Spectrum Determination and Modification of the AFRL Co-60 Cell

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Abstract

The spectrum of a Co-60 facility includes more than the two photopeaks of gamma ray emission. If there is a large low energy contribution from scattering, dose enhancement might be a problem. It is important to know the spectrum of a Co-60 facility and understand how experimental modifications can change that spectrum. The AFRL Co-60 cell spectrum is found to be a clean spectrum with small low energy contributions and dominant Co-60 photopeaks. Experimental modifications to reduce dose enhancement such as the use of a Pb/Al box and even better a Pb/Sn/Cu/Al box are found to be a clean spectrum with small low energy contributions. Some typical Co-60 facility spectra partially are found to slightly alter the spectrum, sometimes creating large low energy contributions.

I. INTRODUCTION

The AFRL Co-60 cell at Phillips Research Site, Kirtland Air Force Base, is a 1500 ft² concrete room with a 5200 Ci, as of 18 December 1996, J.L. Shepherd [1] Co-60 source. The source provides high dose rate ionizing radiation up to 12000 rad(Si)/min. The Co-60 cell is used to characterize total-dose gamma effects of microelectronic and photonic devices, circuits, and subsystems.

Co-60 decays with an emission of 1.17 and 1.33 MeV gamma rays. However, source encapsulation, facility support structures, shielding, and or collimation scatter the principal gamma rays. The resulting spectrum can have a significant low energy contribution. Some typical Co-60 facility spectra are given in reference [2]. This low energy contribution to the Co-60 spectrum can have an important effect on the device under test through dose enhancement [3].

Experimenter often harden the lower energy component of the spectrum through the use of a Pb/Al box, as an experimental setup shield, which can suppress the dose enhancement effects [4]. The dose enhancement inside the Pb/Al box was recently reported for the AFRL Co-60 cell and other facilities [5,6]. Experimenters may also soften the spectrum when trying to decrease the dose rate of a high dose rate irradiator. Hardness and softness are relative specifications of the quality or penetration power of radiation. In general, the lower the energy the softer the radiation.

This paper determines that the spectrum of the AFRL Co-60 cell has a small low energy contribution and is therefore a clean source. This spectrum is for a narrow geometry and will be used in transport calculations for specific setups that individual experimenters require. A narrow geometry was chosen as the basic starting point to expand on for possible experimental modifications. Specific experimental modifications are investigated that harden and soften the spectrum. For hardening, the Pb/Al box decreases the low energy contributions to the spectrum, but an alternative box eliminates these low energy contributions. For softening, use of lead attenuators in front of the source and raising the source height partially, while decreasing dose rate, can drastically distort the spectrum and are discouraged.

II. EXPERIMENTAL SETUP

A high resolution Canberra x-ray spectrometry system was used to measure a pulse-height distribution of differential energy deposition. In general, the differential energy deposition can be related to the energy spectrum. This system is made up of a cryogenically cooled, reverse-electrode, high-purity germanium (HPGe), 4.6 cm diameter, 3.45 cm thick, coaxial detector (GR1018), a high count-rate preamplifier, and a computer controlled multi-channel pulse-height analyzer. The detector has a FWHM energy resolution of 0.9 keV at 122 keV and 1.8 keV at 1.3 MeV and a useful energy range of 6 keV to 10 MeV.

The HPGe detector and cryostat were placed 7.5 m from the source; both surrounded by at least 20 cm of lead on all six sides. The collimation included a 0.5 mm radius hole through a 20 cm lead brick leading into a 12.5 cm brass collimator with a 2 mm radius hole leading to the detector face. The brass collimator fit into a lead sleeve that was made specifically for this detector and used in previous experiments. The collimation was aligned and uniformity checked with a small footprint laser.

A diagram of the experimental layout is given in Figure 1. The detector and collimators were aimed directly at the source (0 degrees), at the side wall (90 degrees), and at the back wall (180 degrees). The detector was 2 m from the back wall and

Figure 1: AFRL Co-60 cell and experimental setup.
4.5 m from the side wall. The setup was chosen so the direct measurement at 0 degrees gave an average dead time of 10%. A dead time of 10% is acceptable for spectrum measurements and will result in a distortion of only a few percent [7].

The integrity of the lead shielding around the detector was verified by placing 20 cm of lead in front of the 0.5 mm collimator hole. Measurements showed negligible counts, but these were still treated as background and subtracted from all measurements.

To study the effects of the Pb/Al box on the AFRL Co-60 spectrum, a section of the box was placed in front of the 0.5 mm collimator hole. This accurately represents the box for a narrow geometry because the other five sides are blocked by the lead shielding around the detector. The Pb/Al box for the AFRL Co-60 cell consists of 0.3175 cm of lead on the outside and 0.1588 cm of aluminum on the inside.

III. SPECTRUM DETERMINATION

Direct measurement of the AFRL Co-60 pulse-height distribution of differential energy deposition in the detector is possible, but this is not the actual spectrum. The response function, or influence on the true spectrum, of the experimental setup needs to be taken into account to obtain the spectrum from the pulse-height distribution.

A. Measured Pulse-Height Distribution

There are distinct characteristics of gamma ray measurements that are evident in the pulse-height distribution measured for the AFRL Co-60 cell. Some of these characteristics are due to the Co-60 source and surrounding material and others are due to the experimental setup.

Figure 2 shows pulse-height distributions for a direct measurement of the spectrum and for a measurement through the Pb/Al box. The numbers in the figures correspond to specific characteristics of gamma ray measurements [8]. Characteristics one through five are due to the experimental setup, while six and seven are due to the Co-60 source and surrounding material.

In Figure 2 the characteristics are: 1) characteristic x-ray photopeaks from surrounding materials, 2) photopeak from the backscatter of gamma rays from surrounding materials at 0.21 MeV, 3) Compton continuum from surrounding materials, 4) Compton edge from the 1.17 MeV Co-60 emission at 0.96 MeV, 5) Compton edge from the 1.33 MeV Co-60 emission at 1.12 MeV, 6) 1.17 MeV Co-60 photopeak, and 7) 1.33 MeV Co-60 photopeak.

The energy of a gamma ray that undergoes Compton scattering is given by,

$$E' = \frac{E}{1 + \left(\frac{E}{E_0}\right)(1 - \cos \theta)},$$  \hspace{1cm} (1)

where $E$ is the initial gamma ray energy, $E_0$ is the electron rest mass energy of 0.511 MeV, and $\theta$ is the scattering angle. The backscatter photopeak and the Compton edge locations can be calculated using equation 1 with $\theta$ equal to $\pi$. The backscatter photopeak is located at $E'$, while the Compton edge is located at $E - E'$ [8].

These characteristics due to the experimental setup (1-5) alter the true spectrum. To find the degree of alteration a response function can be calculated for the experimental setup.

B. Response Function

A response function was calculated for the experimental setup and then checked for accuracy with a calibration source. The experimental setup included the detector, the collimators, and the lead shielding around the detector. The model of the detector was taken from reference [9].

1) Calculation

The response function ($R$) relates the measured pulse-height distribution ($\Phi$) to the incident spectrum ($\Psi$). The relationship between these three quantities is:

$$\Phi = R \cdot \Psi \quad \text{or} \quad \Psi = R^{-1} \cdot \Phi.$$  \hspace{1cm} (2)

This equation represents a set of $n$ dimensional linear equations where the response function is the connection between the incident spectrum and the measured pulse-height distribution. The response function is a matrix containing the calculated pulse-height distributions for a known incident spectrum over the entire energy range of measurements. The key to this applied theory is determining the response matrix. The CYLTRAN code within the ITS Monte Carlo software package was used to calculate the response matrix [10]. The CYLTRAN code is a cylindrical geometry transport code that was run on a Windows based PC.

The calculated energy range was grouped into 0.05 MeV wide bins, resulting in 27 bins from 0 to 1.35 MeV. The number of Monte Carlo event histories for each initial energy bin was chosen to give a standard error of less than 10% per
bin. The average standard error per bin was 2.7% with a maximum of 8%.

A graphical representation of the response function is shown in Figure 3. This shows that the initial energy is spread from the maximum down to zero with a Compton edge and backscatter photopeak that follow equation 1. There is also a contribution from the characteristic x-ray photopeaks. The response along the diagonal shows that the experimental setup is more efficient at measuring lower energies.

2) Calibration

The results of the response function were verified using measurements of an 86.7 μCi, as of 1 July 1989, Co-60 calibration source. These measurements were obtained using the complete experimental setup of detector, collimators, and lead shielding around the detector. The binned pulse-height distribution and the spectrum (using equation 2 and the Mathcad® computer program) are shown in Figure 4.

The binned pulse-height distribution produced only low photopeaks at 1.17 and 1.33 MeV. However, incorporating the detector response matrix into the pulse-height distribution substantially enhanced both photopeaks.

The two photopeaks do not have an equal contribution. Their ratio to each other should be 1.0 instead of 0.9. This 10% difference is a result of the uncertainty associated with the response function. This uncertainty comes from the approximation of the model geometry, the energy resolution of the response, the standard error of the Monte Carlo process, and the 5% uncertainty in the cross section database of the CYLTRAN code. Therefore, taking all of these into account a 10% difference is acceptable.

The measurement uncertainty takes into account the counting statistics only and the measurement with response takes into account the counting statistics and the standard error from the Monte Carlo process only. Because these uncertainties for each bin did not exceed 0.3% of the total spectrum, the measurement and measurement with response uncertainties are not shown in Figures 4-7 and 9-11.

Figure 4 shows an alignment error that created a contribution of energies less than 100 keV. The alignment was accomplished by eye because the laser could not be used with the calibration source.

C. Direct Spectrum

Knowing that an accurate response function for the detection system had been produced, the pulse-height distribution of the AFRL Co-60 cell was then adjusted to give the spectrum. The measured pulse-height distribution is shown in Figure 2. The measured pulse-height distribution was put into 0.05 MeV bins and adjusted with the response function to obtain the spectrum. The binned pulse-height distribution and spectrum are shown in Figure 5.

The components that are in the spectrum are from the source and the source interaction with the cell. There are two high energy components that correspond to the 1.17 and 1.33 MeV Co-60 emissions. There is also a low energy
component that is not a result of the experimental setup. This low energy component centered at 225 keV is due to the supporting structures of the AFRL Co-60 cell setup, which has the Co-60 source rising out of a lead pig, all above ground.

An area of concern is that the spectrum has slightly negative values. This is a nonphysical result of the uncertainty associated with the response function. The negativities are extremely small, on the order of 1E-3, and can be regarded as zero. Therefore, the spectrum of the AFRL Co-60 cell that will be used in transport calculations is given in Table 1.

D. Scattered Spectrum

The next step in investigating the AFRL Co-60 cell spectrum is to look at scattered spectra from the cell walls. To accomplish this, the experimental setup was turned to face 90 and 180 degrees as shown in Figure 1.

The results of these measurements show that the scattering off the walls is insignificant compared to the radiation from the direction of the source. The number fluence from the 90 degree measurement was 0.01% and the 180 degree measurement was 0.001% of the contribution from the source direction. The 180 degree measurement may be slightly low because the experimental setup blocked some radiation from getting to the wall. Because of these extremely low numbers, the scattering off the walls can be ignored for high dose rate exposures near the source.

<table>
<thead>
<tr>
<th>Range (MeV)</th>
<th>Direct (Number Fraction)</th>
<th>With Pb/Al Box (Number Fraction)</th>
</tr>
</thead>
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<tr>
<td>1.35-1.30</td>
<td>0.0146</td>
<td>0.0126</td>
</tr>
<tr>
<td>1.30-1.25</td>
<td>0.0214</td>
<td>0.0203</td>
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<tr>
<td>1.25-1.20</td>
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<td>1.20-1.15</td>
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<td>0.0504</td>
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<td>1.15-1.10</td>
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<tr>
<td>1.05-1.00</td>
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<td>0.0242</td>
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<tr>
<td>1.00-0.95</td>
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It is important to note that the radiation coming from directions other than the source can be ignored in the case of all directions being shielded equally. If shielding is placed only in the direction of the source, then the radiation from the source might be reduced enough to make radiation from the other directions significant.

E. Spectra Comparison

With the AFRL Co-60 cell spectra determined it is possible to compare it to other facility spectra. The other facility spectra were taken from reference [2] and were chosen for various reasons. The Gammacell-220 was chosen as a commonly used spectrum. The National Bureau of Standards (NBS) teletherapy source was chosen to show the optimum facility. Spectra comparison of the AFRL Co-60 cell to the Gammacell-220 is shown in Figure 6 and to the NBS teletherapy source in Figure 7.

Comparing the spectra, the Gammacell-220 has the greatest low energy contribution. The NBS teletherapy source, which is used to calibrate instruments, has the smallest...
low energy contribution. The AFRL Co-60 cell is close to the NBS at the low energies, but does not have as large a contribution from the two high energy photopeaks. Therefore, the AFRL Co-60 cell spectrum can be considered a clean spectrum. The contribution from the low energy is present but small, and the high energy photopeak radiation is dominant.

IV. SPECTRUM MODIFICATION

Experimenters sometimes make modifications that can harden or soften the spectrum. Hardening may decrease dose enhancement effects, while softening may increase these effects. To model modifications that were not experimentally measured, verification of a transport code for the AFRL Co-60 cell spectrum is needed.

A. Transport Code Verification

Verification of the transport code for the AFRL Co-60 spectrum is relatively straightforward as shown in Figure 8. The steps for verifying the transport code involved measuring the AFRL Co-60 pulse-height distribution inside (ΩPb/Al) and outside (Ω) the Pb/Al box. The measured pulse-height distribution was then adjusted for the response (R) of the detector to get the spectrum inside (ΩPb/Al) and outside (Ω) the Pb/Al box. Next, the direct spectrum outside the box was used as input for a transport calculation through the box to get the calculated spectrum inside the box (ΩPb/Al). Finally, the calculated spectrum inside the box was compared to the spectrum inside the box.

The CEPXS/ONELD code was used to calculate the AFRL Co-60 spectrum inside the Pb/Al box. The CEPXS/ONELD code [11,12] is a discrete ordinates code package for solving one-dimensional coupled electron-photon transport down to 1 keV. It was run on an IBM RISC 6000 UNIX workstation. This code was chosen because of the one-dimensional geometry of the problem.

The direct spectrum, given in Table 1, was used as input to CEPXS/ONELD to calculate the spectrum through the box. The spectrum and the calculated spectrum (all inside the box) are compared in Figure 9.

The CEPXS/ONELD calculations show excellent agreement with the spectrum. The difference between the two is within the expected uncertainty. This check shows that CEPXS/ONELD is an acceptable program to simulate the AFRL Co-60 spectrum through materials in one dimension.

B. Hardening

Two methods are investigated to harden the spectrum. The Pb/Al box is the standard method while the alternative box is a new method.

1) Pb/Al Box

Measurements of the AFRL Co-60 pulse-height distributions were made inside and outside the Pb/Al box. These results are shown in Figure 2. The response function of the detector was applied to the measured pulse-height distribution inside the Pb/Al box to give a spectrum.

This spectrum again has results that are slightly negative. The negativities are extremely small, on the order of 1E-3, and within the response uncertainty so they are set to zero. The spectrum results are given in Table 1 and a graphical representation given in Figure 10.
The Pb/Al box has the effect of reducing the low energy contribution below 400 keV. This places more of a contribution to the spectrum on the higher energy photopeaks of interest. The Pb/Al box does not completely reduce the low energy component around 225 keV and could be improved.

2) Alternative Box

An alternative box has been proposed to replace the Pb/Al box [13]. This box would consist of 5 mm of Pb, outside 0.76 mm of Sn, outside 0.25 mm of Cu, outside an optional 0.25 mm of Al. A multilayered arrangement like this is good at reducing the low energy components of a spectrum. This is because the outside high atomic number material reduces the low energy radiation but creates lower energy characteristic x-ray photopeaks. These lower energy photopeaks in turn are stopped by the next material, which creates lower energy characteristic x-ray photopeaks. The next material stops these even lower energy photopeaks and so on until the characteristic x-ray photopeaks are low enough to ignore.

The AFRL Co-60 cell spectrum was used as input to the CEPXS/ONELD code along with this Pb/Sn/Cu/Al box arrangement. The results are shown in Figure 10. This Pb/Sn/Cu/Al box greatly reduces the low energy contribution to the spectrum, however there is not as much contribution from the two photopeaks as with the Pb/Al box.

Note that the Pb/Al box reduces the number fluence by 19% while the Pb/Sn/Cu/Al box reduces it by 44%, thereby changing the dose rate. Calculations were also done without the optional Al at the innermost layer. The differences between the arrangement with and without the Al were insignificant with respect to both spectrum and number fluence for the AFRL Co-60 cell and at 50 keV energy resolution. When the energy resolution is finer, the 8 keV Cu fluorescence line is visible and the Al will reduce it. The importance of the 8 keV line depends on the experimental device sensitivity.

C. Softening

Two methods that experimenters use to decrease the dose rate also soften the spectrum. The first is using lead attenuators in front of the experiment and the second is not raising the source completely.

1) Lead Attenuators

The use of lead attenuators in front of the experiment to decrease dose rate can seriously alter the spectrum. The CEPXS/ONELD code was used to model the transport of the AFRL Co-60 spectrum through a typical 2" (5.08 cm) lead brick. The resulting spectrum is shown in Figure 11.

The introduction of the lead causes the contribution of the photopeaks to decrease and scatters much of the radiation to the middle energies. This does take out the low energy photopeak but it is only shifted to the middle energies. When multiple bricks are used, the spectrum alteration is even more drastic. One, two, or three bricks decrease the number fluence by 95%, 99.8%, or ~100%, respectively. This reduction in number fluence can cause the scattered cell spectra to become significant. Therefore the method of placing lead bricks in front of the experiment is discouraged. If this is the only method available, use of the Pb/Sn/Cu/Al box in addition to the lead attenuators is recommended.

2) Partial Source Height

An alternative method for reducing the dose rate of an experiment is to raise the source out of the lead pig partially. A measurement was taken with the AFRL Co-60 source raised to 60%. The resulting spectrum is shown in Figure 11.

The resulting spectrum is completely composed of low energy scattered radiation. With the source raised partially, much of the source is still within the lead pig and undergoes a great deal of scattering through the lead and supporting structures. Therefore, this method of raising the source partially is highly discouraged.

V. CONCLUSIONS

The spectrum determination of the AFRL Co-60 cell has been accomplished for narrow geometry through measurement and transport calculations. Scattering from the walls of the AFRL Co-60 cell was shown to be negligible for high dose rate exposures so the spectrum from the direction of the source only need be considered. This spectrum is shown to have small low energy contributions and can therefore be considered relatively clean.

Investigating modifications to the spectrum that experimenters do to either reduce dose enhancement effects or to decrease dose rate found the spectrum can be significantly hardened or softened. The standard practice of using a Pb/Al box does a good job of decreasing low energy contributions, but the use of a Pb/Sn/Cu/Al box does a better job. The use of lead attenuators in front of an experiment and/or raising a source partially can decrease dose rate, but can also modify the spectrum significantly and are therefore discouraged.

Future work in this area will be to develop a more accurate response function for the experimental setup. The uncertainty due to the number of event histories was small so the problem

![Figure 11: Comparison of the AFRL Co-60 cell spectrum without modification, with lead bricks, and using partial source height.](image)
lies in the model and the inherent 5% uncertainty in the cross section database of the CYLTRAN code. Alternatives like a more detailed model and using a set of calibration sources can be investigated. Improvements to the response function should also investigate the count rate effect of a 10% dead time.

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