Total-to-Peak Ratios of High Purity Germanium Gamma Ray Detector

by

Justin Mathew Nelson

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Author ....
Department of Physics
May 7th, 2004

Certified by ....
Richard Milner
Professor, Department of Physics
Thesis Supervisor

Accepted by..
David Pritchard
Senior Thesis Coordinator, Department of Physics

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Abstract:

This study is concerned with the percentage of γ-rays of a certain energy having their energy correctly measured by a high purity Germanium γ-ray detector. The ratio between the total counts and the counts within the energy peak (total-to-peak ratio) is determined for seven energies ranging from 89 keV to 1275 keV. A Monte Carlo based on the physical parameters of the detector was used to extrapolate between these points and after an energy independent scaling factor fit the data with a reduced χ^2 slightly below 1. The same experiment was repeated with a lead brick and then a β detector near the Ge detector and these objects were found to not have an effect on the total-to-peak ratios within the precision of the experiment.

Thesis Supervisor: Richard Milner
Title: Professor, Department of Physics

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I also must take the time to thank Prof. Richard Milner of MIT. Even though it was of no reward to him, he agreed to be my thesis advisor when rules mandated an MIT advisor. I had to ask several professors and I am truly grateful that he took the time out of his schedule in order to read and edit my thesis in the early stages.

Contents

1. Introduction

High purity Germanium γ-ray detectors are highly important in many areas of physics research. Due to the nature of the detector, the efficiency of the detector to detect γ-rays at certain energies is dependent upon the energy of the γ-rays. Furthermore, it is reasonable to assume that the environment directly surrounding the detector can have an effect on the measurements. In order for these detectors to be of use in certain experiments, a high degree of accuracy is needed for the efficiency of the detector at a wide range of energies.

An example (and particular motivation for this study) is the measurement of the β-decay branching ratios involved in super-allowed 0^+-to-0^+ β-decays. These ratios must be measured using the relative intensity of occurring γ-rays. These ratios are needed in order to measure a specific entry of interest in the Cabibo-Kobayashi-Maskawa (CKM) matrix. [3]

The CKM matrix is the complex 3 x 3 matrix whose entries are the mixing angles between the up-type and down-type quarks. It represents a change of basis between the mass eigenstates and the weak interaction eigenstates. Because it has this interpretation, this mandates the matrix to be unitary in the Standard Model. The particular value measured through these super-allowed 0^+-to-0^+ β-decays (V_{ud}, mixing angle between the up quark and the down quark) is part of a unitary relationship which is currently being investigated. If this relationship were to be found not to be unity, it would suggest physics beyond the Standard Model.

This matrix is also important because the value of charge-parity (CP) violation can be deduced from the same entries. CP violation is the break in symmetry between the behavior of matter and anti-matter. The amount of matter that was favored over anti-matter post-Big Bang gives a value for CP violation. There is currently a large disparity between the measured amount of CP violation found by the CKM matrix and the amount of CP violation needed for the observed amount of matter in the universe. Obtaining more precise measurements of the CKM matrix will allow physicists to place better limits on the amount of CP violation the Standard Model allows. [5]

1.1 Detector's Relative Efficiency

The relative efficiency of a detector is an important quantity. This is defined as the probability of a γ-ray entering the detector and depositing all of its energy in the detector. Thus, the correct energy is recorded and using this information, the activity of a certain source can be measured with precision often limited by uncertainty in the relative efficiency. To improve the precision of this quantity for a detector is to improve the precision of all measurements by this detector. It is important to note that in the past Ge detectors have been calibrated in the middle energy range (150-1500 keV) to about 0.5%. In the upper and lower energy ranges, uncertainties were larger. The work reported here is part of a study which reduced the uncertainty in the relative efficiency of a Ge detector to 0.2% from 50 keV to 1400 keV [1]

In order to achieve the type of precision that was desired, a correction factor had to be applied to the peaks measured at a specific energy. This factor was based on what is called coincidence summing. This is the simultaneous detection of two γ-rays of the same event. Thus, the detector adds the two energies that is detected for each γ -ray. This can have two effects. It can add to the peak area by the two energies adding to a peak of interest (often referred to as crossover peaks). It can also subtract from this peak by having one γ-ray deposit all its energy and having the other γ-ray deposit no energy at all. The former correction is undertaken in Ref. [1] and references therein. The latter correction is the main purpose of this study.

1.2 Total Efficiency

In order to see how often this situation occurs, the total efficiency of the detector is needed. This is defined as the probability that a γ-ray will be detected at all. One can see that if there are two γ-rays then one must know the probability of one being fully detected and one must know the probability that any amount of energy is recorded for the other. This when combined with the angular correlation of the two γ-rays in conjunction with the angle subtended by the detector will allow one to calculate the probability of this effect occurring. Thus, these can be added back into the peak in order to correctly calculate the relative efficiency of the detector. [1]

The term total-to-peak ratio is used to refer to the ratio of the total counts recorded by the detector to the counts recorded in a peak associated with a specific energy. Using the total-to-peak ratio, one can use the relative efficiency to deduce the total efficiency of the detector. This in turn can be used to correct for coincidence summing within the detector in order to account for small corrections in the relative efficiencies. The relative efficiency is of great importance for it is the probability that a γ-ray of a particular energy is recorded at that energy. This type of correction is needed for precision necessary in certain experiments.

This study will be concerned with the measurement of the total-to-peak ratios of a range of energies from 88 keV to 1275 keV. With measurements at eight different energies, a Monte Carlo code can be used to calculate an extrapolation curve with precision limited by the measurements made. [1] The study will also investigate the effects of the characteristics of the spectrum and the energy peaks based on the detector's surrounding.

2. Monte-Carlo Code

The Monte Carlo code used to extrapolate the data points was the CYLTRAN code from the ITS (integrated tiger series) package. The Integrated Tiger Series is a Monte Carlo that allows solutions to the linear time-integrated coupled electron/photon transport problems with an electrical bias which is found in the Ge detector. [4] The ITS package is obtained from the Oak Ridge National Library.

The parameters used in the Monte Carlo were improved in order to accurately model the Ge detector. For instance, the physical dimensions of the detector affects greatly the efficiencies. Due to the complicated manufacturing of these detectors, determinatin of the detector's position and dimensions below a few millimeters is difficult. Therefore, the Ge detector in use in this study was x-rayed in order to properly determine these parameters relating to the crystal and other features within the detector. Furthermore, preliminary studies were done in order to extract photon and electron cross section information within the detector. In depth description of the Monte Carlo can be found in Ref. [1].

3. Experimental Setup

The detector used was an ORTEC Gamma-X high purity germanium detector. It has an active volume of 280 cm^3. The detector is mounted horizontally and is a coaxial type with an n-type Ge semiconductor. With a Be window it is can detect photons down to 10 keV. The manufacturer states that it has 70% efficiency at 1.33 MeV with a 3 in. by 3 in. NaI(Tl) crystal.

3.1 Data Acquisition

The detector's pre-amplified signal was first sent to a Tennelec Spectroscopy amplifier (TC-249). Then it went through an Ortec TRUMP™ -8k/2k card to convert the signal from analog to digital. The TRUMP™ card is controlled by the MAESTRO™ software which was run on a PC with Windows-95 (Figure 1) [1].

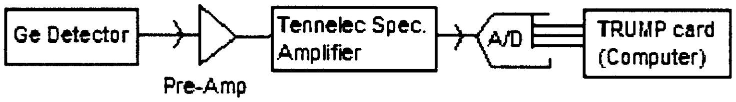

Figure 1: Signal Processing

3.2 Sources

There was used a total of 8 different sources each corresponding to a different radionuclides. The sources (^{22}Na, ^{60}Co, ^{57}Co, ^{120}Sb, ^{54}Mn, and ^{137}Cs) were purchased from the Nycomed Amersham (currently AEA Technology). These sources were absorbed on a 1-mm diameter ion-exchanging bead and placed inside a plastic capsule with 1-mm-thick walls.

4. Experimental Procedure

The procedure involved placing the source 15.1 cm from the detector along the detector's coaxial direction. This distance was chosen because it is the optimal distance for the on-line measurements of super-allowed β-decays. For the sake of consistency, we also measured a source at 100 cm and found the results to be consistent. The distance was measured with a micrometer caliper which gave a 0.2 mm uncertainty at 15.1 cm. This relates to an uncertainty of 0.22% in the calculations of absolute efficiency as determined by a precisely calibrated ^{60}Co source (Figure 2) [1].

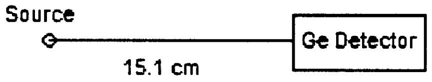

Figure 2: The source was positioned directly in the center of the cylindrical face of the detector.

All measurements were made in a laboratory well removed from any accelerator-based radioactivity. Although no shielding was used, frequent background spectra were taken. These background spectra were then scaled using the live time and subtracted from the spectra using a source. The TRUMP™ card employs the Gedcke-Hale method [2] in order to determine live time that takes into account dead time and random summing. The counting rate which comes from dividing the counts by this calculated live time is a good approximation to the true counting rate. Although this study is concerned with a ratio, this live time is important for background subtraction which is discussed later.

4.1 Dead Time vs. Live Time

The calculated live time had been carefully tested as well. A fractional dropped of $2.5 * 10^{-4}$ of the counting rate was found per 1% increase in dead time [1]. The measurements had 2-3% dead time and therefore this effect was negligible and the live time stated could be used. In order to obtain the statistics that were wanted, all runs had enough live time in order to accumulate a million counts in each energy peak considered.

The analysis involved counting two things: the counts within energy peaks and the total counts.

4.2 Peak Areas

All peak areas were analyzed with the least-squares peak-fitting program GF2 which is in the RADware series. [1] All peaks were fitted with a symmetric Gaussian with a smoothed step-function and a linear or quadratic background (Figure 3). Using these functions, reasonable fits were found for all peaks within the spectral data. The area of the Gaussian is used to provide the number of counts within the peak.

4.3 Step-Function Background

The step-function is a smoothed step-function centered at the center of the Gaussian (Figure 3). It is the result of two phenomena. The first is the phenomena of when γ-rays Compton scatter in external material and secondary photons of lesser energy enter the detector. The second effect is coming from γ-rays which have the appropriate energy to be within the energy peak, but deposit less than its full energy into the detector and thus is detected at a lower energy value. At energies higher than the energy peak, this can not happen and therefore the background follows a step function. The first effect dominates at lower energies and the latter at high energies. [1]

It was often the case that each peak was fitted several times. Each time factors would be changed and the resulting fit and value of the area being measured would be viewed. Such factors included changing the number of channels used to calculate the background, toggling between a linear and quadratic background, and fixing certain values if the fit warranted it. Often this was the height of the step-function. The peak areas, the statistical uncertainties, and the goodness of the fit were analyzed as a function of fit. The value finally chosen was the one that appeared to fit the data best and the quoted uncertainty was often enlarged in order to properly account for the variation in the appropriate different fits. Using this method, reasonable fits were found for all peaks within the spectral data.

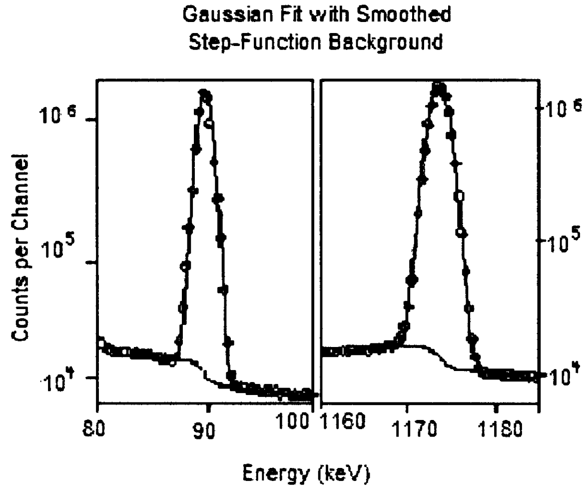

Figure 3 [1]: The left panel is the 89.8 keV peak of ^{120}Sb. The plotted line is the GF2 fit. It is a Gaussian peak with a smoothed step-function times polynomial factor for the background. The counts of a peak is the area of the Gaussian above the background. The errors associated with each peak reflected both the statistical error and the variation of the area obtained through different comparably good fits. Different fits are achieved through varying the size of the background, the degree of the polynomial used for the background, and/or fixing the height of the step-function.

4.4 Total Areas

The total area was a measure of all the counts recorded by the detector associated with the energy peak. Since a γ-ray of a given energy can never be recorded as having a higher energy, the total area only took into account those counts lower than the energy peak. Thus, any counts at a higher energy were deemed background and subtracted from the total count. This subtraction was in addition to the previously mentioned background subtraction performed on every spectrum. Also, since the Ge detector has a lower limit of reliably detected energy, a constant extrapolation was performed at the lower energy levels to account for those energy channels not detected. These two corrections were made to the total counts beneath the curve to account for the total area of the spectrum.

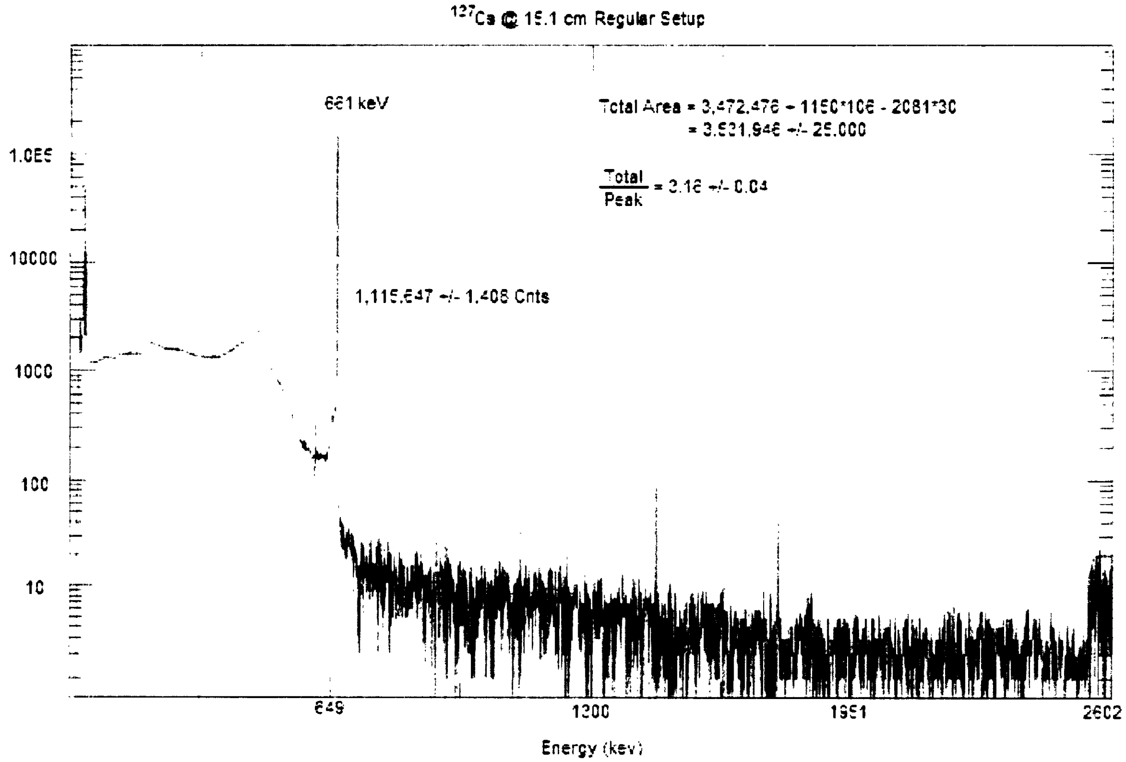

Figure 4: The total area is obtained by taking the total counts recorded by the spectrum and subtracting all counts after the peak and adding back in counts in the lower energy ranges by a constant extrapolation. Error bars are assigned to reflect both statistical errors and the uncertainty in the correction factors just mentioned.

4.5 Double Peaks

Two different situations arose with sources that had two different energy peaks within their spectrum. The first situation involved ^{22}Na which has energy peaks at roughly 511 keV and 1275 keV [1]. Each of these energy peaks was considered separately and the total areas associated with each energy peak had to be determined. The total area associated with the first peak could be analyzed as if the second peak did not exist. The level of background found directly after the peak is subtracted off of the total counts and the fact that there is another peak does not affect this.

The second peak must be handled with the assumption that the γ-rays found directly after the 511 keV peak are 1275 keV γ-rays which were partially detected. No 511 keV γ-ray could account for these counts. Therefore, this level of background was extrapolated to zero energy and the total counts obtained from integrating this constant over all the energy channels was added to the total area associated with the 1275 keV peak. Looking at the graph, the assumption of this level remaining constant all the way down to zero energy is somewhat suspect and therefore one will also notice much larger error bars associated with this energy peak.

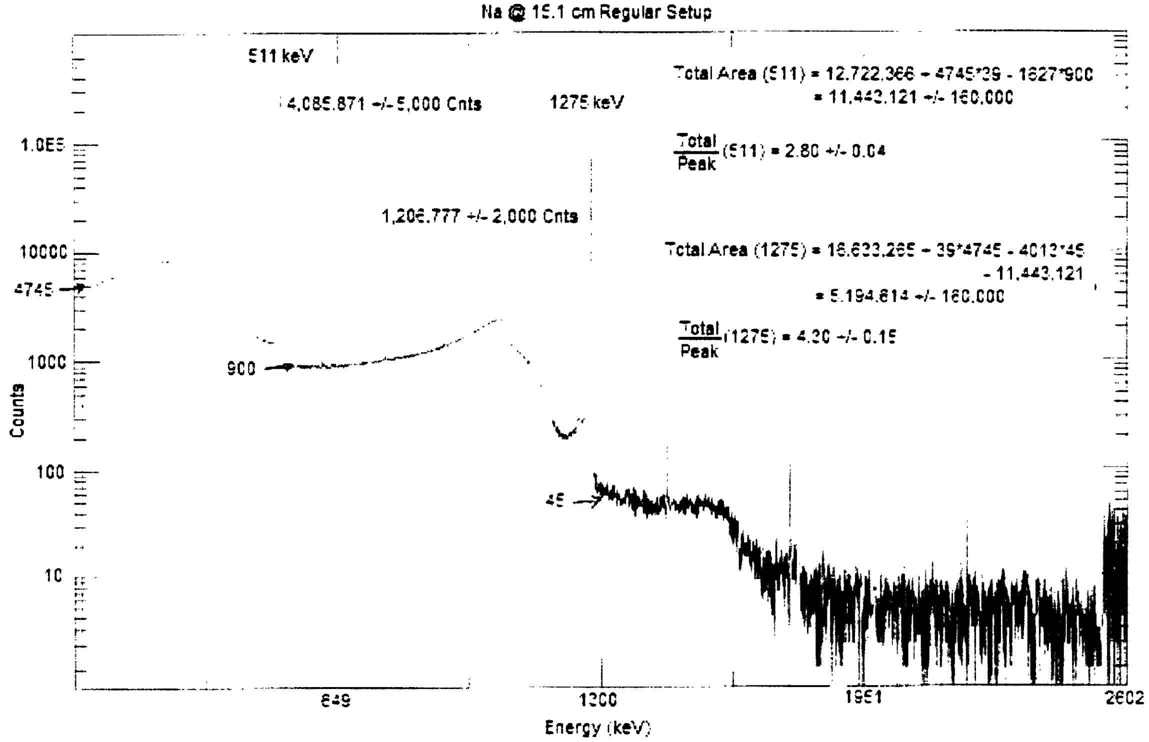

Figure 5: The two peaks of ^{22}Na are separately considered. The total area is also separately considered by determining which counts "came from" the two different energy peaks and were recorded at lower energies than they actually were.

The second double peak situation involved ^{57}Co and ^{60}Co. ^{57}Co has two peaks that are found at roughly 122 keV and 137 keV. ^{60}Co has them at 1173 keV and 1331 keV. [1] These two peaks were too close to be considered separately and therefore they were combined. The peak areas were merely added and the total area found as it was in the other cases. The energy level associated with this data was the weighted average of the two energies with the peak areas.

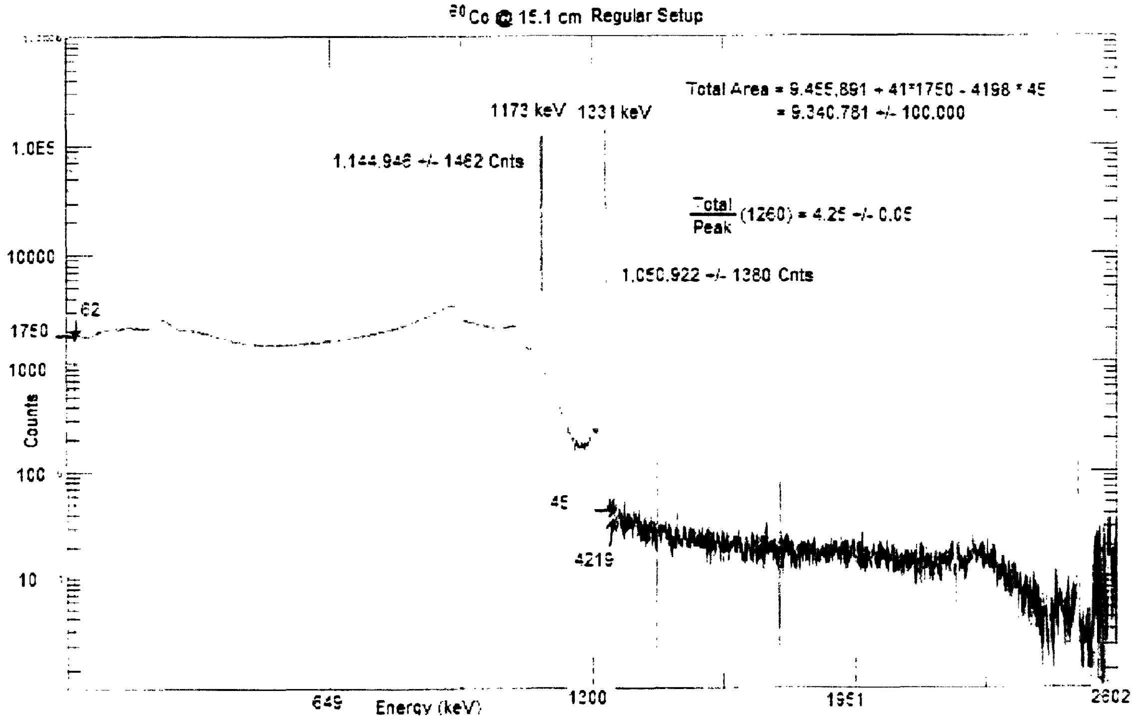

Figure 6: The two peaks of ^{60}Co are close in energy to be considered separately and therefore the area within the energies peaks are added and one Total-to-Peak ratio is determined. The energy associated with this value is the weighted average of the energies with the number of counts within the peak.

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5. Results

5.1 Total-to-Peak Ratios

The results for the eight different energies can be see in Table 1 and plotted in Figure 7 along with a fitted Monte Carlo extrapolation (it is increased by an energy-independent constant to fit the data).

5.2 Lab Environment Effects

Since these measurements would be made in a lab with various objects close to the detector, the experiment was extended to find the effect such materials could have on these ratios. Two different situations were used. The first one involved placing a β detector on the opposite side of the source from the detector. This mimicked how the super-allowed β decay experimental setup would be and thus was of specific importance. The second situation involved placing one to several lead bricks of size approximately 2" by 3" by 6" in various positions trying to maximize the number of γ-rays that would bounce off of the brick and into the detector. The results stated are those of one brick in the position shown in Figure 6.

In all of the situations, no changes in the total-to-peak ratios were observed within the precision of this experiment. One can see that these objects did have an effect to the spectrum. This can be seen in Table 1 and also in Figures 7, 8, and 9.

Figure 6: The two drawings show the two different setups used to determine the effect of lead and a β detector. Both of these materials would be found in the surrounding environment for a particular study of interest involving super-allowed 0^+-to-0^+ β-decays

Source	Energy (keV)	Total-to-Peak Ratio No objects added	Total-to-Peak Ratio Pb Brick Added	Total-to-Peak Ratio Beta detector added
^{120}Sb	89.8	1.25 ± 0.04	1.40 ± 0.07	1.27 ± 0.06
^{57}Co	123.66	1.32 ± 0.03	1.30 ± 0.05	1.34 ± 0.03
^{22}Na	510.999	2.80 ± 0.07	2.76 ± 0.07	2.76 ± 0.06
^{137}Cs	661.657	3.16 ± 0.04	3.12 ± 0.04	3.17 ± 0.06
^{54}Mn	834.841	3.48 ± 0.03	3.45 ± 0.09	3.46 ± 0.05
^{60}Co	1252.9	4.25 ± 0.05	4.28 ± 0.05	4.27 ± 0.04
^{22}Na	1274.537	4.30 ± 0.18	4.45 ± 0.18	4.36 ± 0.21

6. Conclusion

The data in Figures 7, 8, and 9 verify a Monte Carlo extrapolation by [1] with a reduced χ^2 slightly below 1 if the Monte Carlo is allowed an energy independent scaling factor. This data was used in order to determine the total efficiency of a particular Ge detector. This in turn made corrections to the relative efficiency of the detector which were significant. It introduced errors of ± 2.5%. This uncertainty was low enough to generally not affect the overall uncertainties. However the corrections made because of these measurements were substantial and ranged up to several percent in some cases [1]. The effects of various common lab materials were found to have no effect at the level of precision in this study on the total-to-peak ratios of the detector.

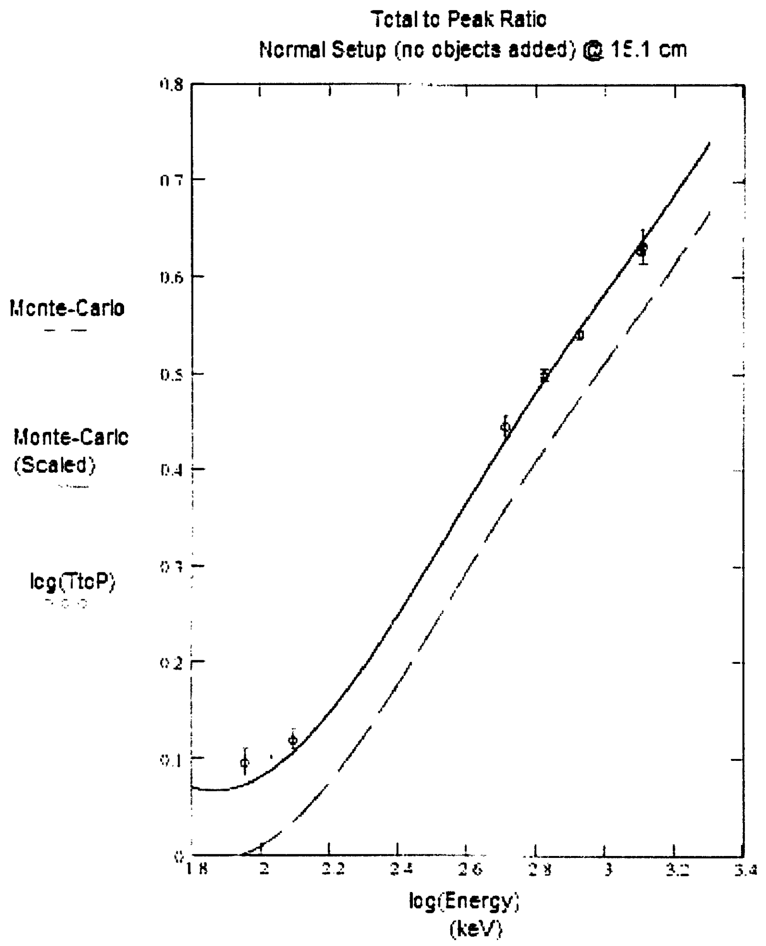

Figure 7: The Monte Carlo code is used to extrapolate between data points. There is an energy independent scaling factor used in order to align the Monte Carlo code to the data.

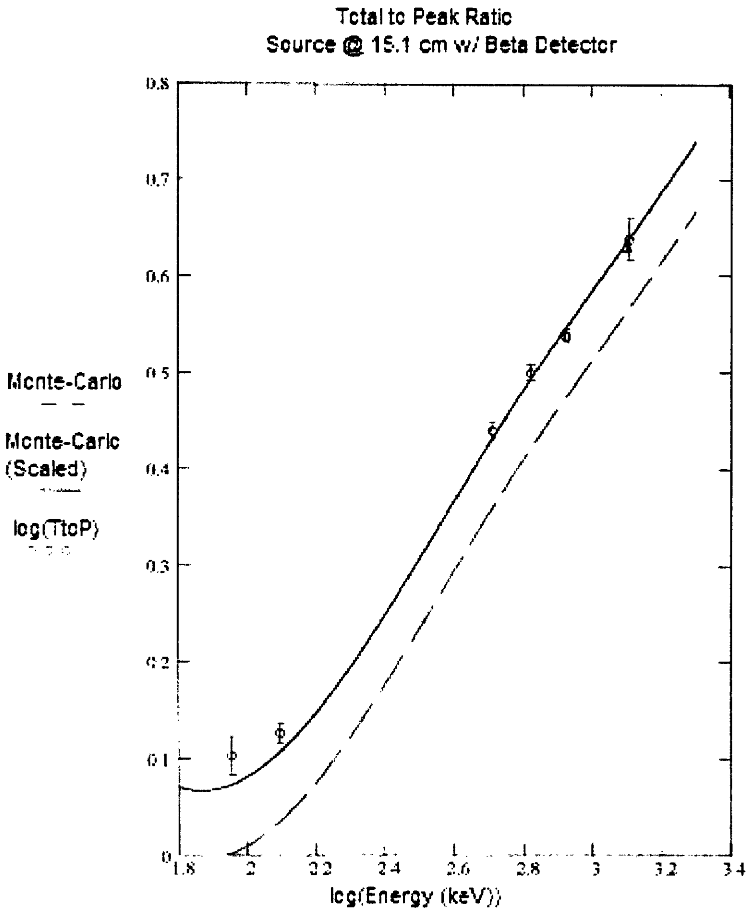

Figure 8: The total-to-peak ratios with the addition of a β detector behind the source. The β detector is often accompanied with the Ge detector during certain experiments.

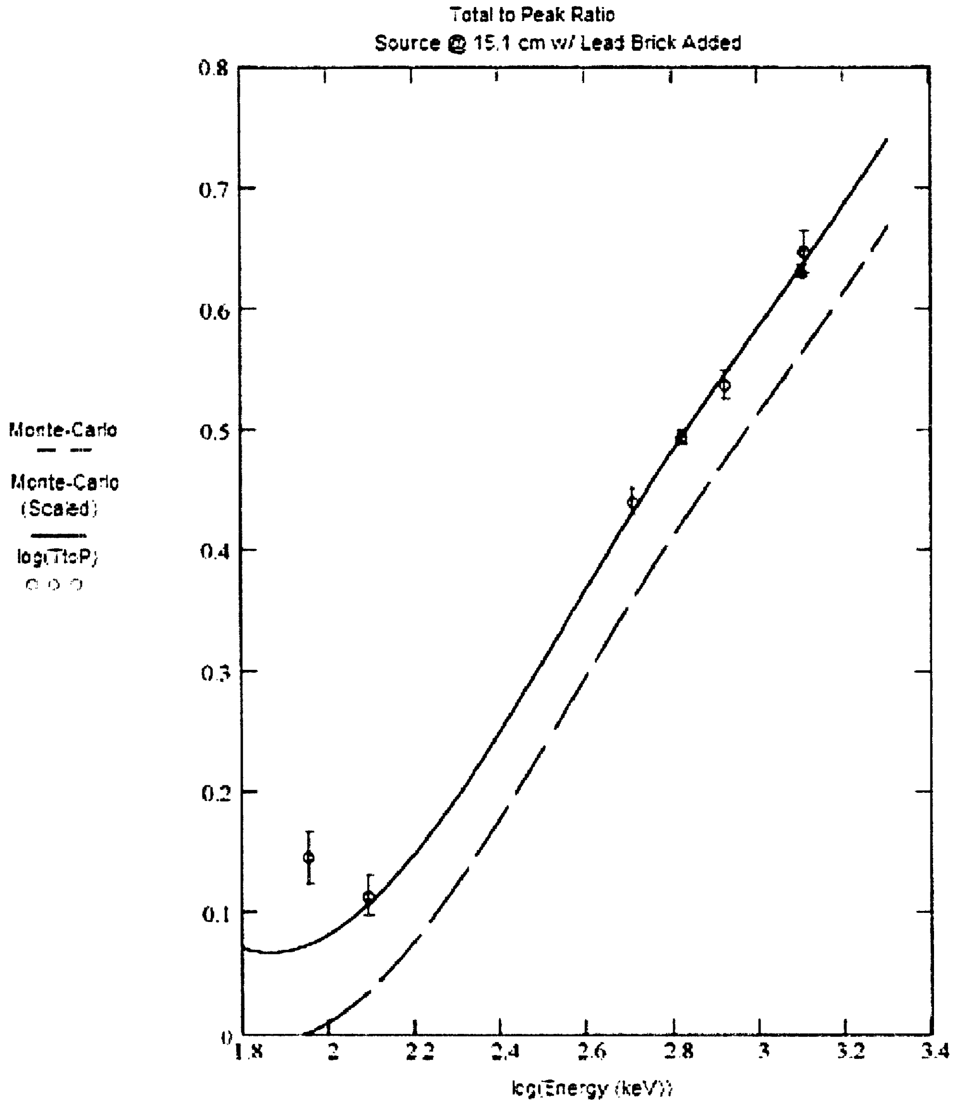

Figure 9: The Total-to-Peak ratios with a lead brick near the detector. There are often lead bricks near the Ge detector during certain experiments for shielding reasons.

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