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by

C.M. Frankle and C.E. Moss

ABSTRACT

We have used a 150 MBq ^{56}Co source to perform gamma-ray total absorption cross section measurements with very high precision. The use of ^{56}Co allowed us to simultaneously measure the total cross section at 15 energies ranging from 0.847 MeV to 3.451 MeV. Seven sample materials were measured: Be, C, Cu, Ta, W, Pb, and U. In general, the measurement precision is better than 0.5% and in all cases better than 1.3%.

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1. INTRODUCTION

The accurate knowledge of the gamma-ray total cross sections is important for almost any application where gamma rays are used as a tool, whether it be radiography, medical treatments, gauging, etc. Equally as important is the need for the same accurate data when gamma-ray shielding is to be designed [Hu68]. Over the years many compendia of calculated values have been published; see for example References [Hu69, MM69, St70, Pl81, and Hu82]. Few high-precision experiments have been published in this energy range [Co70]. Variations between the different compendia typically run in the range of two to three percent in the MeV energy range. It is generally acknowledged that this represents the best the current theoretical models are capable of.

It is well known that the narrow beam transmission of gamma rays follows the simple relation

$$I = I_0 e^{-n\sigma}, \tag{1}$$

where I_0 is the incident intensity, I is the transmitted intensity, n is the target thickness in at/b, and σ is the total cross section. In certain applications where quantitative information on the thickness of a material measured by gamma-ray absorption is desired, the current level of accuracy in the published cross section compilations is insufficient. In particular if the material to be measured is many path lengths thick, then small variations in the cross section are amplified through the exponential behavior (Eq. [1]) of the absorption to give large differences in the transmission. It was therefore our objective to measure the total cross sections to a precision of ~0.5% in order to improve the ability to make quantitative material-thickness measurements.

2. EXPERIMENTAL PROCEDURES

The use of ^{56}Co as a source of gamma rays for gamma-ray total absorption cross-section measurements is very attractive from a number of standpoints. There are a wide variety of

gamma-ray energies emitted, ranging from 0.26 MeV to 3.61 MeV, though many are too weak to be useful. However, the 3.451 MeV is of satisfactory strength and provides an end-point energy significantly higher than 2.754 MeV ^{24}Na line [Co70] that has been a typical end point in the past. In addition, the half-life of ^{56}Co is 77 days, which allows one to transport and use it in a reasonable way, unlike some other sources that would otherwise be attractive, such as ^{66}Ga. The emitted gamma rays used in this experiment are shown in Table I.

Table I. Prominent Gamma Rays from ^{56}Co Used in this Experiment ([Ju99])

E_γ (keV)	I_γ (%)
846.771	99.935
977.373	1.449
1,037.84	14.17
1,238.282	66.9
1,360.215	4.29
1,771.351	15.47
2,015.181	3.04
2,034.755	7.89
2,598.459	17.3
3,009.596	1.16
3,201.962	3.32
3,253.416	8.12
3,272.99	1.93
3,451.152	0.972

In concept, the measurement of the gamma-ray total cross section involves a "sample-in/sample-out" process. The "sample-out" case is the measurement of the beam intensity without a sample, corresponding to I_0 of Eq. (1). The "sample-in" case is the measurement of the beam intensity with a sample of known thickness n in place, corresponding to I in Eq. (1). Then by simple rearrangement of Eq. (1) into the form

$$\sigma = -\frac{1}{n}\ln\left(\frac{I}{I_0}\right) , \qquad (2)$$

the cross section σ is obtained. The source was placed inside of a lead and tungsten box with a tungsten collimator to form a 0.51-cm-diameter beam. The active diameter of the source material is 0.53 cm. The beam then passes through a mechanical sample holder/changer that contains the four sample thicknesses, plus a blank. Each of the four sample positions is moved into the beam for one minute at a time, with a complete cycle of all four positions taking just over five minutes with various overheads. The detector used was a nominal 100% relative efficiency high-purity germanium (HPGe) detector. The samples were run for between two and seven days each, in order to accumulate the statistics necessary to allow the cross section to be measured at the 0.5%

level at the 3.451 MeV line. For ease of storage, handling, and analysis, the data were accumulated into "runs" of approximately one day each, and the data was then analyzed on a run-by-run basis.

The process of acquiring data was fully automated under computer control. The computer was first linked through RS232 to an industrial single-axis linear motor. The motor has a position reproducability of better than 0.001 cm. Once the feedback from the linear motor indicated that it was in the proper position, the computer then started a one-minute acquisition of data using an ORTEC DSPEC plus a multichannel analyzer (MCA). The sequence of sample changes was one-half path length, four path lengths, blank, two path lengths, one path length, and repeat. The MCA was set to acquire data in 16,384 channels with a nominal gain of 0.32 keV per channel. The resolution of the detector and MCA system was about 2.3 keV FWHM at 1,332 keV.

All of the samples were machined right circular cylinders with a 2.54-cm diameter. Except for the Be and C samples, four lengths were fabricated for each material corresponding to approximately one-half, one, two, and four path lengths at 3.45 MeV. Because of the fact of the low Z and low density of Be and C, the thickest samples would have been excessively long; therefore, two samples were fabricated of Be, corresponding to one-half and one path length for the Be, and three samples were fabricated of the C, corresponding to one-half, one, and two path lengths. All sample material was of 99.99% or better chemical purity. The measured length and density of each sample is given in The uranium samples are depleted uranium, containing a nominal 0.21% ^{235}U.

Table II. Physical Data of the Samples

Sample	Length (cm)	Density (g/cm^3)	Thickness (at/b)
Be-1	12.802 ± 0.003	1.8485 ± 0.0006	1.5815 ± 0.0006
Be-2	25.644 ± 0.004	1.8486 ± 0.0006	3.1628 ± 0.0008
C-1	7.653 ± 0.003	1.835 ± 0.009	0.704 ± 0.004
C-2	15.288 ± 0.003	1.844 ± 0.009	1.414 ± 0.007
C-3	30.81 ± 0.03	1.840 ± 0.009	2.843 ± 0.014
Cu-1	1.793 ± 0.003	8.93 ± 0.02	0.1517 ± 0.0005
Cu-2	3.584 ± 0.003	8.93 ± 0.02	0.3034 ± 0.0007
Cu-3	7.178 ± 0.003	8.935 ± 0.018	0.6079 ± 0.0013
Cu-4	14.351 ± 0.003	8.936 ± 0.018	1.216 ± 0.003
Ta-1	0.6741 ± 0.0005	16.63 ± 0.13	0.0373 ± 0.0003
Ta-2	1.4430 ± 0.0005	16.66 ± 0.06	0.0800 ± 0.0003
Ta-3	2.8791 ± 0.0013	16.68 ± 0.03	0.1598 ± 0.0003
Ta-4	5.7645 ± 0.0013	16.672 ± 0.016	0.3199 ± 0.0003

Table II. Physical Data of the Samples (continued)

W-1	0.6129 ± 0.0005	19.18 ± 0.17	0.0385 ±0.0003
W-2	1.2365 ± 0.0005	19.15 ± 0.09	0.0776 ± 0.0004
W-3	2.4684 ± 0.0005	19.19 ± 0.04	0.1552 ± 0.0003
W-4	4.9416 ± 0.0013	19.19 ± 0.02	0.3107 ± 0.0003
Pb-1	1.0058 ± 0.0003	11.35 ± 0.06	0.0332 ± 0.0002
Pb-2	2.0104 ± 0.0003	11.34 ± 0.03	0.0663 ± 0.0002
Pb-3	4.0229 ± 0.0005	11.339 ± 0.015	0.1326 ± 0.0002
Pb-4	8.0462 ± 0.0010	11.342 ± 0.008	0.2653 ± 0.0002
U-1	0.650 ± 0.004	19.08 ± 0.16	0.0314 ± 0.0003
U-2	1.270 ± 0.004	19.07 ± 0.08	0.0613 ± 0.0003
U-3	2.535 ± 0.004	19.04 ± 0.04	0.1221 ± 0.0003
U-4	5.088 ± 0.008	19.03 ± 0.02	0.2450 ± 0.0005

3. RESULTS

For each of the approximately day-long runs discussed above, the spectral data from each sample movement cycle was stored individually. Upon completion of a run, the data from the approximately 250 cycles were summed for each of the sample positions, leaving five spectra to be fitted. Fitting of the known ^{56}Co gamma-ray peaks in the spectra was performed using ORTEC's GammaVision software. For each peak in each spectrum, a net area was computed, along with an error containing both statistical and fitting components. Each peak area was then divided by the live time recorded by the DSPECplus for that spectrum to obtain a true count rate for that peak. This then allowed a simple transmission to be computed for each gamma-ray line by dividing the count rate for each sample by the count rate for the blank, along with an error for each. The cross section was then computed using Equation 2. An overall cross section for each run was then computed by taking the weighted average of the cross sections for all the sample thicknesses. Finally, a weighted average was taken across all of the runs to obtain an overall value for the cross section. In addition, a weighted average cross section was computed across each sample thickness to examine for possible systematic deviation from the overall computed cross section.

A correction was applied for the elastically scattered gamma rays that reached the detector. This correction was applied individually for each target thickness. The maximum number of elastically scattered gamma rays reaching the detector occurs at the highest Z and lowest energy. Therefore, the worst case for our experiment was uranium at 847 keV. The correction applied for this case was ~0.1%, with all others being less. Results for the seven sample materials are shown in Tables III-IX. It should be noted that the tables give the total cross section, which include both atomic and nuclear components. In evaluated data only the atomic components are normally given. In this energy range the nuclear component is insignificant, except in the case of Be where it is of order ~1 mb.

Table III. Measured Gamma-Ray Total Absorption Cross Sections for Be

E_γ (MeV)	σ (b)
0.847	0.9146 ± 0.0007
0.977	0.861 ± 0.003
1.038	0.826 ± 0.002
1.238	0.7586 ± 0.0014
1.360	0.721 ± 0.002
1.771	0.6292 ± 0.0012
2.015	0.5834 ± 0.0012
2.035	0.5824 ± 0.0007
2.598	0.5086 ± 0.0005
3.010	0.460 ± 0.009
3.202	0.4529 ±0.0008
3.254	0.4489 ± 0.0006
3.273	0.4451 ± 0.0010
3.451	0.4336 ± 0.0013

Table IV. Measured Gamma-Ray Total Absorption Cross Sections for C

E_γ (MeV)	σ (b)
0.847	1.358 ± 0.004
0.977	1.273 ± 0.010
1.038	1.238 ± 0.004
1.238	1.125 ± 0.003
1.360	1.076 ± 0.004
1.771	0.941 ± 0.003
2.015	0.871 ± 0.005
2.035	0.866 ± 0.003
2.598	0.766 ± 0.002
3.010	0.709 ± 0.009
3.202	0.679 ± 0.003
3.254	0.676 ± 0.002
3.273	0.670 ± 0.004
3.451	0.656 ± 0.003

Table V. Measured Gamma-Ray Total Absorption Cross Sections for Cu

E_γ (MeV)	σ (b)
0.847	6.751 ± 0.010
0.977	6.26 ± 0.05
1.038	6.093 ± 0.015
1.238	5.536 ± 0.008
1.360	5.27 ± 0.02
1.771	4.672 ± 0.008
2.015	4.41 ± 0.03
2.035	4.383 ± 0.013
2.598	3.989 ± 0.007
3.010	3.77 ± 0.04
3.202	3.705 ± 0.016
3.254	3.692 ± 0.009
3.273	3.682 ± 0.018
3.451	3.64 ± 0.02

Table VI. Measured Gamma-Ray Total Absorption Cross Sections for Ta

E_γ (MeV)	σ (b)
0.847	22.243 ± 0.019
0.977	19.51 ± 0.12
1.038	18.68 ± 0.03
1.238	16.453 ± 0.014
1.360	15.56 ± 0.04
1.771	13.801 ±0.016
2.015	13.01 ± 0.04
2.035	13.00 ± 0.02
2.598	12.282 ± 0.015
3.010	11.92 ± 0.11
3.202	11.95 ± 0.04
3.254	11.986 ± 0.017
3.273	11.97 ± 0.05
3.451	11.96 ± 0.05

Table VII. Measured Gamma-Ray Total Absorption Cross Sections for W

E_γ (MeV)	σ (b)
0.847	22.66 ± 0.02
0.977	19.96 ± 0.15
1.038	19.08 ±0.03
1.238	16.717 ± 0.016
1.360	15.88 ±0.05
1.771	13.845 ± 0.019
2.015	13.17 ± 0.05
2.035	13.19 ± 0.03
2.598	12.516 ± 0.018
3.010	12.17 ± 0.15
3.202	12.12 ± 0.04
3.254	12.18 ± 0.02
3.273	12.20 ± 0.05
3.451	12.19 ± 0.05

Table VIII. Measured Gamma-Ray Total Absorption Cross Sections for Pb

E_γ (MeV)	σ (b)
0.847	27.926 ± 0.016
0.977	24.26 ± 0.12
1.038	22.94 ± 0.03
1.238	19.828 ± 0.011
1.360	18.62 ± 0.04
1.771	16.371 ± 0.014
2.015	15.47 ± 0.04
2.035	15.45 ± 0.02
2.598	14.605 ± 0.014
3.010	14.42 ± 0.11
3.202	14.289 ± 0.016
3.254	14.308 ± 0.019
3.273	14.33 ± 0.03
3.451	14.33 ± 0.04

Table IX. Measured Gamma-Ray Total Absorption Cross Sections for U

E_γ (MeV)	σ (b)
0.847	36.35 ± 0.03
0.977	31.1 ± 0.3
1.038	29.13 ± 0.05
1.238	24.68 ± 0.02
1.360	23.04 ± 0.05
1.771	19.83 ± 0.02
2.015	18.72 ± 0.05
2.035	18.76 ± 0.03
2.598	17.649 ± 0.019
3.010	17.36 ± 0.15
3.202	17.24 ± 0.05
3.254	17.21 ± 0.03
3.273	17.17 ± 0.05
3.451	17.16 ± 0.10

4. DISCUSSION

We have compared our data with the experimental results of Conner et al. [Co70]. Although different sources were used between Conner et al. and ourselves, the energy range spanned was similar. We find that if a smooth curve is drawn though our data as an eye guide, then in general the data of Conner et al. also lie upon the curve. See, for example, data for tungsten in Figure 1. In addition to comparing to the aforementioned experiment we also compared our data with three evaluations, the current NIST evaluation, as posted on XCOM [Hu95], and the EPDL-78 [Pl81] and EPDL-97 [Cu97] evaluations. In our comparisons, differences between the lighter elements (Be, C, and Cu) and the heavier elements (Ta, W, Pb, and U) became apparent.

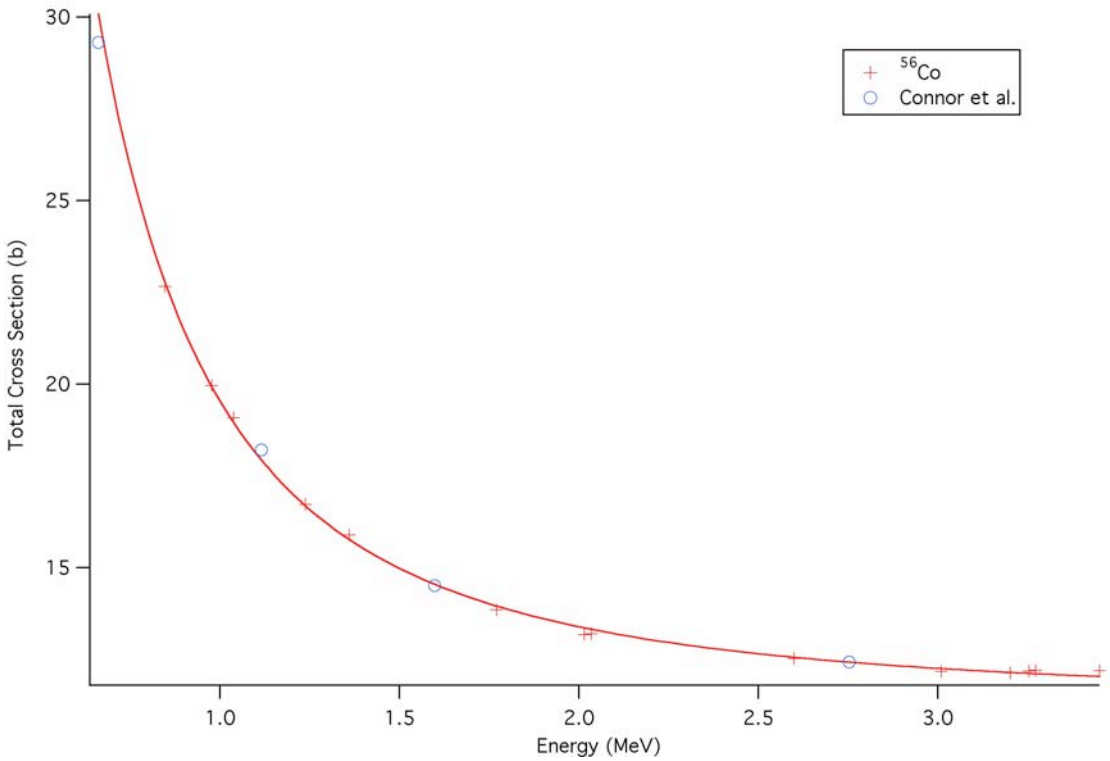

Figure 1. Comparison of current data on W with that of Conner et al.

For the lighter elements, all three evaluations are quite similar, with differences between any of them on the order ~0.3% or less. The data are essentially always slightly below the evaluations. In the case of Be, the differences are quite small, usually less than ~0.3%. For both C and Cu the differences are somewhat larger, but still usually less than 0.5% and never more than 1%.

For the heavier elements, the National Institutes of Standards and Technology (NIST) and EPDL-97 evaluations are fairly similar, differing typically by less than ~0.5%. The EPDL-78 evaluation is systematically lower than both the NIST and EPDL-97 evaluations by ~1%–2% in this energy range. The difference between them is greater at lower energies. Our data, and that of Conner et al., is systematically lower than all three evaluations, by ~2%–3% lower than NIST and EPDL-97 and ~1% lower than EPDL-78 at low energies. A comparison of our data, the data of Conner et al., and the three evaluations for tungsten is shown in Figure 2. Our data agree quite well with EPDL-78 in the ~3 MeV region. The trend in differences between the data and all the evaluations is to be greater at lower energies.

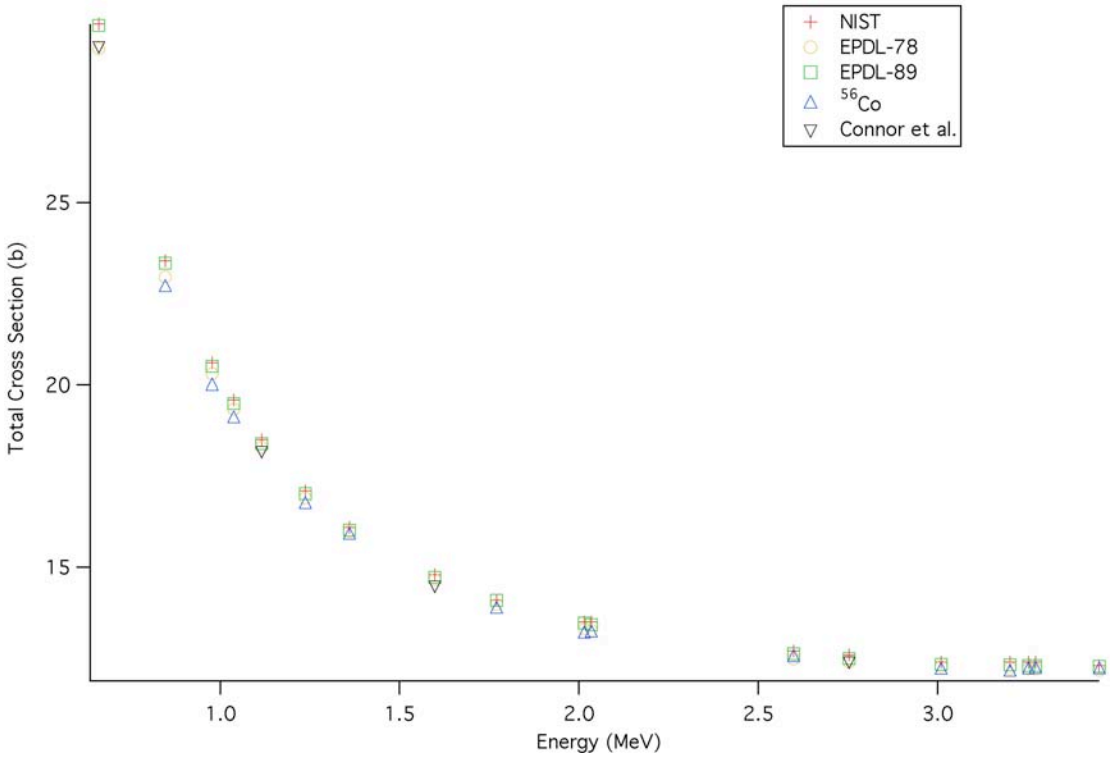

Figure 2. A comparison of the present data, the data of Connor et al., and three evaluations for W.

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