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HOTSPUR
Neutron and Gamma-Ray Emission from the
Transport of 14 MeV Neutrons
Through H₂O

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INTRODUCTION

A series of measurements was performed recently at the RTNS-1 facility on many materials from Be to ^{238}U to study the gamma-ray leakage spectra resulting from the interaction of 14 MeV neutrons with these materials. The targets were spherical assemblies pulsed with the 14 MeV neutron source positioned at the center of the assembly. The detector was an NE-213 scintillator, 5.1 cm in diameter and 5.1 cm long, which allowed simultaneous measurement of the gamma-ray (electron recoil spectra) and the neutron leakage spectra by using pulse shape discrimination.

The calculational analysis was done with the TART and SANDYL codes^{1,2} using the ENDL and ENDF/B-V photon-neutron libraries^{3,4}. In several cases, sizeable discrepancies were found between the measured and calculated gamma-ray-induced recoil electron spectra, while the agreement among the respective measured and calculated neutron spectra was quite good. In the present report the measurements and calculations for ^{160}Gd will be discussed and will serve to illustrate the above discrepancies. A water-filled glass vessel was the target used to study the transport of 14 MeV neutrons through ^{160}Gd and the respective emission of secondary neutrons and gamma-rays. The design and execution of the experiment and the re-evaluations of the nuclear cross-section data base for ^{160}Gd in the ENDL library that resulted in a considerable improvement in the agreement with the measured electron recoil spectra are presented.

EXPERIMENTAL APPARATUS AND PROCEDURE

Measurements of the gamma-ray and neutron emission spectra were made using spherical assemblies pulsed with 14-MeV neutron source positioned at the center of the spheres. The 14-MeV nominal energy neutrons from the $\text{T(d,n)}^4\text{He}$ reaction were generated using the LLNL ICT (insulated-core-transformer) accelerator. The tritium-loaded titanium target mounted at the end of a low-mass conical assembly was positioned at the center of the spherical assembly. The 14 MeV neutron production at the tritium target was monitored by counting the associated alpha particle with a thin (25- μm) silicon surface-barrier detector mounted on the conical assembly. Details of this assembly and the tritium target can be found elsewhere⁵.

The gamma-ray and neutron emission spectra from the pulsed spheres were measured simultaneously by recording the electron recoil and proton recoil spectra respectively using time-of-flight (TOF) and pulse shape discrimination techniques. The detector was a NE-213 scintillator, 5.1 cm in diameter and 5.1 cm long. Fig. 1 shows the separation between the gammas and neutrons obtained from the p-e discriminator. The linearity of the detector as a function of gamma-ray energy was measured with calibrated gamma sources up to 6.13 MeV, while the efficiency was measured up to 2.75 MeV. In Ref. 6 the sources used in this calibration and their absolute strength are given. The detector response, pulse height versus electron energy, was

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linear between 0 and 5.88 MeV (-Compton electron energy from the 6.13 MeV gamma-ray. A recent calibration with a light pulser (BNC 6000) allows us to infer the linear response of the NE-213 detector up to 12 MeV. The relative efficiency of this detector as function of neutron energy (with reference to its absolute efficiency at 14 MeV) in the 1 to 14 MeV interval has been discussed in Ref. 5.

The container for the water target used to study the interactions of the 14-MeV neutrons with oxygen is shown schematically in Fig. 2. The water vessel was fabricated from a pyrex round-bottom spherical flask of nominal 12 liter capacity. The pyrex density is 2.23 g/cm³ and its composition is⁶

Si.2553 O.6411 B.0705 Na.0233 Al.0082 K.0016

Access for the tritium target mounted on the low-mass assembly to the center of the flask was achieved by fusing a pyrex test tube to the edges of a hole in the flask wall. The neck of the tube was removed, leaving a hole of about 9 cm diameter for filling and emptying the flask. The dimensions of the water vessel are given in Table I. The neutron source was positioned at the center of curvature of the flask.

The gamma ray output from the sphere centrally pulsed by neutrons is a strong function of the size of the assembly. As the size increases, the probability of neutron interaction increases. On the other hand, self-absorption of the neutron induced gamma-rays increases also with size. Consequently, there exists an optimum size beyond which the gamma leakage starts to decrease. For the water target, this effect is illustrated in Fig. 3, where the results of a series of simple calculations with TART are displayed. Assuming uniform spheres of H₂O ($\rho = 1.00$) with a central 14 MeV neutron source, the number of γ -MeV per source neutron versus ρR is plotted. A maximum leakage fluence of 1.08 γ -MeV/14 MeV-n is found for $\rho R = 22$ g/cm². This latter value is consistent with the removal cross section per unit mass of 0.0627 cm²/g for 14 MeV neutrons in water as calculated by Logan and Komoto⁷. This result is also consistent⁸ with the mass energy absorption coefficient for gamma-ray energies between 2-6 MeV of 0.021 cm²/g.

CALCULATIONS

Monte Carlo calculations of the gamma-ray and neutron production from the spherical assemblies were done with the TART code¹. In these calculations an accurate description of the geometries and compositions of the tritium target, light-mass assembly and spherical target were input into the problem. The dependence of the energy and neutron flux of the T(d,n)⁴He reaction with angle⁵ was also included. The gamma-rays and neutrons emerging from the sphere were tallied at a zone located at the detector position. Appendix A lists the TART input for the H₂O target (Prob. PSH206).

TART calculates the energy and time of arrival (for the neutrons) of each gamma-ray and neutron reaching the detector. To compare them with the measured electron recoil spectrum and TOF neutron-counts spectra, the TART output needs to be edited. For the neutrons, a direct comparison with the experimental data can be done by folding into the calculations the detector efficiency as a function of neutron energy and the resolution of the detector (full width at half maximum of the transmitted neutron peak). To convert the calculated gamma-ray spectra as an electron recoil spectrum suitable for comparison with the measurements, the TART output is edited to a format compatible with the SANDYL code². SANDYL output (edited by folding the resolution and correction for absolute efficiency of the detector as function of gamma-ray energy) in electron recoil counts per channel can be compared directly with the measured spectra. Details of the TART/SANDYL calculations can be found in Ref. 6.

The measured electron recoil and neutron spectra from water are compared with calculations done with the ENDL library in Figs. 4 and 5 respectively. The dashed curves correspond to the calculation using the neutron induced cross sections for ^{16}O , as they existed in ENDL previous to these measurements (library PP840818). The large disagreement with the measured electron recoil spectrum required a re-evaluation of some of the cross sections values in the library. The calculations done with this new version of the ENDL library for oxygen are given by the solid curves (library TG861229). A discussion of the changes in the cross sections follows.

EVALUATED DATA IN THE ENDL LIBRARY

Evaluated data for neutron interactions with ^{16}O were first entered into the ENDL data file in the early sixties. Cross sections and secondary particle distributions were extensively revised during the early seventies when photon production data were entered. In late 1981 and early 1982, explicit distributions for secondary charged particles were entered into ENDL and at that time the ^{16}O (n,p) and (n, α) reactions were modified to include explicit excitation functions for known levels for each reaction. Some changes were required at that time in the photon production data to be consistent with the level excitation functions for the (n,p) and (n, α) reactions.

When the first TART/SANDYL calculations were done in September of 1986, it was apparent that there were serious discrepancies between measurements and calculations (Fig. 4). This led us to review the photon production data in the ENDL ^{16}O evaluation. The source of the photon energy spectrum from the continuum (n,x γ) reactions was lost in antiquity. As a first step, these data were replaced with model calculations using a version⁹ of Blann's ALICE code. The calculated data provided only the shape of the spectrum and the normalization was obtained by detailed energy balance after all other changes were made in the photon production data. These changes were as follow:

- a) It was found that an error had been made in 1982 when the explicit level excitations for the (n,α) reaction were entered into the data file. In the earlier version, done in 1972, a line at 3.75 MeV was used to represent the sum of the photons from the 3.68 and 3.85 MeV levels from the (n,α_2) and (n,α_3) reactions. Through an oversight, the cross section for this line was not removed when the two more accurate lines were inserted. This resulted in an approximate doubling of the production of photons in the 3.7 MeV region. The correction of this error resulted in the elimination of a major discrepancy between TART/SANDYL calculations and the data.
- b) A modification of the $(n,n\alpha)$ continuum cross section was made to better agree with the measurements of the alpha production cross section by Kneff *et al.*¹⁰. To compensate for the change in the $(n,n\alpha)$ reaction, the $(n,n'\gamma)$ continuum cross section was changed. The alpha and neutron spectra from the $(n,n'\alpha)$ continuum cross section were modified to divide the available energy equally between the two particles on the average. In TABLE II the values for the $(n,n'\alpha)$ and $(n,n'\gamma)$ cross sections for the 1984 and 1986 libraries are given.
- c) The last change to the data file was to use the measurements of Morgan and Chapman¹¹ for the 6.13, 6.92, and 7.12 MeV photons. The normalization of the $(n,x\gamma)$ continuum cross section was obtained by adjusting its value such that total available energy is conserved. A comparison of the integrated gamma ray production cross sections for 14 MeV neutrons incident on ^{160}Gd , as used in the 1984 (library PP840818, dashed-line) and the present version of ENDL (library TG861229, solid line) is shown in Fig. 6. Also shown are the corresponding values for the ENDF/B-V library.

After the changes described above were implemented, new TART/SANDYL calculations were done (library TG861229). These results are shown by the solid curves in Figs. 4 and 5. The agreement with the measured electron recoil spectrum was greatly improved by this calculation, although the calculated values are about 20% higher over most of the electron energy range. This discrepancy can not be resolved until further microscopic experiments indicate where the evaluated data can be improved.

DISCUSSION OF THE RESULTS AND CONCLUSIONS

The changes in the $(n,x\gamma)$ cross sections for ^{160}Gd between the 1984 and 1986 versions of the ENDL library produced a large improvement in the agreement between the TART/SANDYL calculations and the measured electron recoil spectrum, although the calculated values overestimate

the measurements by as much as 20% over most of the electron energy range. However, the measured neutron TOF spectrum was fitted equally well (with minor differences between 300 and 400 ns) by both versions. This behavior allows us to conclude that the major source of the discrepancies with the measurements of the electron recoil spectrum resulted from the magnitude and representation of the $(n,x\gamma)$ cross sections in ENDL. A similar conclusion can be reached in the comparisons between the calculations with the ENDL (1986 version), the ENDF/B-V libraries and the data shown in Figs. 7 and 8. The calculations with the ENDF/B-V library underestimate the measured electron recoil spectrum by 30 to 50 % (Fig. 7), in contrast to the calculations with the ENDL library where the measurements are exceeded. However, the neutron spectra is well represented (Fig. 8) by both libraries.

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TABLE I

Dimensions of the Water Vessel.

Outer radius of vessel	14.76 cm
Inner radius of vessel	14.48 cm
Wall thickness of vessel	0.28 cm
Outer diameter of access tube	4.44 cm
Wall thickness of access tube	0.20 cm
Distance from the center of curvature of the bottom of the access tube to the center of curvature of the vessel	1.10 cm

TABLE II

(n,n' γ) and (n,n' α) Continuum Cross Sections for ^{160}Gd in the 1984 and 1986 Versions of the ENDL Library.

Neutron Energy [MeV]		$\sigma(n,n'\gamma)$ [mb]		Neutron Energy [MeV]		$\sigma(n,n'\alpha)$ [mb]	
		1984	1986			1984	1986
				9.2	0.00	0.00	
				9.7	25.00	25.00	
12.0	0.00	3.00		12.0	147.00	155.00	
12.5	15.00	5.00		12.5	173.00	183.00	
13.0	75.00	7.50		13.0	200.00	256.00	
13.5	95.00	9.50		13.5	215.00	312.00	
14.0	100.00	10.00		14.0	230.00	320.00	
15.0	110.00	11.00		15.0	250.00	350.00	
16.5	120.00	12.00		16.5	260.00	368.00	
18.0	150.00	15.00		18.0	150.00	285.00	
20.0	205.00	75.00		20.0	120.00	250.00	

FIGURE CAPTIONS

- Fig. 1 Typical gamma-neutron separation obtained with the pulse shape discrimination circuit.
- Fig. 2 Schematic representation of the water vessel for the purpose of the Monte Carlo calculations. The insert shows the details of the tritium target positioned at the end of the access pyrex test tube.
- Fig. 3 The number of gamma-MeV per 14 MeV neutron source from the water sphere is plotted as function of the product of the density times the radius of the sphere [$\rho = 1.00$ for water].
- Fig. 4 Comparison of the measured and calculated electron recoil spectra from water. The calculations have been done with the codes TART/SANDYL using the ENDL library.
- Fig. 5 Comparison of the measured and calculated neutron spectra from water. The calculations have been done with the code TART using the ENDL library.
- Fig. 6 Comparison of the calculations of the integrated gamma production with the code TART and the libraries.
- Fig. 7 Comparison of the measured and calculated electron recoil spectra from water. The calculations utilize the ENDL 1986 and ENDF/B-V libraries.
- Fig. 8 Comparison of the measured and calculated neutron spectra from water. The calculations utilize the ENDL 1986 and ENDF/B-V libraries.

APPENDIX A

```

name psh2og water sphere, r=14.76 cm (81-85-87)
box #91 gene g.
* new howerton o16 ppd set, 12-29-86
* file tg861229 renamed tartppd
* file tn861223 utilized in prob. input
zplane 27 1.12
sphere 28 2.82 -1.18 8. 8.
zplane 29 1.16288e-81
zplane 30 7.67888e-82
zplane 31 5.88888e-84
zplane 32 -5.88888e-84
zplane 33 -1.19888e+81
zplane 34 -2.49888e+81
zplane 35 -2.74888e+81
sphere 36 2.22 -1.18 8. 8.
zplane 37 -1.18
jb 1 -32 31 1
jb 2 -31 30 1
jb 3 -30 29 1
jb 4 28 -29 -32
jb 5 28 -1 29 -32
jb 6 37 4 8 -3
jb 7 3 -2 32 -34
jb 8 2 32 -33
jb 9 2 -34 -10 33
jb 10 10 -9 33 -34
jb 11 9 33 -34
jb 12 3 34 -35
jb 13 7 -6 27 -4
jb 14 8 -7 -4 27
jb 15 7 -6 -27
jb 16 8 -7 -27
jb 17 36 -28 -37
jb 18 5 -4 6 37
jb 19 6 -5 37
jb 20 6 -27
jb 21 11 27 -3 -35 -8
jb 22 11 -27 -8
jb 23 11 35
jb 24 12 -11 15 -27
jb 25 12 -11 -27 -15
jb 26 12 -11 27 -17
jb 27 12 -11 17 -16 27
jb 28 12 -11 16 27
jb 29 13 -12 16 27
jb 30 13 -12 -16 17 27
jb 31 13 -12 -17 27
jb 32 13 -12 15 -27
jb 33 14 -13 15 -27
jb 34 14 -13 -15 -27
jb 35 14 -13 -17 27
jb 36 14 -13 17 -16 27
jb 37 14 -13 16 27
jb 38 13 -12 -27 -15
jb 39 -14
jb 40 6 -36 27 -37
jb 41 28 -3 32 -37
surf 1 1.83188e+88 8. 8. 8. 8. 1.e+88 1.e+88
surf 2 8. -4.76888e-83 1.11898e+81 8. 8. 1.e+88 1.e+88
surf 3 8. -4.76888e-83 1.19388e+81 8. 8. 1.e+88 1.e+88

```

APPENDIX A

```

cyl 4 2.02 0. 0.
cyl 5 2.22 0. 0.
sphere 6 14.40 0. 0. 0.
sphere 7 14.76 0. 0. 0.
sphere 8 14.761 0. 0. 0.
surf 9 6.30000e-01 0. 0. 0. 1.e+00 1.e+00
surf 10 7.50000e-01 0. 0. 0. 1.e+00 1.e+00
surf 11 0.79000e+02 1.00000e+00 0. 0. 1.e+00 1.e+00
surf 12 8.79010e+02 1.00000e+00 0. 0. 1.e+00 1.e+00
surf 13 9.82500e+02 1.00000e+00 0. 0. 1.e+00 1.e+00
surf 14 9.82510e+02 1.00000e+00 0. 0. 1.e+00 1.e+00
surf 15 0. -3.33333e-01 0. 0. 1.e+00 1.e+00
surf 16 0. -1.42039e+00 0. 0. 1.e+00 1.e+00
surf 17 0. -7.54076e+00 0. 0. 1.e+00 1.e+00
mat1 1 1.60000e+00 5.00000e-01 1003 5.00000e-01 22000
mat1 2 1.00000e+01 1.00000e+00 74000
mat1 3 0.00000e+00 4.50000e-01 25000 3.20000e-01 29000 0.00000e-02 0016 &
2.00000e-02 13027 6.00000e-02 6012 1.30000e-01 1001
mat1 4 3.00000e+00 5.00000e-01 13027 3.00000e-01 1001 2.00000e-01 5012
mat1 5 2.70000e+00 1.00000e+00 13027
mat1 6 1.20000e-03 7.00000e-01 7014 2.11500e-01 0016
mat1 7 0.00000e+00 5.00000e-01 13027 5.00000e-01 29000
mat1 8 7.00000e+00 6.00000e-01 26000 0.40000e-02 20000 2.00000e-02 14000 &
1.00000e-02 25055 2.00000e-01 24000
mat1 9 1.0000 0.6667 1001 0.3333 0016
mat1 10 2.3000 0.3333 14000 0.6667 0016
mat2 0 39
mat2 1 1
mat2 2 2
mat2 3 3
mat2 4 5
mat2 5 7 10
mat2 6 4 6 8 9 11 21 22 23 24 25 26 27 28 29
mat2 7 12
mat2 8 19 20 40
mat2 10 13 14 15 16 17 18
sent1 1 0 2 20 3 60000 5 3 12 2 21 20 22 1 33 3
sent1 6 2.00000e+00 7 -1.00000e+00 0 -1.00000e-01 9 -1.00000e-04
sent1 10 5.00000e-05 13 5.00000e-01 14 1.00000e-04 15 2.00000e+01
sent1 16 1.60000e+01
eang1 1 1.00000e+00 1.00000e+00 9.96000e-01 9.39690e-01
eang1 3 9.84550e-01 7.66040e-01 9.67200e-01 5.00000e-01
eang1 5 9.46220e-01 1.73650e-01 9.24270e-01 -1.73650e-01
eang1 7 9.84000e-01 -5.00000e-01 8.87732e-01 -7.66040e-01
eang1 9 8.77232e-01 -9.39690e-01 8.73600e-01 -1.00000e+00
enerang1 1 1.51000e+01 1.00000e+00 1.50450e+01 9.39690e-01
enerang1 3 1.40000e+01 7.66040e-01 1.46050e+01 5.00000e-01
enerang1 5 1.42000e+01 1.73650e-01 1.39550e+01 -1.73650e-01
enerang1 7 1.36510e+01 -5.00000e-01 1.35070e+01 -7.66040e-01
enerang1 9 1.32510e+01 -9.39690e-01 1.31970e+01 -1.00000e+00
source2 1 0. 6.00000e-01 0. 0. 0. 0.
centim 00.00
cphota1 1 1 127 128 129 130 131 132 133 134 135 136 137 138 139
cphota1 15 140 141 142 143 144 145 146 147 148 149 150 151 152
cphota1 20 153 154 155 156 157 158 159 160 161 162 163 164 165
cphota1 41 166 167 168 169 170 171 172 173 174 175 176
1type 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
1type 0 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
1type 0 36 37 38 39 40
1type 12 24
1typeg 12 24
tinspec 0 0. 1.26000e+01 3.17400e-01
tinspec 3 3.78000e+01 7.93500e-01 5.67000e-01 9.52200e-01
tinspec 5 9.45000e-01 1.11100e-01 2.39400e-02 1.27000e+00
tinspec 7 3.49000e+03 1.42000e+00 3.70025e+04 1.50700e+00
tinspec 9 1.54220e+05 1.74600e+01 1.26963e+05 1.90400e+00
tinspec 11 2.45054e+04 2.06300e+00 7.46000e+03 2.22200e+00
tinspec 13 3.00700e+03 2.30100e+00 2.15500e+03 2.53900e+00
tinspec 15 0. 2.690
end

```