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P. G. Young

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

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AN EVALUATION OF GAMMA-RAY PRODUCTION CROSS SECTIONS
FROM NEUTRON-INDUCED REACTIONS ON TUNGSTEN

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ABSTRACT

An evaluation of neutron-induced gamma-ray production cross sections and secondary spectra for the major tungsten isotopes has been completed for neutron energies from 10^{-5} eV to 20 MeV. The evaluation for energies in the kiloelectron-volt region is based on calculations. In the thermal and million-electron-volt regions, the evaluation is based on experimental data for natural tungsten that were fitted with a simple statistical theory. This theory facilitates smoothing and extrapolation to unmeasured neutron and gamma-ray energies and allows derivation of the constituent ^{182}W , ^{183}W , ^{184}W , and ^{186}W data from the natural element measurements, thus enabling the gamma-ray evaluation to be combined with recent evaluations of isotopic neutron-production cross sections performed elsewhere.

The combined data sets for the isotopes are available in ENDF/B format from the Defense Nuclear Agency's cross-section library at the Radiation Shielding Information Center in Oak Ridge. They are also available from the National Neutron Cross Section Center at Brookhaven in Version IV of ENDF/B.

I. INTRODUCTION

This report describes an evaluation of gamma-ray production from neutron-induced reactions on tungsten for neutron energies from 10^{-5} eV to 20 MeV. The evaluated data are in ENDF/B format and consist of photon-production multiplicities (ENDF/B File 12) and cross sections (File 13), secondary photon angular distributions (File 14), and secondary photon energy distributions (File 15) for ^{182}W , ^{183}W , ^{184}W , and ^{186}W . The photon-production data were combined with recent evaluations of neutron-production data by Rose et al.¹ for the same isotopes. The complete data sets are available from the Defense Nuclear Agency's cross-section library at the Radiation Shielding Information Center (RSIC) in Oak Ridge and from the National Neutron Cross Section Center at Brookhaven in Version IV of ENDF/B. The material numbers of the ENDF/B evaluations are 1128, 1129, 1130, and 1131 for ^{182}W , ^{183}W , ^{184}W , and ^{186}W , respectively.

The evaluated data are based mainly on measurements using natural tungsten that were analyzed with a simple statistical theory. This theory was used to interpolate and extrapolate the data into unmeasured neutron and gamma-ray energy regions and to analyze the natural element measurements in terms of contributions from the individual isotopes. Although the evaluated gamma-ray data are most accurate for natural tungsten, these data were broken down into isotopic contributions so that they could be combined with Rose's¹ neutron-production evaluations.

The experimental gamma-ray spectrum measurements by Jurney² for thermal neutrons and by Dickens et al.³ for neutrons in the million-electron-volt (MeV) region were used in the analysis. Similarly, theoretical calculations by Yost et al.⁴ were included in the electron-volt (eV) and kiloelectron-volt (keV) neutron energy regions.

The gamma-ray data for each of the isotopes are separated into two parts: (1) an (n, γ) radiative

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capture component expressed as multiplicities in File 12, and (2) a combined (n,xy) component from gamma-ray de-excitation of levels following (n,n'), (n,2n), and (n,3n) reactions, expressed as production cross sections in File 13. The (n,γ) photon energy distributions are given entirely as continuous spectra in File 15. The (n,xy) photon energy distributions are given as discrete photon cross sections in File 13 up to a neutron energy at which knowledge of the level decay properties of each isotope becomes unsatisfactory. At higher neutron energies, continuous spectra in File 15 are used.

The nuclear properties of tungsten and its major isotopes are summarized in Sec. II. In Sec. III, the techniques used in the statistical theory calculations are discussed, and comparisons of the calculated and measured spectra are presented. In Sec. IV, the evaluation of the (n,γ) cross sections and spectra is described, and in Sec. V, the analysis of experimental (n,xy) data from (n,n'γ), (n,2nγ), and (n,3nγ) reactions is summarized. In Sec. VI, the quality of the evaluated photon-production data is discussed, with a brief description of the uncertainties in the results.

II. NUCLEAR PROPERTIES OF TUNGSTEN

Natural tungsten ($Z = 74$) is composed of ^{180}W (0.13%), ^{182}W (26.3%), ^{183}W (14.3%), ^{184}W (30.7%), and ^{186}W (28.6%).⁵ The small amount of ^{180}W present in natural tungsten is ignored in this evaluation.

Table I gives the Q-values⁶ and thresholds of important gamma-ray producing reactions for the major tungsten isotopes over the 0- to 20-MeV neutron energy range. Because the charged-particle-producing reactions such as (n,p), (n,α), and (n,np) have cross sections less than ~20 mb in this energy range,¹ gamma rays from these reactions are not included explicitly in the evaluation, but they are lumped into the continuous spectra that represent the (n,n'γ), (n,2nγ), and (n,3nγ) reactions. Similarly, gamma rays from (n,4n) reactions are barely possible near 20 MeV, but these were not included explicitly in the theoretical calculations used to analyze the gamma-ray emission spectra.

Cross sections for discrete gamma rays produced in inelastic scattering through the first few levels of each of the major isotopes were calculated at low neutron energies from level excitation cross sec-

TABLE I
Q-VALUES AND THRESHOLDS FOR IMPORTANT
PHOTON-PRODUCING REACTIONS ON TUNGSTEN

Reaction	Q-Value (MeV)	Threshold (MeV)
$^{182}\text{W}(n,\gamma)^{183}\text{W}$	+ 6.191	---
$^{182}\text{W}(n,n')^{182}\text{W}^*$	- 0.1001	0.1007
$^{182}\text{W}(n,2n)^{181}\text{W}$	- 8.055	8.100
$^{182}\text{W}(n,3n)^{180}\text{W}$	-14.701	14.782
$^{183}\text{W}(n,\gamma)^{184}\text{W}$	+ 7.412	---
$^{183}\text{W}(n,n')^{183}\text{W}^*$	- 0.0465	0.0468
$^{183}\text{W}(n,2n)^{182}\text{W}$	- 6.191	6.225
$^{183}\text{W}(n,3n)^{181}\text{W}$	-14.245	14.324
$^{184}\text{W}(n,\gamma)^{185}\text{W}$	+ 5.750	---
$^{184}\text{W}(n,n')^{184}\text{W}^*$	- 0.1112	0.1118
$^{184}\text{W}(n,2n)^{183}\text{W}$	- 7.412	7.453
$^{184}\text{W}(n,3n)^{182}\text{W}$	-13.602	13.677
$^{186}\text{W}(n,\gamma)^{187}\text{W}$	+ 5.467	---
$^{186}\text{W}(n,n')^{186}\text{W}^*$	- 0.1225	0.1232
$^{186}\text{W}(n,2n)^{185}\text{W}$	- 7.202	7.241
$^{186}\text{W}(n,3n)^{184}\text{W}$	-12.951	13.021

tions. The energy level decay schemes used to obtain the discrete gamma-ray cross sections are shown in Figs. 1-4 for ^{182}W , ^{183}W , ^{184}W , and ^{186}W , respectively. The decay schemes are based on information compiled in Refs. 7-10. The numbers in parentheses under the branching ratios for several of the transitions are corrections for internal conversion¹¹ and indicate the fraction of transitions that occur by gamma-ray emission.

III. STATISTICAL THEORY CALCULATIONS

A. Theory

Existing experimental data on gamma-ray production from tungsten consist mainly of (n,xy) spectrum measurements from natural tungsten targets that are limited to gamma-ray energies greater than ~0.7 MeV. Therefore, to facilitate more accurate interpolation and extrapolation of these data into unmeasured neutron and gamma-ray energy regions and to estimate the spectra for individual isotopes, much of the

Ignoring radiative capture, Fig. 5 shows the formation of the compound nucleus $[A + 1]$ at excitation energy $E_0 + S_1$ by an incident neutron of energy E_0 , and the subsequent decay of $[A + 1]$, $[A]$, and $[A - 1]$ by emission of one, two, and three neutrons, respectively. The neutron separation energies for the various nuclei are indicated by S_1 , so that the maximum neutron energy from (n, n') reactions is $\epsilon_1^{\max} = E_0$, from $(n, 2n)$ reactions it is $\epsilon_2^{\max} = E_0 - S_2$,

For inelastic scattering, the probability of the compound nucleus emitting a neutron of energy ϵ to a state at excitation E in the nucleus [A] is taken to be of the form

where $\sigma_I(\epsilon)$ is the usual inverse cross section with $\epsilon = E_0 - E$, and $C_n(E_0)$ is a normalization factor. In Eq. 1, $N_n(E)$ represents the absolute differential cross section for "first neutron" emission in units of cross section per unit energy, so that $C_n(E_0)$ was determined from

Fig. 3. Energy level decay scheme for ^{184}W .

$$\int_{E_c}^{E_0} N_n(E) dE + \sum_{i=1}^N \sigma(E_i) = \sigma_0(E_0) \quad (2)$$

where $\sigma_0(E_0)$ is the total cross section for neutron emission from the compound nucleus. In Fig. 5, where radiative capture and charged particle emission are assumed negligible, $\sigma_0(E_0)$ is simply the compound nucleus formation cross section and equals the sum of the inelastic, $(n,2n)$, and $(n,3n)$ cross sections, that is,

$$\sigma_0(E_0) = \sigma_{n,n'}(E_0) + \sigma_{n,2n}(E_0) + \sigma_{n,3n}(E_0) \quad (3)$$

States in the various residual nuclei populated by Eq. (1) were required to decay by further neutron emission if their excitation energy lay above the neutron separation energy, that is, if $E > S$. States with $E \geq S$ were required to gamma decay to lower states in the same nucleus, with transition probabilities given by

Fig. 4. Energy level decay scheme for ^{186}W .

Fig. 5. Schematic representation of neutron and gamma-ray emissions from $(n,n'\gamma)$, $(n,2n\gamma)$, and $(n,3n\gamma)$ reactions.

$$S_Y(E, E') \Delta E' = C_Y(E) (E - E')^{2l+1} \rho(E') \Delta E', \quad (4)$$

where l is the multipole order of the transition. Again, $C_Y(E)$ is a normalization factor that requires all levels at energy E to decay to lower lying levels and is determined by

$$\int_0^E S_Y(E, E') dE' = N_n(E) + N_Y(E), \quad (5)$$

where $N_n(E)$ is defined by Eqs. (1) and (2) and represents the population of levels (in units of cross section per unit energy) at energy E formed in neutron transitions. Similarly, $N_Y(E)$ is the population at E as a result of gamma-ray transitions from all higher levels, or

$$N_Y(E) = \int_E^{E_0} S(E', E) dE'. \quad (6)$$

Finally, the spectrum of gamma rays from transitions within the continuum can be obtained by suitably summing the transitions defined in Eq. (4)

$$P(E_Y) = \int_{E_Y + E_c}^{E_0} S(E, E - E_Y) dE, \quad (7)$$

where $P(E_Y) dE_Y$ is the differential cross section for production of gamma rays with energy between E_Y and $E_Y + dE_Y$.

Numerical techniques were used in calculating the gamma-ray spectra. The available region of excitation energy for each possible residual nucleus was divided into many equally spaced energy bins. The calculation was begun by populating all the energy bins in nucleus [A] by inelastic scattering using Eqs. (1) and (2). Then, starting with the bin at highest excitation energy, each bin was successively depopulated, either by neutron emission to bins in the adjacent nucleus or by gamma-ray emission to the bins at lower excitation energy in the same nucleus using Eqs. (4) and (5). For gamma-ray emission, the contribution to the gamma-ray spectrum from each transition, as well as the increase in popula-

Fig. 6. Calculated gamma-ray spectra from the $(n, n'\gamma)$ reaction with 8-MeV incident neutrons assuming pure dipole and pure quadrupole gamma-ray transitions.

tion of excited levels in each lower energy bin, was recorded. When discrete levels were not included, the calculation for a given residual nucleus terminated when all but the lowest energy bin was depopulated.

Typical shapes of spectra calculated without discrete states are shown in Figs. 6 and 7. These calculations are for $(n, n'\gamma)$ reactions with a bombarding energy of 8 MeV, and $\sigma_0 (= \sigma_{n, n'})$ in Eq. (2) is assumed to be 1 b. A level density of the form $\exp(E/T)$ is used in each case, and the inverse cross section is assumed to be constant. Figure 6 compares the spectra obtained with $T = 0.7$ MeV, assuming $l = 1$ (pure dipole) and $l = 2$ (pure quadrupole) for the multipole order in Eq. (4). Similarly, Fig. 7 shows spectra calculated at several different temperatures with a pure dipole assumption. The spectral shapes are strongly dependent on the level-density parameter and become harder with increasing temperature. Consequently, the gamma-ray multiplicity decreases as the temperature increases.

All the calculations used in the present evaluation include discrete levels. Transitions from the continuum to the discrete region were handled separately by distributing those transitions among the known discrete levels with relative probability

7. Calculated gamma-ray spectra from the $(n,n')\gamma$ reaction with 8-MeV incident neutrons assuming several different temperatures in the level density expression.

$$S_Y^I(E) = (E - E_I)^{2I+1} (2J_I + 1) \quad (8)$$

where J_I is the spin of the i^{th} discrete level.^a The normalization of Eq. (8) was determined by

$$\sum_{i=1}^N S_Y^I(E) = \int_0^E S(E, E') dE' \quad (9)$$

Transitions among the discrete levels were computed directly using known level branching ratios. The (n,n') level excitation cross sections were also inputted directly into the calculations, and Eqs. (8) and (9) were used to calculate the discrete level excitation from continuum gamma-ray transitions.

The above discussion outlines the present application of statistical theory to calculate gamma-ray spectra from (n,n') , $(n,2n)$, and $(n,3n)$ reactions. The same technique was used to calculate spectra from radiative capture, but it will not be detailed here. A major difference in the (n,γ) calculations is that only the capturing states in the compound nucleus are initially excited, that is, $N_n(E) = 0$ except

^aThe $(2J_I + 1)$ term is an empirical factor that was added because it improved agreement with experimental data.

when $E = E_0$. Also, adequate account must be taken of $(n,\gamma n')$ reactions, which result when neutron emission occurs following primary gamma-ray transitions from the capturing state to levels with $E > S_0$. In these calculations, levels formed in primary transitions that have $E > S_0 + 0.3$ MeV were assumed to decay completely by neutron emission. A third difference in the radiative capture calculations is that ρ_0 in Eq. (2) is now given by

$$\rho_0 = \rho_{n,\gamma} + \rho_{n,\gamma n'} \quad (10)$$

B. Fits to Experimental Data

The fitting code GFITIN, which is based on the above theory, was used to extract parameters from experimental measurements of secondary gamma-ray spectra. The spin-independent composite form of the level-density function given by Gilbert and Cameron¹³ was assumed in the calculations, and gamma-ray emission was taken to be dipole ($\lambda = 1$) in nature. A constant inverse cross section was assumed in all cases.

In the Gilbert and Cameron formulation, the level density is represented by the function $\rho_1(E)$ for $E \leq E_N$ and $\rho_2(E)$ for $E > E_N$, where

$$\rho_1(E) = (1/T) \exp[(E - E_0)/T] \quad (11)$$

and

$$\rho_2(E) = \frac{\sqrt{\pi}}{12} \frac{\exp(2\sqrt{aU})}{U^{5/4}} \frac{1}{\pi\sqrt{2\pi}} \quad (12)$$

with

$$U = E - P(Z) - P(N) \quad (13)$$

and

$$\sigma^2 = 0.0888\sqrt{aU} A^{2/3} \quad (14)$$

The quantity A is atomic weight, and $P(Z)$ and $P(N)$ are proton and neutron pairing energies obtained from Gilbert and Cameron.¹³ For this analysis, the primary level density parameter was taken to be "a" in Eq. (12). Once the value for "a" was

selected, the constants E_s , K_0 , and T were determined by the requirements that $\rho_1(E)$ agree with the known level structure at low excitation energies and that $\rho_1 = \rho_2$ and $\rho_1' = \rho_2'$ at $E = E_s$.

Because the calculations involved (n,γ) , $(n,n'\gamma)$, $(n,2n\gamma)$, and $(n,3n\gamma)$ reactions on the four major tungsten isotopes, level decay scheme data were required for the ^{180}W - ^{187}W isotopes. Table II summarizes the discrete level data that were used. The decay schemes for ^{182}W , ^{183}W , ^{184}W , and ^{186}W are also shown in Figs. 1-4, although additional levels were sometimes used for the calculations. The number of levels included for each isotope depends on how well the particular decay scheme is known, and there is a wide variation among the isotopes. In general, levels were not included past the maximum excitation energy at which the branching ratios were reasonably well established. The transition energy E_c between the discrete and continuum regions was chosen to lie just above the excitation energy of the highest level included.

The only two parameters that were varied in fitting a spectrum measured at a given energy were the Gilbert and Cameron level density parameter a , which determined the shape of the spectrum, and the overall normalization factor σ_0 , which is defined in Eq. (2) and is related to other cross sections by either Eqs. (3) or (10). Because all the data used were for natural tungsten, the level density param-

eter was assumed to be the same for the four major isotopes at each neutron energy. In addition, at energies where $(n,2n\gamma)$ or $(n,3n\gamma)$ reactions were possible, the same level density parameter was assumed for each of the possible residual nuclei.

The normalization quantity σ_0 was also assumed to be the same for each isotope at incident neutron energies in the MeV region, and the natural element spectra were obtained by weighting the spectra calculated for the isotopes by their natural abundances. When the theory was applied to (n,γ) spectra in the resonance region, however, the spectra for the isotopes were weighted by the product of natural abundance and capture cross section, as calculated from resonance parameters.

Although the theory was also used to fit experimental data for thermal neutrons² and to represent (n,γ) data from other calculations⁴ at neutron energies in the eV and keV regions, the major emphasis was in fitting Dickens' spectrum measurements³ for neutron energies between 1 and 20 MeV. These measurements were taken at the Oak Ridge Electron Linear Accelerator, using a continuous energy neutron source and time of flight to establish neutron energies. A NaI detector located 125° relative to the incident neutron beam was used for the measurements, and the detector response was unfolded to obtain the gamma-ray spectra. Data were obtained for gamma-ray energies between 0.68 and 10.6 MeV, and the experimental results were binned in both neutron and gamma-ray energies. The neutron energy bin widths range from 0.5 to 3 MeV, and the gamma-ray bin widths range from 20 to 160 keV, although the spectra were combined further for the calculations. The accuracy of the overall normalization of the measurement is ~ 10%.

Figure 8 shows the fit to the (n,γ) capture part of Dickens' measurement for the 1.0- to 1.5-MeV neutron energy bin. The error bars on the experimental data indicate relative errors only. The rapid rise in the measured spectrum at gamma-ray energies below 1.5 MeV results from $(n,n'\gamma)$ reactions. Here the calculated curve corresponds to the parameters $\sigma_0 = 0.10$ b and $a = 11.75 \text{ MeV}^{-1}$; the total gamma-ray production cross section from radiative capture is 0.39 b.

A similar comparison is shown in Fig. 9 for the 4.0- to 4.5-MeV neutron energy bin. In this case

TABLE II
SUMMARY OF DISCRETE LEVEL DATA USED
IN CALCULATIONS

Element	Number Excited Levels	Number Gamma Rays	Maximum Level Energy (MeV)	E_c (MeV)	Reference Number
^{180}W	3	3	0.690	0.749	14
^{181}W	3	4	0.385	0.395	15
^{182}W	17	52	1.661	1.748	7
^{183}W	10	32	0.554	0.638	8
^{184}W	8	15	1.135	1.199	9
^{185}W	2	2	0.085	0.148	16
^{186}W	5	6	0.850	0.950	10
^{187}W	4	6	0.205	0.293	17

Fig. 8. Measured and calculated gamma-ray spectra from the $^{182}\text{W}(n,\gamma)$ reaction for the 1.0- to 1.5-MeV neutron energy bin. The histogram is a theoretical fit to the (n,γ) part of the Dickens et al.³ measurements.

Fig. 9. Measured and calculated gamma-ray spectra from the $^{182}\text{W}(n,\gamma)$ reaction for the 4.0- to 4.5-MeV neutron energy bin. The histogram is a theoretical fit to the (n,γ) part of the Dickens et al.³ measurements.

the $(n,n'\gamma)$ contribution is more important and the production cross section for radiative capture gamma rays is ~ 0.14 b, as compared with ~ 7.8 b for $(n,n'\gamma)$ reactions.

Fits to the capture cross-section segments of Dickens' data at other neutron energies below ~ 5 MeV were of comparable quality to those shown in Figs. 8 and 9. The shape of the capture part of the spectra is poorly defined by the measurements at higher neutron energies because of the decreasing capture cross section and the increasing importance of $(n,n'\gamma)$ reactions. Consequently, average level density values were used to calculate (n,γ) spectra for the evaluation at higher energies.

Fits to the $(n,n'\gamma)$, $(n,2n\gamma)$, and $(n,3n\gamma)$ parts of Dickens' spectra are given by the solid histograms in Figs. 10-16. In each case the calculated spectrum was averaged over the neutron energy bin of the measurement and smeared with the experimental gamma-ray resolution function. Discrete (n,n') cross sections for the 2^+ and 4^+ levels of ^{182}W , ^{184}W , and ^{186}W were inputted directly into the spectrum fitting code. The 2^+ and 4^+ excitation cross sections were calculated using parameters from Lister et al.¹⁸ and the nonspherical optical model code FORPLUS by Dunford.¹⁹ The (n,n') cross sec-

tions to all other levels were assumed to be negligible compared to excitation by gamma-ray cascades from higher levels.

Figure 10 shows the analysis of the measurement for the 4.0- to 4.5-MeV neutron energy bin. For comparison, the spectrum from (n,γ) reactions given in Fig. 9 is included in Fig. 10 (dashed curve). The fits to the $(n,n'\gamma)$ spectra near 4 MeV were the poorest achieved with Dickens' data.

Figure 11 shows the fitted and measured spectra for the 6.0- to 6.5-MeV neutron energy bin, and Fig. 12 compares the results for the 8.0- to 9.0-MeV energy bin. Gamma rays from $(n,n'\gamma)$ reactions predominate in the spectra at both energies, but a contribution from $(n,2n\gamma)$ reactions is present in the 8.5-MeV spectrum. The rising spectrum at low gamma-ray energies in Fig. 12 is indicative of the softening of the spectrum from the onset of $(n,2n\gamma)$ reactions. The fits at these energies are considerably improved over those at 4.25 MeV.

The measured and calculated spectra for the 10- to 12- and 12- to 14-MeV neutron energy bins are given in Figs. 13 and 14, respectively. At these neutron energies, the spectra are composed mainly of gamma rays following $(n,2n)$ reactions, $\sim 80\%$ for the 11-MeV spectrum and 90% for the 13-MeV spectrum.

Fig. 10. Measured and calculated gamma-ray spectra from the $^{235}\text{W}(n,x\gamma)$ reaction for the 4.0- to 4.5-MeV neutron energy bin. The histogram is a theoretical fit to the $(n,n'\gamma)$ part of the Dickens et al.³ measurements, and the dashed curve is a fit to the (n,γ) part of the data.

Fig. 12. Measured and calculated gamma-ray spectra from the $^{235}\text{W}(n,x\gamma)$ reaction for the 8.0- to 9.0-MeV neutron energy bin. The histogram is a theoretical fit to the $(n,n'\gamma)$ and $(n,2n\gamma)$ part of the Dickens et al.³ measurements.

Fig. 11. Measured and calculated gamma-ray spectra from the $^{235}\text{W}(n,xy)$ reaction for the 6.0- to 6.5-MeV neutron energy bin. The histogram is a theoretical fit to the $(n,n'\gamma)$ part of the Dickens et al.³ measurements.

Fig. 13. Measured and calculated gamma-ray spectra from the $^{235}\text{W}(n,xy)$ reaction for the 10- to 12-MeV neutron energy bin. The histogram is a theoretical fit to the $(n,n'\gamma)$ and $(n,2n\gamma)$ part of the Dickens et al.³ measurements.

Again, the agreement is good between the fitted and measured spectra.

Figures 15 and 16 show the measured and calculated spectra for the 14- to 17- and 17- to 20-MeV neutron energy bins. The 15.5-MeV spectrum results mainly from $(n,2n\gamma)$ reactions (~85%), whereas about

60% of the gamma rays in the 18.5-MeV spectrum come from $(n,3n\gamma)$ reactions. The agreement is still reasonably good between the measured and fitted shapes, although the calculated curve is somewhat low at the lowest gamma-ray energies of the measurements.

Fig. 14. Measured and calculated gamma-ray spectra from the $^{238}\text{W}(n,XY)$ reaction for the 12- to 14-MeV neutron energy bin. The histogram is a theoretical fit to the $(n,n'\gamma)$, $(n,2n\gamma)$, and $(n,3n\gamma)$ part of the Dickens et al.³ measurements.

Fig. 16. Measured and calculated gamma-ray spectra from the $^{238}\text{W}(n,XY)$ reaction for the 17- to 20-MeV neutron energy bin. The histogram is a theoretical fit to the $(n,n'\gamma)$, $(n,2n\gamma)$, and $(n,3n\gamma)$ part of the Dickens et al.³ measurements.

Fig. 15. Measured and calculated gamma-ray spectra from the $^{238}\text{W}(n,XY)$ reaction for the 14- to 17-MeV neutron energy bin. The histogram is a theoretical fit to the $(n,n'\gamma)$, $(n,2n\gamma)$, and $(n,3n\gamma)$ part of the Dickens et al.³ measurements.

Fig. 17. Values of the normalization factor σ_0 and the level density parameter a , obtained by fitting the Dickens et al.³ $^{238}\text{W}(n,XY)$ measurements. The crosses represent parameters obtained by fitting the (n,γ) part of the measurements, and the circles indicate points obtained by analyzing the $(n,n'\gamma)$, $(n,2n\gamma)$, and $(n,3n\gamma)$ parts of the spectra. The curves connecting the points indicate parameter values used to calculate the spectra at intermediate energies in the evaluation.

The values of the normalization parameter σ_0 and the level density parameter a , obtained from Dickens' data, are presented as functions of neutron energy in Fig. 17. The level density parameter results oscillate about an average value of

$a \approx 12 \pm 2 \text{ MeV}^{-1}$. The σ_0 curve also shows structure, particularly near the thresholds for the $(n,2n)$ and $(n,3n)$ reactions. Because σ_0 approximately equals the nonelastic cross section, one would expect a reasonably smooth behavior even near the particle thresholds. Therefore, although the good fits achieved in Figs. 8-16 are gratifying from such a simple theory, the oscillatory effects in the parameter curves of Fig. 17 are indicative of the approximate nature of the theory and indicate the need for improvement.

It is interesting to compare the results from these calculations with the simpler, empirical representations used by Howerton and Plechaty²⁰ and Perkins et al.²¹ In Ref. 20, the shape of the gamma-ray spectrum is assumed to have the form

$$P(E_\gamma) \propto E_\gamma e^{-RE_\gamma} \quad (15)$$

in analogy to the shape of a neutron evaporation spectrum, that is, R is equivalent to an inverse temperature. This representation was refined by Perkins et al.²¹ in the following manner. Below a gamma-ray energy of $\bar{E}_\gamma^T$, Eq. (15) was assumed to hold; for $E_\gamma > \bar{E}_\gamma^T$, however, an empirical factor was added to Eq. (15) so that

$$P(E_\gamma) \propto E_\gamma e^{-RE_\gamma} \left[\frac{E_\gamma^{\max} - E_\gamma}{E_\gamma^{\max} - \bar{E}_\gamma^T} \right], \quad (16)$$

where $E_\gamma^{\max}$ is the maximum gamma-ray energy from the reaction under consideration and $\bar{E}_\gamma^T$ is the total energy removed by gamma rays, which equals the product of the average gamma-ray energy in the spectrum times the gamma-ray multiplicity. The improvement brought about by Eq. (16) is to force $P(E_\gamma)$ to zero at the maximum possible gamma-ray energy, although inclusion of the factor introduces a discontinuity in the slope of the spectrum at $E_\gamma = \bar{E}_\gamma^T$.

In Figs. 18-20 we compare spectra calculated for ^{184}W using the present technique (solid curves) and those obtained from Eqs. (15) and (16) (dashed curves) at three incident neutron energies. These three figures show radiative capture at 1.25, $(n,n'\gamma)$ at 6.25, and $(n,2n\gamma)$ at 13.0 MeV. In each case,

$P(E_\gamma)/E_\gamma$ is plotted so that Eq. (15) results in a straight line on the semilog graphs. The lower dashed curves indicate the calculations with Eq. (16). Although the calculated shapes are for ^{184}W , Dickens' natural tungsten measurements³ are included for comparison. The parameter $R(\bar{E}_\gamma^T)$ in Eqs. (15) and (16) was chosen to agree reasonably with Dickens' data and to be consistent with the $R(\bar{E}_\gamma^T)$ vs $\bar{E}_\gamma^T$ graph obtained for tantalum by Perkins et al.²¹ The normalization of the dashed curves was chosen arbitrarily to agree with the solid curves.

Although differences are apparent, particularly for $E_\gamma < 1 \text{ MeV}$, the shapes obtained from the empirical formulas agree reasonably with the present calculations over much of the gamma-ray energy region. The closest agreement occurs for the radiative capture calculation in Fig. 18. For the case of capture, the Howerton and Plechaty and the Perkins et al. representations are equivalent and result in straight lines on the semilog plot. Even in the capture case, however, there is a small but systematic departure by the present calculations from the straight-line behavior predicted by Eq. (15).

The agreement between the present calculations and the empirical formulas is not as good for the $(n,n'\gamma)$ case in Fig. 19, but is much better with Eq. (16) (short dashes) than Eq. (15). Again, the solid curve shows a small but systematic departure from linearity.

The comparison for the $(n,2n\gamma)$ case in Fig. 20 is complicated by the fact that corrections for the $(n,n'\gamma)$ events were included in the present calculations but were not applied to the predictions of Eqs. (15) and (16). This partly accounts for the disagreement at high gamma-ray energies. Overall, however, the agreement is reasonable and quite good for $E_\gamma = 1$ to 4 MeV.

IV. $W(n,\gamma)$ EVALUATED SPECTRA

The evaluated (n,γ) data are in the form of photon multiplicities in File 12 of the ENDF/B format and in relative energy distributions in File 15, tabulated in 0.25-MeV-wide gamma-ray energy bins. The multiplicities and tabulated spectra are given as functions of neutron energy using the radiative capture reaction type number MT = 102. Note, however, that because of the multiplicity representation,

Fig. 18. Gamma-ray spectra from the $^{184}\text{W}(n,\gamma)$ reaction induced by 1.25-MeV neutrons calculated with the present technique (solid curve) and with the methods of Howerton and Plechaty²⁰ and Perkins et al.²¹ (dashed curve). The Dickens et al.³ $\text{NatW}(n,\gamma)$ data are shown for comparison. Note that the data are divided by gamma-ray energy to facilitate comparison with Eq. (15).

Fig. 19. Gamma-ray spectra from the $^{184}\text{W}(n,n'\gamma)$ reaction induced by 6.25-MeV neutrons calculated with the present technique (solid curve) and with the methods of Howerton and Plechaty²⁰ and Perkins et al.²¹ (dashed curves). See Fig. 18 caption for additional details.

the radiative capture cross section in File 3 is required to obtain the absolute gamma-ray production cross section from capture. The photon angular distributions were assumed isotropic in all cases; this information is given in File 14.

The evaluated spectra in File 15 are based on the NatW spectrum measurement by Jurney² for thermal neutrons and on calculations by Yost et al.⁴ for neutron energies between 3 eV and 0.1 MeV. In both instances the relative spectral shapes were fitted with the theory described in Sec. III to obtain evaluated spectra for the individual isotopes. In fitting the NatW data, the calculated isotopic spectra were weighted by the product of natural abundance and capture cross section, which was estimated from resonance parameters. Correction factors $F(E_\gamma)$ were applied to the evaluated isotopic spectra in regions where the calculations agreed poorly with the $\text{NatW}(n,\gamma)$ data of Jurney and Yost et al. These corrections were interpolated smoothly over neutron energy. The largest corrections were required at higher gamma-ray energies where primary transitions are important; for $E_\gamma < 4.5$ MeV, corrections were typically about 10%.

Fig. 20. Gamma-ray spectra from the $^{184}\text{W}(n,2n\gamma)$ reaction induced by 13-MeV neutrons calculated with the present technique and with the methods of Howerton and Plechaty²⁰ and Perkins et al.²¹ (dashed curves). See Fig. 18 caption for additional details.

Fig. 21. Evaluated gamma-ray spectra from the $\text{NatW}(n,\gamma)$ reaction induced by thermal, 10-eV, and 100-eV neutrons. The solid circles represent Jurney's² revised thermal measurements, the squares represent Orphan's²² thermal data, and the crosses and triangles represent Orphan and John's²³ measurements for the 0.02- to 1- and 60- to 120-eV neutron energy bins, respectively.

The evaluated photon multiplicities for neutron energies less than 100 keV were obtained from the relation

$$M = (B_n + E_0) / \bar{E}_\gamma \quad (17)$$

where B_n is the neutron binding energy in the compound nucleus, E_0 is the incident neutron energy in the center-of-mass system, and $\bar{E}_\gamma$ is the average gamma-ray energy in the File 15 evaluated spectra. Equation (17) is necessary to satisfy the requirement of total energy conservation.

Examples of the evaluated gamma-ray production spectra are shown at six neutron energies between thermal and 100 keV in Figs. 21 and 22. The natural

Fig. 22. Evaluated gamma-ray spectra from the $\text{NatW}(n,\gamma)$ reaction induced by 1-, 10-, and 100-keV neutrons. The solid circles represent Orphan and John's²³ measured spectra for the 1- to 100-keV neutron energy bin.

tungsten spectra were constructed from the isotopic data using radiative capture cross sections calculated at $T = 0^\circ\text{K}$ from the resonance parameters and smooth cross sections given in the Rose et al.¹ evaluations.

The evaluated spectrum for thermal neutrons in Fig. 21 (solid histogram) was obtained from a preliminary measurement by Jurney.² Because of a problem in the gamma-ray detector used in the preliminary measurement (particularly for low-energy photons), the experiment had to be repeated with a new detector. The final results are indicated by the crosses in Fig. 21. The new results were received too late to be included in the ENDF/B Version IV evaluation, but a revised evaluation including the new results is available from the DNA cross-section library at RSIC. A thermal measurement by Orphan et al.²² and the near-thermal measurements

by Orphan and John²³ are compared to the Journey² results in Fig. 21. Large discrepancies occur between the Orphan data and the final Journey results.

Epithermal spectrum measurements by Orphan and John²³ are also shown in Figs. 21 and 22. These data were obtained in fairly wide neutron energy bins, generally covering several resonances in the tungsten isotopes, and were not included directly in the evaluation. In Fig. 21 the triangles indicate data for the 60- to 120-eV neutron energy bin, and the closed circles in Fig. 22 represent the spectrum measured for the 1- to 100-keV neutron energy bin. In each case the epithermal relative measurements were normalized to the capture cross section used to compute the evaluated histograms.

Because of the large energy bins in the measurements, the comparisons in Figs. 21 and 22 of the evaluated data at particular energies with the Orphan epithermal results are only approximate. The Orphan data seem to indicate a generally harder spectrum than given by the evaluation, which was based on calculations by Yost et al.⁴ In an earlier paper, however, Penny, Yost, and White²⁴ demonstrated good agreement between the Orphan measurement and a similar calculation with a different level density representation.

For neutron energies >0.1 MeV, the File 15 spectra from radiative capture were based entirely on calculations using level density parameters obtained by fitting Dickens' measurements, as described in Sec. III. The level density parameters used for the (n,γ) calculations are given by the dashed curve in Fig. 17.

Because contributions from the $(n,\gamma n')$ reactions were included in the evaluated spectra from (n,γ) reactions, Eq. (17) does not apply at neutron energies where $(n,\gamma n')$ reactions are important relative to (n,γ) . Therefore, photon multiplicities above $E_n = 0.1$ eV were derived from the production cross sections, which were obtained by fitting the radiative capture part of Dickens' measurements and the (n,γ) cross sections from the Rose et al.¹ evaluations. The multiplicities were biased somewhat low to partially compensate for possible multiple reaction effects in the experimental data. The magnitude of the adjustment was crudely estimated from results given by Devaney,²⁵ but detailed calculations were not performed.

Comparisons of Dickens' measurements at neutron energies between 1 and 20 MeV with composite evaluated spectra of photons from all sources, including radiative capture, are presented in Sec. V.

V. $W(n,n'\gamma)$, $W(n,2n\gamma)$, and $W(n,3n\gamma)$ EVALUATED CROSS SECTIONS AND SPECTRA

The evaluated data for $(n,n'\gamma)$, $(n,2n\gamma)$, and $(n,3n\gamma)$ reactions were combined into general $(n,x\gamma)$ files using the ENDF/B reaction type number MT = 4. The data are given as cross sections in File 13 for production of discrete gamma rays up to the neutron energy where knowledge of the level decay schemes for the various isotopes becomes unsatisfactory. File 15 gives the tabulated energy distributions at higher neutron energies. The gamma-ray angular distributions were assumed isotropic at all energies.

The discrete gamma-ray representation was used up to incident neutron energies of 1.4 MeV for ¹⁸²W, 0.6 MeV for ¹⁸³W, 1.1 MeV for ¹⁸⁴W, and 1.0 MeV for ¹⁸⁶W. Below these energies, the gamma-ray cross sections were obtained from the (n,n') level excitation cross sections evaluated by Rose et al.,¹ together with the level decay schemes for ¹⁸²W, ¹⁸³W, ¹⁸⁴W, and ¹⁸⁶W, as shown in Figs. 1-4.

At higher neutron energies, the evaluated $(n,x\gamma)$ data are based on the analysis described in Sec. III of Dickens' spectrum measurements.³ Bin widths of 0.25 MeV were used for all the gamma-ray spectra. Similar to the (n,γ) case, correction factors $F(E_\gamma)$ were applied to the fitted spectra in regions of poor agreement with Dickens' measurement. Examples of the fitted $(n,x\gamma)$ spectra are shown in Figs. 10-16. The agreement between calculated and measured spectra is poorest for neutron energies below 6 MeV and gamma-ray energies below 1.5 MeV, and corrections were required mainly in those regions.

The evaluated gamma-ray production cross sections for the individual tungsten isotopes are given in the lower half of Fig. 23, and the resulting natural tungsten cross section is shown in the upper half of the figure. The cross sections for each of the isotopes go through minima ~2 MeV past the thresholds for the $(n,2n)$ reactions, and less pronounced minima occur after the $(n,3n)$ thresholds. The minima occur at different energies for the various isotopes because of different Q -values for the reactions (see Table I). The overall effect of the

Fig. 23. Evaluated gamma-ray production cross sections for the major tungsten isotopes and for natural tungsten as constructed from the isotopic data.

structure in the isotopic data appears as minima near 10 and 16 MeV in the composite NAT_W curve.

Combined evaluated spectra for the (n,γ) and $(n,x\gamma)$ reactions are compared to Dickens' measurements at neutron energies between 1 and 20 MeV in Figs. 24-43. The histograms were obtained by combining the isotopic data for the (n,γ) and $(n,x\gamma)$ reactions into fine-grouped spectra, adding the spectra weighted by isotopic abundances to obtain natural tungsten data, averaging the spectra over the neutron energy bins used in the measurements, and smearing with the resolution function of the gamma-ray detector.

The radiative capture components of the gamma-ray spectra are most prominent at the lower neutron energies, accounting for all gamma rays in the evaluation with $E_\gamma > E_n$. As discussed in Sec. IV, the capture component was deliberately biased somewhat

low to compensate for possible multiple reaction effects in the experiment.

The structure in the evaluated spectra at low gamma-ray energies results from gamma-ray transitions between discrete levels included in the calculations. The discrete levels are populated mainly by transitions from the continuum region. The structure that occasionally appears in the experimental data at higher gamma-ray energies was smoothed in the evaluation.

VI. DISCUSSION

The statistical theory calculations used to obtain isotropic data from natural tungsten measurements are most valid for neutron energies in the keV and MeV regions, that is, well above the resonance region. Consequently, the evaluated spectra for the isotopes at thermal and eV neutron energies should be regarded as approximate and used individually with caution. However, the gamma-ray spectra from (n,n') , $(n,2n)$, and $(n,3n)$ reactions in the MeV region are expected to be reasonably valid for the isotopes. Similarly, the isotopic spectra from (n,γ) reactions at neutron energies above 100 keV should be valid up to an energy of a few MeV, where direct (n,γ) reactions become important. At higher energies, the present treatment will tend to underestimate the high-energy part of the (n,γ) spectra.

Because the experimental data included here were for natural tungsten, the evaluated results are most reliable for applications dealing with natural tungsten. When combined into NAT_W , the thermal spectrum (based on the final Journey data) has a relative accuracy of $\sim 10\%$. The radiative capture cross section for thermal neutrons is known to $\sim 3\%$,²⁶ and the overall photon multiplicity is accurate to $\sim 5\%$.

The normalization of the $\text{NAT}_W(n,x\gamma)$ spectra at MeV neutron energies is known to $\sim 10\%$ over the region of Dickens' measurements,³ and the accuracy of the spectral shapes is best estimated by comparing the evaluated and measured shapes in Figs. 24-43, with consideration for the statistical error bars on the experimental data. The contribution to the total production cross section from gamma rays at energies below the minimum energy in the measurement is as much as 50%. At these energies, internal conversion, which was only partly taken into

account in the calculations, competes strongly with level decay by gamma-ray emission. Therefore, the calculated part of the spectrum at low energies is probably no better than 30%, and the overall error in the total production cross section (^{235}U curve in Fig. 23) is about 20% below 10 MeV and about 25% at higher energies.

The region of greatest uncertainty in the data is at energies between the thermal measurements and Dickens' data in the MeV region. A precise estimate of uncertainties in this region is impossible, but comparisons with Orphan's epithermal data given in Figs. 21 and 22 indicate that the evaluated data

might underestimate the high-energy part of the gamma-ray spectra for epithermal neutrons.

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Fig. 24. Evaluated and measured³ gamma-ray spectra from the NatW(n,γ) reaction for the 1.0- to 1.5-MeV neutron energy bin.

Fig. 25. Evaluated and measured³ gamma-ray spectra from the NatW(n,γ) reaction for the 1.5- to 2.0-MeV neutron energy bin.

Fig. 26. Evaluated and measured³ gamma-ray spectra from the $\text{NatW}(n, x\gamma)$ reaction for the 2.0- to 2.5-MeV neutron energy bin.

Fig. 27. Evaluated and measured³ gamma-ray spectra from the $\text{NatW}(n, x\gamma)$ reaction for the 2.5- to 3.0-MeV neutron energy bin.

Fig. 28. Evaluated and measured³ gamma-ray spectra from the $\text{NatW}(n, \gamma)$ reaction for the 3.0- to 3.5-MeV neutron energy bin.

Fig. 29. Evaluated and measured³ gamma-ray spectra from the $\text{NatW}(n, \gamma)$ reaction for the 3.5- to 4.0-MeV neutron energy bin.

Fig. 30. Evaluated and measured³ gamma-ray spectra from the $\text{NatW}(n,xy)$ reaction for the 4.0- to 4.5-MeV neutron energy bin.

Fig. 31. Evaluated and measured³ gamma-ray spectra from the $\text{NatW}(n,xy)$ reaction for the 4.5- to 5.0-MeV neutron energy bin.

Fig. 32. Evaluated and measured³ gamma-ray spectra from the $\text{NatW}(n, \gamma)$ reaction for the 5.0- to 5.5-MeV neutron energy bin.

Fig. 33. Evaluated and measured³ gamma-ray spectra from the $\text{NatW}(n, \gamma)$ reaction for the 5.5- to 6.0-MeV neutron energy bin.

Fig. 34. Evaluated and measured³ gamma-ray spectra from the $\text{NatW}(n, \gamma)$ reaction for the 6.0- to 6.5-MeV neutron energy bin.

Fig. 35. Evaluated and measured³ gamma-ray spectra from the $\text{NatW}(n, \gamma)$ reaction for the 6.5- to 7.0-MeV neutron energy bin.

Fig. 36. Evaluated and measured³ gamma-ray spectra from the $\text{NatW}(n, \gamma)$ reaction for the 7.0- to 7.5-MeV neutron energy bin.

Fig. 37. Evaluated and measured³ gamma-ray spectra from the $\text{NatW}(n, \gamma)$ reaction for the 7.5- to 8.0-MeV neutron energy bin.

Fig. 38. Evaluated and measured³ gamma-ray spectra from the $\text{NatW}(n,\gamma)$ reaction for the 8.0- to 9.0-MeV neutron energy bin.

Fig. 39. Evaluated and measured³ gamma-ray spectra from the $\text{NatW}(n,\gamma)$ reaction for the 9.0- to 10.0-MeV neutron energy bin.

Fig. 40. Evaluated and measured³ gamma-ray spectra from the $\text{NatW}(n, \gamma)$ reaction for the 10- to 12-MeV neutron energy bin.

Fig. 41. Evaluated and measured³ gamma-ray spectra from the $\text{NatW}(n, \gamma)$ reaction for the 12- to 14-MeV neutron energy bin.

Fig. 42. Evaluated and measured³ gamma-ray spectra from the $\text{NatW}(n,\gamma)$ reaction for the 14- to 17- MeV neutron energy bin.

Fig. 43. Evaluated and measured³ gamma-ray spectra from the $\text{NatW}(n,\gamma)$ reaction for the 17- to 20-MeV neutron energy bin.

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