11. FILE 11. GENERAL COMMENTS OF PHOTON PRODUCTION

Photon production data not represented in MF=6 may be presented in four distinct files.

File	Description
12	Multiplicities and transition probability arrays
13	Photon production cross sections
14	Photon angular distributions
15	Continuous photon energy spectra

With the exception of File 12, all the files are closely analogous to the corresponding neutron data files with the same number (modulo 10). The purpose of File 12 is to provide additional methods for representing the energy dependence of photon production cross sections. The allowed reaction type (MT) numbers are the same as those assigned for neutron reactions, Files 1 through 7. However, they may have somewhat different meanings for photon production that require additional explanation in some cases:

1. MT=3 should be used in File 12 through 15 to represent composite cross sections, that is, photon production cross sections from more than one reaction type that have been lumped together.
2. There is no apparent reason to have redundant or derived data for the photon production files, as is the case for the neutron files, *i.e.*, MT=3, 4, *etc.* Therefore, to avoid confusion, the join of all sections of Files 6, 12 and 13 should represent the photon production, with each section being disjoint from all others.
3. Using Figure 11.1 as a guide, let us consider how one might represent inelastic γ-ray production. The differential cross section for producing γ-ray of energy E_γ resulting from the excitation of the m_0^{th} level of the residual nucleus and the subsequent transition between two definite levels (j→i), which need not be adjacent, including the effects of cascading from the m_0-j levels higher than j, is

$$\frac{d\sigma}{dE_\gamma}(E_\gamma, E, m_0, i, j) = \delta\left[E_\gamma - (\varepsilon_j - \varepsilon_i)\right] A_{ji}\sigma_{m_0}(E) \sum_{\alpha=1}^{m_0-j} R_{m_0 j\alpha} \ , \qquad (11.1)$$

where

σ_{m0} = Cross section for exciting the m_0^{th} level with incident particle energy E, taken from file 3 for MT corresponding to the m_0^{th} level,

$\delta[E_\gamma-(\varepsilon_j-\varepsilon_i)]$ = Delta function defining the discrete gamma of energy E_γ that results from the transition level j to level i,

A_{ji} = Probability that a gamma ray of energy of E_γ is emitted in the transition from level j to i, taken as the gamma ray branching ratio of j→i,

$R_{m_0 j\alpha}$ = Probability that the nucleus initially excited at level m_0 will de-excite to level j in α transitions, where α ranges from 1 to m_0-j,

$$= \sum_{m_1=\alpha+(j-1)}^{m_0-1} \sum_{m_2=\alpha+(j-2)}^{m_1-1} \cdots \sum_{m_{\alpha-1}=j+1}^{m_{\alpha-2}-1} \sum_{m_\alpha}^{j} \prod_{l=1}^{\alpha} TP_{m_{l-1}m_l}$$

$Tp_{k,l}$ = probability of the residual nucleus having a transition to the l^{th} level given that it was in the excited state corresponding to the k^{th} level, *i.e.*, the branching ratio for a gamma ray transition from the k→*l* level.

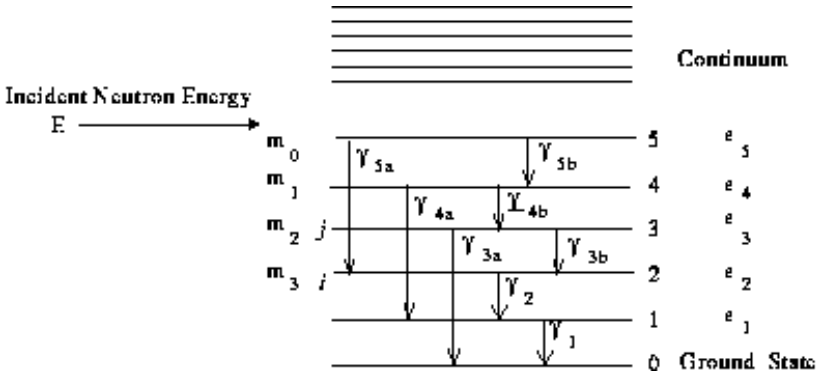
In general, $R_{m0j\alpha}$ is the sum of the products of α transition probabilities (branching ratios) leading from level m_0 through intermediate levels to level j. In the example shown for initial excitation of level m_0=5 and interest being in the resulting γ-ray due to transition between levels 2 and 1

$$R_{m_0 j} = TP_{m_0 j} = TP_{52}$$
$$R_{m_0 j2} = TP_{m_0 m_1}\, TP_{m_1 j} + TP_{m_0 m_2}\, TP_{m_2 j} = TP_{52} \cdot TP_{42} + TP_{53} TP_{32} = 0 + 0 = 0$$

[$E\gamma = E_{\gamma 2} = (\varepsilon_2 - \varepsilon_1)$], the relevant quantities are
for this example, and

$$R_{m_0 j3} = TP_{m_0 m_1}\, TP_{m_1 m_2}\, TP_{m_2 j} = TP_{54} \cdot TP_{43} \cdot TP_{32}$$

If m_0 and j are separated by many levels, the scheme becomes very involved.



We are at once beset by the problem that no clear choice of ENDF representation in terms of section number is possible. The data may naturally be identified with both the m_0^{th} level and the j^{th} level. To avoid this problem, we can sum Eq. (11.1) over m_0:

$$\frac{d\sigma_1}{dE_\gamma}(E_\gamma, E, i, j) = \sum_{m_0 = j}^{N} \frac{d\sigma}{dE_\gamma}(E_\gamma, E, m_0, i, j) \tag{11.2}$$

where N is the highest level that can be excited by a neutron of incident energy E [*i.e.*, $\varepsilon_N \leq$ AWR/(AWR + E)]. This gives a ***de-excitation*** cross section that can single out a definite γ-ray transition and has the advantage when experimental data are to be represented. The de-excitation cross section is identified with the j^{th} level.

Alternatively, we can sum Eq. (11.1) over i and j:

$$\frac{d\sigma_2}{dE_\gamma}\left(E_\gamma, E, m_0\right) = \sum_{j=1}^{m_0} \sum_{i=0}^{j-1} \frac{d\sigma}{dE_\gamma}\left(E_\gamma, E, m_0, i, j\right) \tag{11.3}$$

This gives an ***excitation*** cross section that can single out a definite excited state and has the advantage when calculated data are to be represented. The excitation cross section is identified with the m_0^{th} level. If Equation (11.2) is summed over i and j, or if Equation (11.3) is summed over m_0 then

$$\begin{aligned}\frac{d\sigma}{dE_\gamma}\left(E_\gamma, E\right) &= \sum_{m_0=1}^{N} \frac{d\sigma_2}{dE_\gamma}\left(E_\gamma, E, m_0\right) \\ &\equiv \sum_{j=1}^{N}\sum_{i=0}^{j-1} \frac{d\sigma_1}{dE_\gamma}\left(E_\gamma, E, i, j\right).\end{aligned} \tag{11.4}$$

This gives a cross section for all possible excitations and transitions and thus corresponds to the total inelastic neutron cross section for discrete levels. It is recommended that MT=4 be used for the data represented by Equation (11.4), as well as for the continuum. If, however, it is expedient or useful to use MT=51 through 91, then one must use either the de-excitation cross sections of Equation (11.2) or the excitation cross sections of Equation (11.3), but not both. A restriction is imposed if the transition probability array option is used and if the entire neutron energy range is not covered by the known transition probabilities. Then, for MT=51 through 90 in File 12 to be used for the remaining neutron energy range, a representation by ***excitation*** multiplicities must be used. The integrated cross sections of File 13 are obtained by integrating Equations (11.1) through (11.4) over E_γ.

4. The remarks in Item 3 apply for discrete rays from (n,pγ), (n,dγ), (n,tγ), (n,^{3}Heγ), (n,αγ) reactions, and the use of MT=103, 101, 105, 106, and 107 is recommended for these cases.