LA-3801

ENDF 111

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ENDF/B Format Requirements

for Shielding Applications

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UNIVERSITY OF CALIFORNIA

LOS ALAMOS SCIENTIFIC LABORATORY
(CONTRACT W-7405-ENG-36)
P.O. Box 1663
LOS ALAMOS, NEW MEXICO 87544

IN REPLY
REFER TO:

January 9, 1968

TO: Holders of LA-3801

SUBJECT: ERRATA TO LA-3801

Page 8, Line 2:   Change "increasing" to "decreasing."

Appendix A: In file 14 of the sample data, all values of E_i, EG, and ES should be multiplied by 10^6 to convert from MeV to eV.

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ENDF/B Format Requirements
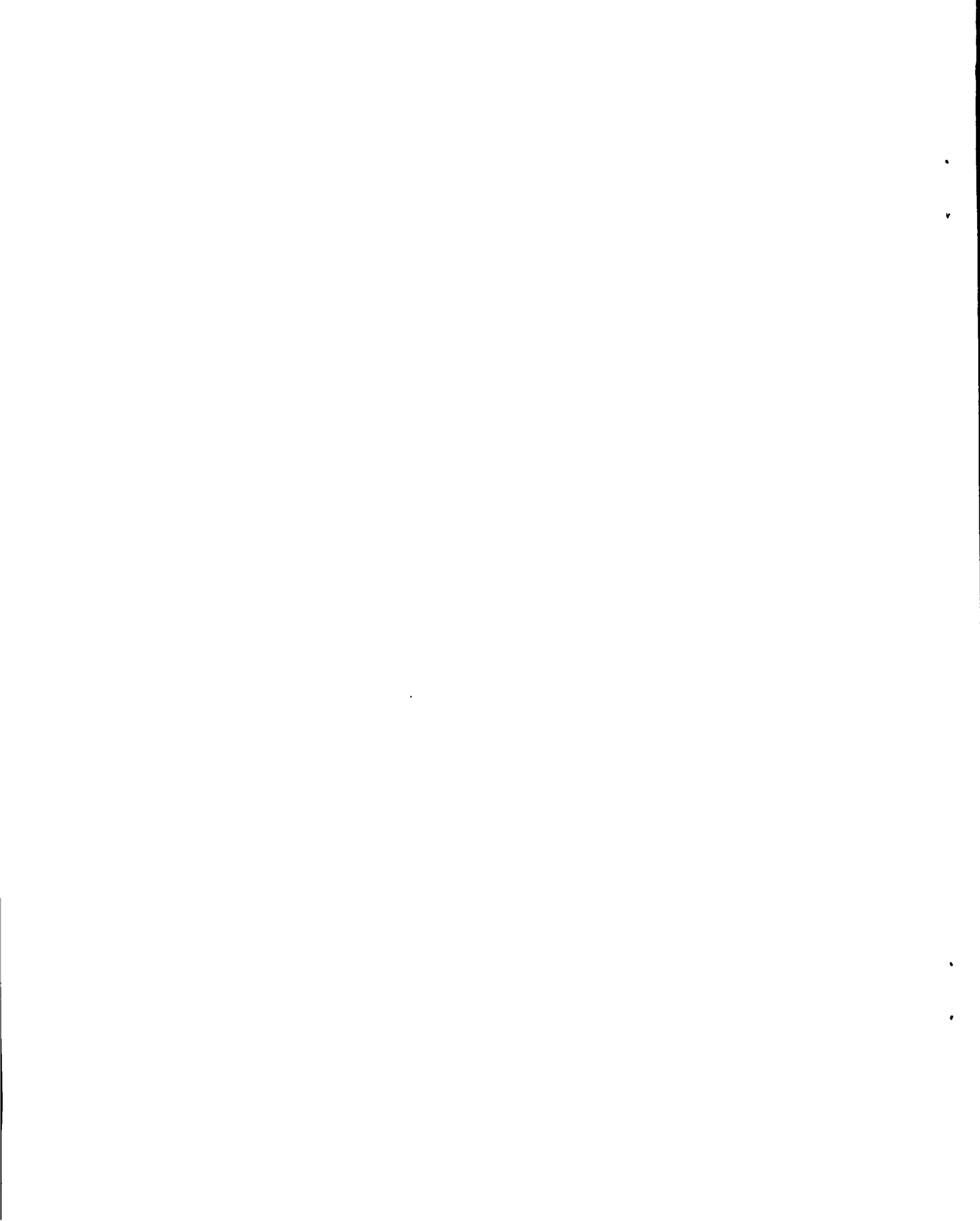
for Shielding Applications

Contributors:

M. E. Battat, LASL
D. J. Dudziak, LASL
J. M. Ferguson, USNRDL
D. C. Irving, ORNL
R. J. LaBauve, LASL
R. B. Lazarus, LASL

Compiled and edited by:

Donald J. Dudziak

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ENDF/B FORMAT REQUIREMENTS FOR SHIELDING APPLICATIONS

compiled and edited by

Donald J. Dudziak

ABSTRACT

The present (April 1967) Evaluated Nuclear Data File/B (ENDF/B) format has been designed primarily to satisfy the requirements of nuclear reactor core neutronics calculations. This paper proposes extensions of the format specifications to include data of interest for shielding calculations for reactor and other applications. Alternate methods of presenting the necessary data are discussed, and the correspondence of ENDF/B to the United Kingdom Atomic Energy Authority Nuclear Data File (UK) is maintained wherever practical. In the case of photon interactions, detailed formats are recommended for cross sections for secondary angular, energy, and energy-angle distributions, and for incoherent and coherent scattering atomic form factors. Format recommendations for photon production data include those for photon angular distributions, photon production multiplicities, and photon energy-angle distributions.

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1. INTRODUCTION

At its inception, the Evaluated Nuclear Data File/B (ENDF/B) was intended primarily to store data of interest to nuclear reactor core designers. An ENDF/B tape now exists with such data. However, the data are also of considerable interest for analysis of nuclear reactor and weapons shielding, as well as for other shielding applications. With this fact in mind, the Cross Section Evaluation Working Group (CSEWG), which is charged with the responsibility for implementing the ENDF/B, formed a Shielding Subcommittee. This Subcommittee was charged with several tasks, among which were to:

a. Recommend additional types of data to be added to ENDF/B for shielding and specify the detailed formats for storing such data. The formats should conform as nearly as possible to the existing ENDF/B formats.

b. Examine data presently on the ENDF/B tape to determine its completeness from the point of view of shielding calculations.

c. Recommend a list of priorities for data on materials of interest to shielders, to be evaluated and translated to the ENDF/B format.

d. Recommend data checking and processing codes required for shielding data to be placed on the ENDF/B tape.

e. Recommend calculational and experimental programs for testing the shielding data.

The Shielding Subcommittee held its initial meeting on February 6, 1967, at Oak Ridge National Laboratory. At this meeting, a cooperative effort with the Department of Defense (Defense Atomic Support Agency) was explored. As a result of the meeting, the Los Alamos Scientific Laboratory accepted the first task listed above: to recommend types of shielding data to be included on the ENDF/B and to devise formats for these data. The completion of this task is documented in this paper, a rough draft of which was submitted to the Shielding Subcommittee at its second meeting on April 7, 1967, at the U.S. Naval Radiological Defense Laboratory.

Two general classifications of shielding data are presented for the ENDF/B in this report. Section 2 contains the data types and formats for photon interactions (i.e., reactions in which a photon is the primary, which include the ordinary atomic interactions as well as photonuclear reactions). Section 3 contains the data types and formats for photon production induced by neutron reactions. The discussions in these sections assume a familiarity on the part of the reader with the present ENDF/B format and terminology.

2. PHOTON INTERACTIONS

Five files, the first four of which are analogous to Files 3 through 6, are allowed for photon interactions:

File	Description
23	"Smooth" cross sections
24	Secondary angular distributions
25	Secondary energy distributions
26	Secondary energy-angle distributions
27	Form factor data for incoherent and coherent scattering.

Optionally, some of the photon interaction data could have been included in Files 3 through 6. The format of these files seems to be adequate to handle the data, so the choice was based primarily upon (1) convenience in handling the data with processing codes, and (2) a desire not to "clutter" Files 3 through 6 with photon data of no interest for core neutronic calculations. An arbitrary decision was thus made to include the photon interaction data in separate files.

For Compton scatter at the higher energies (≥ 1 MeV), the energy and angular distribution files are not essential because a simple analytical representation of these distributions is available. However, they have been included for the convenience of those who prefer to have the data tabulated and for possible use in other (γ,x) reactions, such as (γ,f) and (γ,n). Also, the format is thus kept as consistent as possible with the United Kingdom Atomic Energy Authority data file (UK).[1] If data for incoherent and coherent scatter energy-angle distributions are to be given, they should be presented as form factors in any event (see discussion of File 27 in Section 2.5).

It is recommended, again consistent with UK, that all total and partial cross sections be specified at the same energy points wherever the energy ranges intersect. The total cross section must be given at all energy points for which one of its partial components is given. It is further recommended that the minimum energy range considered for the primarily "atomic" interactions (i.e., photoelectric, Compton, pair production, and perhaps Rayleigh effects) be that used by Grodstein[2] and the UK Photon Data Library,[3] viz., 0.01 to 20 MeV. For those materials given by Hubbell and Berger,[4] their data up to 100 MeV, and in some cases 10 GeV, should be used. Sources of data, scope of data, and other general information should be included in File 1, MT = 451.

2.1 File 23: "Smooth" Cross Sections

Recommended reaction-type numbers:

MT	Symbol	Description
501		total
502		elastic or coherent (Rayleigh) scatter
503		nonelastic = total-elastic
504		inelastic or incoherent (Compton) scatter
516	$(\gamma,2\gamma)$	pair production
602	(γ,e^-)	photoelectric effect
531		energy "absorption" (or kerma)
518	(γ,f)	photofission
532	(γ,n)	photoneutron
533		total photonuclear
etc.		

Choosing the 500 and 600 series of reaction-type numbers for photon interactions departs from the UK system, in order to have an internally consistent scheme. Following the UK analogy with neutron reactions would give the following system in ENDF/B:

MT	Photon Interaction Symbol	Analogous Neutron Reaction Symbol	Photon Interaction Description
1			total
2			elastic
3			nonelastic
16	$(\gamma,2\gamma)$	$(n,2n)$	pair production
102	(γ,e^-)	(n,γ)	photoelectric

Logical perplexities then occur in trying to find an analogy for the energy absorption cross section (kerma cross section) or in deciding on a neutron analogy for the (γ,n) reaction. Hopefully, the scheme adopted will also simplify the processing codes. The last two digits of the 500 series might

be kept in some approximate relation to the analogous neutron reaction-type numbers, however, for purely mnemonic purposes. The correspondence is:

Neutron Reactions	Photon Interactions
1-100	501-600
101-150	601-650

If the kerma is desired for each partial cross section, the UK system could be used; that is, add 200 to the MT number of an interaction for its kerma cross section MT number.

The structure of File 23 is identical to File 3, which is reproduced here for illustrative purposes.

Structure of a File 23 Section

[MAT, 23,MT/ZA, AWR; 0, LFS; 0, 0]HEAD
[MAT, 23, MT/T, Q; LT, 0; NR, NP/E int/σ(E)]TAB1
[MAT, 23, 0/0.0, 0.0; 0, 0; 0, 0]SEND

2.2 File 24: Secondary Angular Distributions

The general structure of File 4 appears to be adequate for photon interactions. The angular distribution for Compton scatter can be represented by its energy-dependent Legendre coefficients, if desired for photon slowing-down or transport calculations. A transfer matrix from the (C) to (L) system (or its inverse) need not be provided because the processing codes should have subroutines to construct such matrices.

For the case where the secondary particle is a photon, the following convention is adopted:

    (1)   LCT = 1 [data is given in (L) system]

    (2)   LVT = 0 [transformation matrix not given].

2.3 File 25: Secondary Energy Distributions

Again, the structure of the analogous File 5 appears to be entirely adequate.

2.4 File 26: Secondary Energy-Angular Distributions

This file is analogous to File 6, the secondary energy-angular distribution file for neutrons. It is not completely necessary for Compton scatter, since the energy-angular relationships can be generated analytically. Again, in the case where the secondary particle is a photon, the convention is adopted that LCT = 1. Where a secondary particle

other than a photon is emitted, either the (L) or the (C) system may be used. Doing this will require the processing codes to provide an energy-independent transfer matrix from either system to the other. It is recommended that this requirement on the processing codes be incorporated in File 6 also.

2.5 File 27: Form Factors for Coherent and Incoherent Scattering

The present ENDF/B system allows two alternatives for storing angular distribution data. One is by probability per unit cos θ vs cos θ, and the other is by Legendre coefficients. Actually, neither of these is a "natural" method for photons. The natural method for storing photon distributions would be atomic form factors. We discuss these briefly below.

2.5.1 Incoherent Scattering. The cross section for incoherent scattering is given by

$$\frac{d\sigma_i}{d\mu} = Z \ K(q;Z) \ \frac{d\sigma_c}{d\mu} \ ,$$

where $d\sigma_c/d\mu$ is the Klein-Nishina cross section, which can be written in closed form. The factor $K(q;Z)$ is the form factor. The quantity q is the momentum of the recoil electron (in units of $m_o c$),

$$q = \alpha \left[1 + \left(\frac{\alpha'}{\alpha}\right)^2 - \left(2\mu \ \frac{\alpha'}{\alpha}\right) \right]^{\frac{1}{2}}$$

where

$$\alpha = E/m_o c^2$$

and

$$\mu = \cos \theta.$$

Obviously, the angular distribution can easily be calculated, given a table of $K(q;Z)$. Since K is a smoothly varying function of q, it can be represented by a reasonably small array of numbers. The quantities $K(q;Z)$ will be tabulated as a function of q in File 27. The user presumably will have subroutines available for calculating q for energies and angles of interest and for calculating Klein-Nishina cross sections. He will then generate his cross sections for the appropriate cases by calculating q's, looking up the appropriate values of K, and substituting them into the above formula.

2.5.2. Coherent Scattering.

The coherent scattering cross section is given by

$$\frac{d\sigma_{coh}}{d\mu} = \pi r_o^2 \, Z^2 (1 - \mu^2) \, G(q;Z),$$

where

$q = \alpha[2(1 - \mu)]^{\frac{1}{2}}$, the recoil momentum of the atom (in units of $m_o c$), and

$r_o = e^2/m_o c^2$, the classical radius of the electron.

The quantity $G(q;Z)$ is another form factor, which also is easily tabulated. At high (≥ 1 MeV) energies, G approaches zero.

An alternative way of presenting the photon scattering data, then, would be to tabulate form factors and provide processing codes to generate the cross sections from this information. The calculation is quite straightforward and allows the user to generate all his scattering data from a relatively small table of numbers. The computation required to translate the form factors into cross sections is quite straightforward. The incoherent and coherent scattering data should always be presented as form factors, regardless of whether data are included in Files 24, 25, or 26.

2.5.3. Section Structure.

The structure of a section is then very similar to File 3 (and 23), as follows:

[MAT, 27, MT/ZA, AWR; 0, 0; 0, 0]HEAD
[MAT, 27, MT/0.0, Z; 0, 0; NR, NP/q int/H(q;Z)]TAB1
[MAT, 27, 0/0.0, 0.0; 0, 0; 0, 0]SEND

Here, $H(q;Z)$ can be either $G(q;Z)$ or $K(q;Z)$ for incoherent and coherent scattering, respectively.

Z is entered in floating-point format. Values of G and K should be entered for the respective entire energy range for which integrated incoherent and coherent cross sections are given in File 23.

3. PHOTON PRODUCTION DATA

Three files analogous to Files 4, 5, and 6 are allotted to photon production data, a system somewhat consistent with the UK data file. The files are allotted as follows:

File	Description
14	photon angular distributions
15	photon production multiplicities
16	photon energy-angle distributions

In general, the formats follow the record types used for the neutron interaction files already in existence (i.e., CONT, HEAD, LIST, TAB1, TAB2, etc.). Thus, the descriptions of Files 4 and 5 have been used as much as possible in the discussions to follow.

Reaction-type (MT) numbers for photon production data are the same as those assigned for Files 1 through 7. In order to maintain as closely as possible a one-one correspondence of MT number with corresponding PCN numbers in the UK file, MT numbers 5 to 15 are activated as follows:

MT		
5	(n,n') to the	1st excited state
6	"	2nd "
7	"	3rd "
8	"	4th "
9	"	5th "
10	"	6th "
11	"	7th "
12	"	8th "
13	"	9th "
14	"	10th "
15	(n,n') to the	continuum

Reaction-type (MT) numbers 51 through 80 are assigned for excitation to states 11 through 40, respectively; MT = 4 remains the total inelastic scatter cross section. For MT = 15, the word "continuum" is used loosely to include everything not accounted for in MT = 5 through 14 and 51 through 80. Data are not required to be given for MT = 5 through 15 and 51 through 80, but their inclusion is an aid to the evaluator. Data for MT = 4 must be included, however, regardless of whether data are present for MT = 5 through 15 and 51 through 80.

Since photon production data are given as multiplicities instead of cross sections, the corresponding neutron cross sections must be given in Files 2 and/or 3 for every MT number used in the photon data.

A sample set of photon production data is given in Appendix A. These data are translations of sodium data evaluated by Drake et al.[5] They placed the data in their extension of the UK format. The information for File 15 was deduced from the de-excitation diagram in Vol. II of their report. All the data are from a preliminary release and are included for illustrative purposes only.

3.1 File 14: Photon Angular Distributions

In general, the format follows that of File 4, with the principal exception being that angular distributions must be given separately for each discrete photon energy, for the continuous spectrum, or for both. Angular distributions are always given as normalized probability densities, either in tabular form or as Legendre coefficients $a_\ell(E)$. In the Legendre expansion

$$\frac{d\sigma(E_\gamma,E,\mu)}{d\mu} = \sigma(E_\gamma \leftarrow E) \sum_{\ell=0}^{NL} \frac{2\ell + 1}{2} a_\ell(E) P_\ell(\mu),$$

E is the neutron energy and $\sigma(E_\gamma \leftarrow E)$ is the cross section to produce a photon of energy E_γ. It is understood that $a_0(E) = 1$. The function $\sigma(E_\gamma \leftarrow E)$ is generated from Files 2, 3, and 15; it may be a delta function in E_γ. For photons there is, of course, no distinction made between the laboratory and center-of-mass coordinate systems. This file assumes separability of the photon energy and angular distributions for the <u>continuous</u> spectrum. If this is not the case, a File 16 (analogous to File 6) must be used instead of Files 14 and 15. (Note that File 14 implicitly specifies an energy-angle distribution for discrete photons, and therefore File 16 is required only for the continuous spectrum.)

As usual, sections are ordered by increasing reaction-type (MT) numbers. Let us define the following quantities:

LTT = 1, data are given as Legendre coefficients.
  = 2, data are given as a tabulation.

LI = 0, distribution is not isotropic.
  = 1, distribution is isotropic.

ND = number of discrete photon energies for which an angular distribution is given.

NC = number (0 or 1) of continuous photon energy spectra for which an angular distribution is given. The continuous spectrum must appear last in the section. If NC = 1, a continuous spectrum must necessarily appear in File 15.

NE = number of neutron energy points given.

NP = number of tabulated points for $p(\mu,E_i)$ as a function of μ.

NL = highest value of ℓ required at each and every photon energy.

NR = number of interpolates.

ES = energy of the state excited to produce the photon of energy EG_i. If all levels which contain EG_i in their cascade are considered,

ES = 0.0 is used. Thus, for MT = 4, one will usually have ES = 0.0. For MT = 5 through 14, ES will be the energy of the respective excited level. (Note that ES must be constant throughout any section.) For radiative capture, ES may be used for the excitation energy.

EG_i = <u>i</u>th discrete photon energy.

If LI = 1, then all photons for the reaction type (MT) in question are assumed to be isotropic. This is a flag which processing codes can sense, thus avoiding the necessity to enter needless data on the tape. In this case, the section is composed of the single card in addition to the SEND card:

[MAT, 14, MT/ZA, AWR; LI, LTT, ND, NC]HEAD

where LI = 1 and LTT = 1 or 2. Depending upon the value of LTT, the processing codes can easily construct an isotropic distribution either as a trivial Legendre expansion or as a short tabulation.

If LI = 0, there are two possible structures for a section, depending upon the value of LTT, but the section always starts with HEAD and TAB2 records of the form:

[MAT, 14, MT/ZA, AWR; LI, LTT; ND, NC]HEAD
[MAT, 14, MT/ES, EG_i; 0, 0; NR, NE/E int]TAB2

Here LI = 0. For a continuous spectrum, $EG_i \triangleq 0.0$.

3.1.1. Legendre Coefficients (LTT = 1).

The structure of a section is

[MAT, 14, MT/ZA, AWR; 0, 1; ND, NC]HEAD

Then ND sets of records as follows:

[MAT, 14, MT/ES, EG_1; 0, 0; NR, NE/E int]TAB2
[MAT, 14, MT/0.0, E_1; 0, 0; NL, 0/$a_\ell(E_1)$]LIST
[MAT, 14, MT/0.0, E_2; 0, 0; NL, 0/$a_\ell(E_2)$]LIST
.
.
.
[MAT, 14, MT/0.0, E_{NE}; 0, 0; NL, 0/$a_\ell(E_{NE})$]LIST

If NC = 1, there is then a set of records for the continuous spectrum, as follows:

[MAT, 14, MT/0.0, 0.0; 0, 0; NR, NE/E int]TAB2
[MAT, 14, MT/0.0, E_1; 0, 0; NL, 0/$a_\ell(E_1)$]LIST
.
.
[MAT, 14, MT/0.0, E_{NE}; 0, 0; NL, 0/$a_\ell(E_{NE})$]LIST

and finally

[MAT, 14, 0/0.0, 0.0; 0, 0; 0, 0]SEND

Note that the ND sets of data for discrete pho-
tons should be ordered in Decreasing magnitude of
EG_i. Also, the structure can be viewed more con-
cisely by noting that it is the same for a contin-
uous or a discrete spectrum, if we define $EG_i \equiv 0.0$.
An angular distribution (or the flag LI = 1) is
required for every discrete photon or photon energy
distribution for which multiplicity data are given
in File 15. The EG_i for discrete photons should,
of course, be consistent with those given in File
15 (explicitly under Option 1 of File 15 and im-
plicitly under Option 2 of File 15).

3.1.2. Tabulation (LTT = 2).

The structure of
a section is:

[MAT, 14, MT/ZA, AWR; 0, 2; ND, NC]HEAD

Then ND sets of records as follows:

[MAT, 14, MT/ES, EG_1; 0, 0; NR, NE/E int]TAB2
[MAT, 14, MT/0.0, E_1; 0, 0; NR, NP/μ int/p(μ,E_1)]TAB1
[MAT, 14, MT/0.0, E_2; 0, 0; NR, NP/μ int/p(μ,E_2)]TAB1

.
.
.

[MAT, 14, MT/0.0, E_{NE}; 0, 0; NR, NP/μ int/p(μ,E_{NE})]TAB1

If NC = 1, there is then a set of records for the
continuous spectrum as follows:
[MAT, 14, MT/0.0, 0.0; 0, 0; NR, NE/E int]TAB2
[MAT, 14, MT/0.0, E_1; 0, 0; NR, NP/μ int/p(μ,E_1)]TAB1

.
.
.

[MAT, 14, MT/0.0, E_{NE}; 0, 0; NR, NP/μ int/p(μ,E_{NE})]TAB1

and finally,
[MAT, 14, 0/0.0, 0.0; 0, 0; 0, 0]SEND

3.2 File 15: Photon Production Multiplicities

Data for File 15 may be entered in either of
two options. The first option is a system analo-
gous to File 5 but gives the photon production mul-
tiplicities instead of normalized energy distribu-
tions. The second option is a scheme especially
suited to photon production from the de-excitation
of specific levels, presenting the data in a quite
concise form.

For example, data might be provided under Op-
tion 2 for MT = 5 through 14 and 51 through 80 and

under Option 1 for MT = 15 and MT = 102 (in Appen-
dix A, this is done for the sample case of sodium).
Data for MT = 4 (total inelastic) could be entered
under Option 2 or left for the processing codes to
construct from the data for MT = 5 through 15 and
51 through 80.

Let us define a parameter
LØ = 1, data are presented according to Option 1.
   = 2, data are presented according to Option 2.

3.2.1. Multiplicities for Photon Production (Option 1, LØ = 1).

With this option, we follow
File 5, the principal exception being that photon
energy distributions are not normalized to unity
(probability densities) but rather are multiplici-
ties (photons/eV-event). Also, new laws may be
added to those in File 5; e.g., for the prompt fis-
sion gamma-ray spectrum.

The density functions p(E'→E) of File 5 are re-
placed by photon yield functions $y(E_\gamma \to E)$ such that

$$\int_0^\infty dE_\gamma \ y(E_\gamma \to E) = Y(E) \qquad \text{(photons/event)},$$

the total photon yield for an interaction at neutron
energy E. The differential photon production cross
section is then obtained from

$$\frac{d\sigma(E_\gamma \to E)}{dE_\gamma} = \sigma(E) \ y(E_\gamma \to E) \quad \text{(barns-photons-eV}^{-1}\text{)},$$

where σ(E) is the cross section for the reaction
type being considered, as determined by Files 2 and
3. The energy distribution is broken into NK por-
tions, $f_k(E_\gamma \to E)$, each following a different law or
the same law with different parametric representa-
tions. A superposition gives

$$y(E_\gamma \to E) = \sum_{k=1}^{NK} y_k(E) \ f_k(E_\gamma \to E).$$

This subdivision can be used for both partial dis-
tributions (e.g., superposition of several contin-
uous photon spectra) and different distributions in
different energy ranges. The $f_k(E_\gamma \to E)$ are neces-
sarily normalized to unity, and the $y_k(E)$ contain
the multiplicities. For example, where $f_k(E_\gamma \to E)$
follows Law 2 (i.e., a delta function in E_γ) as

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given in File 5, then it will of necessity be normalized to unity. The photon multiplicities then appear in the $y_k(E)$ function. In using Law 1 (LF = 1), the $f_1(E_\gamma \leftarrow E) \equiv g(E_\gamma \leftarrow E)$ function is normalized to unity.

As before, sections are ordered by increasing reaction-type (MT) numbers. Recall:

EG_i = ith discrete photon energy (eV).

ES = energy of the state excited to produce the photon of energy EG_i.

NK = number of partial energy distributions.

NE = number of E values in a tabulation of $g(E_\gamma \leftarrow E)$

ND = number of discrete photon energies for which photon yields are given.

The number of laws required to specify the continuous spectrum is determined from NK-ND.

The structure of a section is then:

[MAT, 15, MT/ZA , AWR; LØ = 1, 0; ND, NK]HEAD
[MAT, 15, MT/0.0, 0.0; 0, 0; NR, NP/E int/Y(E)]TAB1

  ⟨subsection for k = 1⟩

  ⟨subsection for k = 2⟩

    .
    .
    .

  ⟨subsection for k = NK⟩
[MAT, 15, 0/0.0, 0.0; 0, 0; 0, 0]SEND

The structure of a subsection depends upon the value of LF but always starts with a record of the form

[MAT, 15, MT/ES, EG_i; 0, LF; NR, NP/E int/$y_k(E)$]TAB1

Except in the case of Law 1 (LF = 1), where EG_i = 0.0 is used, EG_i refers to the ith discrete gamma energy. (Law 1 always implies a continuous photon spectrum.) The total yield, Y(E), is a check number which should agree with the sum of the integrals over secondary energies; i.e.,

$$Y(E) = \sum_{k=1}^{NK} y_k(E).$$

SUBSECTION STRUCTURES

LF = 1, Arbitrary Tabulated Function

[MAT, 15, MT/0.0, 0.0; 0, 1; NR, NP/E int/$y_k(E)$]TAB1
[MAT, 15, MT/0.0, 0.0; 0, 0; NR, NE/E int]TAB2
[MAT, 15, MT/0.0, E_1; 0, 0; NR, NP/E_γ int/$g(E_\gamma \leftarrow E_1)$]TAB1
[MAT, 15, MT/0.0, E_2; 0, 0; NR, NP/E_γ int/$g(E_\gamma \leftarrow E_2)$]TAB1

    .
    .
    .

[MAT, 15, MT/0.0, E_{NE}; 0, 0; NR, NP/E_γ int/$g(E_\gamma \leftarrow E_{NE})$]TAB1

In this case, $y_k(E)$ should indicate the probability of this law occurring for any given neutron energy, E, times the multiplicity for that energy; $g(E_\gamma \leftarrow E)$ would give the normalized photon yield probabilities of the reaction. For example, if σ_{CO} is the cross section for inelastic scatter to the continuum and σ_4 is the total inelastic cross section, then

$$Y(E) \cdot \frac{\sigma_{CO}(E)}{\sigma_4(E)} = y_k(E) \text{ for MT = 4, LF = 1.}$$

LF = 2, Discrete Final Energy

[MAT, 15, MT/ES, EG_i; 0, 2; NR, NP/E int/$y_k(E)$]TAB1

In this case, $y_k(E)$ should be the photon yield (photons/event) of EG_i electron-volt photons, for a reaction occurring at E electron volts.

3.2.2. **Transition Probability Arrays for Photon Production (Option 2, LØ = 2).** With this option, we merely list the level energies, the deexcitation transition probabilities, and, where necessary, the conditional photon emission probabilities. Given this information, the photon energies and their multiplicities can readily be calculated for any given level. Also, photon production cross sections can easily be determined for any given level from the neutron interaction cross section for exciting that level in conjunction with the transition probability arrays. Appendix B shows in more detail how this can be accomplished. Similarly, multiplicities and photon production cross sections can be constructed for the total cascade (e.g., for total inelastic scatter). The transition and photon emission probability data

given for any level are for photons <u>originating</u> at that level only; any further cascading is determined from the data for the lower levels.

Let us define

LG = 1, simple case (all transitions are γ emission).

= 2, complex case (internal conversion or other competing processes occur).

NS = number of levels below the present one, including the ground state. (The present level is also uniquely defined by the MT number and by its energy level).

NT = number of transitions for which data are given in a list to follow (i.e., number of nonzero transition probabilities). NT ≤ NS.

ES_i = energy of the <u>i</u>th state, i = 0(1)NS. (ES_o ≡ 0.0, the ground state.)

TP_i = probability of a <u>direct</u> transition from level NS to level i, i = 1(1)NS-1.

GP_i = probability that, given a transition from level NS to level i, the transition is a photon transition (i.e., the conditional probability of photon emission).

Note that each level can be identified by its NS number. Then the energy of a photon from a transition to level i is given by $E_\gamma = ES_{NS} - ES_i$, and its multiplicity is given by $y(E_\gamma \to E) = (TP_i)(GP_i)$. It is implicitly assumed that the transition probability array is independent of incident neutron energy.

The structure of a section in File 15 under Option 2 is then given by

[MAT, 15, MT/ZA, AWR; L∅ = 2, LG; NS, 0]HEAD

where, if LG = 1, the array is given by

[MAT, 15, MT/ES_{NS}, 0.0; 0, 0; 2*NT, NT/(ES_i,TP_i)]LIST

or, if LG = 2, by

[MAT, 15, MT/ES_{NS}, 0.0; 0, 0; 3*NT, NT/(ES_i,TP_i,GP_i)]LIST

In either case, the last record is

[MAT, 15, 0/0.0, 0.0; 0, 0; 0, 0]SEND

The doublets (ES_i,TP_i) and triplets (ES_i,TP_i, GT_i) are given in decreasing magnitude of energy ES_i.

3.3 File 16: Photon Energy-Angle Distributions

If the photon energy dependence and angular dependence of the cross section for production of the continuous spectrum are not separable, then a file analogous to File 6 is required instead of Files 14

and 15. The energy-angle distributions for discrete photons are completely determined in File 14 and should never appear in the present file. A knowledge of the formats for Files 14 and 15 is assumed in this discussion.

Consider a non-normalized energy-angle distribution function $h(E_\gamma \to E,\mu)$, where the angular dependence is normalized such that

$$\int_{-1}^{1} d\mu\, h(E_\gamma \to E,\mu) = y(E_\gamma \to E).$$

The differential photon production cross section is then obtained from

$$\frac{\partial^2 \sigma(E_\gamma \to E,\mu)}{\partial E_\gamma\, \partial\mu} = \sigma(E)\, h(E_\gamma \to E,\mu)$$

$$(\text{barns-photons-eV}^{-1}),$$

where σ(E) is the cross section for the reaction type being considered, as determined by Files 2 and 3.

As in File 14, the angular part of the distribution may be specified either in tabular form or as Legendre coefficients, $n_\ell(E_\gamma \to E)$. The Legendre expansion is

$$h(E_\gamma \to E,\mu) = \sum_{\ell=0}^{NL} \frac{2\ell+1}{2} n_\ell(E_\gamma \to E)\, P_\ell(\mu).$$

Now consider the structure of a section for the two possible forms of the angular distribution. In either case, the section starts with a HEAD record of the form:

[MAT, 16, MT/ZA, AWR; 0, LTT; 0, 0]HEAD

3.3.1. Legendre Coefficients (LTT = 1).

The second card for a section of Legendre coefficients (LTT = 1) is always a record of the form:

[MAT, 16, MT/0.0, 0.0; 0, 0; NL, 0]CONT

A typical section for LTT = 1 is then given by:

[MAT, 16, MT/ZA, AWR; 0, 1; 0, 0]HEAD
[MAT, 16, MT/0.0, 0.0; 0, 0; NL, 0]CONT
⟨subsection for $n_0(E_\gamma \to E)$⟩
⟨subsection for $n_1(E_\gamma \to E)$⟩
.
.
.
⟨subsection for $n_{NL}(E_\gamma \to E)$⟩
[MAT, 16, 0/0.0, 0.0; 0, 0; 0, 0]SEND

The section contains subsections for the energy distributions. The structure of a subsection is identical to the structure of a section for photon energy distributions (File 15), with the following exceptions:

a. The SEND record is deleted,

b. The HEAD record is changed to read

[MAT, 16, MT/0.0, 0.0; 0, 0; NK, 0]CONT,

c. $y(E_\gamma \leftarrow E)$ is replaced by $n_i(E_\gamma \leftarrow E)$. The same normalization rules as apply to $y(E_\gamma \leftarrow E)$ in File 15 apply to the $n_i(E_\gamma \leftarrow E)$ in the present file.

3.3.2. Tabulation (LTT = 2).

A typical section for LTT = 2 is then given by

[MAT, 16, MT/ZA, AWR; 0, 2; 0, 0]HEAD
[MAT, 16, MT/0.0, 0.0; 0, 0; NR, NA/µ int]TAB2

⟨subsection for $h(E_\gamma \leftarrow E, \mu_1)$⟩
⟨subsection for $h(E_\gamma \leftarrow E, \mu_2)$⟩
.
.
.
⟨subsection for $h(E_\gamma \leftarrow E, \mu_{NA})$⟩
[MAT, 16, 0/0.0, 0.0; 0, 0; 0, 0]SEND

As in the case of the Legendre coefficient representation, this section in tabular form contains subsections. The structure of a subsection is identical to the structure of a section for File 15, with the following exceptions:

a. The SEND record is deleted,

b. The HEAD record is changed to read

[MAT, 16, MT/0.0, μ_j; 0, 0; NK, 0]CONT

c. $y(E_\gamma \leftarrow E)$ is replaced by $h(E_\gamma \leftarrow E, \mu_j)$, where each subsection is for a particular value of μ_j, j = 1(1)NA.

APPENDIX A

SODIUM PHOTON PRODUCTION DATA IN THE PROPOSED ENDF/B FORMAT

Presented below is a listing of the sodium photon production data of Drake et al.,[5] as it appears after translation into the proposed ENDF/B format. For the ENDF/B File 15 data on photon multiplicities, Option 2 (transition probability arrays) was used for inelastic scatter gamma rays from the discrete levels. Option 1 (multiplicities) was used for "inelastic scatter to the continuum" (actually a potpourri of photons not accounted for in the discrete level data) and for radiative capture. In File 14, the angular distribution was kept in the form of a tabulation of $p(E_i, \mu)$.

The sodium data were all received in a personal communication from Drake before publication and should be regarded as preliminary. The translation appears here only to illustrate the application of the format. All translations, except the transition probability arrays, were performed with LUTE, a LASL code written in FORTRAN IV for this purpose.

SODIUM PHOTCN PRODUCTION DATA IN THE ENDF/B FORMAT, TRANSLATED FROM
M. DRAKE-S FORMAT BY D.J. CUDZIAK.

```
 1.1023E+04 2.2786E+01          0          2          1          0105914  5    1
 4.3920E-01 4.3920E-01          0          0          1         19105914  5    2
         19          2                                             105914  5    3
 0.         4.5800E-01          0          0          1         21105914  5    4
         21          2                                             105914  5    5
-1.0000E+00 4.6846E-01-9.0000E-01 4.7747E-01-8.0000E-01 4.8523E-01105914  5    6
-7.0000E-01 4.9214E-01-6.0000E-01 4.9880E-01-5.0000E-01 5.0404E-01105914  5    7
-4.0000E-01 5.0839E-01-3.0000E-01 5.1163E-01-2.0000E-01 5.1394E-01105914  5    8
-1.0000E-01 5.1536E-01 0.         5.1599E-01 1.0000E-01 5.1550E-01105914  5    9
 2.0000E-01 5.1394E-01 3.0000E-01 5.1163E-01 4.0000E-01 5.0839E-01105914  5   10
 5.0000E-01 5.0404E-01 6.0000E-01 4.9880E-01 7.0000E-01 4.9214E-01105914  5   11
 8.0000E-01 4.8523E-01 9.0000E-01 4.7747E-01 1.0000E+00 4.6846E-01105914  5   12
 0.         5.0000E-01          0          0          1         21105914  5   13
         21          2                                             105914  5   14
-1.0000E+00 5.0264E-01-9.0000E-01 5.0190E-01-8.0000E-01 5.0130E-01105914  5   15
-7.0000E-01 5.0154E-01-6.0000E-01 5.0058E-01-5.0000E-01 5.0042E-01105914  5   16
-4.0000E-01 4.9997E-01-3.0000E-01 4.9995E-01-2.0000E-01 4.9998E-01105914  5   17
-1.0000E-01 4.9957E-01 0.         4.9963E-01 1.0000E-01 4.8986E-01105914  5   18
 2.0000E-01 4.9998E-01 3.0000E-01 4.9995E-01 4.0000E-01 4.9997E-01105914  5   19
 5.0000E-01 5.0042E-01 6.0000E-01 5.0058E-01 7.0000E-01 5.0154E-01105914  5   20
 8.0000E-01 5.0130E-01 9.0000E-01 5.0190E-01 1.0000E+00 5.0264E-01105914  5   21
 0.         1.0000E+00          0          0          1         21105914  5   22
         21          2                                             105914  5   23
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-7.0000E-01 4.9323E-01-6.0000E-01 4.9896E-01-5.0000E-01 5.0347E-01105914  5   25
-4.0000E-01 5.0718E-01-3.0000E-01 5.1001E-01-2.0000E-01 5.1210E-01105914  5   26
-1.0000E-01 5.1348E-01 0.         5.1404E-01 1.0000E-01 5.1493E-01105914  5   27
 2.0000E-01 5.1210E-01 3.0000E-01 5.1001E-01 4.0000E-01 5.0718E-01105914  5   28
 5.0000E-01 5.0347E-01 6.0000E-01 4.9896E-01 7.0000E-01 4.9323E-01105914  5   29
 8.0000E-01 4.8695E-01 9.0000E-01 4.8001E-01 1.0000E+00 4.7186E-01105914  5   30
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         21          2                                             105914  5   32
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 5.0000E-01 5.0346E-01 6.0000E-01 4.9895E-01 7.0000E-01 4.9325E-01105914  5   38
 8.0000E-01 4.8688E-01 9.0000E-01 4.7982E-01 1.0000E+0C 4.7174E-01105914  5   39
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         21          2                                             105914  5   41
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 5.0000E-01 5.0361E-01 6.0000E-01 4.9886E-01 7.0000E-01 4.9283E-01105914  5   47
 8.0000E-01 4.8605E-01 9.0000E-01 4.7851E-01 1.0000E+00 4.6994E-01105914  5   48
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 5.0000E-01 5.0373E-01 6.0000E-01 4.9879E-01 7.0000E-01 4.9250E-01105914  5   56
 8.0000E-01 4.8539E-01 9.0000E-01 4.7746E-01 1.0000E+00 4.6848E-01105914  5   57
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 2.0000E-01 5.1439E-01 3.0000E-01 5.1200E-01 4.0000E-01 5.0853E-01105914  5   64
 5.0000E-01 5.0383E-01 6.0000E-01 4.9876E-01 7.0000E-01 4.9225E-01105914  5   65
 8.0000E-01 4.8489E-01 9.0000E-01 4.7668E-01 1.0000E+00 4.6736E-01105914  5   66
 0.         3.5000E+00          0          0          1         21105914  5   67
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 5.0000E-01 5.0390E-01 6.0000E-01 4.9875E-01 7.0000E-01 4.9209E-01105914  5   74
 8.0000E-01 4.8455E-01 9.0000E-01 4.7616E-01 1.0000E+0C 4.6658E-01105914  5   75
 0.         4.0000E+00         0         0         1         21105914  5   76
          21             2                                              105914  5   77
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-7.0000E-01 4.9216E-01-6.0000E-01 4.9887E-01-5.0000E-01 5.0390E-01105914  5   79
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 5.0000E-01 5.0390E-01 6.0000E-01 4.9887E-01 7.0000E-01 4.9216E-01105914  5   83
 8.0000E-01 4.8469E-01 9.0000E-01 4.7653E-01 1.0000E+0C 4.6663E-01105914  5   84
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 5.0000E-01 5.0395E-01 6.0000E-01 4.9888E-01 7.0000E-01 4.9211E-01105914  5   92
 8.0000E-01 4.8456E-01 9.0000E-01 4.7631E-01 1.0000E+0C 4.6635E-01105914  5   93
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 8.0000E-01 4.8452E-01 9.0000E-01 4.7619E-01 1.0000E+0C 4.6627E-01105914  5  102
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-7.0000E-01 4.9216E-01-6.0000E-01 4.9889E-01-5.0000E-01 5.04C4E-01105914  5  1C6
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 8.0000E-01 4.8455E-01 9.0000E-01 4.7617E-01 1.0000E+0C 4.6640E-01105914  5  111
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          21             2                                              105914  5  113
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-7.0000E-01 4.9229E-01-6.0000E-01 4.9890E-01-5.0000E-01 5.041CE-01105914  5  115
-4.0000E-01 5.0869E-01-3.0000E-01 5.1205E-01-2.0000E-01 5.1456E-01105914  5  116
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 8.0000E-01 4.8469E-01 9.0000E-01 4.7620E-01 1.0000E+00 4.6683E-01105914  5  120
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          21             2                                              105914  5  122
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-7.0000E-01 4.9240E-01-6.0000E-01 4.9890E-01-5.0000E-01 5.0412E-01105914  5  124
-4.0000E-01 5.0864E-01-3.0000E-01 5.1189E-01-2.0000E-01 5.1434E-01105914  5  125
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 8.0000E-01 4.8487E-01 9.0000E-01 4.7641E-01 1.0000E+0C 4.6731E-01105914  5  129
 0.         7.0000E+00         0         0         1         21105914  5  130
          21             2                                              105914  5  131
-1.0000E+00 4.6794E-01-9.0000E-01 4.7677E-01-8.0000E-01 4.8511E-01105914  5  132
-7.0000E-01 4.9252E-01-6.0000E-01 4.9890E-01-5.0000E-01 5.0411E-01105914  5  133
-4.0000E-01 5.0855E-01-3.0000E-01 5.1168E-01-2.0000E-01 5.1407E-01105914  5  134
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 2.0000E-01 5.1407E-01 3.0000E-01 5.1168E-01 4.0000E-01 5.0855E-01105914  5  136
 5.0000E-01 5.0411E-01 6.0000E-01 4.9890E-01 7.0000E-01 4.9252E-01105914  5  137
 8.0000E-01 4.8511E-01 9.0000E-01 4.7677E-01 1.0000E+0C 4.6794E-01105914  5  138
 0.         7.5000E+00         0         0         1         21105914  5  139
```

13

```
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-7.0000E-01 4.9265E-01-6.0000E-01 4.9890E-01-5.0000E-01 5.0409E-01105914  5 142
-4.0000E-01 5.0840E-01-3.0000E-01 5.1143E-01-2.0000E-01 5.1374E-01105914  5 143
-1.0000E-01 5.1519E-01 0.          5.1587E-01 1.0000E-01 5.1519E-01105914  5 144
 2.0000E-01 5.1374E-01 3.0000E-01 5.1143E-01 4.0000E-01 5.0840E-01105914  5 145
 5.0000E-01 5.0409E-01 6.0000E-01 4.9890E-01 7.0000E-01 4.9265E-01105914  5 146
 8.0000E-01 4.8542E-01 9.0000E-01 4.7727E-01 1.0000E+00 4.6870E-01105914  5 147
 0.         8.0000E+00          0           0           1         21105914  5 148
        21           2                                              105914  5 149
-1.0000E+00 4.6960E-01-9.0000E-01 4.7791E-01-8.0000E-01 4.8579E-01105914  5 150
-7.0000E-01 4.9279E-01-6.0000E-01 4.9889E-01-5.0000E-01 5.0405E-01105914  5 151
-4.0000E-01 5.0819E-01-3.0000E-01 5.1113E-01-2.0000E-01 5.1335E-01105914  5 152
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-4.0000E-01 4.9604E-01-3.0000E-01 5.0306E-01-2.0000E-01 5.3494E-01105914 53   73
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 2.0000E-01 5.3494E-01 3.0000E-01 5.0306E-01 4.0000E-01 4.96C4E-01105914 53   75
 5.0000E-01 5.1333E-01 6.0000E-01 5.0252E-01 7.0000E-01 4.8901E-01105914 53   76
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 7.1100E+00 4.4700E+00          0          0          1         4105914 53   78
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 5.0000E-01 5.0928E-01 6.0000E-01 4.9940E-01 7.0000E-01 4.7787E-01105914 53   87
 8.0000E-01 4.6414E-01 9.0000E-01 4.4542E-01 1.0000E+00 4.2177E-01105914 53   88
 0.         8.0000E+00          0          0          1        21105914 53   89
              21          2                                                105914 53   90
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-4.0000E-01 5.1214E-01-3.0000E-01 5.1983E-01-2.0000E-01 5.36C9E-01105914 53   93
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 2.0000E-01 5.3609E-01 3.0000E-01 5.1983E-01 4.0000E-01 5.1214E-01105914 53   95
 5.0000E-01 5.1046E-01 6.0000E-01 5.0032E-01 7.0000E-01 4.8114E-01105914 53   96
 8.0000E-01 4.6699E-01 9.0000E-01 4.4869E-01 1.0000E+00 4.2643E-01105914 53   97
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 8.0000E-01  4.7021E-01 9.0000E-01  4.5238E-01 1.0000E+00  4.3169E-01105914 53   106
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 8.0000E-01  4.7388E-01 9.0000E-01  4.5659E-01 1.000CE+0C  4.3768E-01105914 53   115
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-7.0000E-01  4.7787E-01-6.0000E-01  4.9940E-01-5.0000E-01  5.0928E-01105914 53   121
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 8.0000E-01  4.6699E-01 9.0000E-01  4.4869E-01 1.0000E+00  4.2643E-01105914 53   135
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 8.0000E-01  4.7021E-01 9.0000E-01  4.5238E-01 1.0000E+00  4.3169E-01105914 53   144
 0.          9.0000E+00         0          0          1        21105914 53   145
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-7.0000E-01  4.8901E-01-6.0000E-01  5.0252E-01-5.0000E-01  5.1333E-01105914 53   148
-4.0000E-01  4.9604E-01-3.0000E-01  5.0306E-01-2.0000E-01  5.3494E-01105914 53   149
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 2.0000E-01  5.3494E-01 3.0000E-01  5.0306E-01 4.0000E-01  4.96C4E-01105914 53   151
 5.0000E-01  5.1333E-01 6.0000E-01  5.0252E-01 7.0000E-01  4.89C1E-01105914 53   152
 8.0000E-01  4.7388E-01 9.0000E-01  4.5659E-01 1.0000E+0C  4.3768E-01105914 53   153
 0.          C.                 0          0          0        0105914  0   154
 11023.0     22.786             1          2         31        0105914102     1
 0.0         0.0                0          0          0        0105914  0     2
 0.0         0.0                0          0          C        01059 0   0  4444
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0.0        0.0                       0          0          C          0105915  0    4
11023.0    22.786                    2          1          2          0105915  6    5
2.080  E+6 0.0                       0          0          4          2105915  6    6
.4392  E+6 0.91       0.0                0.09                          105915  6    7
0.0        0.0                       0          0          C          0105915  0    8
11023.0    22.786                    2          1          3          0105915  7    9
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.4392  E+6 0.23       0.0                0.67                          105915  7   11
0.0        0.0                       0          0          C          0105915  0   12
11023.0    22.786                    2          1          4          0105915  8   13
2.640  E+6 0.0                       0          0          2          1105915  8   14
0.0        1.0                                                         105915  8   15
0.0        0.0                       0          0          C          0105915  0   16
11023.0    22.786                    2          1          5          0105915  9   17
2.705  E+6 0.0                       0          0          4          2105915  9   18
2.080  E+6 0.32       0.4392 E+6 0.68                                  105915  9   19
0.0        0.0                       0          0          C          0105915  0   20
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0.4392 E+6 0.4        0.0                0.6                            105915 10   23
0.0        0.0                       0          0          C          0105915  0   24
11023.0    22.786                    2          1          7          0105915 11   25
3.678  E+6 0.0                       0          0          8          4105915 11   26
2.640  E+6 0.15       2.080  E+6 0.1        0.4392 E+6 C.71            105915 11   27
0.0        0.04                                                        105915 11   28
0.0        0.0                       0          0          C          0105915  0   29
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2.080  E+6 0.5        0.0                0.5                            105915 12   32
0.0        0.0                       0          0          C          0105915  0   33
11023.0    22.786                    2          1          9          0105915 13   34
3.915  E+6 0.0                       0          0          4          2105915 13   35
0.4392 E+6 0.2        0.0                0.8                            105915 13   36
0.0        0.0                       0          0          C          0105915  0   37
11023.0    22.786                    2          1          1C         0105915 14   38
4.431  E+6 0.0                       0          0          2          1105915 14   39
0.0        1.0                                                         105915 14   40
0.0        0.0                       0          0          C          0105915  0   41
1.1023E+04 2.2786E+01               1          0          C          1105915 15    1
0.         0.                       0          0          1          7105915 15    2
         7            2                                                105915 15    3
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1.4000E+07 1.0836E+00 1.6000E+07 1.1726E+00 1.800CE+07 1.2911E+00105915 15    5
2.0000E+07 1.4039E+00                                                  105915 15    6
0.         0.                       0          1          1          7105915 15    7
         7            2                                                105915 15    8
9.0500E+06 9.7285E-01 1.0000E+07 9.7689E-01 1.2000E+07 1.0050E+00105915 15    9
1.4000E+07 1.0836E+00 1.6000E+07 1.1726E+00 1.8000E+07 1.2911E+00105915 15   10
2.0000E+07 1.4039E+00                                                  105915 15   11
0.         0.                       0          0          1          7105915 15   12
         7            2                                                105915 15   13
0.         9.0500E+06               0          0          1         23105915 15   14
        23            2                                                105915 15   15
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2.8000E+06 1.2944E-01 3.0000E+06 1.2243E-01 3.500CE+06 1.1382E-01105915 15   21
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7.0000E+06 1.2863E-02 8.0000E+06 1.1485E-20                            105915 15   23
0.         1.0000E+07               0          0          1         24105915 15   24
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2.8000E+06 1.2660E-01 3.0000E+06 1.1962E-01 3.5000E+06 1.1135E-01105915 15    31
4.0000E+06 1.0154E-01 5.0000E+06 7.6479E-02 6.0000E+06 5.0119E-02105915 15    32
7.0000E+06 2.5060E-02 8.0000E+06 8.3926E-03 9.0000E+06 1.1821E-20105915 15    33
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7.0000E+06 3.0090E-02 8.0000E+06 1.5045E-02 9.0000E+06 4.0457E-03105915 15    43
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7.0000E+06 3.2007E-02 8.0000E+06 1.8671E-02 9.0000E+06 1.20C3E-02105915 15    54
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7.0000E+06 4.0154E-02 8.0000E+06 3.1599E-02 9.0000E+06 2.3045E-02105915 15    88
1.0000E+07 1.6934E-02 1.2000E+07 9.0783E-03 1.4000E+07 3.6662E-03105915 15    89
1.6000E+07 8.7291E-04 1.8000E+07 1.7458E-20                    105915 15    90
0.         0.                  0          0          C  0105915  0    91
11023.0    22.786              2          1         11  0105915 51    42
4.778   E+6 0.0                0          0         10  5105915 51    43
3.678   E+6 0.05     2.984   E+6 0.1        2.08   E+6 0.2  105915 51    44
0.4392  E+6 0.6      0.0        0.05                  105915 51    45
0.0        0.0                 0          0          C  0105915  0    46
```

```
11023.0     22.786                    2          1          12         0105915 52    1
6.27   E+6  0.0                       0          0          2          1105915 52    2
2.391  E+6  1.0                                                         105915 52    3
0.0         0.0                       0          0          0          0105915  0    4
11023.0     22.786                    2          1          13         0105915 53    5
7.11   E+6  0.0                       0          0          8          4105915 53    6
2.984  E+6  0.03      2.640  E+6 0.12            0.4392 E+6 0.22       105915 53    7
0.0         0.63                                                        105915 53    8
0.0         0.0                       0          0          0          0105915  0    9
1.1023E+04  2.2786E+01                1          0          31         31105915102    1
0.          0.                        0          0          1          2105915102    2
         2           2                                                  105915102    3
1.0000E-04  3.0870E+00  1.0000E+06  3.0870E+00                         105915102    4
0.          8.7000E+04               0          2          1          2105915102    5
         2           2                                                  105915102    6
1.0000E-04  4.7800E-01  1.0000E+06  4.7800E-01                         105915102    7
0.          4.7300E+05               0          2          1          2105915102    8
         2           2                                                  105915102    9
1.0000E-04  8.0800E-01  1.0000E+06  8.0800E-01                         105915102   10
0.          7.2000E+05               0          2          1          2105915102   11
         2           2                                                  105915102   12
1.0000E-04  7.0000E-02  1.0000E+06  7.0000E-02                         105915102   13
0.          8.5000E+05               0          2          1          2105915102   14
         2           2                                                  105915102   15
1.0000E-04  7.0000E-02  1.0000E+06  7.0000E-02                         105915102   16
0.          8.7400E+05               0          2          1          2105915102   17
         2           2                                                  105915102   18
1.0000E-04  1.2000E-01  1.0000E+06  1.2000E-01                         105915102   19
0.          1.3670E+06               0          2          1          2105915102   20
         2           2                                                  105915102   21
1.0000E-04  8.0000E-02  1.0000E+06  8.0000E-02                         105915102   22
0.          1.8290E+06               0          2          1          2105915102   23
         2           2                                                  105915102   24
1.0000E-04  3.0000E-02  1.0000E+06  3.0000E-02                         105915102   25
0.          1.9870E+06               0          2          1          2105915102   26
         2           2                                                  105915102   27
1.0000E-04  2.0000E-02  1.0000E+06  2.0000E-02                         105915102   28
0.          2.2090E+06               0          2          1          2105915102   29
         2           2                                                  105915102   30
1.0000E-04  8.0000E-02  1.0000E+06  8.0000E-02                         105915102   31
0.          2.3990E+06               0          2          1          2105915102   32
         2           2                                                  105915102   33
1.0000E-04  1.1000E-01  1.0000E+06  1.1000E-01                         105915102   34
0.          2.5190E+06               0          2          1          2105915102   35
         2           2                                                  105915102   36
1.0000E-04  1.9000E-01  1.0000E+06  1.9000E-01                         105915102   37
0.          2.7590E+06               0          2          1          2105915102   38
         2           2                                                  105915102   39
1.0000E-04  8.0000E-02  1.0000E+06  8.0000E-02                         105915102   40
0.          2.8500E+06               0          2          1          2105915102   41
         2           2                                                  105915102   42
1.0000E-04  8.0000E-02  1.0000E+06  8.0000E-02                         105915102   43
0.          3.0590E+06               0          2          1          2105915102   44
         2           2                                                  105915102   45
1.0000E-04  1.0000E-02  1.0000E+06  1.0000E-02                         105915102   46
0.          3.0930E+06               0          2          1          2105915102   47
         2           2                                                  105915102   48
1.0000E-04  6.0000E-02  1.0000E+06  6.0000E-02                         105915102   49
0.          3.3390E+06               0          2          1          2105915102   50
         2           2                                                  105915102   51
1.0000E-04  5.0000E-02  1.0000E+06  5.0000E-02                         105915102   52
0.          3.5490E+06               0          2          1          2105915102   53
         2           2                                                  105915102   54
1.0000E-04  1.5000E-01  1.0000E+06  1.5000E-01                         105915102   55
0.          3.6200E+06               0          2          1          2105915102   56
         2           2                                                  105915102   57
1.0000E-04  5.0000E-02  1.0000E+06  5.0000E-02                         105915102   58
0.          3.8800E+06               0          2          1          2105915102   59
         2           2                                                  105915102   60
1.0000E-04  3.0000E-02  1.0000E+06  3.0000E-02                         105915102   61
0.          3.9000E+06               0          2          1          2105915102   62
```

```
        2              2                                        105915102    63
1.0000E-04 1.0000E-02 1.0000E+06 1.0000E-02                     105915102    64
0.         3.9670E+06          0          2         1          2105915102    65
        2              2                                        105915102    66
1.0000E-04 1.0000E-01 1.0000E+06 1.0000E-01                     105915102    67
0.         4.0000E+06          0          2         1          2105915102    68
        2              2                                        105915102    69
1.0000E-04 1.1000E-01 1.0000E+06 1.1000E-01                     105915102    70
0.         4.1800E+06          0          2         1          2105915102    71
        2              2                                        105915102    72
1.0000E-04 4.8000E-02 1.0000E+06 4.8000E-02                     105915102    73
0.         4.2000E+06          0          2         1          2105915102    74
        2              2                                        105915102    75
1.0000E-04 8.0000E-02 1.0000E+06 8.0000E-02                     105915102    76
0.         4.2770E+06          0          2         1          2105915102    77
        2              2                                        105915102    78
1.0000E-04 1.0000E-02 1.0000E+06 1.0000E-02                     105915102    79
0.         4.4990E+06          0          2         1          2105915102    80
        2              2                                        105915102    81
1.0000E-04 2.0000E-02 1.0000E+06 2.0000E-02                     105915102    82
0.         4.7500E+06          0          2         1          2105915102    83
        2              2                                        105915102    84
1.0000E-04 2.2000E-02 1.0000E+06 2.2000E-02                     105915102    85
0.         5.1190E+06          0          2         1          2105915102    86
        2              2                                        105915102    87
1.0000E-04 1.0000E-02 1.0000E+06 1.0000E-02                     105915102    88
0.         5.1300E+06          0          2         1          2105915102    89
        2              2                                        105915102    90
1.0000E-04 3.0000E-02 1.0000E+06 3.0000E-02                     105915102    91
0.         5.6120E+06          0          2         1          2105915102    92
        2              2                                        105915102    93
1.0000E-04 6.0000E-02 1.0000E+06 6.0000E-02                     105915102    94
0.         6.3990E+06          0          2         1          2105915102    95
        2              2                                        105915102    96
1.0000E-04 2.1000E-02 1.0000E+06 2.1000E-02                     105915102    97
0.         0.                  0          0         C          0105915  0    98
0.0        0.0                 0          0         0          01059 0  0 5555
*     END TAPE                                                      ENDTAPEE
```

APPENDIX B

CONSTRUCTION OF PHOTON PRODUCTION CROSS SECTIONS FROM THE ENDF/B FILE 15, OPTION 2

The discussion of Option 2 in File 15 (transition probability arrays for photon production) mentioned a process for constructing photon production cross sections from neutron interaction cross sections and transition probability arrays. In this appendix, we explain the process in more detail.

B.1. Specific Example

First we describe a method of constructing a production cross section in a sample case. Let us choose the 1.6408 MeV gamma ray from decay of the second level of ^{23}Na (2.080 MeV) to the first level (0.4392 MeV). Consider a neutron of incident energy 3.0 MeV. Figure 1 shows a partial energy level diagram of ^{23}Na, as taken from Drake et al.[5] (The data for File 15, Option 2, were derived from Drake's diagram.) From Fig. 1, we can infer that a 3 MeV neutron can produce a 1.6408 MeV photon in two ways, by inelastic scatter to level number 2 or to level number 5. *The possible modes are indicated by the double arrows on the diagram.* No competing pro-

Note that the photon production cross section is given for transition between specific levels, which implicitly determines the photon energy, rather than for a given photon energy. This scheme avoids ambiguity when two different transitions produce photons of the same energy. Then we can write

$$\sigma_{2,1}(3.0 \text{ MeV}) = [\sigma_2(3.0)][TP_{2,1}] + [\sigma_5(3.0]$$

$$\cdot [TP_{5,2} \cdot TP_{2,1}]$$

Values for $\sigma_2(3.0)$ and $\sigma_5(3.0)$ can be found in File 3, while values for $TP_{2,1}$, $TP_{5,2}$, and $TP_{2,1}$ are in File 15. An algorithm suitable for programming can be constructed by considering the more general case.

B.2 General Case

For the general case, all possible transitions must be considered, as well as the possibility of transitions not involving gamma-ray emission. A simple accounting for all possibilities leads to the following expression:

$$\sigma_{j,1}(E) = A_{j,1} \sum_{m_o=j}^{N} \sigma_{m_o}(E) \sum_{m_1=j}^{m_o-1} A_{m_o,m_1} \sum_{m_2=j}^{m_1-1} A_{m_1,m_2} \sum_{m_3=j}^{m_2-1} A_{m_2,m_3} \cdots \sum_{m_{n+1}=j}^{m_n-1} A_{m_n,m_{n+1}}$$

$$= A_{j,1} \sum_{n_o=j}^{N} \sigma_{m_o} \prod_{\ell=1}^{n+1} \sum_{m_\ell=j}^{m_{\ell-1}-1} A_{m_{\ell-1},m} \quad ,$$

cesses to gamma-ray emission are shown for ^{23}Na, so the general case cannot be illustrated unless we assume, say, internal conversion. In Section B.2, we shall formally carry photon transition probabilities (GP$_i$) for the sake of demonstrating a more general case.

where N = highest level such that $ES_N \leq E$, and $m_n \leq j + 1$ determines the index n.

Let us define:

1. $\sigma_{j,i}(E)$ = cross section to produce the photon which arises from decay of level j to i, with a neutron of incident energy E.

2. $\sigma_k(E)$ = neutron cross section for inelastic scatter to level k, for neutron energy E.

3. $TP_{j,i}$ = probability of a direct transition from level j to level i, i < j.

4. $GP_{j,i}$ = conditional probability of photon emission in a direct transition from level j to level i, i < j.

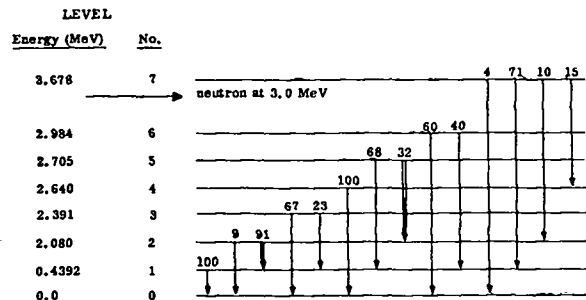5. $A_{j,i} = (TP_{j,i})(GP_{j,i})$.

Fig. 1. Partial energy level diagram for ^{23}Na.

An algorithm suitable for FORTRAN, for example, might then search File 15 for $ES_{NS} \leq E$ to determine N. Levels i and j would be specified by ES_i and ES_j, respectively. A simple search on ES_{NS} to find the MT number for which $ES_{NS} = ES_j$ would provide $TP_{j,i}$ and $GP_{j,i}$ (and thus $A_{j,i}$) from a further search of the LIST record for ES_i. By then going through the file in order of increasing MT numbers, up to MT = 4 + N, products of the $A_{m,n}$ can be accumulated for all cascades leading to the jth level.

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As is true of most reports written by a subcommittee, this one has been reviewed and constructively commented upon by many people. Some of the comments cannot be easily identified with any one individual, so the compiler offers his general apologies to anyone so slighted.

The embryonic form of a photon production format was presented by M. E. Battat and R. J. LaBauve to the first meeting of the Shielding Subcommittee of the CSEWG on February 6, 1967. (Their review and comments patiently followed the document through its metamorphosis to the present form.) D. C. Irving was responsible for an extensive review of the preliminary draft of this report (as presently constituted), and several revisions were made as a result of his cogent suggestions.

The section of this report on "Form Factor Data for Incoherent and Coherent Scattering" (Section 2.5) is due to J. M. Ferguson. Section 3.2.2 on "Transition Probability Arrays for Photon Production" is the result of the joint efforts of R. B. Lazarus and Donald J. Dudziak, with comments from D. C. Irving and H. Honeck incorporated. The remainder of the report is the responsibility of the compiler.

The kind permission from M. K. Drake to use a personal communication of the preliminary set of the sodium data is very much appreciated.

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