MASTER

AN EVALUATED DATA SET FOR TANTALUM

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February 27, 1975

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Contents

Abstract	1
Introduction	1
Neutron Cross Sections	1
Neutron Angular Distributions	5
Neutron Energy Distributions	6
Cross Sections for Gamma-Ray and X-Ray Production	9
Angular Distributions for Gamma-Ray and X-Ray Production	17
Energy Distributions for Gamma-Ray and X-Ray Production	17
Cross Sections for Conversion-Electron Production	19
Angular Distributions for Conversion-Electron Production	20
Energy Distributions for Conversion-Electron Production	20
An Integral Test of the Evaluated Data	21
Acknowledgments	22
References	23

AN EVALUATED DATA SET FOR TANTALUM

Abstract

The methods used to obtain cross sections and angular and energy distributions for neutron-induced reactions

and gamma-ray, x-ray, and conversion-electron production are described for ^{181}Ta .

Introduction

This report describes the derivation of evaluated neutron-interaction, photon-production and conversion-electron-production data for tantalum. It includes bibliographic references to the original experiments upon which the evaluated data are based.

Since natural tantalum is 99.99% ^{181}Ta , it makes no practical difference whether natural tantalum or ^{181}Ta is quoted as the source material in experiments. The evaluated data set covers neutron reactions from 0.00001 eV to 20 MeV. In this energy range, in addition to elastic scattering, a number of nonelastic reactions are energetically possible. Table 1 lists these reactions, their thresholds, and references that give the threshold energies.

Of the reactions that produce charged particles, all but the (n, p) reaction have been ignored, as there are essentially no measurements for them and their cross

sections are estimated to be negligible. The nonelastic reactions that are included in our evaluated data set are (n, n'), (n, 2n), (n, 3n), (n, p), and (n, γ).

Table 1. Nonelastic neutron reactions.

Reaction	Threshold (MeV)	References
n, n'	0.00623	1
n, 2n	7.69	2
n, 3n	14.3	2
n, p	0.24	2
n, np	5.97	2
n, d	3.73	2
n, nd	11.16	2
n, t	4.87	2
n, nt	11.00	2
n, He ₃	6.20	2
n, nHe ₃	13.24	2
n, α	Exoergic (Q = 7.41)	2
n, n α	Exoergic (Q = 1.53)	2
n, γ	Exoergic (Q = 6.06)	2

Neutron Cross Sections

TOTAL CROSS SECTION

In the neutron energy region below 300 eV, the total cross section consists

of elastic scattering plus neutron capture, as expressed in a set of resolved resonance parameters. For this part of the evaluated data set, we have used a standard

set of resolved resonance parameters [BNL-325, Suppl. 2, Vol. IIc, (1966)] to generate the cross sections. In the energy region from 300 eV to 20 MeV, total cross sections were taken from the experimental data of Refs. 3 through 19. Total cross sections have been measured over this energy range to quoted accuracies of about 2%. However, the scatter in data among different experiments amounts to about 10% over the entire energy range. Hence the evaluated total cross sections have an estimated error of about 5%.

NONELASTIC CROSS SECTION

Measurements of the nonelastic cross section have been made at 1 MeV,²⁰ 2.5 MeV,²¹ 4.1 MeV,⁹ 7 MeV,²¹ and 14 MeV.²² The nonelastic cross sections entered into the present evaluation are in agreement with the measured values. At 14 MeV, the evaluated nonelastic cross section lies at the upper edge of the relatively large error band for the experimental value,²² which was obtained from an early emulsion experiment. The choice made for the nonelastic cross section at 14 MeV is in reasonable agreement with systematics. Experimental determinations of the nonelastic cross section have quoted uncertainties of $\pm 10\%$ in the 2.5- to 7-MeV range and $\pm 20\%$ at higher and lower energies. When information from systematics is included, the evaluated nonelastic cross sections are probably accurate to $\pm 10\%$.

ELASTIC CROSS SECTION

Below 300 eV, elastic cross sections were obtained for the evaluated data set

by using the resolved resonance parameters listed in BNL-325, Suppl. 2, Vol. IIc (1966). This resonance parameter set is based on a single-level analysis with an assumed material temperature of 0°K. The elastic cross section is equal to 6.25 b at 0.0253 eV and is essentially constant over the region of thermal and subthermal energies. Above 300 eV, the elastic cross section was set equal to the difference between the evaluated total and nonelastic cross sections, which were obtained from measurements as described above.

Direct measurements of the elastic cross section have been made at some energies,^{20,23-26} These measured values are in general agreement with the values obtained by taking the differences between total and nonelastic cross sections. Since evaluated total and nonelastic cross sections have respective errors of $\pm 5\%$ and $\pm 10\%$, the evaluated elastic cross sections have accuracies of about $\pm 10\%$.

NONELASTIC REACTION CROSS SECTIONS

Nonelastic reaction cross sections include the (n, n') , $(n, 2n)$, $(n, 3n)$, (n, p) , and (n, γ) reactions.

(n, n') Reaction

Inelastic excitation cross sections in tantalum have been measured to six different groups of levels.²⁴ The lowest three groups are probably doublets, the next two are probably triplets, and the highest may be a single level.¹ To resolve the doublets, the recent $(n, n'\gamma)$ gamma ray data of Dickens and Morgan²⁷ were used. The normalization of Ref. 24 was preferred, and a compromise was

made between the excitation functions of Refs. 24 and 27. The levels at 0.1561, 0.1586, 0.3015, 0.3375, 0.4822, 0.495, 0.620, 0.720, and 0.925 MeV are included in this evaluation.

Reference 24 did not include data for the lowest-lying level at 0.00623 MeV, because the inelastic neutrons from that level are experimentally unresolvable from elastic neutrons. Whether the level is included at all in the evaluation is of little importance from the point of view of neutron transport, and it is therefore neglected as a discrete level excitation in the (n, n') reaction. It is, however, of some importance in terms of conversion-electron production. We have used calculated values obtained by Donald Gardner with the COMNUC code²⁸ for this latter purpose.

Continuum inelastic-scattering cross sections were obtained by differencing the total nonelastic cross section and the sum of the partial nonelastic cross sections after the nonelastic cross section and all other nonelastic reactions have been evaluated. In addition to the data of Smith,²⁴ other references to (n, n') scattering are given in Refs. 29 through 35. The evaluated cross sections for excitation to specific levels are accurate to $\pm 20\%$, whereas the continuum $(n, n'\gamma)$ cross section is estimated to be accurate to about $\pm 40\%$.

$(n, 2n)$ Reaction

There have been a number of measurements of this cross section.^{22,35-41} However, most of them were activation measurements based on the 8.1-h isomer.³⁶⁻⁴¹ Since production of this isomer represents less than half of the total $(n, 2n)$ cross

section, these measurements are not very helpful in determining the total $(n, 2n)$ cross section. The only other data are 14-MeV measurements²² so they give no information as to the shape of the $(n, 2n)$ cross section.

Furthermore, Ref. 22 is an early plate experiment. Reference 35, a large scintillator experiment in which one of us (M. H. M.) participated, gives a value for the $(n, 2n)$ cross section that is larger than the nonelastic cross section. Fortunately, taking an average of Refs. 19 and 35 gives an $(n, 2n)$ cross section at 14 MeV (2.2 b) that is in reasonable agreement with the systematics of other reactions in tantalum. But we still have to determine the shape of the $(n, 2n)$ excitation function over the remainder of the energy range from threshold to 20 MeV.

In the first pass at producing a tantalum evaluation, we assumed an $(n, 2n)$ cross section that rose rather slowly from the 7.69-MeV threshold value. However, recent data,⁴² when combined with theory, showed that this slow rise in the $(n, 2n)$ cross section is probably not correct. These new data were combined with theory and incorporated into the evaluation in the following manner.

Howerton and Plechaty⁴³ in 1968 provided a formalism for calculating gamma-ray production cross sections and energy distributions. This formalism implies that the production of gamma rays will fall off sharply just above the $(n, 2n)$ threshold because the emission of a second neutron will compete strongly with the emission of gamma rays. The validity of this implication was strikingly confirmed in a recent measurement of gamma-ray production from neutron bombardment

of tantalum made by an Oak Ridge group.⁴² As predicted by Howerton and Plechaty, the gamma-ray production curve (Fig. 18 of Ref. 42) shows a sharp drop for neutron energies immediately above 8 MeV. Furthermore (and in line with present purposes), the magnitude of the drop in the gamma-ray production data can be used to deduce how fast the $(n, 2n)$ cross section must be rising. The Oak Ridge data shows rather clearly that the slow (first-pass) rise for the $(n, 2n)$ cross section could not be correct.

In examining other heavy elements to see what the shape of the $(n, 2n)$ cross section looks like near threshold, we found that the only element for which a good $(n, 2n)$ shape has been measured is ^{238}U . Thus, as a means of improving the evaluation of the shape of the $(n, 2n)$ cross section, we used the measured shape for ^{238}U , adjusting the abscissa to allow for the difference in threshold energies. The ordinate was changed to match the 14-MeV cross section value of 2.2 b. When this modified $(n, 2n)$ cross section was used in a calculation and compared with the Oak Ridge gamma-ray data, good agreement was obtained.

The gamma-ray calculation is summarized in the section on gamma-ray production. The modified $(n, 2n)$ data was inserted into the final tantalum evaluated data set. When the various systematic constraints on the $(n, 2n)$ cross section are taken into account, the $(n, 2n)$ evaluated cross sections are probably accurate to $\pm 15\%$ in the neighborhood of 14 MeV, although the errors surely exceed this amount in steeply rising regions near threshold and at high energies (15 to 20 MeV).

$(n, 3n)$ Reaction

No measurement of the $(n, 3n)$ reaction has been made for tantalum. The $(n, 3n)$ cross section was deduced from systematics, with (hopefully) judicious adjustment of the $(n, 2n)$ and $(n, n'\gamma)$ cross sections to maintain the estimated nonelastic cross section. The uncertainties in the evaluated cross sections are estimated to be 60 to 80%, since the differences of poorly determined quantities are involved.

(n, p) Reaction

The (n, p) cross section is several orders of magnitude smaller than the cross sections discussed above. Two measurements of tantalum (n, p) cross sections exist, spanning the energy range from 13 to 17.5 MeV.^{44,45} Reference 45 was used together with an extrapolation of the cross section down to the threshold energy of 0.24 MeV as the basis for the evaluation. The evaluated (n, p) data are estimated to be accurate to $\pm 90\%$, which is probably adequate considering the smallness of the cross sections.

(n, γ) Reaction

Many measurements have been made of the (n, γ) cross section.⁴⁵⁻⁷¹ The energy range for these measurements extends from thermal energies to 5 MeV. In the energy region below 300 eV, the resolved resonance-parameter set mentioned above [BNL-325, Suppl. 2, Vol. IIc, (1966)] was used to obtain the neutron-capture cross section. From 300 eV to 5 MeV, the (n, γ) cross section was determined from the measured data. Above 5 MeV, the (n, γ) cross section is very small, and any reasonable extrapolation procedure gives adequate values for it.

In the resolved resonance region, the errors are about $\pm 20\%$. In the unresolved

resonance region and above, the errors are about $\pm 25\%$.

Neutron Angular Distributions

ANGULAR DISTRIBUTIONS FOR ELASTIC SCATTERING

Experimental measurements of the angular distribution for elastic scattering of neutrons from tantalum have been made at a series of energies ranging from 0.06 to 14.6 MeV.^{9,20-22,24,26,30,72-82} At neutron energies below 0.05 MeV, the elastic scattering was assumed to be isotropic in the center-of-mass system. Between 0.05 MeV and 1.0 MeV, the elastic angular distributions were taken from experiment. Optical-model calculations were done for incident neutron energies between 1.0 and 20 MeV.

For all energies in this range where experiments had been done, the agreement between calculation and experiment for angles less than 30° was very good. The locations of maxima and minima were accurate, as were the magnitudes of the relative maxima. As would be expected, the calculated minima showed strong disagreements with the experimental minima, since the experimental resolution could not eliminate either the direct level excitation for low-lying levels or the high-energy preequilibrium component of inelastic scattering. This apparent disagreement in the minima was resolved by using the optical-model results for the evaluation.

The optical-model results agree well with experiment in the region where most of the cross section lies. We knew of no other way of correcting satisfactorily for

the experimental resolution problem in the region of the minima. Elastic-scattering angular distributions have average data-point uncertainties of about $\pm 15\%$ in addition to the normalization uncertainty of $\pm 10\%$ for the total elastic cross section.

ANGULAR DISTRIBUTIONS FOR NONELASTIC SCATTERING

The few available experimental data^{24,26} indicate that angular distributions of the neutrons scattered from specific levels are essentially isotropic in the center-of-mass system. Hence isotropic center-of-mass angular distributions were used to determine the $(n, n'\gamma)$ excitations to specific levels. The $(n, 2n)$ and $(n, 3n)$ processes were assumed to be isotropic in the laboratory frame of reference. Experimentally,⁸³ this approximation appears to be justified.

For incident neutron energies below 7 MeV, the continuum $(n, n'\gamma)$ neutrons were assumed to be isotropic in the laboratory frame of reference. For incident neutron energies greater than 7 MeV, anisotropic angular distributions were assumed, since the neutrons from the $(n, n'\gamma)$ reaction at incident neutron energies greater than 7 MeV show a distinct forward peaking of the nonequilibrium neutrons. Insufficient experimental data exist to provide for the energy-angular correlation of these neutrons, and a correlation cannot be obtained as with a

unique two-body breakup reaction, so an estimated average anisotropy was used.

The errors in the angular distributions for discrete-level scattering and for $(n, 2n)$ and $(n, 3n)$ processes are estimated

to be about 10 to 15%. The errors in the high-energy $(n, n'\gamma)$ continuum angular distributions may be as much as a factor of 3 for some neutrons at some angles.

Neutron Energy Distributions

The formalism that we used to specify the nonelastic neutron spectra is described individually for each of these reactions. Although much of the following discussion is couched in terms of the evaporation model, the energy distributions are presented exclusively as tables. Since not all distributions can be represented in the evaporation formalism, but all can be represented by tables, a tabular representation preserves consistency. A minor but pertinent point is the choice of the low-energy cut-off if nuclear temperatures are presented. The tables make the intended use of the data explicit.

(n, n') REACTION

The energy diagram for continuum (n, n') reactions is shown in Fig. 1. Two energy ranges can be defined:

$$E_n = E_n^L < 7.7 \text{ MeV}$$

and

$$E_n = E_n^H > 7.7 \text{ MeV},$$

where E_n is the incident neutron energy and 7.7 MeV is the $(n, 2n)$ threshold. In the E_n^L energy region, only (n, n') reactions are possible (if n, p and n, γ reactions

are neglected), and the (n, n') neutrons form a typical boilloff spectrum.

Reference 30 gives boilloff temperatures for incident neutron energies between 2.44 and 7 MeV. In general, the temperature will scale⁸⁴ as $U_A^{1/2}$, where U_A is the excitation energy shown in Fig. 1. This temperature is a property of the final-state nucleus, since it characterizes the density of final states available for the inelastic neutron emission. If the matrix elements for decays to these final states are roughly constant, then the decay probabilities, and hence the temperature of the neutron spectrum, will be proportional to the density of final states.

In cases where the temperature is determined by interpolation or extrapolation, an iterative calculational scheme was used: an average neutron secondary energy was estimated, and the corresponding final-state temperature from the U_A value and the average neutron energy corresponding to this temperature

Fig. 1. Available-energy diagram for the (n, n') reaction.

were calculated. If this average neutron energy was different from the original estimate, an iteration was carried out to bring these quantities into agreement.

In the E_n^H incident neutron-energy range, we assumed that for $E_n \geq 7.7$ MeV, the inelastic neutron energy E_n^I (see Fig. 1) will be large enough to leave the residual (A) nucleus below the (n, 2n) threshold; otherwise, the emission of a second neutron was assumed to occur. Thus, for $E_n \geq 7.7$ MeV, the E_n^I neutrons from the (n, n') reaction are all high-energy neutrons, with energies ranging from E_n down to $E_n - 7.7$ MeV. The spectral shape for these high-energy inelastic neutrons has been measured at 14 MeV,⁸⁵ and the same shape is assumed to apply at 20 MeV. At 7 MeV, the inelastic spectrum is the boiloff spectrum described above for the E_n^L region. At incident energies of 9 and 11 MeV, the (n, n') spectrum is taken to be intermediate between the 7- and 14-MeV spectra.

In addition to the (n, n') E_n^L and E_n^H inelastic neutrons from the (n, n') continuum, there are also (n, n') neutrons from the nine low-lying discrete levels described in the section on Partial Nonelastic Cross Sections. For these reactions the secondary neutron energies are determined by two-body kinematics, using the assumption of isotropy in the center-of-mass system.

(n, 2n) REACTION

Figure 2 shows the cascade sequence leading to the (n, 2n) reaction. The first and second neutrons, E_{n1} and E_{n2} , follow boiloff spectra characterized by the temperatures T_1 and T_2 and by the final-state excitation energies U_A and U_{A-1} ,

respectively. In general, experiments measure a combined neutron-energy spectrum for all nonelastic neutrons. However, the method of Lang and Le Couteur⁸⁴ can be used to unfold this spectrum and deduce the temperatures T_1 and T_2 .

In tantalum, the (n, 2n) neutron-energy spectrum has been measured at 14 MeV.^{21,86,87} In the present evaluation, values for T_1 and T_2 at 14 MeV were taken from Ref. 31. At other neutron bombarding energies, the scaling laws $T_1 \propto U_A^{1/2}$ and $T_2 \propto U_{A-1}^{1/2}$ were used to obtain the (n, 2n) neutron spectra. As described in the previous section, an iterative calculation was used to make the assumed average neutron energies $\bar{E}_{n1}$ and $\bar{E}_{n2}$ agree with those calculated from the corresponding temperatures T_1 and T_2 .

In carrying out detailed calculations of the (n, 2n) cascade process (Fig. 2), it is necessary to treat the first and second neutrons separately. However, in the final evaluated (n, 2n) inelastic neutron spectrum, this separation of first and second neutrons seems neither necessary nor justified by our physical knowledge

Fig. 2. Available-energy diagram for the (n, 2n) reaction.

of the situation. Accordingly, in the final evaluated data set the F_{n1} and E_{n2} neutron spectra at each incident energy were combined into a single $(n, 2n)$ neutron spectrum. We calculated an effective temperature T that gives the correct average neutron energy for the combined spectrum consistent with the upper-limit cutoff on the spectrum (the upper limit is determined by the available energy). In Fig. 2, the residual excitation energy, U_{A-1} , was assigned to the production of gamma rays.

$(n, 3n)$ REACTION

The cascade sequence for the $(n, 3n)$ reaction is shown in Fig. 3. The systematics for the calculation of this reaction are similar to the $(n, 2n)$ systematics, though no measurements of the average neutron temperature exist for $(n, 3n)$ reactions in tantalum. However, if it is assumed that the temperature T of a specific nucleus is proportional to the square root of the available energy of that nucleus, the constants of proportionality C_1 and C_2 ($T_1 = C_1 U_A^{1/2}$, $T_2 = C_2 U_{A-1}^{1/2}$) for the first and second neutrons in the $(n, 2n)$ reaction turn out to be almost equal: $C_1 = 0.27$ and C_2

$= 0.24$. These constants should also apply for the first two neutrons in the $(n, 3n)$ cascade. The constant $C_3 = 0.25$ was assumed for the third neutron. Although we used the same constants, C_1 and C_2 , for both $(n, 2n)$ and $(n, 3n)$ reactions, it is much harder to calculate the $(n, 2n)$ than the $(n, 3n)$ spectra. The individual excitations U_A and U_{A-1} for the $(n, 2n)$ reaction are on the average considerably larger than the individual excitations U_A , U_{A-1} , and U_{A-2} for the $(n, 3n)$ reaction.

As in the case for $(n, 2n)$ reactions, the three separate $(n, 3n)$ neutron spectra calculated at each incident neutron energy were combined into a single final $(n, 3n)$ neutron spectrum. An effective temperature was chosen to preserve the correct average energy, using the proper high-energy cutoff on the spectrum. The residual excitation energy, U_{A-2} , was assigned to gamma radiation (Fig. 3).

In the (n, n') , $(n, 2n)$, and $(n, 3n)$ reactions, the available energy that is not taken away by final-state inelastic neutrons was assigned to radiation of photons and conversion electrons. Thus, on the average, energy is conserved in the evaluation for combined neutron emission plus other radiative processes.

This overall conservation of energy has a special significance, because recent accurate gamma-ray production data⁴² can be used to check the accuracy of the associated neutron reactions. Yet, even with the available cross check provided by the data, the uncertainties in the secondary energy distributions at any specific energy are very large, varying from 20 to 30% at best to orders of magnitude at the worst. Measurements of secondary

Fig. 3. Available-energy diagram for the $(n, 3n)$ reaction.

spectra generally have a low-energy cutoff no lower than 500 keV. The nuclear temperatures derived from such experiments are determined only from the

intermediate-energy secondary neutrons, for example from 1.5 to 5 MeV, thereby excluding both the high- and low-energy portions of the spectrum.

Cross Sections for Gamma-Ray and X-Ray Production

The first analysis of the ^{181}Tg (n, γ) cross section and photon spectra was made in 1971. Because of limited experimental data, a good portion of those results were extrapolated from tungsten. Recently, new experimental data on ^{181}Tg have become available. This not only has given specific information on the isotope of interest, but also has allowed the technique of analysis to be improved.

The major component of the (n, γ) reaction in ^{181}Tg comes from continuum gammas.* A review of this theory will therefore be presented, along with a discussion of the extensions made to analysis as a result of new data. Comparisons of calculation to experiment will be shown. Finally, the techniques for obtaining all components of the evaluated (n, γ) cross section and spectra over the various neutron-energy ranges will be presented.

THE FIRST-PASS (n, γ) EVALUATION

In 1968, Howerton and Plechaty⁴³ published a formalism for the calculation of (n, γ) cross sections and spectra above

4-MeV incident neutron energy. Their technique was based on the observation that the experimental spectrum of continuum gammas follows the simple evaporation model. From measured spectra, the R parameter (similar to the inverse of a nuclear temperature in the usual evaporation model) may be determined as a function of incident neutron energy. The multiplicity is uniquely defined in terms of the R parameter; hence the (n, γ) cross section may be obtained, and the problem is completely specified.

Because data were only available at 4 and 14 MeV, Ref. 43 assumed a linear dependence of R on the incident neutron energy. However, in late 1971, all of the (n, γ) spectra in the LLL Experimental Neutron Cross-Section Information Library (ECSIL) were analyzed for R parameters.⁶⁸ From these results, it became apparent that the behavior of the R parameter was not linear over the entire range of neutron energy. In the energy region where the ($n, n'\gamma$) reaction is predominant, the behavior is essentially linear. However, at higher energies (e.g., 14 MeV) the experimental values lie above, and at lower energies [i.e., below the ($n, n'\gamma$) threshold] they lie below this linear behavior. This may be seen in Fig. 4, where the experimental R parameters for tungsten are given.

* In the following discussion and in the evaluation, photons resulting from the (n, p) reaction are ignored because of its small cross section, the lack of experimental data, and the absence of an adequate theory to estimate the contribution from the (n, p) reaction.

In view of the above, a more reasonable assumption is that the R parameter is an explicit function of the excitation energy in the residual nucleus, rather than a function of the incident neutron energy. The results of this assumption can be illustrated by considering tungsten (Fig. 4). If about 6 MeV (the binding energy) is added to the two lowest neutron-energy values [which come mostly from the (n, γ) reaction], and 7 MeV (the $n, 2n$ threshold energy) is subtracted from the 14.8-MeV value [which comes mostly from the $(n, 2n)$ reaction], then the energy scale essentially corresponds to the excitation energy in the residual nucleus, and all values of $R(E_n)$ fall close to a linear behavior.

To obtain a functional relationship of the R parameter on excitation energy, a reaction must be chosen in which the excitation energy is uniquely known, i.e., a reaction that is predominant in the neutron-energy range of interest. For tungsten, the neutron-energy range $4 \leq E_n \leq 7.5$ MeV (four data points) was chosen. The excitation energy was calculated as $U_i(E_n)$

Fig. 4. $R(E_n)$ for tungsten obtained from the experimental data.⁸⁹⁻⁹¹ Crosses denote experimental points.

$= E_n - \bar{E}_{n'}$, where $\bar{E}_{n'}$ is the average energy of the inelastically scattered neutron and where $\bar{E}_{n'} = 2T_{n'} = 0.475 E_n^{1/2}$. This procedure gives two relations for the R parameter, both fitting the data equally well:

$$R_i[U_i(E_n)] = 5.2 U^{-1},$$

$$R_i[U_i(E_n)] = 2.5 U^{-1/2}.$$

The weighted R parameter, $R(E_n)$, was then calculated as follows. For the average energy of the two emergent neutrons from the $(n, 2n)$ reaction, the expression, $2\bar{E}_{2n} - 4T_{2n} = 0.95 (E_n - E_{th, 2n})^{1/2}$ was used. Neutron-induced reaction cross sections were taken from the LLL Evaluated Nuclear Data Library (ENDL). It was further assumed for the continuum gammas that,

- The (n, γ) reaction is predominant for $E_n < 2$ MeV.
- The $(n, n'\gamma)$ reaction is predominant for $4 \leq E_n \leq 7.5$ MeV.
- No gammas occur from the $(n, 2n)$ reaction for $E_{th, 2n} \leq E_n \leq 9.5$ MeV.

A simple hand calculation⁹² was then made, the results of which are shown in Fig. 5. The agreement with experiment

Fig. 5. $R(E_n)$ for tungsten: experiment (denoted by +) vs calculation.

Fig. 6. $R(E_n)$ for ^{181}Ta . The Δ denote experimental data,⁴² and the curve denotes calculated results, using $R = 5.2 \text{ U}^{-1}$ from tungsten.

is relatively good, and the calculations clearly show the trend of $R(E_n)$ with incident neutron energy.

In developing the first set of (n, γ) cross sections and spectra for ^{181}Ta , we extrapolated the tungsten results since no experimental data were then available for ^{181}Ta . The functional behavior for the R parameter was taken as $R_1[U_1(E_n)] = 5.2 \text{ U}^{-1}$. Figure 6 compares the calculated results with subsequent experimental data.⁴² The agreement, although probably fortuitous, is relatively good except just above thresholds, where the simple calculational technique was inadequate. With $R(E_n)$ known, the (n, γ) cross section was calculated by the Howerton and Plechaty formalism.⁴³

RECENT DEVELOPMENTS

In 1972, Perey and coworkers at ORNL performed an (n, γ) experiment on ^{181}Ta ,⁴² in one of the most comprehensive measurements carried out to date. Gamma-ray spectra ($b/s \cdot \text{MeV}$) above

Fig. 7. $^{181}\text{Ta}(n, \gamma)$ spectra for neutron energies $0.500 \leq E_n \leq 0.700 \text{ MeV}$. Data are for 125 degrees.⁴²

1-MeV photon energy were measured at two angles and at incident neutron energies between 0.007 and 20 MeV. These spectra were analyzed for R parameters over the entire incident neutron-energy range.⁸⁸ Some typical results are shown in Figs. 7 through 10. This analysis yielded the following observations.

- The evaporation model adequately describes the spectrum over the entire incident neutron-energy range, even when the only component present is (n, γ) .
- When both the (n, γ) and the $(n, n'\gamma)$ reactions are present ($1 \leq E_n \leq 4 \text{ MeV}$), each appears to have its own evaporation spectrum, yielding two distinct R parameters at each neutron energy. Thus, the R parameter is reaction-dependent at a specific neutron energy.

These results allowed us for the first time to obtain $R_1(U)$, using two reactions $\{(n, \gamma) \text{ and } (n, n'\gamma)\}$ between the excitation energies $1 \leq U \leq 10 \text{ MeV}$. Figure 11

shows the results of taking the average energy of the (n, n') neutrons from the inelastic continuum-neutron spectra in the LLL ENDL. The figure also shows that when the excitation energy for the two reactions is the same, the $R_i(U)$ are equal, indicating essentially no dependence on the specific residual nucleus.

Fig. 8. $^{181}\text{Ta}(n, \gamma)$ spectra for neutron energies $1 \leq E_n \leq 2$ MeV. Data are for 125 degrees.⁴²

Fig. 9. $^{181}\text{Ta}(n, \gamma)$ spectra for neutron energies $9.06 \leq E_n \leq 9.93$ MeV. Data are for 125 degrees.⁴²

Furthermore, at high excitation energies, $R_i(U)$ appears to approach a constant value.

This new information allowed us to extend⁹³ the Howerton and Plechaty formalism, as follows:

- The gamma rays from each individual reaction are assumed to follow an evaporation spectrum, with the R parameter taken from the excitation-function dependence. Hence, (n, γ) cross sections can be calculated for each reaction by the Howerton and Plechaty formalism and then summed to obtain the total continuum (n, γ) cross section.

- The combined spectrum of photons is obtained by weighting the individual spectra by the appropriate cross section and then summing them.

We applied this extended formalism to $R_i(U)$ (Fig. 11) and to the reaction cross sections and average secondary neutron

Fig. 10. $^{181}\text{Ta}(n, \gamma)$ spectra for neutron energies $15.08 \leq E_n \leq 19.97$ MeV. Data are for 125 degrees.⁴²

Fig. 11. $R_i(U)$ for ^{181}Ta as obtained from experimental results.⁴² The $\circ$ denote pure (n, n') and the $\times$ denote pure (n, γ) . The uncertainty in $R_i(U)$ is at least 10%.

energies (LLL ENDL). These calculations were then compared with Perey's ^{181}Ta experimental results. As the experiment only included photons above 1 MeV, just the continuum component of the (n, n') cross section was used; if any reaction at a given neutron energy yielded an excitation energy less than 1 MeV, it was assumed to make no contribution to the (n, γ) calculation.

The results of the comparison are shown in Fig. 12. For the (n, γ) cross section, the agreement between calculation and experiment is about 20% or better at

Fig. 12. $^{181}\text{Ta}(n, xy)$ cross section above 1-MeV photon energy. Solid curve and points are experimental,⁴² dashed curve is the calculation.

all energies except 2 MeV, where the calculation is about 40% low. These calculations show that this technique of analysis is adequate for obtaining continuum (n, γ) cross sections and spectra.

THE SECOND-PASS (n, γ) EVALUATION

In this section, we describe the technique for obtaining a final evaluated set of (n, γ) cross sections over the neutron energy range $10^{-11} \leq E_n \leq 20$ MeV. The total gamma-ray production is considered to be composed of discrete and continuum components, as shown in Table 2.

Table 2. Component and energy description of evaluated (n, γ) production for ^{181}Ta .

(n, γ) component	Energy range (MeV)
Total	10^{-11} to 0.035
Discrete	0.035 to 20
Continuum	0.035 to 20

Total (n, γ) Production ($10^{-11} \leq E_n \leq 0.035$ MeV)

The only reaction that produces gamma rays in this energy region is (n, γ). The discrete and continuum components of the spectrum at thermal energy have been measured.^{94,95} They are combined with a calculated spectral shape as discussed below in the section on gamma-ray energy distributions. The resulting spectrum has an average energy $\overline{E}_\gamma$ (thermal). At other neutron energies, $E_\gamma(E_n)$ can also be obtained. If no internal conversion occurs, the multiplicity as a function of neutron energy E_n is in general taken to be

$$M(E_n) = \frac{181}{182} \frac{E_n + Q_{n,\gamma}}{\overline{E}_\gamma(E_n)}$$

where $Q_{n,\gamma}$ is the (n, γ) Q-value. Corrections necessary to account for internal conversion are indicated in the section on continuum transitions.

The accuracy of this procedure is clearly dependent on how accurate the spectral shape is. The uncertainty for gamma-ray production below 0.035 MeV is estimated to be 20% over and above the uncertainty in the (n, γ) cross section.

(n, γ) Discrete Component ($0.035 \leq E_n \leq 20$ MeV)

After inelastic excitation of ^{181}Ta for neutron energies below 2.6 MeV, some 13 discrete lines have been reported.^{29,33,34,96} Recent unpublished measurements of Dickens and Morgan²⁷ with improved resolution show many more lines and extend the neutron energies to 5 MeV. For our evaluation, 22 gamma rays are considered significant. In cases

where the transitions have been identified, the gamma production cross sections were renormalized to the inelastic-scattering data, especially those of Ref. 24. The correspondence between inelastic neutron cross sections and gamma rays included corrections for internal conversion⁹⁷ and considerations of the known gamma-ray branching ratios.^{1,98}

For some transitions, notably those at 0.1361, 0.1524, 0.4822, 0.3461, 0.1935, and 0.3589 MeV, the renormalization amounted to about a factor of 2. Other transitions required no renormalization. The explanation of this difference is not known. If this problem is ignored, the uncertainties in the production cross sections for each of the 22 lines is estimated to be about 25%.

An unmeasured transition at 0.0062 MeV is expected between the first excited state and ground state of ^{181}Ta . The production cross section for this transition was obtained from the (n, n') cross section calculated with COMNUC by Gardner²⁸ and from the measured²⁷ cascades through the levels at 0.1586 and 0.3375 MeV. Because the transition goes by internal conversion 98% of the time,^{99,100} the production of 0.0062-MeV photons is considered to be negligible.

K and L x rays following internal conversion of the discrete lines and K, L, and M x rays following internal conversion of continuum transitions are also included in the evaluation. The K x rays following discrete transitions are assumed for simplicity to be K_α x rays, for which the average energy is taken to be 0.0574 MeV. The L x rays come from L internal conversion and from K conversion followed by a K_α x ray. In each case there is a

vacancy in the L-shell, which is assumed to lead to the emission of a 0.010-MeV photon. This assumption handles the total energy properly, but it neglects the complicated x-ray cascade involving photons less energetic than 0.010 MeV.

For continuum transitions, the K x rays again was assumed to be a K_{α} x ray ($E = 0.058$ MeV). The L x ray, however, was taken to be an L_{α} x ray ($E = 0.0082$ MeV), which occurs when an L-shell vacancy is filled by an M-shell electron. The M-shell vacancies were assumed to be filled by unbound electrons, giving an M_{∞} x ray ($E = 0.0017$ MeV). The method of calculating the cross sections for these x rays is described in the following section.

For all of the x rays, fluorescent yields of 100% are assumed and Auger processes are ignored. The uncertainties in K, L and M x-ray production cross sections are as large as those in the conversion-electron cross sections discussed later.

(n, xy) Continuum Component (0.035 $\leq E_n \leq 20$ MeV)

The calculation of continuum gamma-ray production cross section and spectra and of the associated x rays has been described at length.¹⁰¹ We give here only a brief outline of the calculation and indicate the modifications to Ref. 101 necessary for this evaluation. The following definitions are required.

The differential energy-production cross section for the y^{th} emergent particle, $\sigma_{n, xy}(E_n \rightarrow E_y)$, is defined as

$$\sigma_{n, xy}(E_n \rightarrow E_y) = \sigma_{n, xy}(E_n) \pi_y(E_n \rightarrow E_y), \quad (1)$$

where

$$y = \begin{cases} \gamma & \text{for gamma rays} \\ \beta & \text{for electrons} \\ i & \text{for the } i^{\text{th}} \text{ x-ray line,} \end{cases}$$

E_n = incident neutron kinetic energy in the lab system,

E_y = emergent kinetic energy of particle y in the lab system,

$\sigma_{n, xy}(E_n)$ = integrated y^{th} production cross section,

$\pi_y(E_n \rightarrow E_y)$ = probability for emission of particle y normalized to unity.

Furthermore, the average excitation energy, $U(E_n)$, in the residual nucleus is equal to

$$U(E_n) = E_n + Q_0 - \overline{E_r(E_n)} - \overline{E_n^i(E_n)}, \quad (2)$$

where

$\overline{E_r(E_n)}$ = average recoil kinetic energy of residual nucleus and charged particles in the lab system,

$\overline{E_n^i(E_n)}$ = average kinetic energy of all emergent neutrons in the lab system,

Q_0 = reaction (binding energy difference) Q -value.

$U(E_n)$ may also be expressed specifically in terms of the average total available energy for particle y , $U_y(E_n)$, as

$$U(E_n) = \sum_y U_y(E_n). \quad (3)$$

The multiplicity of particle y , $M_y(E_n)$, is defined as the average number of emergent particles per reaction; that is,

$$M_y(E_n) = \frac{\sigma_{n, xy}(E_n)}{\sigma(E_n)}, \quad (4)$$

or equivalently,

$$M_y(E_n) = \frac{U_y(E_n)}{E_y(E_n)}. \quad (5)$$

The pertinent x-ray energies, E_i , are given by

$$E_K = \overline{E_{BE}^K} - \overline{E_{BE}^L},$$

$$E_L = \overline{E_{BE}^L} - \overline{E_{BE}^M},$$

and

$$E_M = \overline{E_{BE}^M}.$$

The system of equations that was solved consists of three relationships. The first expresses that the excitation energy in the residual nucleus, after nucleon and other heavy-particle emission ceases, goes into gamma-rays, conversion electrons, and x-rays:

$$U(E_n) = M_\gamma(E_n) \overline{E_\gamma(E_n)} + M_\beta(E_n) \overline{E_\beta(E_n)} + \sum_{i=K, L, M} M_i(E_n) E_i. \quad (6)$$

The second relationship defines the ratio of conversion electrons to gamma rays:

$$\frac{\sigma_{n, x\beta}^\xi(E_n \rightarrow E_\beta^\xi)}{\sigma_{n, \gamma}^\xi(E_n)} = \alpha^\xi(E_\gamma) \pi_\gamma(E_n \rightarrow E_\gamma), \quad (7)$$

where $\alpha^\xi(E_\gamma)$ is the coefficient for internal conversion from the ξ^{th} atomic shell. These coefficients have been tabulated for various multiplicities.⁹⁷ The kinetic energy of the electron, E_β^ξ , is equal to

$$E_\beta^\xi = E_\gamma^\xi(E_\gamma) = E_\gamma - \overline{E_{BE}^\xi}, \quad (8)$$

where $\overline{E_{BE}^\xi}$ (defined to be positive) is the lowest electron binding energy in the ξ^{th} shell.

The third set of relationships gives the x-ray multiplicities in terms of the conversion electron multiplicities.

$$\frac{M_K(E_n)}{M_\gamma(E_n)} = \frac{M_\beta^K(E_n)}{M_\gamma(E_n)}, \quad (9)$$

$$\frac{M_L(E_n)}{M_\gamma(E_n)} = \frac{M_\beta^K(E_n) + M_\beta^L(E_n)}{M_\gamma(E_n)}, \quad (10)$$

and

$$\frac{M_M(E_n)}{M_\gamma(E_n)} = \frac{M_\beta^K(E_n) + M_\beta^L(E_n) + M_\beta^M(E_n)}{M_\gamma(E_n)}. \quad (11)$$

This system of equations was solved given $U(E_n)$, the gamma-ray spectrum, and the multipolarity of the continuum gamma rays. For the evaluation, $U(E_n)$ was taken from the neutron emission spectra and known Q-values. The continuum gamma-ray spectra are discussed in the next section. In the absence of data, the multipolarity of all continuum transitions was taken to be M1.

For the (n, n') reaction, Eq. (6) required a correction because a part of the excitation of ^{181}Ta is described in this evaluation as excitation of discrete states. We call this quantity $U_{n, n'}(E_n \rightarrow \text{discrete levels})$. Furthermore, these levels decay by the emission of discrete gamma rays with total energy $E_{\gamma, d}$, discrete conversion electrons with energy $E_{c, e, d}$ and associated x rays with energy $E_{x, d}$. The following relationships then hold:

$$U_{n, n'}(E_n \rightarrow \text{discrete}) = \sum_j E_j \sigma_j(E_n) / \sigma(E_n),$$

$$E_{\gamma, d} = \sum_l E_{\gamma l} \sigma(E_n \rightarrow E_{\gamma l}) / \sigma(E_n),$$

$$E_{c, e, d} = \sum_l E_{c, e, l} \sigma(E_n \rightarrow E_{c, e, l}) / \sigma(E_n),$$

and

$$E_{i,d} = E_i \sigma(E_n \rightarrow E_{i,d}) / \sigma(E_n),$$

where E_j is the energy of the j^{th} discrete level, $\sigma_j(E_n)$ is the cross section for excitation of that level by (n, n') inelastic scattering, $E_{y,f}$ is the energy, and $\sigma(E_n \rightarrow E_{y,d})$ is the cross section for production of the ℓ^{th} discrete emergent particle y . Then Eq. (6) becomes

$$U(E_n) + U_{n,n'}(E_n \rightarrow \text{discrete}) \\ = M_\gamma(E_n) \overline{E_\gamma(E_n)} + M_\beta(E_n) \overline{E_\beta(E_n)}$$

$$+ \sum_{i=K, L, M} M_i(E_n) E_i + E_{\gamma,d} + E_{c,e,d} \\ + \sum_{i=K, L, M} E_{i,d}. \quad (12)$$

The terms that carry over from Eq. (6) now are defined just for continuum processes.

The evaluated (n, xy) cross sections are estimated to be accurate to about $\pm 25\%$ except near 2 MeV, where the errors can be as large as $\pm 50\%$.

Angular Distributions for Gamma-Ray and X-Ray Production

The only experimental data on gamma-ray angular distributions in tantalum are the recent data of Perey and coworkers.⁴² These data indicate that gamma-ray pro-

duction is essentially isotropic. Hence, isotropy was assumed for all gamma-producing reactions. The x-ray angular distributions were also assumed to be isotropic.

Energy Distributions for Gamma-Ray and X-Ray Production

(n, γ) REACTION ($10^{-10} \leq E_n \leq 0.035$ MeV)

In the (n, γ) reaction, the gamma-ray spectral shape has been measured at thermal neutron energies.^{94,95} The measurements of the spectral shape were combined as follows. For gamma-ray energies below 500 keV, the relative intensities of Ref. 95 were normalized at the 402-keV line to Ref. 94. K and L x rays were added with intensities determined from conversion-electron yields (see below). For $E_\gamma = 500$ keV to 2.25 MeV, the spectral shape was calculated²⁸ from a gamma-ray cascade model. For $E_\gamma = 2.25$ to 5 MeV, the data

of Ref. 94 were used for the spectral shape. Above 5 MeV, the data of Ref. 95 were normalized to Ref. 94 and were used because of their superior resolution. The resulting spectrum is quoted in the form of a normalized probability distribution and binned for convenience.

At $E_n = 2$ -keV, only the high-energy primary gamma rays have been measured.⁹⁵ They were combined with the spectrum below $E_\gamma = 5$ MeV as discussed above. For $E_n = 2$ - to 35-keV, the spectrum was assumed to remain constant. Above $E_n = 35$ keV, all gamma rays from the (n, γ) reaction are included in the continuum component discussed below.

The multiplicity of gamma rays as a function of neutron energy, $M_\gamma(E_n)$, was determined from the equation of the preceding section on continuum gamma-ray cross sections. This method of determining the multiplicity implies a disagreement with the assignments of Ref. 95 for gamma rays below 500 keV. If used, these assignments would imply that in our evaluation there at least twice too many transitions with $E_\gamma < 500$ keV to the ground and 16-keV states of ^{182}Ta per capture. The combined uncertainty in the data used, however, is only about 30%. In any case, a change in the spectrum of a factor of 2 below $E_\gamma = 500$ keV does not change $\bar{E}_\gamma$ or $M_\gamma(E_n)$ very much. We consider the uncertainties for $0.5 \leq E_\gamma \leq 2.25$ MeV to be about 30% and for $E_\gamma > 2.25$ to be 20%. In specific resonances, discrete gamma rays can be strongly enhanced, and hence the errors can be much larger than those given here.

(n, γ) DISCRETE COMPONENT ($0.035 \leq E_n \leq 20$ MeV)

In the (n, $n'\gamma$) reaction, 22 discrete gamma rays and K and L x-rays are included in this evaluation. Discrete gamma rays from (n, $2n\gamma$) and (n, $3n\gamma$) have not been investigated experimentally and hence are not included in this evaluation.

(n, γ) CONTINUUM COMPONENT ($0.035 \leq E_n \leq 20$ MeV)

The manner in which continuum gamma rays were handled is best discussed in the framework of Figs. 1 through 3. In Fig. 1, the (n, $n'\gamma$) reaction in the E_n^L region was always assumed to occur. Thus, the n' neutron had an average energy given by the evaporation spectrum

appropriate to the excitation energy U_A for that bombarding energy E_n (using the iteration procedure described on page 6). The (n, $n'\gamma$) reaction in the E_n^H region required special handling (see pp. 6 and 7) but again an average neutron energy E_n^I corresponding to the incident energy E_n was determined. Thus, for a given incident energy, E_n , a total final-state energy (denoted as U_A in Fig. 1) was available for the gamma rays, conversion electrons, and x rays. Similarly, for the (n, $2n$) and (n, $3n$) reactions (Figs. 2 and 3), average neutron energies E_{n1} , E_{n2} , and E_{n3} were determined, and a single final-state total energy U_γ appears for each incident energy E_n and for each reaction.

In calculating the gamma-ray energy spectrum for each bombarding energy E_n , the value of the average excitation energy $U(E_n)$ of the residual nucleus was first determined from the neutronics file. Then the "best" $R(U)$ value (see p. 13) was used to calculate a gamma-ray spectrum that had a maximum gamma ray energy, $U_{\max}(E_n)$, and a shape given by:

$$\pi_\gamma(E_n \rightarrow E_\gamma) = A(E_n)E_\gamma \exp[-R(U(E_n)|E_\gamma)] \\ \text{for } E_{\gamma_{\min}} \leq E_\gamma \leq U(E_n), \quad (13)$$

and

$$\pi_\gamma(E_n \rightarrow E_\gamma) = A(E_n)E_\gamma \exp[-R(U(E_n)|E_\gamma)] \\ \times \left[\frac{U_{\max}(E_n) - E_\gamma}{U_{\max}(E_n) - U(E_n)} \right] \text{ for } U(E_n) \\ \leq E_\gamma \leq U_{\max}(E_n). \quad (14)$$

As with neutron spectra, the photon spectra have varying degrees of uncertainty, depending upon the emergent

photon energy. The overall error in the spectrum is estimated to be about 30%,

with much larger errors at high and low photon energies.

Cross Sections for Conversion-Electron Production

The internal conversion process competes with gamma emission in the decay of excited states. The production cross sections and spectra of the conversion electrons (c.e.) are evaluated here for discrete and continuum transitions. We have considered only K and L conversion electrons for the discrete transitions with one exception, which is discussed below. The L_I , L_{II} , and L_{III} conversion electrons have been lumped together. K and L x rays following internal conversion have been included with the gamma rays and are necessary to conserve energy. For continuum transitions, K, L, and M internal conversions are included from a calculation. The various M subshells are lumped together.

(n, γ) REACTION ($10^{-10} \leq E_n \leq 0.035$ MeV)

At thermal neutron energy, the conversion-electron spectrum has been measured from the $^{181}\text{Ta}(n, \gamma)^{182}\text{Ta}$ reaction.^{102,103} The multiplicity was determined from this spectrum and from Eqs. (2), (5), (6), and (7) using a value of α determined from the reported c.e./ γ intensity ratio.¹⁰² This normalization therefore involves the same problem discussed for low-energy gamma rays in the reaction: namely, the assignments of Ref. 95 are inconsistent with our normalization and would say

it should be reduced by a factor of two or more. The combined uncertainty in the data quoted is only about 30%, however.

The multiplicity was recalculated at $E_n = 35$ keV and kept constant from there to 20 MeV. Because the spectrum at thermal is dominated by only a few lines, large errors are possible at other neutron energies if the relative intensities of these few lines change.

(n, xc.e.) DISCRETE COMPONENT
($0.035 \leq E_n \leq 20$ MeV)

The 0.0062-MeV state in ^{181}Ta is populated in the (n, n') reaction. It decays by M and N converted transitions¹⁰³ about 97.8% of the time.^{99,100} For $E_n \leq 0.137$ MeV, it can be populated only by the (n, n') reaction; above this energy it can be populated by (n, n') reactions to higher-lying states, which then decay to the 6-keV state [i.e., an (n, n') reaction]. The cross section below $E_n = 0.137$ MeV for conversion electrons is therefore

$$\sigma(\text{c.e.}) = 0.978 \cdot \sigma[n, n'(Q = -6 \text{ keV})] \times 6 \text{ keV} / \bar{E}_{\text{c.e.}},$$

where $\bar{E}_{\text{c.e.}}$ is the average energy of the conversion electrons.

For $E_n = 0.137$ to 7.7 MeV, the data of Dickens and Morgan²⁷ for gamma-ray production (normalized where necessary

as stated above) were combined with branching ratios,^{1,98} interpolated conversion coefficients,⁹⁷ and known¹⁰⁴⁻¹⁰⁶ or assumed multiplicities for the gamma rays given in Table 3.

The other transitions of Refs. 27 and 33 are negligibly small sources of conversion electrons. For $E_n = 7.7$ to 20 MeV, the cross sections were estimated.

(n, xc, e₋) CONTINUUM COMPONENT ($0.035 \leq E_n \leq 20$ MeV)

The continuum component of the cross section for conversion-electron production was obtained for $0.035 \leq E_n \leq 20$ MeV through the formalism¹⁰¹ summarized above. An M1 multiplicity was assumed for all continuum transitions.

Table 3. Known or assumed multiplicities for specified gamma rays.

E_γ (MeV)	Multiplicity
0.1361	M1
0.1378	E2
0.1524	M1
0.1654	M1
0.1789	M1
0.1935	M1
0.225	M1
0.259	M1
0.288	M1
0.301	E2
0.331	E2
0.345	E2
0.3589	E2
0.482	E2

Angular Distributions for Conversion-Electron Production

Isotropy is assumed for all reactions. This is consistent with the same

assumption made for gamma-ray production.

Energy Distributions for Conversion-Electron Production

These spectra are given as normalized probability distributions.

(n, γ REACTION: ($10^{-10} \leq E_n \leq 0.035$ MeV)

The measurements of Refs. 102 and 103 were combined and binned. Where only the L conversion line was reported, a K conversion line was added with an intensity appropriate to the multiplicity. The very low-energy (<25 keV) electrons were estimated and could be significantly in error. This spectrum, while meas-

ured only at thermal, was assumed to obtain at all neutron energies.

(n, xc, e₋) DISCRETE COMPONENT ($0.006 \leq E_n \leq 20$ MeV)

The spectra were deduced from the evaluated gamma-ray data. The intensities of K and L conversion electrons were based on the gamma-ray yields and standard conversion coefficients⁹⁷ for the multiplicities indicated above. The K conversion-electron energies are $E_K = E_\gamma - 0.0674$ MeV, and the L

conversion-electron energies are $E_L = E_\gamma - 0.010$ MeV. In addition, the complicated spectrum of conversion electrons from the deexcitation of the 0.00623-MeV level¹⁰⁰ was treated for simplicity as a line at 3.1 keV. This energy, half the transition energy, was chosen to represent the M and N conversion electrons as well as the Auger cascade electrons and the very low-energy atomic photons, which quickly become photoelectrons.

(n, xc, e.) CONTINUUM COMPONENT
($0.035 \leq E_n \leq 20$ MeV)

The continuum spectra of conversion electrons were derived from the calculated (n, γ) continuum spectra described above according to Eq. (7). A multipolarity of M1 was assumed for all continuum transitions.

Because the spectra and multipolarity of continuum gamma rays had to be assumed, there may be large errors in the cross sections and spectra for continuum conversion-electron production.

An Integral Test of the Evaluated Data

Very recently Bogart and coworkers¹⁰⁷ measured the emission spectrum from a relatively thick (3.4 mfp at 4 MeV) spherical shell of tantalum. The source was

²⁴¹Am-Be intimately mixed and formed into a 5.4-cm-diam sphere.

Fig. 13. Neutron-leakage spectrum for the ²⁴¹Am-Be source sphere. The histogram is the calculation using the June 1974 version of ENDL. Error bars are the experimental points.

Fig. 14. Neutron-leakage spectrum from the small tantalum spherical shell surrounding the ²⁴¹Am-Be source sphere. The histogram is the calculation with the present evaluation. Error bars are the experimental points.

The spectrum from this extended source was calculated using the so-called "virgin source" (Po-Be) described in Ref. 107.

The Monte Carlo code TART was used with evaluated data¹⁰⁸ for Be and for ^{242}Am , since ^{241}Am evaluated data were not available. [The number of $^{242}\text{Am}(n, f)$ events in this calculation and in that for the tantalum shell were each less than 0.4% of the source neutrons. Thus the substitution for ^{241}Am by ^{242}Am , which has a much higher fission cross section at thermal, makes little difference here.] The calculation was normalized to the measured source spectrum and is shown with the experimental data in Fig. 13.

The emission spectrum from the source surrounded by the spherical shell of tantalum was then calculated with the source strength as normalized by the calculation of the bare ^{241}Am -Be source. The results are compared with experiment in Fig. 14. Very good agreement is found for neutron energies above 2 MeV. The disagreement below 2 MeV could be due either to inaccuracies in the experiment near the detector threshold or to inaccurate (n, n') emission spectra in the evaluation. More data are required on the emission spectra to resolve this problem.

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