Nuclear Data for Science and Technology (1988 MITO), 1213-1216,

A MONTE CARLO SIMULATION OF ELECTRON-PHOTON CASCADES INCLUDING PHOTONUCLEAR PROCESSES

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Abstract: A Monte Carlo simulation code - SANDYL - for electron-photon cascades is extended to include photonuclear processes. For this purpose, we introduce a variance reduction technique for the photonuclear processes. Neutron yields and energy-spectra of emitted neutrons from Pb and U targets bombarded by electrons (16 - 45 MeV) are analyzed by the extended version of SANDYL and the use of the evaporation model. The results agree with the experimental data except the energy-spectrum in the case of the Pb target. The possible further investigation is also discussed.

(SANDYL, (γ, n) reaction, variance reduction technique, neutron yields and energy-spectra, evaporation model)

Introduction

As intence pulsed neutron sources, electron beams bombaring targets are commonly being used. In the target, the incident electron beam generates cascades of lesser-energy electrons and photons, and neutrons are produced mainly by the photons interacting with the nucleus in the giant resonance region (10 - 30 MeV).

Although there exist several computational codes[1,2] to simulate high-energy electron-photon cascades (up to a few thousand GeV), the photonuclear processes are not taken into account in those codes. This is mainly because the photonuclear cross sections are much smaller than the photoatomic ones. Namely event number for the photonuclear processes is negligible comparing with the one for the photoatomic processes. It is however crucial to consider neutrons produced even by the "negligible" processes in the simulation codes when one needs to design shields for equipments as well as the neutron sources.

In order to investigate neutrons produced by the photonuclear processes associated with the electron-photon cascades, we introduce a variance reduction technique of biasing the photonuclear cross sections to describe the photonuclear processes comparably with the photoatomic ones. In the present report, we set up the photonuclear processes in the electron-photon cascade code, SANDYL[2], and examine our variance reduction technique. Then with photonuclear events obtained by this extended SANDYL, we analyze energy-spectra of the produced neutrons mainly by the use of the evaporation model[3].

Variance Reduction Technique

In order to bias the photonuclear processes, let us split the total photon cross section (σ) into the photoatomic (σ_A) and photonuclear (σ_N) cross sections:

$$\sigma = \sigma_A + \sigma_N \ . \tag{1}$$

Then the event probabilities for the atomic and nuclear processes are respectively written as

$$P_A = \sigma_A/\sigma \ , \tag{2}$$

$$P_N = \sigma_N/\sigma \ . \tag{3}$$

When one of the two processes with the above probabilities is selected by a random number, the event number is counted as 1 for the selected process and 0 for the other one.

Now introducing a bias for the nuclear cross section as

$$\sigma' = \sigma_A + b\sigma_N \ , \tag{4}$$

where b is a parameter and larger than unit,the event probabilities with the above biased cross section are then written as

$$P_A' = \sigma_A/\sigma' \ , \tag{5}$$

$$P_N' = b\sigma_N/\sigma' \ . \tag{6}$$

We correct event numbers brought by the above biased probabilities as following: If the atomic process is selected by a random number, we count event number 1 for the atomic process and 0 for the nuclear process. If the nuclear process is selected,we count the corrected event number R where

$$R = P_N/P_N' \ , \tag{7}$$

for the nuclear process and 1-R for the atomic process to preserve the averaged yields (history $\rightarrow \infty$). Comparing eq. (3) with eq. (6), we get

$$R = b\sigma/\sigma' \ . \tag{8}$$

We summarize the corrected event number for the biased probabilities in the Table 1.

Table 1. Corrected Event Numbers for Biased Probabilities

	biased probability	event number	corrected event number	averaged yield
Atomic process	$P_A'=\sigma_A/\sigma'$	1, 0	1, $1-\sigma'/b\sigma$	σ_A/σ
Nuclear process	$P_N'=b\sigma_N/\sigma'$	0, 1	0, $\sigma'/b\sigma$	σ_N/σ

In case where several photonuclear processes are possible as

$$\sigma_N = \sum_j \sigma_N^j , \qquad (9)$$

where σ_N^j is cross section of the j-th photonuclear process, and the i-th photonuclear event is further selected by a random number with the probability σ_N^i/σ_N . Thus the final corrected event number for the i-th photonuclear process may be formally written as

$$R_i = R\sigma_N^i/\sigma_N . \qquad (10)$$

Similarly for the final corrected event number for the k-th photoatomic process, we formally write

$$A_k = (1-R)\sigma_A^k/\sigma_A , \qquad (11)$$

when involving the photonuclear processes, and otherwise

$$A_k = \sigma_A^k/\sigma_A , \qquad (12)$$

where σ_A^k is cross section of the k-th atomic process.

The informations of the photonuclear event R_i (magnitude, position and the incident energy) are obtained by the Monte Carlo calculation.

Evaporation and Fission Spectra

In the giant resonance region, the energy-spectrum of the produced neutrons can be mainly described by the evaporation model, and by the Maxwell distribution for fissionable nuclides. Here we employ the following evaporation spectra for the primarily and secondarily produced neutrons, and the following spectrum of the Maxwell distribution for the fission neutrons. In the evaporation model, we assume[3] that the residual nucleus always emits the secondary neutron if its excitation energy is sufficient to do so, and no other processes before it.

(i) Evaporation spectrum: The energy-spectrum of the primary neutron is described by

$$I_n(\varepsilon) = N_n\varepsilon\exp(-\varepsilon/T_n) , \qquad (13)$$

with

$$T_n = (\varepsilon_n/T_n)^{1/2} , \qquad (14)$$

$$\varepsilon_n = \varepsilon_\gamma - \varepsilon_{nt} , \qquad (15)$$

$$a_n = A/c_n , \qquad (16)$$

where ε, ε_γ and ε_{nt} are the energies of the primary neutron, the incident photon and the threshold of the primary neutron respectively, and A is mass number of the target nucleus, and c_n a parameter representing the energy level density[3] of the nucleus. Here we assume constant cross section for formation of the compound nucleus[3]. The normalization factor N_n is obtained by

$$N_n = R_n/\int_0^{\varepsilon_n} I_n(\varepsilon)d\varepsilon , \qquad (17)$$

where R_n is defined by eq. (10) considering σ_N^i as the total (γ, n) cross section.

For the secondary neutron, the spectrum is

$$I_{2n}(\varepsilon') = N_{2n}\varepsilon'\exp(-\varepsilon'/T_{2n}), \qquad (18)$$

with

$$T_{2n} = (\varepsilon_{2n}^M/a_{2n})^{1/2} , \qquad (19)$$

$$\varepsilon_{2n}^M = \varepsilon_\gamma - \varepsilon_{2nt} - \varepsilon , \qquad (20)$$

$$a_{2n} = (A-1)/c_{2n} , \qquad (21)$$

where ε' and ε_{2nt} are the energy and the threshold energy of the secondary neutron respectively, and c_{2n} is a parameter representing the energy level density of the residual nucleus. Under our assumption for the process of the secondary neutron, the normalization factor N_{2n} is obtained by

$$N_{2n} = R_{2n}/\int_0^{\varepsilon_{2n}} I_{2n}(\varepsilon')d\varepsilon' , \qquad (22)$$

where $\varepsilon_{2n} = \varepsilon_\gamma - \varepsilon_{2nt}$, and R_{2n} is defined by eq. (10) considering σ_N^i as $(\gamma, 2n)$ cross section.

(ii) Fission spectrum: For the energy-spectrum of the fission neutron, we employ the Maxwell distribution as

$$I_f(\varepsilon) = N_f\varepsilon^{1/2}\exp(-\varepsilon/T_f) , \qquad (23)$$

with

$$\varepsilon_f = \varepsilon_\gamma - \varepsilon_{ft} , \qquad (24)$$

where ε_{ft} is the threshold energy of $(\gamma$, fission) reaction, T_f the temperature of the nucleus, and the normalization factor N_f is obtained by

$$N_f = R_f/\int_0^{\varepsilon_f} I_f(\varepsilon)d\varepsilon , \qquad (25)$$

and R_f is defined by eq. (10) considering σ_N^i as $(\gamma$, fission) cross section.

Extended SANDYL

In the present work, we set up three photonuclear processes (γ, n), $(\gamma, 2n)$ and $(\gamma, 3n)$ or $(\gamma$, fission) in SANDYL. Throughout this work we use the default parameters for all atomic processes given in SANDYL and the threshold energies of (γ, n) or $(\gamma$, fission) reactions as the cut-off energy of the particle transport. Then for our considering energy region it reproduces the spectrum of bremsstrahlung photons from the thick tungsten target obtained by Berger and Seltzer[5].

Firstly we examine our variance reduction technique for the case of natural Pb target (Pb-VI case given below) bombarded by electron beams of 34.4 MeV. We use the parameterized Lorentz form[6] of the total photonuclear cross section of natural Pb[7]. We show the bias-dependence of the averaged photonuclear event number in fig. 1 from which we see the stable feature of the bias parameter b varing from 20 to 70.

In the case of b=40 where the magnitudes of the biased photonuclear cross sections are comparable to the ones of the photoatomic cross sections, we got 740 photonuclear events and 140 seconds of CPU time (CRAY X-MP). Comparing them with the result in the case of b=1 where we got 583 photonuclear events and 2623 seconds, we thus reduced CPU time to 1/20 with the better statistical reliability.

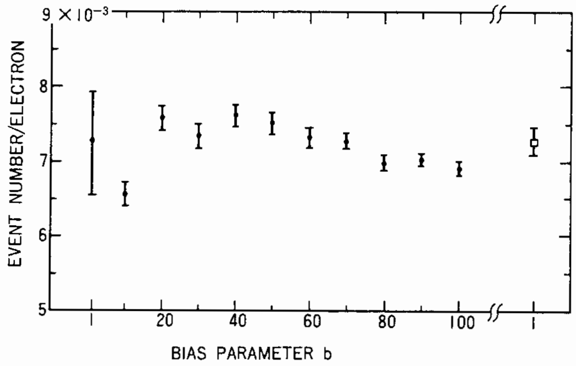

Fig. 1. Bias dependence of photonuclear event number for the natural Pb target. The errors are caused by the statistics of Monte Carlo calculation. The dots correspond to the ones calculated with 4000 histories, and the square to the one in the case of b=1 but 80000 histories instead.

Neutron Yields and Energy-Spectra

In this section we analyze the experimental data for neutron yields[8] and energy-spectra[9] by the method presented in the previous sections.

As for (γ, 2n) cross section of natural Pb, we use the following relation[3],

$$\sigma(\gamma,2n) = \sigma_T(\gamma,n)[1-(1+\varepsilon_{2n}/T_n)\exp(-\varepsilon_{2n}/T_n)],$$

where $\sigma_T(\gamma, n)$ is the total (γ, n) cross section whose parameterized Lorentz form is given in ATLAS[6]. As for the U cross sections, we use our parameterized forms which reproduce the experimental (γ, n), (γ, 2n) and (γ, fission) cross sections[10]. We employ the bias parameters of 40 and 50 for the Pb and U cases respectively to have the comparable photonuclear cross sections with the photoatomic ones. The parameters c_n and c_{2n} are taken as 25 for the Pb cases and 6.5 for the U cases (see ref. 4), and T_f as 1.05 to fit the energy-spectrum to the experimental one.

Fig. 2 and 3 show the energy-dependences of the neutron yields from the natural Pb and U targets of the radius 6 cm for three cases concerning the target thickness. Here we assumed the averaged neutron multiplicity $\bar{\nu}$=3.5 for (γ, fission) reaction of the uranium. Our results agree reasonably with the experimental data within the uncertainties of the experiment.

Fig. 4 and 5 show the neutron energy-spectra from the natural Pb and U targets of 2.5 diameter disk and 3-radiation thickness. We see that the role of the secondary neutrons is important in describing the spectrum in the low-energy region even in the case of the natural Pb target. Our results agree overall with the experimental ones except the case of the natural Pb target in the low-energy region ($\varepsilon < 2$ MeV). Since there exist narrow resonances in the Pb neutron cross sections[11] at these low energies, the deviation in this low-energy region is remedied[12] by considering neutron transport in the target.

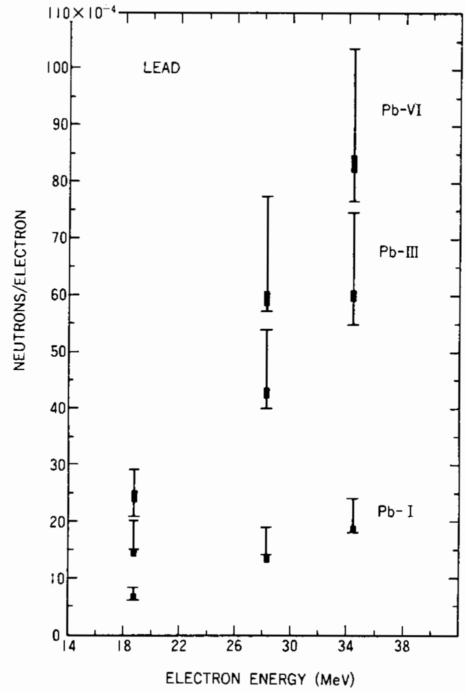

Fig. 2. Neutron yields from the natural Pb targets. The experimental ones are indicated by the thin lines, and the numerical ones by the thick lines. Pb-I corresponds to the target of 0.5185 cm thickness with 12000 histories, Pb-III to the one of 1.526 cm thickness with 6000 histories and Pb-VI to the one of 3.035 cm thickness with 4000 histories.

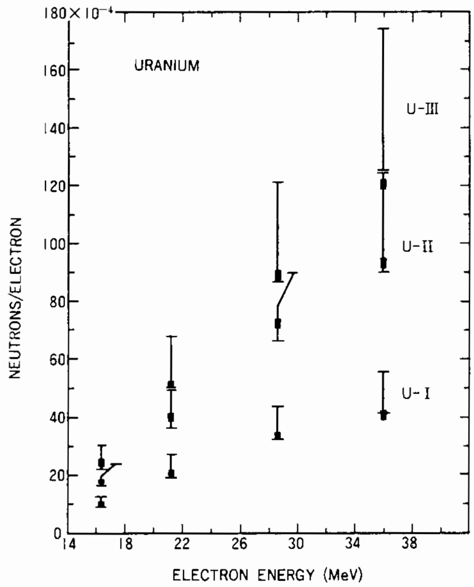

Fig. 3. Neutron yields from the natural U targets. U-I corresponds to the target of 0.330 cm thickness with 12000 histories, U-II to the one of 0.664 cm thickness with 8000 histories, and U-III to the one of 0.995 cm thickness with 8000 histories. See the figure caption of fig. 2.

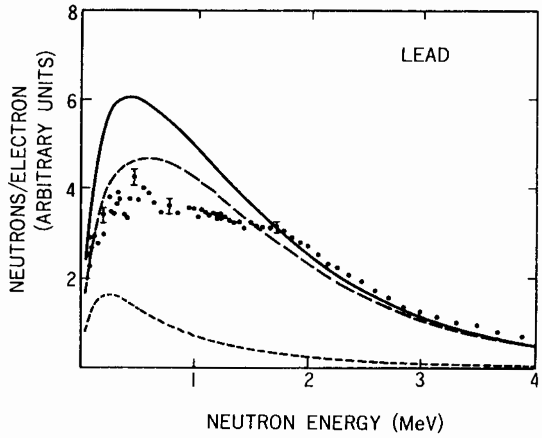

Fig. 4. Neutron energy-spectrum from the natural Pb target. ——— corresponds to the one for the primary neutrons, --- to the one for the secondary neutrons, and —— to the total one. The experimental data are from ref. 9.

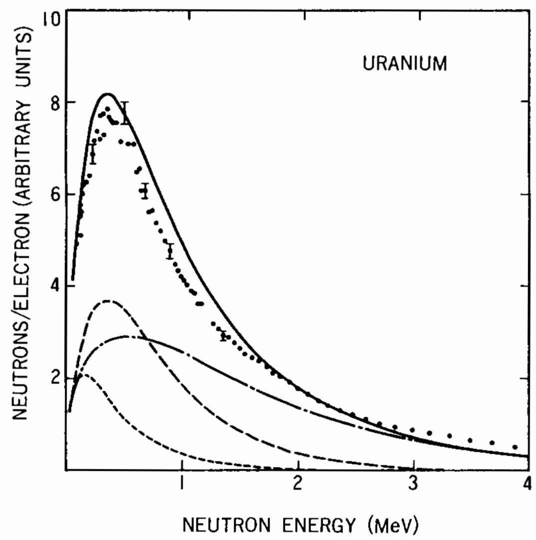

Fig. 5. Neutron energy-spectrum from the natural U target. -·- to the one for the fission neutrons. See the figure caption of fig. 4 for thc rests.

Summary

Our results in the previous sections show that our variance reduction technique of biasing the photonuclear cross sections is successful in the efficiency and the reliability as it reduces CPU time considerably (1/20 or less) with the statistically reasonable reliability. Note that one may reduce CPU time further with the larger bias parameters.

As for the analyses of the produced neutrons by the photonuclear processes, we obtained the reasonable results for the neutron yields from both the natural Pb and U targets, and the reasonable descriptions for the neutron energy-spectra overall from the natural Pb and U targets. We noticed however the deviation from the experimental data in our numerical results for the low-energy spectrum in the case of the natural Pb. This deviation and also the detailed structures of the energy-spectra may be further studied by consideration of neutron transport in the target.

References

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