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GIANT DIPOLE RESONANCE NEUTRON YIELDS PRODUCED BY ELECTRONS AS A FUNCTION OF TARGET MATERIAL AND THICKNESS*

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ABSTRACT

This paper characterizes the functional dependence of the Giant Dipole Resonance (GDR) neutron yield produced by electrons in terms of the atomic number (Z) and thickness (T) of the target. The yields were calculated by integrating, over the photon energy, the product of the differential photon track length and published photoneutron cross sections. The EGS4 Monte Carlo code and analytical formulas were used to calculate the differential photon track length. In thick targets, the GDR neutron yield approaches a saturation value as target thickness T increases to 10 radiation lengths. A formula, $8 \times 10^{-6} \times (Z^{1/2} + 0.12\ Z^{3/2} - 0.001\ Z^{5/2})$ n electron^{-1}MeV^{-1}, developed from EGS4 calculations, estimates thick-target neutron yields for incident electron energies E_o above 50 MeV. GDR neutron yields, calculated by several analytic formulas for the differential photon track length, are compared with EGS4 calculations. Modifications to the analytic formulas are suggested. A scaling function $(100/E_0\ Z^{1/2})\ T^2\ [1+(0.04/T)]$ is derived to estimate, from the thick-target formula, neutron yields produced in thin targets.

INTRODUCTION

Neutrons can be produced by electron beams through photonuclear reactions. The total neutron production is composed of two parts: (1) photonuclear reactions via bremsstrahlung, and (2) electroproduction via virtual photons (NCRP 79). In general, the cross sections of electroproduction are expected to be of the order of the fine structure constant, $\alpha \approx 1/137$, times the cross sections of photonuclear reactions. The neutron yield produced by electroproduction may become important only when the target is thin and the bremsstrahlung yield is low.

Giant Dipole Resonance (GDR) neutron yields as a function of target material and thickness are studied in this paper. GDR neutrons are produced by photons with energies from approximately 7 to 40 MeV. The GDR neutron yields are proportional to the product of the length l of the material traversed by photons of each energy (the photon track-length) and the GDR photoneutron cross section. The dependence of the photon track-length on the photon energy k is expressed as the differential photon track length dl/dk, representing the total track-length of all photons with energy in the interval k, k+dk. The differential track length is calculated by analytical formulas or by a Monte Carlo transport code. Two formulas for the differential photon track length are based on Approximations A and B of analytical shower theory (Rossi 1952), where the former includes only the pair production and bremsstrahlung processes and the latter additionally includes ionization losses. The most satisfactory approach is to calculate the photon track length by a Monte Carlo transport code, such as EGS4 (Nelson et al. 1985). The EGS4 code simulates the major physical processes and estimates the track length of each photon. The GDR neutron yields are calculated by integrating, over the photon energy spectra generated by electrons, the product of the differential photon track length and the published GDR photoneutron cross sections.

In thick targets, the simplest analytic method for calculating the GDR neutron yields produced by high-energy electrons is to use Approximation A of the differential photon track length. We calculated neutron yields for eighteen natural elements from aluminum (Z = 13) to lead (Z = 82) using Approximation A, and then compared the results with EGS4 calculations. Modification to Approximation A is suggested.

For incident electron energies above 50 MeV and target thicknesses greater than 10 radiation lengths (r.l.), the GDR neutron yield reaches a saturation value. A formula for the neutron yields of infinitely thick targets was given by Swanson (1978, 1979). The formula was obtained by a least-squares fit of the calculated yields for ten natural elements from carbon (Z=6) to lead (Z=82). These calculations were based on Approximation B of the differential photon track length, with additional corrections for electron and photon propagation in the materials. To check Swanson's formula, the EGS4 code has been used to calculate neutron yields produced in thick targets of twenty different natural elements. This paper presents a new formula for the GDR neutron yields produced in thick targets of natural elements from aluminum (Z = 13) to lead (Z = 82).

In thin targets, neutrons produced by the direct interaction of electrons with a nuclei may become important. To calculate the neutron yields due to electroproduction, the direct method is to use the cross sections of neutron production by electroproduction. Because of difficulties in the measurement, few such data are available. Tsai (1974) developed analytical formulas to estimate the differential photon track length for bremsstrahlung photons and for virtual photons in thin targets by use of the Weizsacker-Williams method. The neutron yields due to electroproduction can be estimated by using the virtual photon track length and the related GDR photoneutron cross sections (Tsai 1974).

We calculated GDR neutron yields produced by bremsstrahlung photons induced by electrons in thin targets, using Tsai’s approximation, and compared the results with EGS4 calculations. Based on the modified Approximation A and Tsai's Approximation, we developed a scaling function to estimate, from the thick-target formula, the neutron yields produced in thin targets.

The ratio of total neutron yields to neutron yields produced from bremsstrahlung only in thin targets were calculated by Tsai's approximation. The ratio was also estimated by a formula obtained from NCRP 79 (1984). These estimates were compared with the measured data from Barber and George (1959). Tsai's approximation is recommended.

METHODS

The GDR neutron yield per incident electron can be determined analytically for each photoneutron reaction, using

$$Y_{\mathrm{GDR}} = \frac{6.023\times10^{-4}\,\rho\ \mathrm{f}\,\mathrm{N_n}}{A\ E_o}\int_{E_{\mathrm{th}}}^{E_{\max}} \sigma_{\mathrm{GDR}}(\mathrm{k})\left(\frac{dl}{dk}\right)\mathrm{dk}\,, \qquad (1)$$

where

Y_{GDR} = GDR neutron yield (neutron electron^{-1} MeV^{-1});

ρ = density of target (g cm^{-3});

f = isotope fractional abundance;

$\mathrm{N_n}$ = numbers of neutrons produced per photoneutron reaction;

A = atomic weight (g mol^{-1});

E_o = electron energy (MeV);

$\sigma_{\mathrm{GDR}}(\mathrm{k})$ = photoneutron cross section (mb);

$\frac{dl}{dk}$ = differential photon track length (cm MeV^{-1});

k = photon energy (MeV):

E_{th} = threshold energy of the reaction (MeV); and

$E_{\max}$ = upper limit energy of the reaction or the electron energy when upper limit energy of the reaction is larger than the electron energy (MeV) (Swanson 1979).

The sources of the cross sections used in the calculations are listed in Table 1. All cross sections are for natural elements, except nickel, indium, tantalum, and lead, whose individual isotopic cross sections were used. Because of the lack of some isotopic cross section data, the sum of the isotopic abundance is not quite 100%. The cross sections used included:

Table 1. Photoneutron cross sections.

Element	Atomic Number	Cross Section Measured from		Isotopic Abundance (%)	References
		Natural Element	Isotope		
Aluminum	13	Al			Dietrich and Berman (1988)
Chlorine	17	Cl			
Potassium	19	K			
Iron	26	Fe			Costa et al. (1967)
Nickel	28		^{58}Ni	68.27	Dietrich and Berman (1988)
Nickel	28		^{60}Ni	26.10	
Copper	29	Cu			
Gallium	31	Ga			
Rubidium	37	Rb			
Palladium	46	Pd			
Cadmium	48	Cd			
Indium	49		^{115}In	95.7	
Antimony	51	Sb			
Tellurium	52	Te			
Neodymium	60	Nd			
Samarium	62	Sm			
Tantalum	73		^{181}Ta	99.988	
Tungsten	74	W			
Rhenium	75	Re			
Iridium	77	Ir			
Platinum	78	Pt			
Mercury	80	Hg			
Lead	82		^{206}Pb	24.1	Berman et al. (1987)
Lead	82		^{207}Pb	22.1	
Lead	82		^{208}Pb	52.4	

- single photoneutron cross section, $\sigma(\gamma, 1n) = \sigma\,[(\gamma, n) + (\gamma, pn)]$
- double photoneutron cross section, $\sigma(\gamma, 2n) = \sigma\,[(\gamma, 2n) + (\gamma, p2n)]$
- triple photoneutron cross section, $\sigma(\gamma, 3n)$

The calculations of the differential photon track length are divided into two categories: thick targets and thin targets.

Thick targets:

The simplest method for estimating the differential photon track length is to use Approximation A of the analytical shower theory in Rossi (1952):

$$\left(\frac{dl}{dk}\right)_{\text{thick}} = 0.572\,\frac{X_o E_o}{k^2}\,, \tag{2}$$

where X_o = the radiation length of the target material in centimeters.

This approximation applies to infinitely thick targets and to high-energy electrons, and considers only pair production and bremsstrahlung. For these two processes, it also assumes that the cross sections are constant at their asymptotic values. Neutron yields calculated using Eqs. 1 and 2 were compared with the EGS4 calculations to check the accuracy of Approximation A.

The second method is to use Approximation B (Rossi 1952), which cannot be written in closed form. The physical processes are similar to those of Approximation A, except that electron energy loss by ionization is considered. It applies to infinitely thick targets and to all electron energies. Approximation B was used by Swanson to calculate neutron yields produced in thick targets (Swanson 1979).

For the present work, the EGS4 Monte Carlo code (Nelson et al. 1985) was used to calculate neutron yields. The EGS4 code simulates the transport of electrons, positrons, and photons. For the transport of charged particles, EGS4 takes into account bremsstrahlung, multiple Coulomb scattering, continuous energy loss, delta ray production, and positron annihilation. For photon transport, it accounts for pair production, Compton scattering, photoelectric effect, and coherent scattering. The individual track length of each bremsstrahlung photon was multiplied by the GDR photoneutron cross section matched with the photon energy, and the product was then integrated over the energy range of the GDR photoneutron reactions to determine the neutron yield.

Thin target:

For thin targets, neutrons produced by the direct interaction of electrons with a nuclei may become important. The differential photon track length in thin targets must include an electroproduction (i.e., virtual photon) part:

$$\left(\frac{dl}{dk}\right)_{\text{thin}} = \left(\frac{dl}{dk}\right)_{\text{brem}} + \left(\frac{dl}{dk}\right)_{\text{virtual}} . \tag{3}$$

For bremsstrahlung induced by electrons in thin targets, Tsai (1974) derived the approximation of the differential photon track length as

$$\left(\frac{dl}{dk}\right)_{\text{brem}} \approx \frac{X_o}{k}\,\frac{T^2}{2} , \tag{4}$$

where T = target thickness in radiation lengths. The neutron yields calculated using Eqs. 1 and 4 were compared with the EGS4 calculations, which only simulate bremsstrahlung photons, to check the accuracy of Tsai's approximation.

Based on the Weizsacker-Williams method, Tsai (1974) pointed out that the contribution from the direct electroproduction is approximately equal to the contribution from virtual photons produced by letting electrons pass through a radiator with equivalent thickness t_{eq}. For the GDR photonuclear reactions, t_{eq} is equal to 0.02 r.l. For the virtual photon, Tsai (1974) derived the approximation of the photon track length distribution as

$$\left(\frac{dl}{dk}\right)_{\text{virtual}} = \left(\frac{X_o}{k}\right) t_{eq}\, T \,. \tag{5}$$

The ratio of the total neutron yields produced by bremsstrahlung and electroproduction (Y_{total}) to that produced by bremsstrahlung only (Y_{brem}) is given by:

$$\frac{Y_{\text{total}}}{Y_{\text{brem}}} = \frac{\int_{E_{\text{th}}}^{E_{\max}} \left[\left(\frac{\chi_o}{k}\right)\frac{T^2}{2} + \frac{\chi_o}{k}\; t_{\text{eq}}\; T\right] \sigma(k)\; dk}{\int_{E_{\text{th}}}^{E_{\max}} \left(\frac{\chi_o}{k}\right)\; \frac{T^2}{2}\; \sigma(k)\; dk} = 1 + \frac{0.04}{T} \,. \tag{6}$$

Another estimate for Y_{total}/Y_{brem} can be obtained from the NCRP 79 formula (NCRP 1984)

$$\frac{Y_{\text{brem}}}{Y_{\text{electro}}} = \frac{\alpha_\gamma(E_e)}{\alpha(E_e)}\; 68.5\; \varepsilon \;, \tag{7}$$

where

Y_{brem} = the neutron yield produced from bremsstrahlung photons (n electron^{-1} MeV$^{-1)}$;

$Y_{electro}$= the neutron yield produced from electroproduction (n electron^{-1} MeV$^{-1)}$;

E_e= electron energy;

$\frac{\alpha_\gamma(E_e)}{\alpha(E_e)}$ = ratio of radiative to total stopping power; and

= fraction of energy lost by electrons passing through the target.

From Eq. 7, we can write

$$\frac{Y_{\text{total}}}{Y_{\text{brem}}} = 1 + \frac{\alpha(E_e)}{68.5\varepsilon\alpha_\gamma(E_e)} \ . \tag{8}$$

RESULTS AND DISCUSSIONS

Validation of EGS4 calculation

To validate the EGS4 Monte Carlo simulation and to determine its accuracy, a comparison was made between the neutron yields calculated by EGS4 and the measured GDR neutron yields produced by 34 MeV electrons in about 1-r.l.-thick targets of aluminum, copper, tantalum, and lead. The absolute accuracy of the measurement was estimated to be ±15% (Barber and George 1959). Table 2 shows that the calculated yields are generally lower than the measured yields, but within 25%. Uncertainties in the cross sections and the measurement error must account for the differences, because the statistical uncertainty in the calculations is less than 1%.

Table 2. Neutron yields produced by 34 MeV electron beams.

Target material	**Target thickness (r.l.)**	**Measured neutron yield[a] (10^{-5} n e^{-1} MeV^{-1})**	**Neutron yield Calculated by EGS4 (10^{-5} n e^{-1} MeV^{-1})**
	1.00	1.3 ± 0.2	0.98
Copper	1.04	3.8 ± 0.6	2.95
Tantalum	0.98	5.3 ± 0.8	5.01
Lead	1.01	6.2 ± 0.9	4.93

[a] Measured data are from Barber and George (1959).

Thick target (photoneutron yield)

When an energetic incident electron hits a target an electromagnetic cascade is produced. Most of the energy from the electromagnetic cascade initiated by the electron in a thick target is absorbed, so that neutron yields no longer increase with target thickness. The GDR neutron yields resulting from 100 MeV electrons and 1 GeV electrons incident on iron targets with different thicknesses are shown in Fig. 1. These neutron yields reach saturation when the target thickness is greater than about 7 r.l. for 100 MeV electrons or 10 r.l. for 1 GeV electrons. Further calculations indicate that the neutron yield has generally saturated when the target thickness is 10 r.l. for electron energies less than 10 GeV.

Figure 2 shows GDR neutron yields produced from 20-r.l.-thick targets by incident electrons with energies from 18 MeV to 10 GeV.

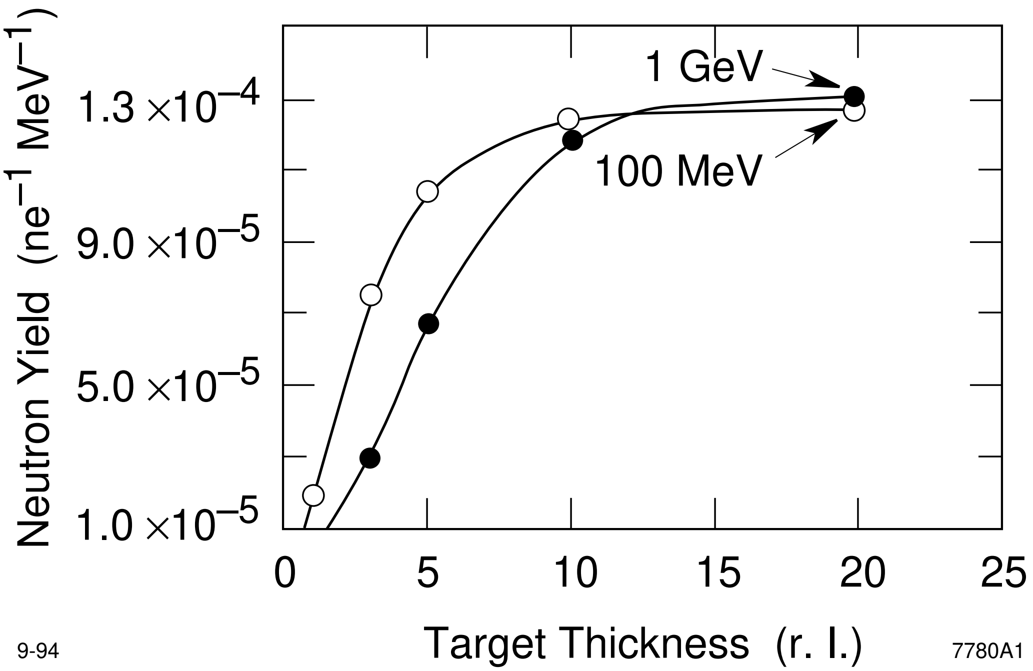

Figure 1. Neutron yield as a function of iron-target thickness for 100 MeV and 1 GeV electron beams.

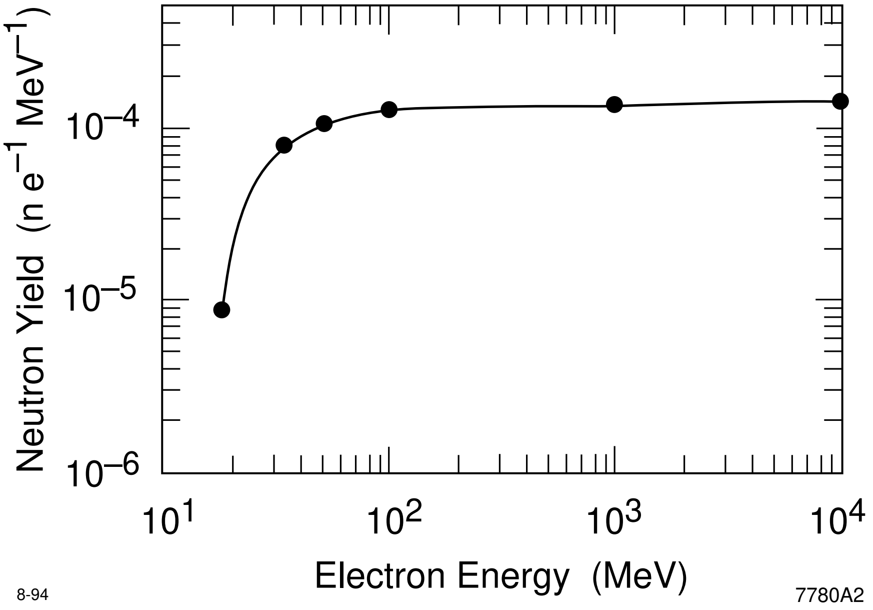

Figure 2. Neutron yields produced in 20 r.l.-thick iron targets as a function of electron energy.

The neutron yields start to decrease when the electron energy is less than 50 MeV. This is explained in Fig. 3, which shows that the photon track length decreases dramatically as the photon energy approaches its maximum, i.e., the incident electron energy. When the incident electron energy is less than 50 MeV, the maximum photon energy is near the upper energy limit of the photoneutron reactions. The photon track lengths in the energy range of the photoneutron reactions become small, and the neutron yield decreases.

Figure 4 plots GDR neutron yields calculated by EGS4, produced by 100 MeV electrons incident on 20-r.l.-thick targets for twenty natural elements, from aluminum (Z = 13) to lead (Z = 82). By fitting the thick-target yields as a function of the atomic number Z, we have developed a simple formula for calculating GDR neutron yield:

$$Y_{\text{thick}} = 8 \times 10^{-6} \times (Z^{1/2} + 0.12Z^{3/2} - 0.001\,Z^{5/2})\ \text{n electron}^{-1}\,\text{MeV}^{-1}\,. \quad (9)$$

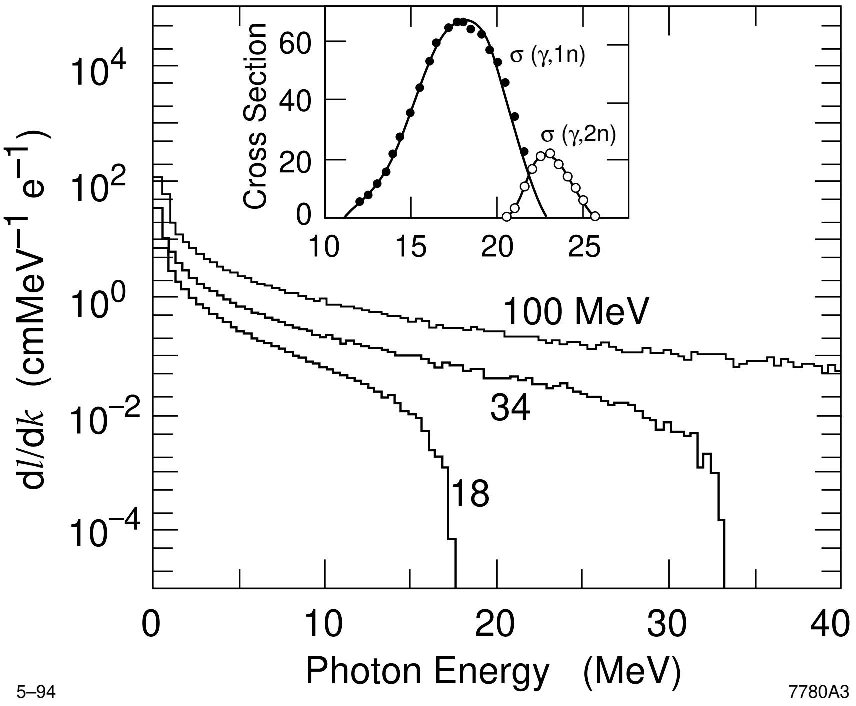

Figure 3. Differential photon track length distributions produced in thick iron targets struck by 18 MeV, 34 MeV, and 100 MeV electrons.

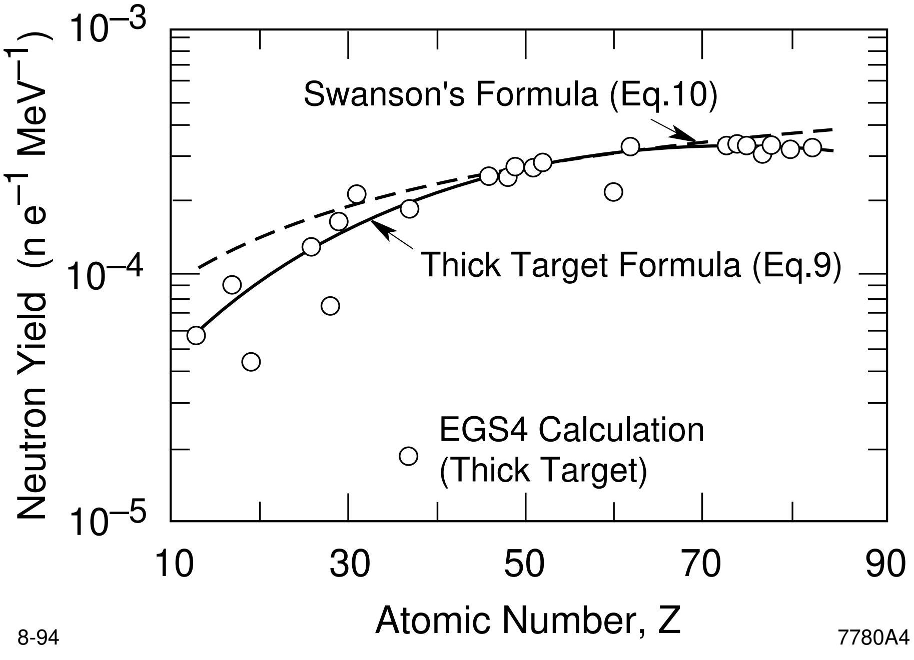

Figure 4. Neutron yields produced in thick targets struck by 100 MeV electrons as a function of the atomic number.

This formula results in a yield estimation within ±30% of the EGS4 calculation for target thicknesses greater than 10 r.l., for electron energies above 50 MeV, and for all natural elements between aluminum (Z=13) and lead (Z=82), except for a few special elements such as potassium, nickel, and neodymium. The neutron yields of potassium and nickel are low because they have magic numbers of neutrons or protons, and the binding energies of nucleons are high. The reason for neodymium is unknown.

Swanson (1979) has also published a formula for estimating thick-target neutron yields by using a modified Approximation B of shower theory; namely,

$$Y_{\text{thick}} = 1.94 \times 10^{-5}\, Z^{0.667 \pm 0.05} \text{ n electron}^{-1}\,\text{MeV}^{-1}, \qquad (10)$$

which applies to target materials having intermediate Z (see Fig. 4).

Neutron yields produced by 100 MeV electrons incident on thick targets were calculated using Eq. 1 together with the differential photon track length according to Approximation A of shower theory (Eq. 2). EGS4 calculations were also performed using a target thickness of 20 r.l. in order to guarantee saturation (see Fig. 1). The ratio of yields obtained using the two methods are compared in Fig. 5, where it is shown that Approximation A overestimates the yield at low Z and underestimates it at high Z. This trend can be explained by considering the asymptotic (constant) cross-section assumptions used in the derivation of Approximation A. Namely, for low-Z materials, the bremsstrahlung cross section in the energy range of the GDR reaction is smaller than its asymptotic value, so that Approximation A will tend to overestimate the production of x-rays (i.e., track length) and, therefore, the neutron yield. For high-Z materials, on the other hand, the bremsstrahlung

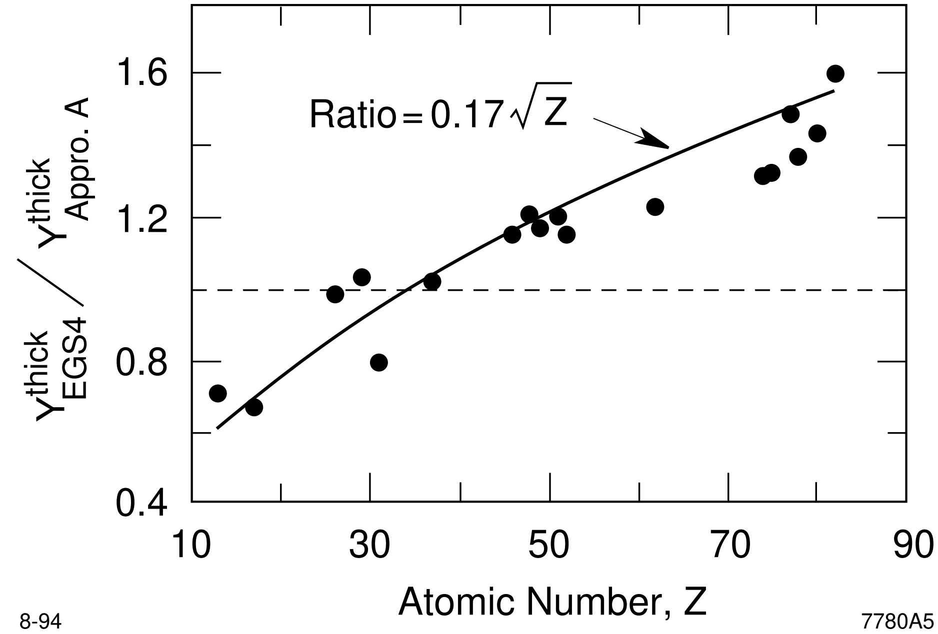

Figure 5. Ratio of the thick-target neutron yield calculated by EGS4 to that by Approximation A vs. the atomic number.

cross section in the energy range of the GDR reaction tends to be closer to its asymptotic value so that x-ray production is more correctly modeled; whereas, the pair production cross section is significantly smaller than asymptotic, so that photons will actually travel further than predicted by Approximation A. This underestimation of the track length leads to a decrease in the calculated production of neutrons.

By fitting the yield ratio as a function of the atomic number (Z), we obtain

$$\frac{Y^{\text{thick}}_{\text{EGS4}}}{Y^{\text{thick}}_{\text{Approx A}}} = 0.17\, Z^{1/2} , \qquad (11)$$

which is shown as a solid line in Fig. 5. To calculate the GDR neutron yields for target thicknesses greater than 10 r.l. and for electron energies above 50 MeV, the photon track length calculated using Approximation A should be modified by a factor of 0.17 $Z^{1/2}$; namely,

$$\left(\frac{dI}{dk}\right)_{\text{thick}} = 0.572\ \frac{X_o E_o}{k^2} \times 0.17\ Z^{1/2} = 0.1\ \frac{X_o E_o}{k^2}\ Z^{1/2}\ , \qquad (12)$$

Thin target (photoneutron yield)

Tsai's thin-target approximation, Eq. 4, has been used in Eq. 1 to calculate neutron yields produced from bremsstrahlung induced by electrons in aluminum, iron, and lead targets. A comparison of these calculations with those of EGS4 is shown in Fig. 6 for iron targets. The neutron yields calculated by Tsai's approximation agree with the EGS4 calculations with uncertainties of less than ±30% for target thicknesses less than 0.75 r.l., electron energies above 50 MeV, and for the three materials studied.

A scaling function, S_n, can be developed to estimate the neutron yields produced in thin targets from the thick target formula as follows:

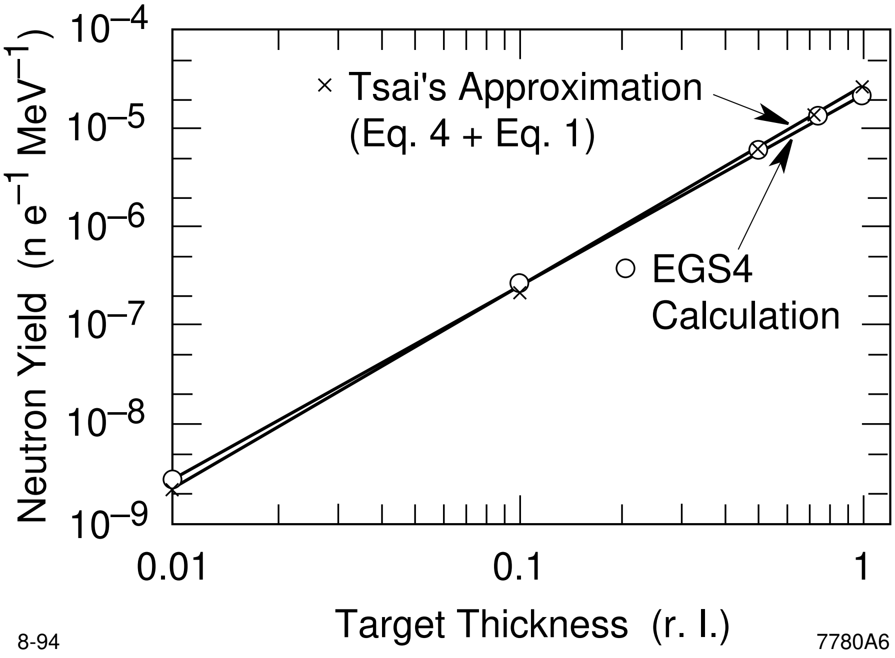

Figure 6. Neutron yields produced by bremsstrahlung in thin iron targets struck by 100 MeV electrons as a function of the target thickness.

$$S_n = \frac{Y_{\text{thin}}^{\text{Approx}}}{Y_{\text{thick}}^{\text{Approx}}} = \frac{\int_{E_{\text{th}}}^{E_{\text{max}}} \frac{X_o}{k} \frac{T^2}{2} \; \sigma(k) \; dk}{\int_{E_{\text{th}}}^{E_{\text{max}}} 0.572 \; \frac{X_o E_o}{k} \; \sigma(k) \times 0.17 \, \mathrm{Z}^{1/2} \, dk} ,$$

$$\approx \frac{1}{0.19 \; Z^{1/2}} \; \frac{E_{\text{max}} \; E_{\text{th}} \; \ln \frac{E_{\text{max}}}{E_{\text{th}}}}{E_{\text{max}} - E_{\text{th}}} \; \frac{T^2}{E_o} , \tag{13}$$

where we have assumed that σ(k) is constant over the integration range (a slight over-approximation).

For elements from aluminum (Z=13) through lead (Z=82),

$$\frac{E_{\text{max}} \; E_{\text{th}} \; \ln \frac{E_{\text{max}}}{E_{\text{th}}}}{E_{\text{max}} - E_{\text{th}}} = 19 , \tag{14}$$

so the scaling function reduces to the simple expression

$$\mathrm{S_n} = \frac{100}{\mathrm{E_o} \, \mathrm{Z}^{1/2}} \; \mathrm{T}^2. \tag{15}$$

In thin targets, both bremsstrahlung production and photonuclear interaction are proportional to the target thickness, so the neutron yields are proportional to the square of the target thickness.

Relative neutron yields produced by electrons of various energies incident on iron targets are plotted in Fig. 7 for four target thicknesses. Similar results were obtained for aluminum and lead targets, and better than ±50% agree-ment was found with the scaling function for target thicknesses less than 0.75 r.l. and electron energies above 50 MeV.

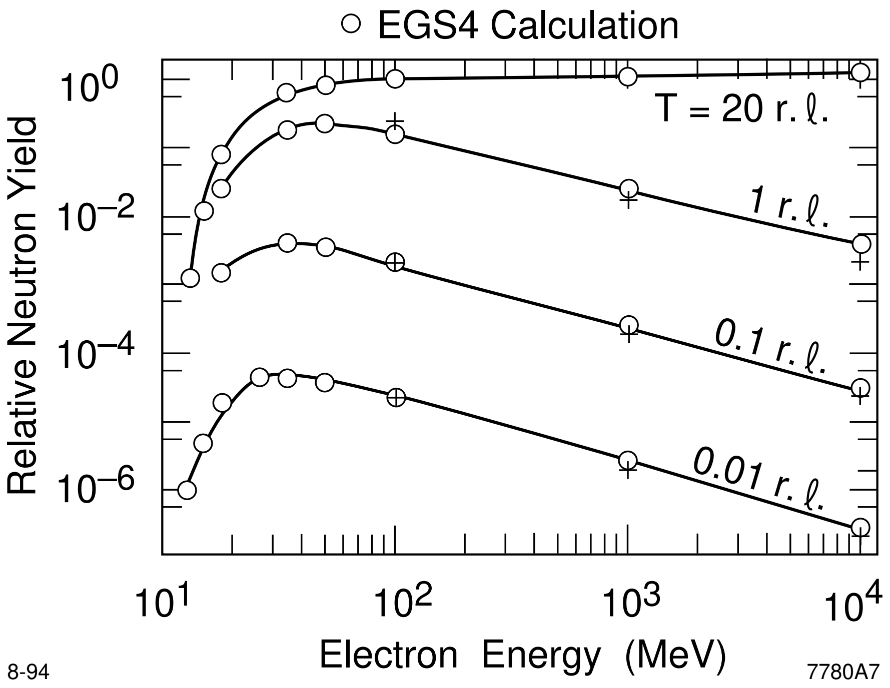

Figure 7. Relative neutron yields produced by bremsstrahlung in thick and thin iron targets as a function of the electron energy. The yield at 10 GeV and 20 r.l. is used as a normalizing point. The +-symbol shows the results of calculations using the scaling function (Eq. 15). The o-symbol shows the results of EGS4 calculations with a solid line drawn through them.

Using the scaling function, S_n, together with the thick-target formula for the GDR neutron yield derived earlier (Eq. 9), we can write

$$Y_{\text{thin}}^{\text{brem}} = Y_{\text{thick}} \times S_n$$

$$= 8 \text{ x } 10^{-6} \text{ x } (Z^{1/2} + 0.12Z^{3/2} - 0.001\, Z^{5/2}) \times \frac{100}{E_o\, Z^{1/2}}\; T^2 \qquad (16)$$

$$= 8 \text{ x } 10^{-4} \text{ x } (1 + 0.12Z - 0.001\, Z^2) \,\frac{T^2}{E_o}\,, \qquad \text{n electron}^{-1}\ \text{MeV}^{-1}.$$

A comparison of Eq. 16 with EGS4 calculations is shown in Fig. 8 for a 0.01 r.l.-thick targets and an electron energy of 100 MeV.

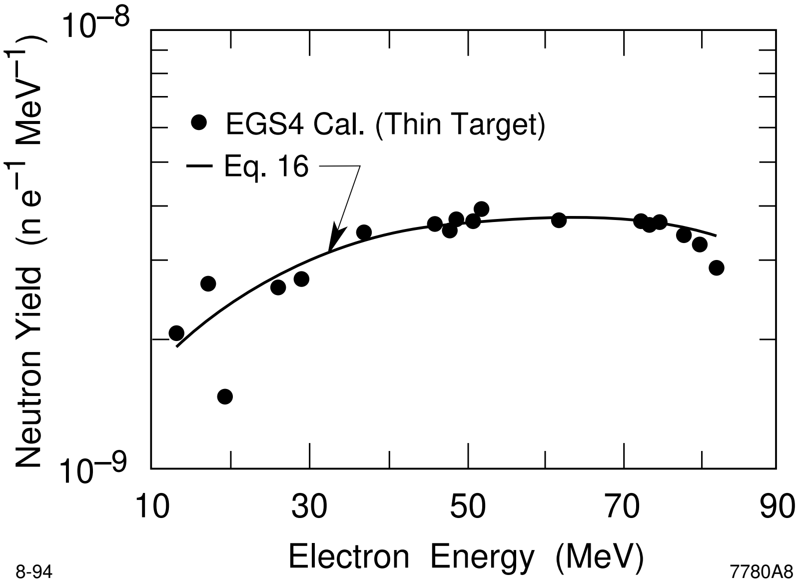

Figure 8. Neutron yields produced by bremsstrahlung in 0.01 r.l., thick targets struck by 100 MeV electrons as a function of the atomic number.

Thin target (photoneutron and electroproduction)

In Table 3, the total neutron yields, Y_{total}, produced by 34 MeV electrons in copper targets of different thicknesses are listed in the second column. The neutron yields calculated by EGS4, Y_{brem}, which only accounts for photoproduction, are listed in the third column. When the target thickness is 4.13 r.l., the neutron yield from electroproduction is relatively small. The measured neutron yield of the 4.13 r.l.-thick target (Column 2) is 27% higher than the neutron yield calculated by EGS4 (Column 3). The difference is attributed to the cross sections used in the EGS4 calculation and to measurement error. The measured Y_{brem} is estimated by multiplying the calculated Y_{brem} by the ratio of 1.27, and is listed in the fourth column. The ratios of the measured Y_{total} (Column 2) to the measured Y_{brem} (Column 4) are listed in Column 5. Barber and George (1959) subtracted an electroproduction

Table 3. Ratio of neutron yields produced by photo and electroproduction to those produced only by bremsstrahlung (34 MeV electrons, copper targets).

Target Thickness T (r.l.)	Measured Y_{total}[a] (10^{-5} n e^{-1} MeV^{-1})	Y_{brem} Calculated by EGS4 (10^{-5} n e^{-1} MeV^{-1})	Measured Y_{brem} Estimated by 1.27[b] x Calculated Y_{brem}	Ratio of Measured Y_{total} to Measured Y_{brem}	From Eq. 6, Tsai's Formula, $1+\frac{0.04}{T}$	From Eq. 8, NCRP No. 79, $1+\frac{\alpha(E_e)}{68.5\varepsilon\alpha_\gamma(E_e)}$
0.11	0.112	0.0591	0.0752	1.49	1.36	1.17
1.04	3.79	2.81	3.57	1.06	1.04	1.02
2.07	6.97	5.18	6.59	1.06	1.02	1.01
3.10	8.59	6.74	8.57	1.0	1.01	1.01
4.13	9.85	7.74	9.85	1.0	1.01	1.0

[a] Measured data are from Barber and George (1959).

[b] 1.27 is the ratio of the measured neutron yield of a 4.13 r.l.-thick target to the neutron yield calculated by EGS4, which accounts for the difference due to the cross sections used in the calculations and to the measurement error.

component, measured by Brown and Wilson (1954), from their total)neutron yield, and estimated that the ratio of $Y_{\text{total}}/Y_{\text{brem}}$ was about 1.33 for a 0.11-r.l.-thick copper target, which is close to the 1.49 value in Column 5. The estimates based on Tsai's approximations (Column 6) agree with those in column 5 within 10%, but the estimates given by NCRP (Column 7) are smaller than expected.

Combining Eqs. 6 and 16, the total neutron yield produced by bremsstrahlung and the direct electroproduction in thin targets can be estimated by

$$Y_{\text{thin}}^{\text{total}} = 8\times 10^{-4}\times(1+0.12\,Z-0.001\,Z^2)$$

$$\times\ \frac{T^2}{E_o}\left(1+\frac{0.04}{T}\right)\text{n electron}^{-1}\,\text{MeV}^{-1}. \qquad (17)$$

CONCLUSIONS

By using the EGS4 Monte Carlo code to calculate neutron yields for targets of varying atomic numbers at incident electron energies from 18 MeV to 10 GeV, this work characterizes the functional dependence of the yield on atomic number Z to better accuracy than previous publications. The thick-target formula (Eq. 9) estimates photoneutron yields within ±30% of EGS4 calculations for targets with thicknesses greater than 10 r.l. and electron energies above 50 MeV.

Comparison of EGS4 yield calculations with those based on Approximation A indicates that the latter yield should be multiplied by a factor of $0.17\ Z^{1/2}$.

The neutron yield produced from bremsstrahlung induced by electrons in thin targets is proportional to the square of the thickness for targets less than 0.75 r.l. and electron energies above 50 MeV. A simple scaling function (Eq. 15) has been developed to estimate, from the thick-target formula, the yields produced from bremsstrahlung in thin targets.

The ratio of the total neutron yield produced by the sum of photo and electroproduction to that produced only by bremsstrahlung is discussed, and a formula (Eq. 17) that can be used to estimate total neutron yields in thin targets is given.

This work marks the beginning of a series of studies on neutron production by electron beams. Future simulations will involve the tracking (transport) of neutrons in order to estimate energy fluences emanating from complex geometries—such as medical accelerator heads, shielding, and so on.

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