UCRL-TR-206607

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Proposal for ENDF formats that describe emission of post-fission beta-delayed photons

D. Brown, J. Pruet, G. Hedstrom, J. Hall, M-a. Descalle

September 16, 2004

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Proposal for ENDF formats that describe emission of post-fission β-delayed photons

David Brown, Jason Pruet, Gerry Hedstrom, James Hall (N-Division, LLNL) and Marie-anne Descalle (M-Division, LLNL)

1 Purpose

Fission of heavy nuclides is accompanied by the birth of neutron rich fragment nuclei born in highly excited states. Following emission of prompt neutrons and γ-rays, these fragments are typically left with atomic numbers that are 3-4 units smaller than stable nuclei with the same mass number. As these nuclides undergo β decay to reach stability, a large number of γ-rays are emitted. Figure 1 illustrates some of the processes leading to emission of β delayed photons. A variety of applications (most notably those concerned with the detection and identification of clandestine fissile material) would benefit from a clear description of the spectral and temporal evolution of these γ-rays. This proposal describes formats for representing emission of delayed photons and is based on the analysis presented in [1].

At the present time, no single evaluated data set exists that directly provides for the temporal evolution of γ rays from the decay of the fission products. However, evaluated data sets containing all of the physical parameters required for such calculations have been prepared. These include estimates of the independent and cumulative fission yields of all fission products, branching ratios in the decay of ground and isomeric states [2], lifetimes of these states, and the spectra of γ rays emitted in their decay. Sizeable uncertainties and possibly significant errors are likely present concerning the shortest-lived fission products. However, the high-energy γ-ray spectra generated from some of these data sets have been shown to be in reasonable agreement with initial experiments designed specifically to test them under conditions likely to be of interest to interrogation of sea-going cargo containers [1,3].

For clarity we emphasize that the relationship between delayed neutron emission and delayed photon emission is tenuous. Only a small fraction of fission fragments – typically those characterized by large decay Q values – undergo β^{-}n emission. However, essentially all fission fragment decays result in the emission of a few photons. Also, it would be impractical to accurately specify and measure energies of delayed neutrons. By contrast, most fission fragments have decay spectra known to sub-keV accuracy that are readily resolved with inexpensive field HpGe detectors.

2 Description

A basic quantity of interest to Monte Carlo modelers is the delayed γ-ray source function s_γ. This function describes the production of photons following spontaneous or induced fission. Specific details of s_γ are given in section 3. Once s_γ has been determined, the spectrum for any fission rate and counting history can be determined.

We propose two different representations of s_γ. This first is compact, similar in spirit to common descriptions for the emission of β-delayed neutrons, and based on simple continuous functions. This is useful when detailed spectral information is not needed. The second proposed representation involves tabulating s_γ for discrete gamma-rays and accommodates detailed spectral information.

So far, parameters describing the two representations have been calculated for thermal, fission-spectrum, and 14 MeV neutron induced fission of ^{239}Pu and ^{235}U. For illustration we show in table 1 fit parameters describing the continuous approximation to photon emission following fission-spectrum neutron induced fission of ^{235}U. In addition, the COG Monte Carlo code at LLNL has been modified to sample photons represented in the discrete approximation described below. Comparisons with experiment have been done and are favorable. One drawback to the discrete approach is the large size of the data files needed to represent photons with keV resolution.

3 Changes to ENDF/B Manual

3.1 MF = 1 Changes:

Page 1.1, General Information:

"File 1 may contain up to four ..." changed to "File 1 may contain up to five additional sections giving fission neutron and photon yields and energy release information."

New Section:

1.6 Delayed Photon Data (MT=460)

This section describes the delayed photon source function resulting from either particle induced or spontaneous fission. The delayed gamma source function is defined as the number of gammas emitted per unit time after the fission event, per unit energy for a fixed incident energy:

$$s_\gamma(E,E_\gamma,t) \equiv \frac{d^2 n_\gamma}{dt dE_\gamma}(E,E_\gamma,t).$$

Here E is the energy of the fission-inducing projectile, E_γ is the energy of the emitted photon, t is the time following fission at which the photon is emitted, and $d^2n_\gamma/dtdE_\gamma$ is the number of photons emitted per fission per second per eV. The source function may be given either in a discrete or continuous representation.

In the discrete representation (LO=1), the source function is given as a series of tables of photon multiplicities, $y_i(E)$, in File 12 with LO=1, with their associated time dependences

$$s_\gamma(E,E_\gamma,t) = \sum_{i=1}^{NG} \delta(E_\gamma - E_i)\, y_i(E)\, T_i(t).$$

The continuous representation (LO=2) is similar in spirit to the delayed neutron data (MT=455). In this representation, one must give the photon multiplicities in File 12 and the fraction of photons emitted at each energy, $f_i(E \leftarrow E_\gamma)$, in an MF=15 table, for each precursor family. The time dependence of each precursor family is given as a list of time constants:

$$s_\gamma(E,E_\gamma,t) = \sum_{i=1}^{NNF} y_i(E)\, f_i(E \leftarrow E_\gamma)\, \lambda_i \exp(-t\lambda_i).$$

Only the precursor family time constants are stored in MF=1.

1.6.1 Formats

1.6.1.1 Discrete Representation (LO=1)

The following quantities are defined:

NG The number of discrete photons.
NR, NP, t_{int} Standard TAB1 parameters.
$T_i(t)$ Time dependence of the i^{th} photon's multiplicity (sec^{-1}).

The structure of the time dependence data block is:

[MAT, 1, 460/ ZA, AWR, LO=1, 0, NG, 0] HEAD
[MAT, 1, 460/ 0.0, 0.0, 1, 0, NR, NP/t_{int}/$T_1(t)$] TAB1
[MAT, 1, 460/ 0.0, 0.0, 2, 0, NR, NP/t_{int}/$T_2(t)$] TAB1
…
[MAT, 1, 460/ 0.0, 0.0, NG, 0, NR, NP/t_{int}/$T_{NG}(t)$] TAB1
[MAT, 1, 0/ 0.0, 0.0, 0, 0, 0, 0] SEND

1.6.1.2 Continuous Representation (LO=2)

The following quantities are defined:

NNF The number of precursor families considered.
λ_i Decay constant (sec^{-1}) for the i^{th} precursor.

The structure of this data block is:

[MAT, 1, 460/ ZA, AWR, LO=2, 0, 0, 0] HEAD
[MAT, 1, 460/ 0.0, 0.0, 0, 0, NNF, 0/λ_1, λ_2, … λ_{NNF}] LIST

[MAT, 1, 0/ 0.0, 0.0, 0, 0, 0, 0] SEND

1.6.2. Procedures

1.6.2.1 Discrete Representation (LO=1)

The photon multiplicity is given in File 12 with LO=1 in File 12 set. Each discrete photon in File 12 must have an associated time dependence table specified in File 1.

1.6.2.2 Continuous Representation (LO=2)

The probability of producing precursors for each family and the energy distributions of photons produced by each precursor family are given in Files 12 and 15. It is extremely important that the same precursor families be given in Files 12 and 15 as in File 1 (MT=460) and the ordering of families should be the same in all files. It is recommended that all families be ordered by decreasing half-lives ($\lambda_1<\lambda_2<\ldots<\lambda_{NNF}$).

3.2 MF = 12 Changes:

First paragraph:

"File 12 can be used to represent ..." change to "File 12 can be used to represent the neutron energy dependence of photon production cross sections <u>or delayed photon source functions</u> by means of either ..."

" Both methods rely upon ..." change to "Both methods rely upon processing codes that use <u>either</u> neutron cross sections from File 2 and/or File 3 to generate absolute photon production cross sections <u>or time constants from File 1 (MT=460) to generate delayed photon source functions.</u>"

References

[1] Pruet, J., Hall, J., Descalle, M.-A. & Prussin, S.G. 2004, NIMB 222, 403

[2] England, T.R. & Rider, B.F. 1994, LA-UR-94-3106, ENDF-349

[3] Norman, E.B., Prussin, S.G., Larimer, R.-M., Shugart, H., Browne, E., Smith, A., McDonald, R.J., Nitsche, H., Gupta, P. Frank, M., Gosnell, T., 2004, NIM A, 521, 608

Table 1: Fit parameters for continuous representation of s_γ for fission spectrum neutrons on ^{235}U (*NNF*=27). Note, all f_i =1/(5.0e5 eV).

E_γ (eV)	y_i	λ_i(sec)
2.50e+05	8.11e-02	4.81e-01
2.50e+05	1.99e-01	8.40e-02
2.50e+05	2.89e-01	1.38e-02
7.50e+05	4.22e-02	5.56e-01
7.50e+05	8.19e-02	8.80e-02
7.50e+05	1.51e-01	1.18e-02
1.25e+06	1.97e-02	4.90e-01
1.25e+06	3.23e-02	9.99e-02
1.25e+06	1.11e-01	1.19e-02
1.75e+06	8.80e-03	7.30e-01
1.75e+06	1.39e-02	1.37e-01
1.75e+06	4.25e-02	1.33e-02
2.25e+06	3.96e-03	1.04e+00
2.25e+06	1.01e-02	9.22e-02
2.25e+06	2.96e-02	1.42e-02
2.75e+06	3.52e-03	7.14e-01
2.75e+06	6.58e-03	1.07e-01
2.75e+06	2.03e-02	1.50e-02
3.25e+06	4.38e-03	3.77e-01
3.25e+06	8.12e-03	1.36e-01
3.25e+06	8.35e-03	1.38e-02
3.75e+06	5.97e-04	3.32e-01
3.75e+06	8.57e-03	1.26e-02
3.75e+06	1.05e-03	9.98e-02
4.25e+06	1.09e-03	7.14e-01
4.25e+06	1.48e-03	1.19e-01
4.25e+06	6.31e-03	1.04e-02

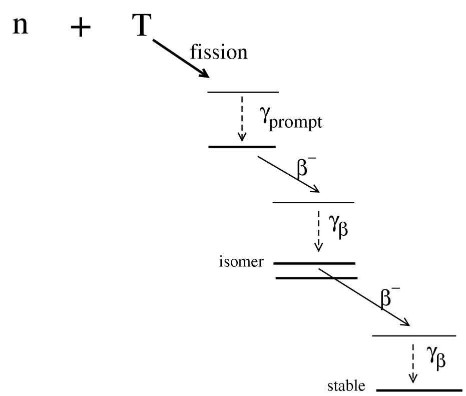

Figure 1: Illustration of some processes leading to the production of post-fission β-delayed photons. Here γ_{prompt} represents the photons emitted by the highly excited fragment nucleus born just after fission. Beta-delayed photons represented by the source function s_γ described in the text are labeled γ_β.