Photon Mass Attenuation Coefficients of Importance to Dosimetry

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Summary

For Medical imaging and radiation therapy applications photon, of energies less than 1.3 MeV, are commonly utilized. The importance of the data of attenuation coefficients for this energy range cannot be overemphasized. In the past, there were many measurements made using multiple sources and low-resolution scintillation detectors. The XCOM database from NIST, based on detailed model calculations, is the most commonly used reference. Our goal is to provide an experimental verification of the database and compare with the earlier measurements for photon energies of interest for medical and environmental considerations. Here, we report our first measurements with water.

1. Introduction

Current and past research into the property of mass attenuation coefficients has, to date, been driven predominantly by models, with support from experimentation. In the fields of diagnostic and treatment medicines the importance of accurate values for common elements and components cannot be stressed strongly enough. It is therefore the intention of this project to explore the most common constituent elements of the human body with respect to mass attenuation to determine accurate, usable values for the industry.

The specific region of interest for this project is 40 keV to 1.4 MeV. This range covers both the region of interest for current medical diagnostic and treatment techniques; along with a significant region of interest to the nuclear materiel science community in general.

The linear attenuation coefficient [μ] [units of inverse distance] is the property of a material that describes the probability of a photon interacting with it. The a common form of which is

$$\frac{I(t)}{I_0} = e^{-\mu t} \qquad (1)$$

So for a given thickness, t, of a material, say lead, the value μ will describe what ratio of photons that will pass through the block of lead unimpeded with respect to the number incident. μ is dependent on the energy of the photon, so different energies will have different linear attenuation coefficients. In general, as the energy rises, μ decreases.

Using μ for comparison is problematic. There is no way to adjust μ to account for varying densities. Densities can vary based on a number of factors including construction technique or temperature.

Thus the density corrected value (μ/ρ) is more commonly used since this value is a property of only the element or molecule of interest.

$$\frac{I(t)}{I_0} = e^{-\left(\frac{\mu}{\rho}\right)\rho t} \tag{2}$$

where the mass attenuation coefficient, (μ/ρ), a single value, is reported, and ρ is the density of the material used for the measurement. Since (μ/ρ) is the most suitable form for comparison, that is the form that this paper will rely upon. (μ/ρ) is the result of a photon either being absorbed or deflected by a material. As such it is directly related to the total cross section, σ.

$$\left(\frac{\mu}{\rho}\right) = \frac{\sigma N_a}{m_a} \tag{3}$$

Where N_a is Avogadro's number and m_a is the atomic molar mass.

2. XCOM

XCOM is the heavily relied upon calculation database for mass attenuation coefficients, from which the values are calculated using equations from Scofield.[1] The equations were originally fixed to observations by normalization with experimental data from before 1970 over the energy range 1 keV to 10 MeV[2]. This means that XCOM is a model based database, and thus susceptible to the models' assumptions. The primary assumption would be how the photoelectric effect's contribution changes about the binding energies of the electrons. The other assumption is which regions each photon-electron interaction is dominant with respect to the energy of the photons and the number of electrons. While the trends may be predictable, relatively fine structure may appear in experimentation that is not predicted by theory which would be important for applications. These regions of uncertainty overlap the regions currently used by medical applications, 40 keV to 1300 keV. [3, Section 27.4].

The data collection methods used up through the 1970's sodium iodide detectors coupled to single channel analyzers and scalars.[4] Sodium iodide detectors are, at best, of a far lower resolution then current standard HPGe detectors. The current multichannel analyzers allow for concurrent data collection of what would have been done in series in the 1970's, thus many sources of systematic and random error are reduced or removed from the data analysis. The lower resolution and longer data collection periods also required sophisticated curve separation techniques for photon energies that would produce overlapping signals. This can be avoided by using high resolution detectors and carefully selecting sources to prevent overlap.

The XCOM database not only contains element mass attenuation values, but also contains the values for compounds and mixtures. Mixtures are calculated by where $(\mu/\rho)_i$ is the mass attenuation coefficient of component *i*, and w_i is the relative mass contribution of element *i*.[5]

$$\left(\frac{\mu}{\rho}\right) = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i \tag{4}$$

For example, if a mechanical mixture of copper (40 %) and aluminum (60 %) then the equation would be

$$\left(\frac{\mu}{\rho}\right)_{CuAl} = 0.4\left(\frac{\mu}{\rho}\right)_{Cu} + 0.6\left(\frac{\mu}{\rho}\right)_{Al} \quad (5)$$

According to the maintainers of XCOM (4) also applies to molecules, however this is an since it relies on the truthfulness of Bragg's Additive Law, papers have shown that this law does not always hold true and as such needs to be tested for the region of interest of this experiment [6]

3. Method

The detector used was a Ortec electrically cooled GEM series High Purity Germanium gamma detector [HPGe], and mounted using the manufacturer's accompanying clamp. Sources used were ^{152}Eu, ^{133}Ba, ^{137}Cs, and ^{241}Am to have the broadest spectrum with a resolution at 1408 keV of 4 keV.

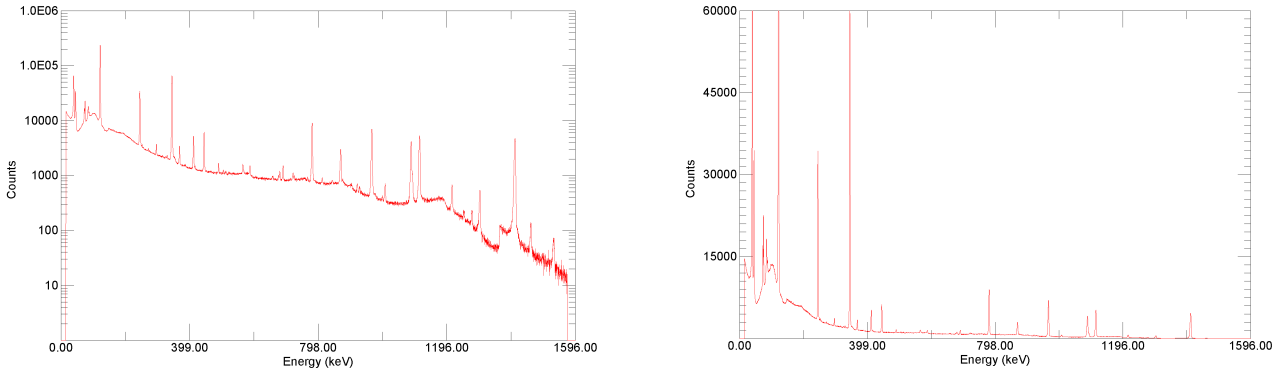

Figure 1: Europium-152 spectra shown both in log and linear intensity

Figure 1 shows the Europium photon energy spectrum, in both logarithmic (right) and linear (left) intensity scaling. From the log scale clear separation can be seen between two emission lines (1085 keV and 1112 keV) illustrating the high resolving power of this detector. The linear plot shows the large signal to noise ratio and narrow peak shape. These features allow for fast high precision measurements of count rates for each energy emission from each source without the need for peak separation techniques.

To measure the mass attenuation coefficient of water, the detector was mounted in a vertical configuration with the absorber contained in a beaker between the sources and the detector, as seen in Figure 2. High precision mass measurements and the geometry of the beaker are used to calculate the thickness of the water. This beaker has uniform walls (less than 2 % variance) to allow for a vertical resolution of thickness to better than 0.1 mm. The base below the beaker ensures that the geometry of the experiment does not change

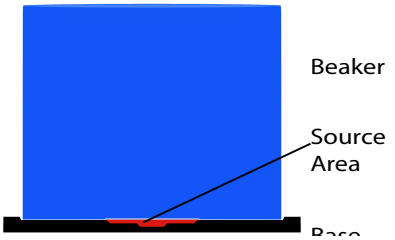

Figure 2: Layout of detector and source mount for vertical configuration of data collection

as the beaker is removed and replaced with greater amounts of water. To hold the sources the base has a recess at its center designed for standard source pucks of 1 and 2 inch diameters. The environmental temperature was held constant at 24.0 ± 0.2°C and the corresponding density correction for water was 0.9973 $^{g}/_{cm^3}$

With the detector and empty beaker in position, background measurements were recorded. Liquid was then added by mass to the beaker. At least 15 separate mass measurements were made for each of the four sources. Knowing the radius of the beaker (9.84 ± 0.05 cm) and temperature, the thickness of the water was calculated. The range of thicknesses measured was between 0.425 ± 0.005 cm and 10.4 ± 0.1 cm. For each source a time was chosen such that the net activity of the smallest peak of interest was over 40,000 counts. For the detector and sources used this ranged between 10 and 15 minutes per measurement. Each peak's net area was calculated as the total counts within the full width-half maximum area, subtracting background. The resultant total counts, corresponding directly to intensity, for each of the energies were plotted in a log plot and the slope (μ) and temperature were used to calculate (μ/ρ). Figure 3 shows the resultant plot for two energies, 1408 keV and 40 keV.

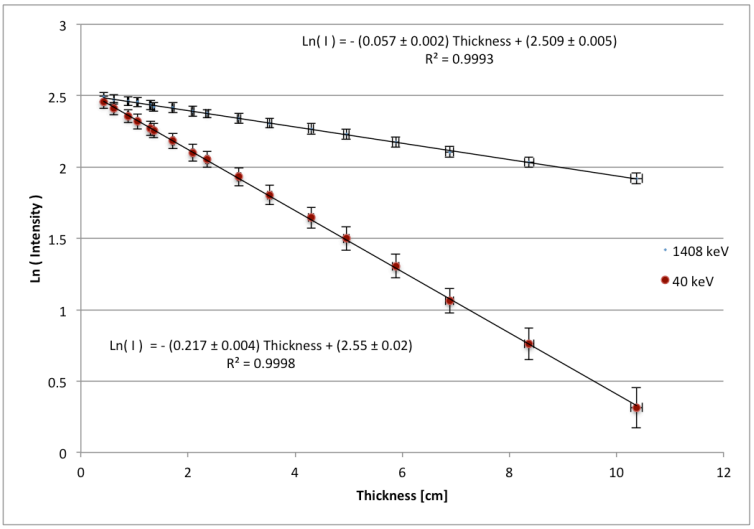

Figure 3: Log of Intensity versus thickness for 40 and 1408 keV ^{152}Eu peaks

By changing only the mass of the water and maintaining all other variables and experimental parameters static, this setup greatly reduced the effect of potential sources of systematic error. The distance between the detector and the source, combined with the detector's active area meant that the acceptance angle for the detector from the source was less than 5°. This small acceptance angle ensured that there were no additional parallax corrections to the thickness of the water in the beaker. Such reductions in potential error sources allowed for the relative error of measured values to be at worst 2%.

4. Results

The measured mass attenuation coefficients, along with their comparisons to corresponding XCOM values are presented in Figure 4. A positive % difference indicates the experimental result is larger than XCOM, while negative indicates XCOM is larger than the experimental result.

Photon Energy [keV]	Mass Attenuation Coefficient $\mu/\rho[cm^2/g]$	% Difference from XCOM
40	0.217 ± 0.004	-23.8
122	0.152 ± 0.003	-5.3
245	0.123 ± 0.002	-3.5
344	0.109 ± 0.002	-3.3
444	0.103 ± 0.004	1.1
964	0.069 ± 0.002	-3.9
1112	0.064 ± 0.002	-4.1
1408	0.057 ± 0.002	-4.0

Figure 4: ass attenuation coefficient of water for various photon energies between 40 keV and 1408 keV, with corresponding percent deviation from XCOM

5. Conclusions

The current go-to database for photon mass attenuation coefficients, XCOM disagrees with experimental data for water, with deviations beyond 20 %. In light of this, similar measurements for materials of interest in the medical community are in progress. Also as seen in charged particle interactions, Bragg's additive law isn't universally valid, similar tests for photons in the range of interest are also in progress.

6. References

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