 8 cm thick magnet, using a 1 μCi ^{60}Co source. A 10% measurement is possible in approximately 25 days.

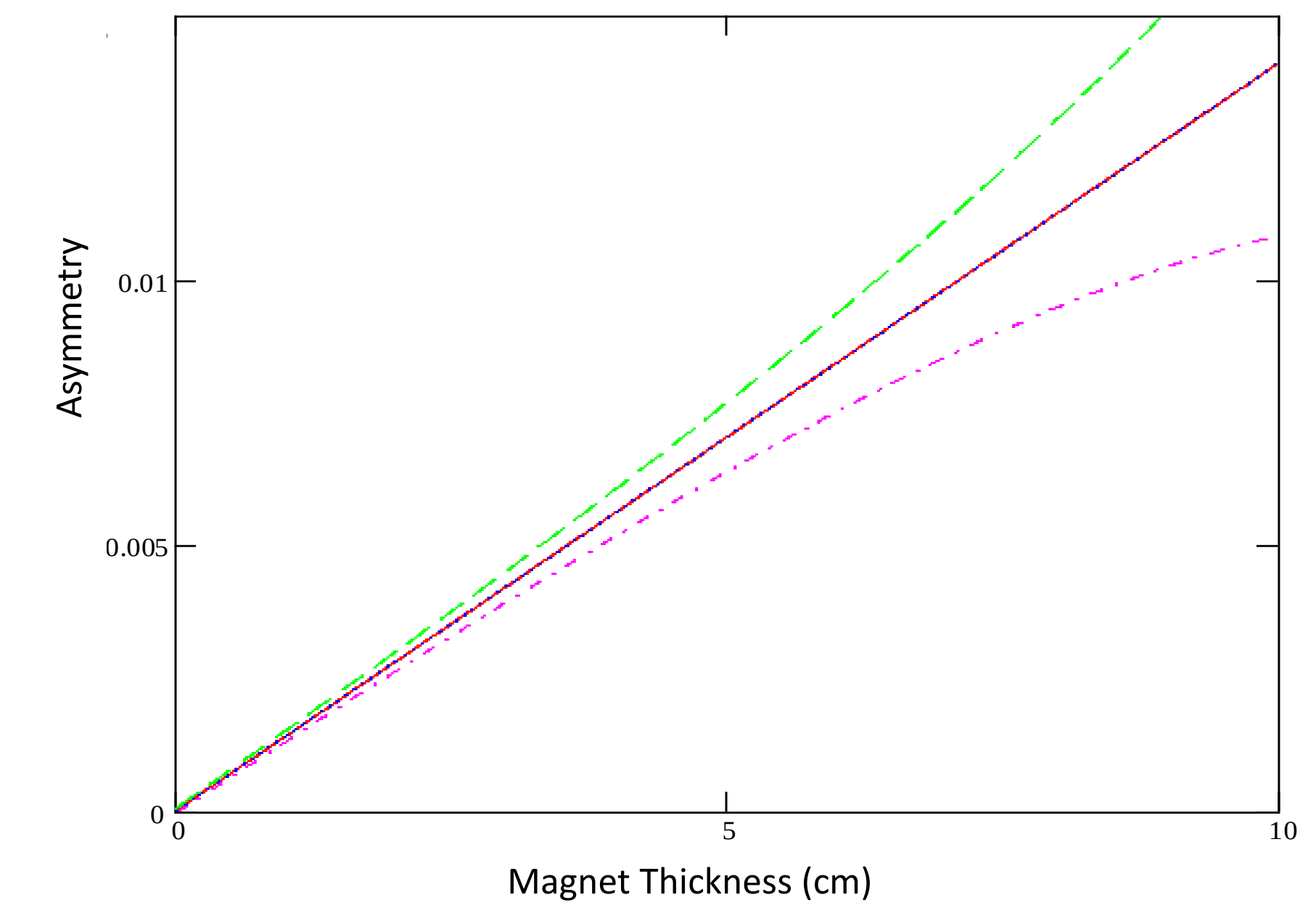


Figure 5. Predicted asymmetry as a function of magnet thickness. Also plotted is the statistical uncertainty in the asymmetry that could be expected for our experiment after 10 days of counting.

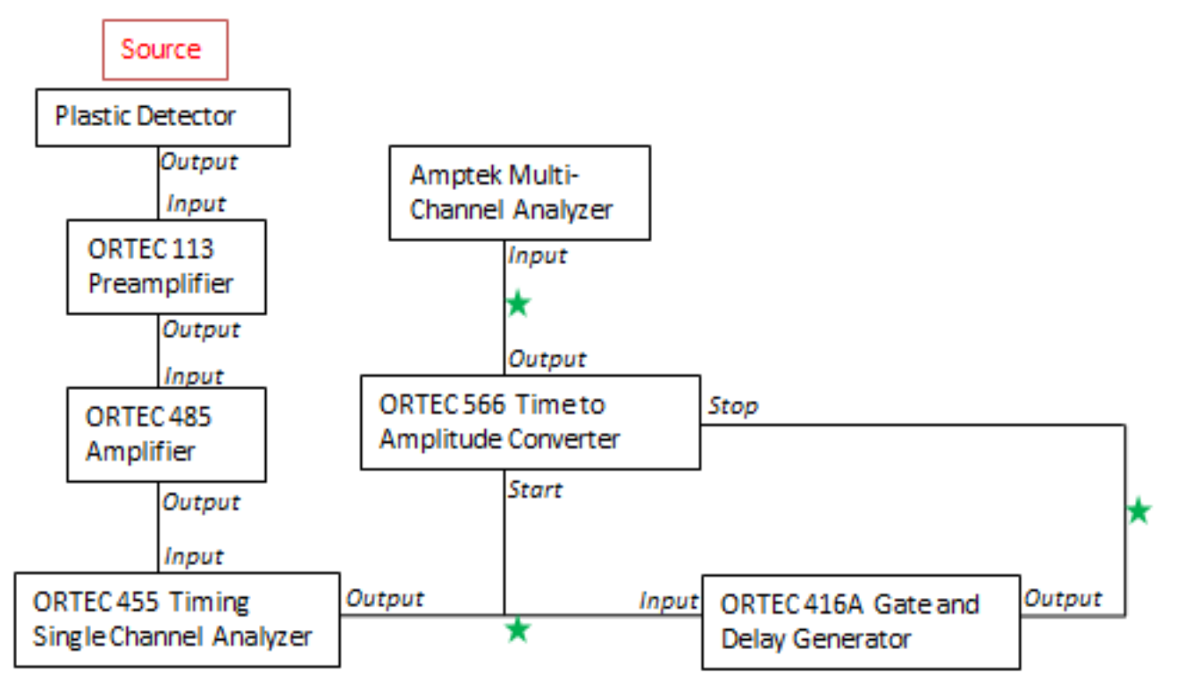


Figure 6. Timing calibration circuit. The signal into the TAC's stop input is a delayed version of the signal going into the TAC's start input. Setting the amount of delay allowed the MCA to be calibrated so that each channel corresponded to a set amount of time (Figure 11).

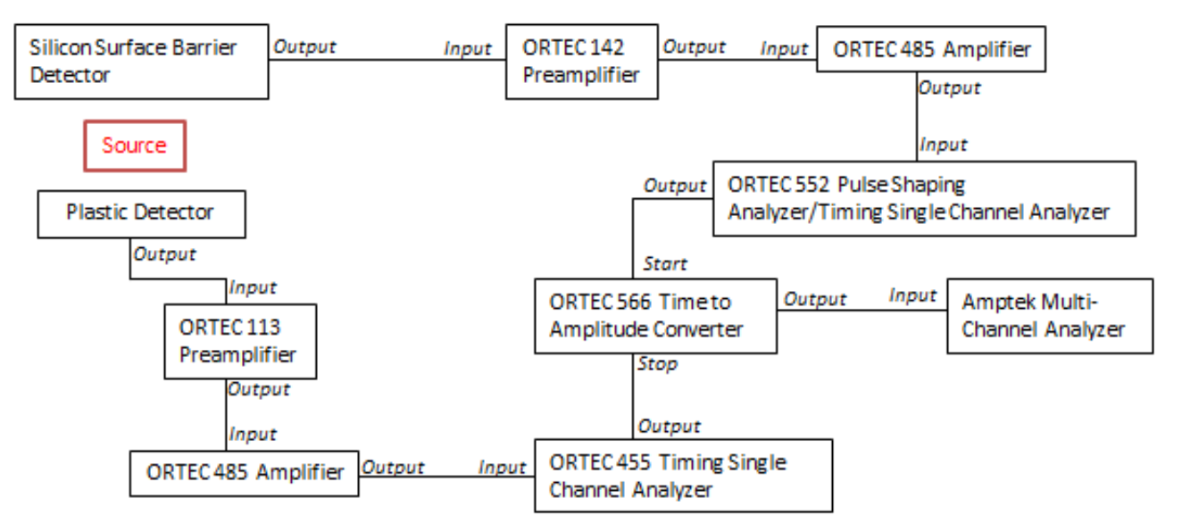


Figure 7. Temporary test setup. Beta particles from the ^{22}Na in the source are detected by the silicon surface barrier detector, and gamma rays in coincidence by the plastic detector. The multi-channel analyzer histogram allowed the timing resolution to be found (Figure 12).

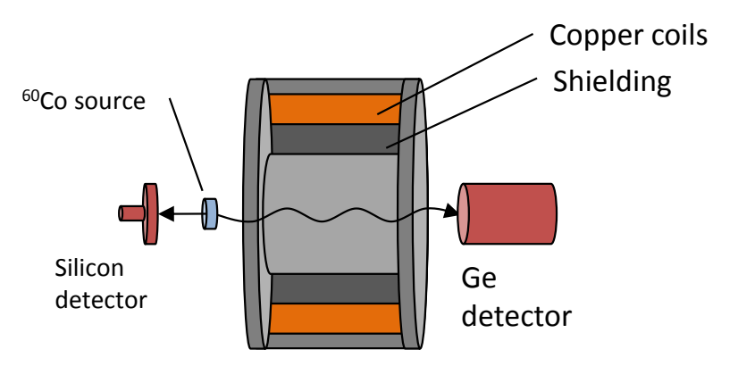


Figure 8. Arrangement of source, magnet, and detectors. The gamma rays from the source will Compton scatter in the magnet.

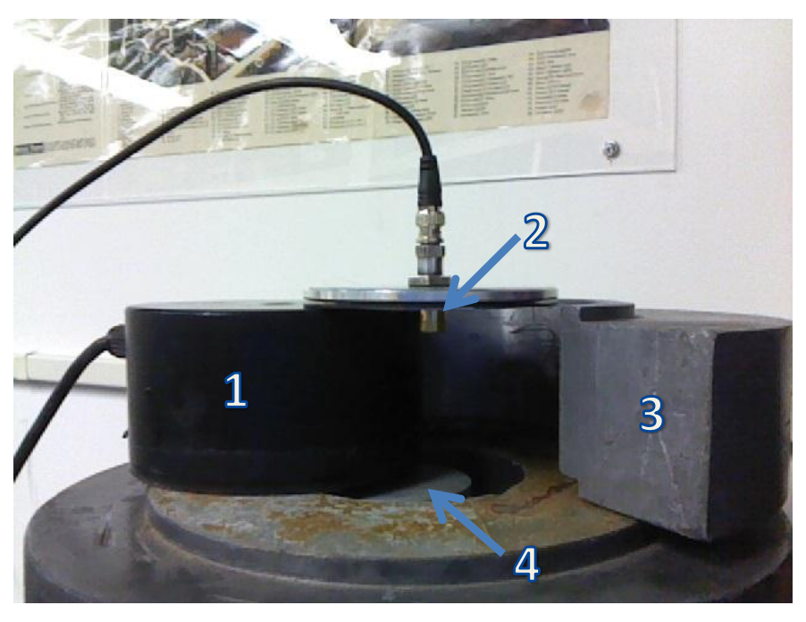


Figure 9. This photograph shows four elements of the final setup: the magnet (1) the silicon surface barrier detector (2), some lead shielding (3), and the Ge detector (4).

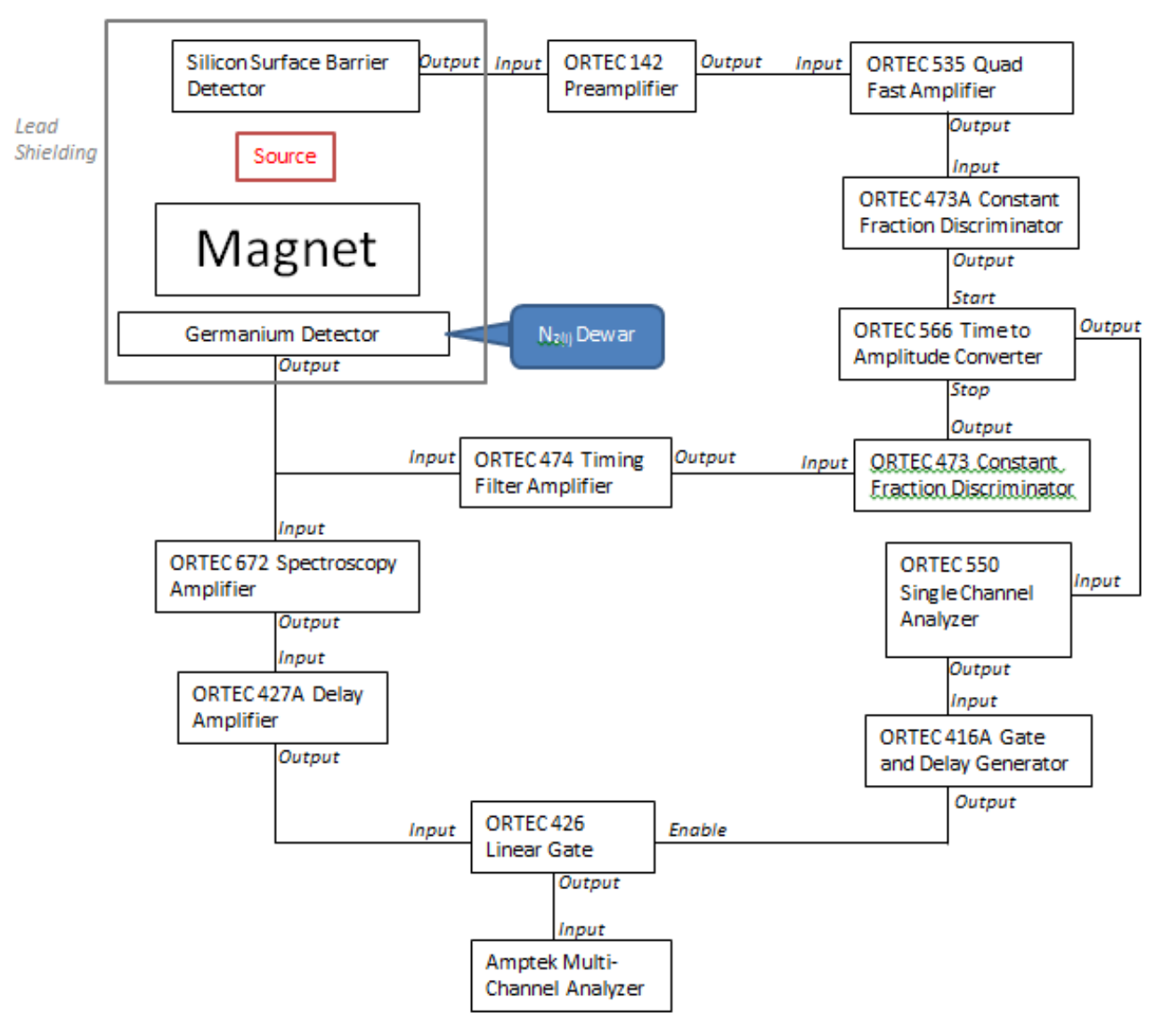
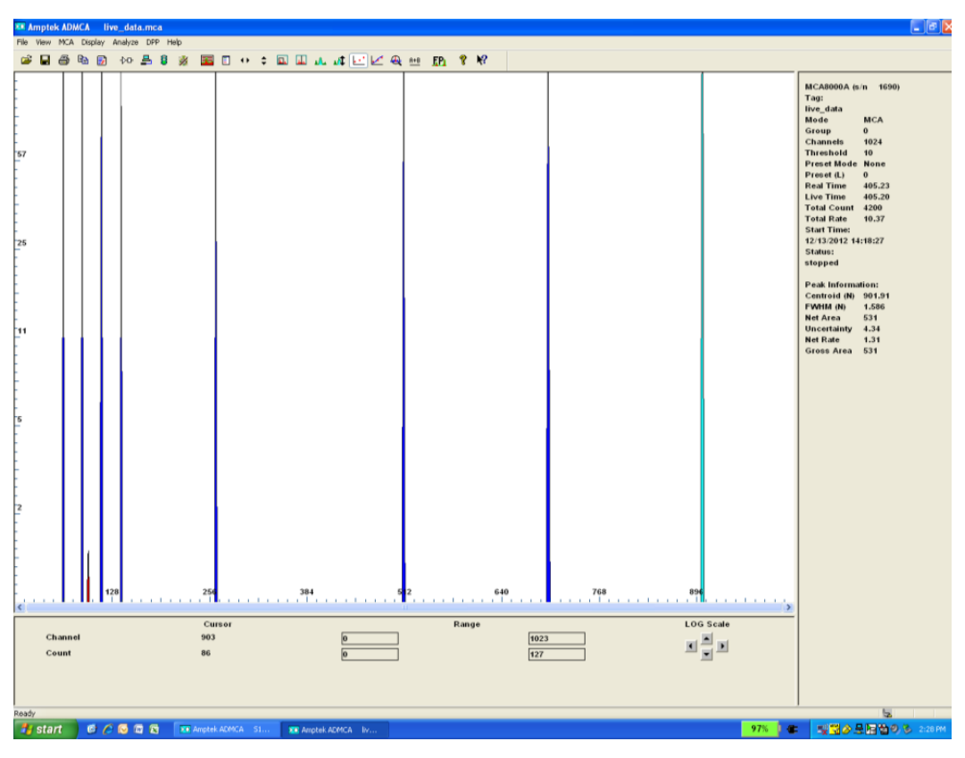


Figure 10. Planned Final Setup. The silicon surface barrier detector detects beta particles (from by the decay of ^{60}Co) from the source, and the germanium detector detects gamma rays (from the decay of ^{60}Ni) in coincidence.

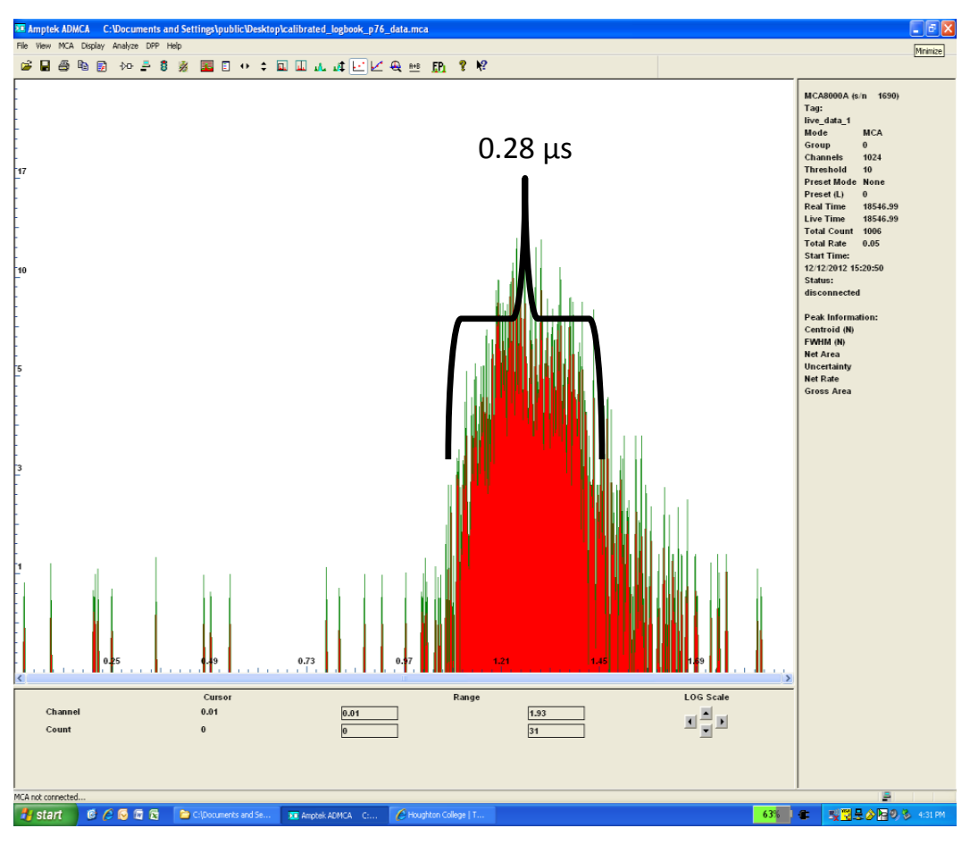


MCA8000A (s/n 1690)
Tag:
live_data
Mode MCA
Group 0
Channels 1024
Threshold 10
Preset Mode None
Preset (L) 0
Real Time 405.23
Live Time 405.20
Total Count 4200
Total Rate 10.37
Start Time:
12/13/2012 14:18:27
Status:
stopped

Peak Information:
Centroid (N) 901.91
FWHM (N) 1.586
Net Area 531
Uncertainty 4.34
Net Rate 1.31
Gross Area 531

Channel 903
Count 86

Figure 11. MCA calibration scan.



MCA8000A (s/n 1690)
Tag:
live_data_1
Mode MCA
Group 0
Channels 1024
Threshold 10
Preset Mode None
Preset (L) 0
Real Time 18546.99
Live Time 18546.99
Total Count 1006
Total Rate 0.05
Start Time:
12/12/2012 15:20:50
Status:
disconnected

Peak Information:
Centroid (N)
FWHM (N)
Net Area
Uncertainty
Net Rate
Gross Area

Channel 0.01
Count 0

Figure 12. The full width half maximum of the timing peak was 0.28 μs.

References

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