*Automated MCNP
Photon Source Generation
for Arbitrary Configurations
of Radioactive Materials and
First-Principles Calculations
of Photon Detector Responses*

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AUTOMATED MCNP PHOTON SOURCE GENERATION FOR ARBITRARY CONFIGURATIONS OF RADIOACTIVE MATERIALS AND FIRST-PRINCIPLES CALCULATIONS OF PHOTON DETECTOR RESPONSES

by

Guy P. Estes, Robert G. Schrandt, and John T. Kriese

ABSTRACT

A patch to the Los Alamos Monte Carlo code MCNP has been developed that automates the generation of source descriptions for photons from arbitrary mixtures and configurations of radioactive isotopes. Photon branching ratios for decay processes are obtained from national and international data bases and accessed directly from computer files. Code user input is generally confined to readily available information such as density, isotopic weight fractions, atomic numbers, etc. of isotopes and material compositions. The availability of this capability in conjunction with the “generalized source” capability of MCNP Version 3A makes possible the rapid and accurate description of photon sources from complex mixtures and configurations of radioactive materials, resulting in improved radiation transport predictive capabilities. This capability is combined with a first-principles calculation of photon spectrometer response—functions for NaI, BGO, and HPGe for $E_\gamma \lesssim 1$ MeV.

I. INTRODUCTION

The radioactive decay photon source patch to MCNP Version 3A¹ was developed to make possible the rapid and accurate determination of radioactive isotope decay photon source strengths and spectra for use in transport calculations. It is an extension of the Version 3A generalized source,¹⁻⁵ and to a large degree, motivated the development of the generalized source. The passive photon patch in conjunction with the generalized source in Version 3A allows the material (that is, cell)

isotope and photon line structure of the “real” world to be modeled in terms of generally available physical characteristics rather than in “merged” and/or “binned” collections of data that bear little direct resemblance to physical reality. For example, characteristic photon lines (monoenergetic photons that provide a unique signature for a given isotope) are started in the continuous-energy MCNP calculation at discrete energies (that is, “lines”) rather than in bins where they may lose their identity. This feature makes the task of comparison with experiment much more straightforward when detector resolution-broadening is factored into the calculations.

There is no time dependence built into the calculations. Isotope inventories must be input and do not change with time.

In addition to the automated source portion of the patch, two other options are described that greatly facilitate the comparison of calculations with measurements. These are a detector resolution-broadening option and a detector response option. The broadening option makes it possible to emulate the actual finite resolution of a detector rather than have the zero resolution inherent in a continuous energy code such as MCNP. The detector response option allows for first-principles calculation of detector response (that is, count rate spectra) to photon radiation, which can eliminate the need for spectrum unfolding and simplify comparisons with measurements. This option has been used successfully to calculate the response of sodium iodide (NaI), bismuth germanate (BGO), and High Purity Germanium (HPGe) detectors for energies $\lesssim 1$ MeV.

II. THEORY

A. Radioactive Decay Sources

In a typical MCNP photon radioactive decay problem, one may have a number of source cells c , each containing a number of source isotopes i , with each isotope emitting a number of photons of various energies ℓ per decay of isotope i . The parameters needed to calculate the probability of a photon being emitted in a specific cell of a collection of source cells, in a specific isotope within the specific cell, and at a given energy for the specific isotope in the specific cell ($P_{ci\ell}$) are defined below:

- c = source cell index
- i = source isotope index
- ℓ = source photon line (energy) index
- W_c = weight fraction of all source isotopes in cell c
- W_{ci} = weight fraction of source isotope i in all source isotopes of cell c
- V_c = volume of cell c (cm^3)
- a_i = atomic number of isotope i (g/mole)
- N_o = Avagadro's number (atoms/mole)
- λ_i = decay constant for isotope i (sec^{-1})
- t = decay time for ^{241}Am concentration time dependency (yrs)
- ρ_c = mass density of cell c (g/cm^3)

$B_{i\ell}$ = branching ratio for photon line ℓ in decay of isotope i ($\gamma_\ell/\text{decay } i$) (see Sec. III.3)
 N_{ci} = number density of source isotope i in cell c (atoms i/cm^3)
 A_{ci} = activity of source isotope i in cell c (disintegrations $i/\text{cm}^3\text{-sec}$)
 B_i = total photons per decay of isotope i ($\gamma/\text{decay } i$)

Using these definitions one can calculate quantities relating to the natural decay of the isotopes:

$$N_{ci} = W_{ci} W_c \rho_c N_o / a_i \quad (\text{atoms } i/\text{cm}^3) \quad (1)$$

$$A_{ci} = \lambda_i N_{ci} \quad (\text{decays } i/\text{cm}^3\text{-sec}) \quad (2)$$

$$B_i = \sum_{\ell} B_{i\ell} \quad (\gamma_i/\text{decay } i) \quad (3)$$

Then one can sum and normalize the various branching ratios and activities to obtain normalized line, isotope, and cell probabilities as follows:

Probability for line ℓ of isotope i in cell c :

$$P_{ci\ell} = \frac{B_{i\ell}}{\sum_{\ell} B_{i\ell}} = \frac{B_{i\ell}}{B_i} \quad (4)$$

Probability of isotope i in cell c :

$$P_{ci} = \frac{A_{ci} B_i}{\sum_i A_{ci} B_i} \quad (5)$$

Probability of cell c :

$$P_c = \frac{V_c \sum_i A_{ci} B_i}{\sum_c V_c \left[\sum_i A_{ci} B_i \right]} \quad (6)$$

Weight (WGT) for problem source strength (that is, total photons emitted):

$$WGT = \sum_c V_c \left[\sum_i A_{ci} B_i \right] [\gamma/\text{sec}] \quad (7)$$

In general, this is the procedure followed in the patch with three exceptions:

- (1) The presence of the AMn card in a problem triggers a calculation of the ^{241}Am concentration based on the initial concentration and decay time specified on the card. The ^{241}Am calculation is based on the radioactive decay formula⁶

$$N_{ca}(t) = N_{ca}(t=0)e^{-\lambda_a t} + \frac{N_{cp}(t=0)\lambda_p(e^{-\lambda_p t} - e^{-\lambda_a t})}{\lambda_a - \lambda_p}, \quad (8)$$

where the subscripts a and p refer to ^{241}Am and ^{241}Pu , respectively, and $N_{ca}(t=0)$ and t are input on the AMn card. The initial ^{241}Pu concentration is reduced by $e^{-\lambda_p t}$.

- (2) If a daughter nuclide is designated as described later, then a special calculation is triggered. The daughter concentration is calculated from the parent nuclide concentration and a daughter/parent concentration obtained from a Sandia National Laboratories ORIGEN⁷ calculation⁸ for the natural radioactive decay of most long-lived isotopes of elements thorium and above.
- (3) Continuous photon sources from decay processes such as spontaneous fission in ^{240}Pu and Bremsstrahlung produced by the 2.29-MeV beta particle from ^{234m}Pa (a daughter of ^{238}U) may be needed in a problem. These particular special cases were handled by creating histogram probability distributions to be used in conjunction with the photon line files. Nuclides –94240 and –92238 were chosen to represent these sources. They are treated much like other nuclides and should be assigned the 94240 and 92238 nuclide weight fractions, respectively, so their photon emission rates can be calculated. However, because they are, in effect, duplicates of other nuclides, their concentrations are not reflected in the diagnostic output for a problem.

B. Detector Resolution Broadening

The comparison of calculated photon line spectra with measured spectra is complicated by the fact that photon detectors have a finite resolution; that is, an unfolded flux spectrum for a monoenergetic photon source will appear as a broadened peak, usually with an approximate Gaussian shape centered at the actual source energy. On the other hand, a continuous-energy code such as MCNP treats a monoenergetic photon as monoenergetic and will tally it in the appropriate tally bin. This difference between MCNP tallies and unfolded detector spectra makes a detailed spectral comparison of the results difficult when the energy difference between two or more photon lines is on the order of the detector resolution full width-half maximum (FWHM) or less.

A solution⁹ to this problem for NaI, BGO, and HPGe detectors has been incorporated into the photon source patch. In essence, coding was added that simply changes the energy of a particle just before it is tallied by randomly choosing an energy consistent with a Gaussian distribution centered at the unmodified tally

energy. This procedure produces a Gaussian distribution of energies for monoenergetic particles and is approximately equivalent to the actual detector response to monoenergetic particles.

The following functional forms of detector resolutions were obtained from experimentalists at Los Alamos National Laboratory:¹⁰

$$\text{NaI/HPGe: } \sigma(E) = A + B\sqrt{E}, E \text{ in keV}$$

$$\text{BGO: } FWHM(\Delta E/E) = A + B/\sqrt{E}, E \text{ in MeV.}$$

The relationships between σ and $FWHM$ were obtained from Ref. 11 and the random number sampling algorithm for a Gaussian (or normal) distribution was obtained from Ref. 12.

C. First-Principles Calculation of Detector Response

When a photon interacts with a detector such as NaI, BGO, or HPGe, it may deposit all or part of its energy in the active volume of the crystal. This energy is transferred for the most part to electrons that in turn produce a measurable signal (light or electrical) approximately proportional to the photon energy deposited. An event is then registered when a “count” appears in the channel of a multichannel pulse-height analyzer (MCA) that corresponds to the energy deposited. Calibration of the spectrometer with standard, monoenergetic sources allows for a count rate spectrum (counts/energy bin-sec versus energy) to be obtained. Often this information is the measurement result desired. In cases where it is important to know the absolute flux spectrum (photons/cm²-sec) incident on the detector, the count rate spectrum can be “unfolded” or “stripped” into the flux spectrum using measured detector response functions for a range of monoenergetic calibration sources.

The objective of measurements usually determines which of these procedures is to be followed. For the most part, it is sufficient just to obtain the count rate spectrum as a response to a particular source. In some cases, such as when a biological dose rate from a complex source is needed, the unfolding must be done.

On the other hand, calculations of photon radiation produce flux spectra by virtue of the fact that particles are transported to locations in space. If detector responses are needed, they must be generated by either folding in detector response functions or by calculating the response from first principles. If response functions are folded in, they are generally obtained from measurements such as those required for the unfolding of experimental data.

Each of the measurement and calculational approaches have been used to some extent and have certain advantages and disadvantages. One of the disadvantages of measuring detector response function for use in unfolding measurements or folding with calculations is that detector response is affected by the environment in which the detector is placed. Photons may scatter from nearby structures, the ground, and so forth, before they enter the detector, thus making the lower energy response different for different detector placements.

It is for the changing detector environment scenario that the first-principles detector response calculational capability was developed. Using such a technique eliminates, at least in some cases, the need to recalibrate when the detector environment changes.

Incidentally, to be able to better interpret measured data, it is desirable to isolate the detector from its environment as much as possible. This can be done by using a collimator and/or shield with the system.

In practice, the first-principles detector response capability is simply a new type of tally in MCNP. This tally counts the energy deposited by a photon as it interacts with the active volume of the detector. At present, electron transport is ignored and all electron (or positron) recoil energy is assumed deposited at the photon collision site. This has been shown to be accurate for 3- × 3-in. (and greater) NaI and BGO detectors for photon energies of ~1 MeV or less. Currently electron transport is being incorporated into a special version of MCNP (MCNPE), and accurate calculations for higher energies and smaller detectors will soon be possible. The code treatment of annihilation photons was changed to release two photons going in opposite directions so that single and double escape would be properly accounted for.

Based on experience with the detector response tally used for NaI, BGO, and HPGe detectors, it appears that a tally of this type would be of general use in the code. In fact, it is somewhat similar to the heating tallies that exist except that the energy deposited is calculated from first principles rather than from the somewhat artificial "heating numbers." It is thought, based on recent work, that this type of tally belongs in a modern Monte Carlo code for the purposes described here. However, because it is a recent addition and its potential use for other types of detectors (for example, neutron proportional counters, neutron spectrometers, and so forth) has not been fully explored, it has been added as a patch for the current work. As experience with other detectors develops, it may be extended and ultimately added to the production code.

For HPGe p-type coaxial detectors, the so-called "dead layer" or inactive region of the germanium must be excluded from the active volume to obtain accurate results.

The various detectors may have inefficiencies that cannot be accounted for explicitly in MCNP because they involve different physics. For example in NaI, the light collection efficiency of the system is a function of energy deposited. Effects such as this, if important and quantitatively defined, can be accounted for using the MCNP DE and DF tally cards or modifications to the code.

III. DATA

To perform calculations using the theory of Sec. II, it is necessary to decide what photon line-branching ratio data to use. These data in conjunction with Avogadro's number (N_o), isotope atomic weights (a_i), and decay constants (λ_i) constitute the basic physics data needed for a problem. These data are distinguished from physical characteristics of the system such as cell volumes, isotope weight fractions, mass densities of materials, and so forth, that change for different systems of materials.

A. Photon Branching Ratios

Photon branching ratios can be obtained from a number of sources with the fundamental sources generally accepted to be Refs. 13 and 14. However, these references contain much more and varied data than branching ratios and are somewhat cumbersome to use for this purpose. In recent years, rather specific collections of photon branching ratios have been published. One of these, by Erdtman and Soyka,¹⁵ was published about the time this work was started and had available computer files of the data. Therefore, it was chosen as the basic photon branching ratio data library.

In early calculations of the photon spectral output from uranium metal, it was observed that the calculations did not agree well with HPGe measurements for the 1.001- and 0.766-MeV lines from ^{234m}Pa in the ^{238}U decay chain. Investigation¹⁶ of this disagreement led to the observation that photon branching ratios for the ^{238}U decay chain reported by Gunnink and Tinney at Lawrence Livermore National Laboratory¹⁷ (and documented in a convenient form in Ref. 18) gave much improved agreement with measurements. No reason could be found for this discrepancy, although it was determined that the 1.001- and 0.766-MeV line intensities from Erdtman and Soyka agreed with the values derived from Nuclear Data Sheets. For information, Gunnink *et al.* later reevaluated, in Ref. 19, some of the data in Ref. 17.

In view of this evidence, the program at Los Alamos uses the limited data in Ref. 18 when possible. Calculations of the photon line intensity output from various configurations of special nuclear materials (SNM) have been extensively compared with measurement benchmarks with good results.

B. Bremsstrahlung

In radioactive materials that emit energetic beta particles, the Bremsstrahlung process can produce significant sources of secondary photons. The resulting photon spectrum is a continuum extending to the maximum energy of the emitted beta particles with an average energy of approximately one-third the maximum beta-particle energy. In studies of SNM systems of interest (to the authors) to date, only the Bremsstrahlung from the 2.29-MeV beta particle of ^{234m}Pa decay has been found to be important. CYLTRAN²⁰ calculations²¹ were performed for 0.1- to 0.3-cm-thick uranium metal slabs to determine the unattenuated Bremsstrahlung photon production inside the metal. This is used as an additional internal photon source when uranium metal is being calculated. Comparison of calculations with measurements has shown that this source apparently underestimates the leakage spectrum from uranium metal in a configuration-dependent way. Consequently, normalization factors for various configurations have been determined empirically to deal with this problem. Investigation of this discrepancy is continuing as time permits.

C. Spontaneous Fission Photons

Because ^{240}Pu has a relatively high spontaneous fission rate, an approximate photon spectrum for this process has been developed. The data were taken from Ref. 22 for ^{235}U spontaneous fission. This contribution has been found to be small in comparison with other photon sources for systems of interest to the authors.

D. Miscellaneous Constants

The decay constants (λ_i) and photons/decay (B_i) were obtained from Ref. 15 as part of the computer data files and are carried in the header lines of the files described in Sec. IV. A value of 0.602472×10^{24} is used for Avogadro's number. Atomic masses for the number density (N_{ci}) calculations must be input using the MCNP AWTAB card because the photon cross-section files do not contain them. For consistency with neutron calculations, atomic mass ratios are assumed to be input. These are then converted to atomic masses by multiplying by the neutron mass, 1.00866, in calculating the source nuclide number densities.

IV. INPUT DESCRIPTION

A. Radioactive Decay Sources

The photon radioactive decay source patch is currently compatible with Version 3A of MCNP. The code executable and the associated data files needed for execution are on the Los Alamos Common File System (CFS) as follows:

/SCHRANDT/MCNPIR3A (executable for Cray X-MPs)
/GPE/IR/TAPE11L (Gunnink line intensities, Ref. 18)
/GPE/IR/TAPE11E (Erdtman and Soyka line intensities, Ref. 15)
/GPE/IR/SFBREM (Photons from ^{240}Pu spontaneous fission and
Bremsstrahlung from the ^{234m}Pa beta particle in
uranium metal, Refs. 21 and 22)

The authors should be contacted by those outside of Los Alamos National Laboratory who wish to use the patch.

For information, the descriptive header lines from TAPE11L, TAPE11E, and SFBREM are given in Tables I-III, respectively.

The photon radioactive decay source patch is implemented by using the MCNP generalized source option¹ in conjunction with a few additional cards, options, and/or internal interpretations of existing options. The differences are outlined in Table III.

Basically the input data and photon line intensities obtained from data files allow for the automatic normalization of the calculation (total photons/sec emitted) and the fractional probabilities needed to sample the photon emission rates of the various cells, isotopes, and photon lines.

TABLE I

NUCLIDES IN DATA FILE TAPE11L

nuclide	90228,	$\lambda_i = 0.115000E - 07,$	no. lines= 19,	$B_i = 0.147625E + 01$
nuclide	90231,	$\lambda_i = 0.751900E - 05,$	no. lines= 24,	$B_i = 0.115134E + 00$
nuclide	92235,	$\lambda_i = 0.308085E - 16,$	no. lines= 20,	$B_i = 0.868489E + 00$
nuclide	92237,	$\lambda_i = 0.118900E - 05,$	no. lines= 20,	$B_i = 0.115360E + 01$
nuclide	92238,	$\lambda_i = 0.487100E - 17,$	no. lines=101,	$B_i = 0.183335E - 01$
nuclide	94238,	$\lambda_i = 0.250700E - 09,$	no. lines= 28,	$B_i = 0.477550E - 03$
nuclide	94239,	$\lambda_i = 0.900600E - 12,$	no. lines=143,	$B_i = 0.612620E - 03$
nuclide	94240,	$\lambda_i = 0.332900E - 11,$	no. lines= 9,	$B_i = 0.526480E - 03$
nuclide	94241,	$\lambda_i = 0.387600E - 13,$	no. lines= 15,	$B_i = 0.542110E + 00$
nuclide	95241,	$\lambda_i = 0.507100E - 10,$	no. lines= 90,	$B_i = 0.360454E + 00$

TABLE II

NUCLIDES IN DATA FILE TAPE11E

nuclide	81194,	$\lambda_i = 0.350074E - 03,$	no. lines= 9,	$B_i = 0.215100E + 01$
nuclide	81194m,	$\lambda_i = 0.352209E - 03,$	no. lines= 14,	$B_i = 0.407400E + 01$
nuclide	81195m,	$\lambda_i = 0.198042E + 00,$	no. lines= 1,	$B_i = 0.950000E + 00$
nuclide	81196m,	$\lambda_i = 0.136554E - 03,$	no. lines= 6,	$B_i = 0.269110E - 01$
nuclide	81197,	$\lambda_i = 0.677961E - 04,$	no. lines= 57,	$B_i = 0.152316E + 01$
nuclide	81197m,	$\lambda_i = 0.128361E + 01,$	no. lines= 6,	$B_i = 0.140100E + 01$
nuclide	81198,	$\lambda_i = 0.363285E - 04,$	no. lines=174,	$B_i = 0.280616E + 01$
nuclide	81198m,	$\lambda_i = 0.102963E - 03,$	no. lines= 43,	$B_i = 0.312909E + 01$
nuclide	81199,	$\lambda_i = 0.260190E - 04,$	no. lines= 14,	$B_i = 0.140500E + 01$
nuclide	81200,	$\lambda_i = 0.737365E - 05,$	no. lines= 84,	$B_i = 0.265152E + 01$
nuclide	81201,	$\lambda_i = 0.261918E - 05,$	no. lines= 10,	$B_i = 0.164990E + 01$
nuclide	81202,	$\lambda_i = 0.657585E - 06,$	no. lines= 8,	$B_i = 0.179240E + 01$
nuclide	81204,	$\lambda_i = 0.581470E - 08,$	no. lines= 5,	$B_i = 0.223000E - 01$
nuclide	81206,	$\lambda_i = 0.288811E - 02,$	no. lines= 1,	$B_i = 0.650000E - 04$
nuclide	81207,	$\lambda_i = 0.242190E - 02,$	no. lines= 1,	$B_i = 0.270000E - 02$
nuclide	81207m,	$\lambda_i = 0.533190E + 00,$	no. lines= 6,	$B_i = 0.195500E + 01$
nuclide	81208,	$\lambda_i = 0.372660E - 02,$	no. lines= 25,	$B_i = 0.238270E + 01$
nuclide	81209,	$\lambda_i = 0.525111E - 02,$	no. lines= 7,	$B_i = 0.293590E + 01$
nuclide	81210,	$\lambda_i = 0.875186E - 02,$	no. lines= 23,	$B_i = 0.314000E + 01$
nuclide	82197m,	$\lambda_i = 0.275058E - 03,$	no. lines= 31,	$B_i = 0.380349E + 01$

TABLE II (Cont'd.)

nuclide	82198,	$\lambda_i = 0.802253\text{E} - 04,$	no. lines= 26,	$B_i = 0.209065\text{E} + 01$
nuclide	82199,	$\lambda_i = 0.128361\text{E} - 03,$	no. lines=117,	$B_i = 0.295750\text{E} + 01$
nuclide	82199m,	$\lambda_i = 0.946922\text{E} - 03,$	no. lines= 5,	$B_i = 0.560500\text{E} + 00$
nuclide	82200,	$\lambda_i = 0.895539\text{E} - 05,$	no. lines= 24,	$B_i = 0.127952\text{E} + 01$
nuclide	82201,	$\lambda_i = 0.204831\text{E} - 04,$	no. lines= 66,	$B_i = 0.229666\text{E} + 01$
nuclide	82201m,	$\lambda_i = 0.113631\text{E} - 01,$	no. lines= 5,	$B_i = 0.805000\text{E} + 00$
nuclide	82202,	$\lambda_i = 0.732652\text{E} - 13,$	no. lines= 4,	$B_i = 0.830000\text{E} + 00$
nuclide	82202m,	$\lambda_i = 0.531881\text{E} - 04,$	no. lines= 21,	$B_i = 0.307550\text{E} + 01$
nuclide	82203,	$\lambda_i = 0.369532\text{E} - 05,$	no. lines= 7,	$B_i = 0.179600\text{E} + 01$
nuclide	82203m,	$\lambda_i = 0.111798\text{E} + 00,$	no. lines= 10,	$B_i = 0.978400\text{E} + 00$
nuclide	82204m,	$\lambda_i = 0.167427\text{E} - 03,$	no. lines= 9,	$B_i = 0.207860\text{E} + 01$
nuclide	82207m,	$\lambda_i = 0.866434\text{E} + 00,$	no. lines= 6,	$B_i = 0.197050\text{E} + 01$
nuclide	82210,	$\lambda_i = 0.107743\text{E} - 08,$	no. lines= 2,	$B_i = 0.283000\text{E} + 00$
nuclide	82211,	$\lambda_i = 0.320012\text{E} - 03,$	no. lines= 18,	$B_i = 0.889100\text{E} - 01$
nuclide	82212,	$\lambda_i = 0.180959\text{E} - 04,$	no. lines= 9,	$B_i = 0.821700\text{E} + 00$
nuclide	82214,	$\lambda_i = 0.431062\text{E} - 03,$	no. lines= 32,	$B_i = 0.104751\text{E} + 01$
nuclide	83200,	$\lambda_i = 0.320901\text{E} - 03,$	no. lines= 28,	$B_i = 0.448800\text{E} + 01$
nuclide	83201,	$\lambda_i = 0.104076\text{E} - 03,$	no. lines= 5,	$B_i = 0.805000\text{E} + 00$
nuclide	83202,	$\lambda_i = 0.106967\text{E} - 03,$	no. lines= 34,	$B_i = 0.406600\text{E} + 01$
nuclide	83203,	$\lambda_i = 0.163725\text{E} - 04,$	no. lines=154,	$B_i = 0.295827\text{E} + 01$
nuclide	83204,	$\lambda_i = 0.170390\text{E} - 04,$	no. lines=244,	$B_i = 0.456610\text{E} + 01$
nuclide	83205,	$\lambda_i = 0.524006\text{E} - 06,$	no. lines=100,	$B_i = 0.297710\text{E} + 01$
nuclide	83206,	$\lambda_i = 0.128504\text{E} - 05,$	no. lines= 82,	$B_i = 0.540365\text{E} + 01$
nuclide	83207,	$\lambda_i = 0.578409\text{E} - 09,$	no. lines= 11,	$B_i = 0.296930\text{E} + 01$
nuclide	83208,	$\lambda_i = 0.597270\text{E} - 13,$	no. lines= 5,	$B_i = 0.169500\text{E} + 01$
nuclide	83210m,	$\lambda_i = 0.627987\text{E} - 14,$	no. lines= 12,	$B_i = 0.119110\text{E} + 01$
nuclide	83211,	$\lambda_i = 0.534836\text{E} - 02,$	no. lines= 23,	$B_i = 0.257070\text{E} + 00$
nuclide	83212,	$\lambda_i = 0.190792\text{E} - 03,$	no. lines= 30,	$B_i = 0.217700\text{E} + 00$
nuclide	83213,	$\lambda_i = 0.253066\text{E} - 03,$	no. lines= 11,	$B_i = 0.329800\text{E} + 00$
nuclide	83214,	$\lambda_i = 0.580525\text{E} - 03,$	no. lines=186,	$B_i = 0.135424\text{E} + 01$
nuclide	84203,	$\lambda_i = 0.312228\text{E} - 03,$	no. lines= 33,	$B_i = 0.282430\text{E} + 01$
nuclide	84204,	$\lambda_i = 0.546991\text{E} - 04,$	no. lines= 25,	$B_i = 0.221500\text{E} + 01$
nuclide	84205,	$\lambda_i = 0.106967\text{E} - 03,$	no. lines= 46,	$B_i = 0.230510\text{E} + 01$
nuclide	84206,	$\lambda_i = 0.908554\text{E} - 06,$	no. lines= 61,	$B_i = 0.251459\text{E} + 01$
nuclide	84207,	$\lambda_i = 0.337791\text{E} - 04,$	no. lines= 46,	$B_i = 0.229903\text{E} + 01$
nuclide	84207m,	$\lambda_i = 0.247553\text{E} + 00,$	no. lines= 3,	$B_i = 0.182000\text{E} + 01$
nuclide	84208,	$\lambda_i = 0.758438\text{E} - 08,$	no. lines= 9,	$B_i = 0.418000\text{E} - 04$
nuclide	84209,	$\lambda_i = 0.213394\text{E} - 09,$	no. lines= 6,	$B_i = 0.867000\text{E} - 02$
nuclide	84210,	$\lambda_i = 0.579747\text{E} - 07,$	no. lines= 1,	$B_i = 0.110000\text{E} - 04$
nuclide	84211,	$\lambda_i = 0.133298\text{E} + 01,$	no. lines= 2,	$B_i = 0.100000\text{E} - 01$
nuclide	84211m,	$\lambda_i = 0.271822\text{E} - 01,$	no. lines= 2,	$B_i = 0.169000\text{E} + 01$
nuclide	84212m,	$\lambda_i = 0.154033\text{E} - 01,$	no. lines= 2,	$B_i = 0.460000\text{E} - 01$

TABLE II (Cont'd.)

nuclide	84214,	$\lambda_i = 0.422651\text{E} + 04,$	no. lines=	1,	$B_i = 0.140000\text{E} - 03$
nuclide	84215,	$\lambda_i = 0.389408\text{E} + 03,$	no. lines=	1,	$B_i = 0.400000\text{E} - 03$
nuclide	85206,	$\lambda_i = 0.361014\text{E} - 03,$	no. lines=	1,	$B_i = 0.100000\text{E} + 00$
nuclide	85208,	$\lambda_i = 0.118123\text{E} - 03,$	no. lines=	36,	$B_i = 0.464600\text{E} + 01$
nuclide	85209,	$\lambda_i = 0.355241\text{E} - 04,$	no. lines=	15,	$B_i = 0.275000\text{E} + 01$
nuclide	85210,	$\lambda_i = 0.231977\text{E} - 04,$	no. lines=	52,	$B_i = 0.288448\text{E} + 01$
nuclide	85215,	$\lambda_i = 0.693147\text{E} + 04,$	no. lines=	1,	$B_i = 0.500000\text{E} - 03$
nuclide	86211,	$\lambda_i = 0.131877\text{E} - 04,$	no. lines=	17,	$B_i = 0.301400\text{E} + 01$
nuclide	86218,	$\lambda_i = 0.198042\text{E} + 02,$	no. lines=	1,	$B_i = 0.124000\text{E} - 02$
nuclide	86219,	$\lambda_i = 0.175037\text{E} + 00,$	no. lines=	7,	$B_i = 0.183750\text{E} + 00$
nuclide	86220,	$\lambda_i = 0.124667\text{E} - 01,$	no. lines=	1,	$B_i = 0.100000\text{E} - 02$
nuclide	86222,	$\lambda_i = 0.209849\text{E} - 05,$	no. lines=	1,	$B_i = 0.730000\text{E} - 03$
nuclide	87221,	$\lambda_i = 0.240676\text{E} - 02,$	no. lines=	18,	$B_i = 0.149450\text{E} + 00$
nuclide	87223,	$\lambda_i = 0.529929\text{E} - 03,$	no. lines=	53,	$B_i = 0.860670\text{E} + 00$
nuclide	88220,	$\lambda_i = 0.301368\text{E} + 02,$	no. lines=	1,	$B_i = 0.100000\text{E} - 01$
nuclide	88221,	$\lambda_i = 0.247553\text{E} - 01,$	no. lines=	7,	$B_i = 0.319000\text{E} + 00$
nuclide	88222,	$\lambda_i = 0.182407\text{E} - 01,$	no. lines=	10,	$B_i = 0.293880\text{E} - 01$
nuclide	88223,	$\lambda_i = 0.703731\text{E} - 06,$	no. lines=	40,	$B_i = 0.860471\text{E} + 00$
nuclide	88224,	$\lambda_i = 0.219195\text{E} - 05,$	no. lines=	8,	$B_i = 0.435300\text{E} - 01$
nuclide	88225,	$\lambda_i = 0.542063\text{E} - 06,$	no. lines=	1,	$B_i = 0.290000\text{E} + 00$
nuclide	88226,	$\lambda_i = 0.137372\text{E} - 10,$	no. lines=	9,	$B_i = 0.390667\text{E} - 01$
nuclide	88227,	$\lambda_i = 0.273755\text{E} - 03,$	no. lines=	58,	$B_i = 0.568510\text{E} + 00$
nuclide	89223,	$\lambda_i = 0.525111\text{E} - 02,$	no. lines=	17,	$B_i = 0.188000\text{E} - 01$
nuclide	89224,	$\lambda_i = 0.663934\text{E} - 04,$	no. lines=	49,	$B_i = 0.154026\text{E} + 01$
nuclide	89225,	$\lambda_i = 0.802253\text{E} - 06,$	no. lines=	50,	$B_i = 0.192660\text{E} + 00$
nuclide	89226,	$\lambda_i = 0.780402\text{E} - 05,$	no. lines=	14,	$B_i = 0.733750\text{E} + 00$
nuclide	89227,	$\lambda_i = 0.100824\text{E} - 08,$	no. lines=	22,	$B_i = 0.133840\text{E} - 02$
nuclide	89228,	$\lambda_i = 0.314096\text{E} - 04,$	no. lines=	167,	$B_i = 0.124059\text{E} + 01$
nuclide	90224,	$\lambda_i = 0.660140\text{E} + 00,$	no. lines=	8,	$B_i = 0.125000\text{E} + 00$
nuclide	90225,	$\lambda_i = 0.144406\text{E} - 02,$	no. lines=	11,	$B_i = 0.724300\text{E} + 00$
nuclide	90226,	$\lambda_i = 0.373866\text{E} - 03,$	no. lines=	14,	$B_i = 0.572289\text{E} - 01$
nuclide	90227,	$\lambda_i = 0.433651\text{E} - 06,$	no. lines=	243,	$B_i = 0.549665\text{E} + 00$
nuclide	90228,	$\lambda_i = 0.114896\text{E} - 07,$	no. lines=	5,	$B_i = 0.168350\text{E} - 01$
nuclide	90229,	$\lambda_i = 0.299449\text{E} - 11,$	no. lines=	34,	$B_i = 0.176430\text{E} + 01$
nuclide	90230,	$\lambda_i = 0.285449\text{E} - 12,$	no. lines=	12,	$B_i = 0.456210\text{E} - 02$
nuclide	90231,	$\lambda_i = 0.754707\text{E} - 05,$	no. lines=	50,	$B_i = 0.125341\text{E} + 01$
nuclide	90232,	$\lambda_i = 0.155883\text{E} - 17,$	no. lines=	1,	$B_i = 0.190000\text{E} - 02$
nuclide	90233,	$\lambda_i = 0.518047\text{E} - 03,$	no. lines=	108,	$B_i = 0.868860\text{E} - 01$
nuclide	90234,	$\lambda_i = 0.332885\text{E} - 06,$	no. lines=	15,	$B_i = 0.196954\text{E} + 00$
nuclide	91227,	$\lambda_i = 0.301631\text{E} - 03,$	no. lines=	8,	$B_i = 0.233500\text{E} + 00$
nuclide	91228,	$\lambda_i = 0.740770\text{E} - 05,$	no. lines=	179,	$B_i = 0.144668\text{E} + 01$
nuclide	91229,	$\lambda_i = 0.534836\text{E} - 05,$	no. lines=	7,	$B_i = 0.111000\text{E} + 01$

TABLE II (Cont'd.)

nuclide	91230,	$\lambda_i = 0.461065\text{E} - 06,$	no. lines= 61,	$B_i = 0.134993\text{E} + 01$
nuclide	91231,	$\lambda_i = 0.670926\text{E} - 12,$	no. lines= 79,	$B_i = 0.394402\text{E} + 00$
nuclide	91232,	$\lambda_i = 0.612407\text{E} - 05,$	no. lines= 46,	$B_i = 0.135990\text{E} + 01$
nuclide	91233,	$\lambda_i = 0.292793\text{E} - 06,$	no. lines= 18,	$B_i = 0.134455\text{E} + 01$
nuclide	91234,	$\lambda_i = 0.287374\text{E} - 04,$	no. lines=203,	$B_i = 0.449622\text{E} + 01$
nuclide	91234m,	$\lambda_i = 0.987389\text{E} - 02,$	no. lines=130,	$B_i = 0.203812\text{E} - 01$
nuclide	91236,	$\lambda_i = 0.126950\text{E} - 02,$	no. lines= 23,	$B_i = 0.546768\text{E} + 00$
nuclide	91237,	$\lambda_i = 0.132787\text{E} - 02,$	no. lines= 15,	$B_i = 0.741240\text{E} + 00$
nuclide	91238,	$\lambda_i = 0.502280\text{E} - 02,$	no. lines= 89,	$B_i = 0.149400\text{E} + 02$
nuclide	92228,	$\lambda_i = 0.125570\text{E} - 02,$	no. lines= 7,	$B_i = 0.495000\text{E} - 01$
nuclide	92229,	$\lambda_i = 0.199180\text{E} - 03,$	no. lines= 5,	$B_i = 0.755000\text{E} + 00$
nuclide	92230,	$\lambda_i = 0.385699\text{E} - 06,$	no. lines= 15,	$B_i = 0.976774\text{E} - 02$
nuclide	92231,	$\lambda_i = 0.191013\text{E} - 05,$	no. lines= 12,	$B_i = 0.994765\text{E} + 00$
nuclide	92232,	$\lambda_i = 0.305271\text{E} - 09,$	no. lines= 10,	$B_i = 0.411272\text{E} - 01$
nuclide	92233,	$\lambda_i = 0.138672\text{E} - 12,$	no. lines= 74,	$B_i = 0.648000\text{E} - 02$
nuclide	92234,	$\lambda_i = 0.884845\text{E} - 13,$	no. lines= 13,	$B_i = 0.105671\text{E} + 00$
nuclide	92235,	$\lambda_i = 0.312298\text{E} - 16,$	no. lines= 50,	$B_i = 0.840034\text{E} + 00$
nuclide	92236,	$\lambda_i = 0.938896\text{E} - 15,$	no. lines= 1,	$B_i = 0.190000\text{E} - 03$
nuclide	92237,	$\lambda_i = 0.118852\text{E} - 05,$	no. lines= 21,	$B_i = 0.119608\text{E} + 01$
nuclide	92238,	$\lambda_i = 0.467650\text{E} - 17,$	no. lines= 2,	$B_i = 0.877500\text{E} - 01$
nuclide	92239,	$\lambda_i = 0.490758\text{E} - 03,$	no. lines=149,	$B_i = 0.672754\text{E} + 00$
nuclide	92240,	$\lambda_i = 0.136554\text{E} - 04,$	no. lines= 1,	$B_i = 0.169000\text{E} - 01$
nuclide	93232,	$\lambda_i = 0.785881\text{E} - 03,$	no. lines= 30,	$B_i = 0.222456\text{E} + 01$
nuclide	93233,	$\lambda_i = 0.186330\text{E} - 02,$	no. lines= 4,	$B_i = 0.805000\text{E} + 00$
nuclide	93234,	$\lambda_i = 0.182330\text{E} - 05,$	no. lines= 38,	$B_i = 0.159821\text{E} + 01$
nuclide	93235,	$\lambda_i = 0.202576\text{E} - 07,$	no. lines= 18,	$B_i = 0.803004\text{E} + 00$
nuclide	93236,	$\lambda_i = 0.191126\text{E} - 12,$	no. lines= 8,	$B_i = 0.246412\text{E} + 01$
nuclide	93236m,	$\lambda_i = 0.855737\text{E} - 05,$	no. lines= 9,	$B_i = 0.439779\text{E} + 00$
nuclide	93237,	$\lambda_i = 0.102708\text{E} - 13,$	no. lines= 50,	$B_i = 0.338590\text{E} + 00$
nuclide	93238,	$\lambda_i = 0.378958\text{E} - 05,$	no. lines= 33,	$B_i = 0.937505\text{E} + 00$
nuclide	93239,	$\lambda_i = 0.340660\text{E} - 05,$	no. lines= 35,	$B_i = 0.164232\text{E} + 01$
nuclide	93240,	$\lambda_i = 0.177785\text{E} - 03,$	no. lines= 37,	$B_i = 0.348501\text{E} + 01$
nuclide	93240m,	$\lambda_i = 0.156114\text{E} - 02,$	no. lines= 91,	$B_i = 0.867762\text{E} + 00$
nuclide	94233,	$\lambda_i = 0.552749\text{E} - 03,$	no. lines= 4,	$B_i = 0.805000\text{E} + 00$
nuclide	94235,	$\lambda_i = 0.456619\text{E} - 03,$	no. lines= 19,	$B_i = 0.759061\text{E} + 00$
nuclide	94236,	$\lambda_i = 0.771212\text{E} - 08,$	no. lines= 7,	$B_i = 0.113822\text{E} + 00$
nuclide	94237,	$\lambda_i = 0.175817\text{E} - 06,$	no. lines= 5,	$B_i = 0.525000\text{E} + 00$
nuclide	94237m,	$\lambda_i = 0.385082\text{E} + 01,$	no. lines= 5,	$B_i = 0.257500\text{E} - 01$
nuclide	94238,	$\lambda_i = 0.250479\text{E} - 09,$	no. lines= 46,	$B_i = 0.116468\text{E} + 00$
nuclide	94239,	$\lambda_i = 0.910881\text{E} - 12,$	no. lines=154,	$B_i = 0.445415\text{E} - 01$
nuclide	94240,	$\lambda_i = 0.336233\text{E} - 11,$	no. lines= 17,	$B_i = 0.110527\text{E} + 00$
nuclide	94241,	$\lambda_i = 0.144984\text{E} - 08,$	no. lines= 14,	$B_i = 0.510906\text{E} - 04$

TABLE II (Cont'd.)

nuclide	94242,	$\lambda_i = 0.567947\text{E} - 13,$	no. lines= 4,	$B_i = 0.131250\text{E} + 00$
nuclide	94243,	$\lambda_i = 0.386500\text{E} - 04,$	no. lines= 21,	$B_i = 0.254530\text{E} + 00$
nuclide	94244,	$\lambda_i = 0.266096\text{E} - 15,$	no. lines= 1,	$B_i = 0.780000\text{E} - 01$
nuclide	94245,	$\lambda_i = 0.183372\text{E} - 04,$	no. lines=114,	$B_i = 0.107683\text{E} + 01$
nuclide	94246,	$\lambda_i = 0.736012\text{E} - 06,$	no. lines= 17,	$B_i = 0.140103\text{E} + 01$
nuclide	95238,	$\lambda_i = 0.118123\text{E} - 03,$	no. lines= 72,	$B_i = 0.247561\text{E} + 01$
nuclide	95239,	$\lambda_i = 0.161799\text{E} - 04,$	no. lines= 31,	$B_i = 0.358740\text{E} + 00$
nuclide	95240,	$\lambda_i = 0.378958\text{E} - 05,$	no. lines= 41,	$B_i = 0.183609\text{E} + 01$
nuclide	95241,	$\lambda_i = 0.507611\text{E} - 10,$	no. lines=100,	$B_i = 0.671021\text{E} + 00$
nuclide	95242,	$\lambda_i = 0.120188\text{E} - 04,$	no. lines= 7,	$B_i = 0.509800\text{E} + 00$
nuclide	95242m,	$\lambda_i = 0.144602\text{E} - 09,$	no. lines= 15,	$B_i = 0.303555\text{E} + 00$
nuclide	95243,	$\lambda_i = 0.297826\text{E} - 11,$	no. lines= 14,	$B_i = 0.893588\text{E} + 00$
nuclide	95244,	$\lambda_i = 0.190634\text{E} - 04,$	no. lines= 11,	$B_i = 0.167400\text{E} + 01$
nuclide	95244m,	$\lambda_i = 0.444325\text{E} - 03,$	no. lines= 3,	$B_i = 0.202000\text{E} - 01$
nuclide	95245,	$\lambda_i = 0.943828\text{E} - 04,$	no. lines= 7,	$B_i = 0.186600\text{E} + 00$
nuclide	95246,	$\lambda_i = 0.296217\text{E} - 03,$	no. lines= 15,	$B_i = 0.159100\text{E} + 01$
nuclide	95246m,	$\lambda_i = 0.462098\text{E} - 03,$	no. lines=143,	$B_i = 0.104558\text{E} + 01$
nuclide	96241,	$\lambda_i = 0.222848\text{E} - 06,$	no. lines= 9,	$B_i = 0.256025\text{E} + 01$
nuclide	96242,	$\lambda_i = 0.492180\text{E} - 07,$	no. lines= 9,	$B_i = 0.114367\text{E} + 00$
nuclide	96243,	$\lambda_i = 0.771212\text{E} - 09,$	no. lines= 23,	$B_i = 0.135065\text{E} + 01$
nuclide	96244,	$\lambda_i = 0.121434\text{E} - 08,$	no. lines= 21,	$B_i = 0.105285\text{E} + 00$
nuclide	96245,	$\lambda_i = 0.258583\text{E} - 11,$	no. lines= 8,	$B_i = 0.122210\text{E} + 01$
nuclide	96246,	$\lambda_i = 0.456007\text{E} - 11,$	no. lines= 1,	$B_i = 0.930000\text{E} - 01$
nuclide	96247,	$\lambda_i = 0.140895\text{E} - 14,$	no. lines= 9,	$B_i = 0.106200\text{E} + 01$
nuclide	96248,	$\lambda_i = 0.608852\text{E} - 13,$	no. lines= 1,	$B_i = 0.710000\text{E} - 01$
nuclide	96249,	$\lambda_i = 0.179945\text{E} - 03,$	no. lines= 23,	$B_i = 0.381063\text{E} - 01$
nuclide	97243,	$\lambda_i = 0.427869\text{E} - 04,$	no. lines= 12,	$B_i = 0.811065\text{E} + 00$
nuclide	97245,	$\lambda_i = 0.162399\text{E} - 05,$	no. lines= 18,	$B_i = 0.141605\text{E} + 01$
nuclide	97246,	$\lambda_i = 0.438390\text{E} - 05,$	no. lines= 16,	$B_i = 0.204133\text{E} + 01$
nuclide	97247,	$\lambda_i = 0.159272\text{E} - 10,$	no. lines= 6,	$B_i = 0.905000\text{E} + 00$
nuclide	97249,	$\lambda_i = 0.250704\text{E} - 07,$	no. lines= 6,	$B_i = 0.321800\text{E} - 06$
nuclide	97250,	$\lambda_i = 0.597953\text{E} - 04,$	no. lines= 7,	$B_i = 0.877632\text{E} + 00$
nuclide	98246,	$\lambda_i = 0.539149\text{E} - 05,$	no. lines= 5,	$B_i = 0.459000\text{E} - 03$
nuclide	98247,	$\lambda_i = 0.785881\text{E} - 04,$	no. lines= 7,	$B_i = 0.729000\text{E} + 00$
nuclide	98249,	$\lambda_i = 0.626912\text{E} - 10,$	no. lines= 38,	$B_i = 0.941218\text{E} + 00$
nuclide	98250,	$\lambda_i = 0.168039\text{E} - 08,$	no. lines= 1,	$B_i = 0.100000\text{E} - 05$
nuclide	98251,	$\lambda_i = 0.244761\text{E} - 10,$	no. lines= 20,	$B_i = 0.258600\text{E} + 00$
nuclide	98252,	$\lambda_i = 0.893478\text{E} - 08,$	no. lines= 8,	$B_i = 0.713450\text{E} - 01$
nuclide	99249,	$\lambda_i = 0.113259\text{E} - 03,$	no. lines= 51,	$B_i = 0.142888\text{E} + 01$
nuclide	99250m,	$\lambda_i = 0.916861\text{E} - 04,$	no. lines= 6,	$B_i = 0.113706\text{E} + 01$
nuclide	99251,	$\lambda_i = 0.583457\text{E} - 05,$	no. lines= 7,	$B_i = 0.741600\text{E} + 00$
nuclide	99252,	$\lambda_i = 0.170384\text{E} - 07,$	no. lines= 44,	$B_i = 0.474117\text{E} + 00$

TABLE II (Cont'd.)

nuclide	99253,	$\lambda_i = 0.391917\text{E} - 06$,	no. lines= 68,	$B_i = 0.185754\text{E} - 02$
nuclide	99254,	$\lambda_i = 0.290672\text{E} - 07$,	no. lines= 17,	$B_i = 0.298400\text{E} - 01$
nuclide	99254m,	$\lambda_i = 0.489926\text{E} - 05$,	no. lines= 25,	$B_i = 0.704093\text{E} + 00$
nuclide	100251,	$\lambda_i = 0.363285\text{E} - 04$,	no. lines= 20,	$B_i = 0.185003\text{E} - 01$
nuclide	100253,	$\lambda_i = 0.267418\text{E} - 05$,	no. lines= 11,	$B_i = 0.649500\text{E} + 00$
nuclide	100254,	$\lambda_i = 0.594262\text{E} - 04$,	no. lines= 3,	$B_i = 0.490000\text{E} - 03$
nuclide	100255,	$\lambda_i = 0.948477\text{E} - 05$,	no. lines= 54,	$B_i = 0.252861\text{E} - 01$
nuclide	100257,	$\lambda_i = 0.798262\text{E} - 07$,	no. lines= 8,	$B_i = 0.785900\text{E} + 00$

TABLE III

NUCLIDES IN DATA FILE SFBREM

nuclide	-94240,	$\lambda_i = 0.189670\text{E} - 19$,	no. lines=14,	$B_i = 0.141234\text{E} + 02$
nuclide	-92238,	$\lambda_i = 0.487100\text{E} - 17$,	no. lines=15,	$B_i = 0.725238\text{E} + 00$
nuclide	-83212,	$\lambda_i = 0.190792\text{E} - 03$,	no. lines=15,	$B_i = 0.725238\text{E} + 00$
nuclide	-81208,	$\lambda_i = 0.372660\text{E} - 02$,	no. lines=15,	$B_i = 0.725238\text{E} + 00$

Card	What	Input
SPn	New option, mnemonic <i>N</i>	Source material density, weight fraction, and isotope weight fractions.
SIn	New option, mnemonic <i>F</i>	Isotope ZAID, data file name, ground/ metastable, state indicator parent ZAID.
SBn	New option, mnemonic <i>B</i>	Energy-dependent biasing factors.
AMn	New card	^{241}Am ppm($t = 0$), * decay time (yrs).
DET	New card	A, B where $FWHM = A + Bf(E)$ for NaI, HPGe, and BGO detectors.
RDUM(1)	—	f (Bremsstrahlung normalization factor).**
IDUM(1)	—	$\frac{1}{2}$ (invokes uniform sampling scheme, described later).

*ppm = parts per million ^{241}Am in plutonium by weight.

**Must be determined empirically by comparison with experiment, if necessary.

The input for the passive photon line source can best be visualized by thinking of a set of source cells in the problem each containing a number of source isotopes. In turn, each isotope has associated with it probabilities for the emission of a number of unique photon lines when the isotope decays by β^- or α -decay. This scenario is depicted schematically in Fig. 1.

Figure 1. Photon line source from radioactive decay (energy and position are functions of cell).

This source example has levels of hierarchy of source dependence as discussed in the MCNP Version 3A manual. The isotope energy distributions for the problem are a function of cell. In turn, photon lines are a function of isotope, leading to a third level of dependency as depicted in Fig. 1. If all of the source strength probabilities and isotope number densities were calculated beforehand, this problem could be set up entirely using the generalized source, and the passive photon line source patch would not be needed. An example of this input is given in Ref. 1.

As mentioned earlier, one of the main motivations for the passive photon line source patch was to relate the required input to readily available physical parameters of the system. Another motivation was the automation of the data handling for the many photon lines associated with the various nuclides. The following input is used to accomplish these goals.

1. Source Isotope Input

Form: SIn *F* ZAID filename ms ZAID'

F = data file input option invoked

ZAID = source isotope ID

filename = file from which photon line data will be obtained

ms = metastable indicator (0/1 for ZAID (0 = ground state))
 ZAID' = parent isotope to ZAID (0/ZAID') (ZAID' must exist on another SIn
 F card and its distribution number used on an SIn card specifying
 isotopes in a cell)

Form: SPn – not allowed (probabilities obtained from data file line intensities)

Form: SBn *B* *f*₁ *E*_{i1} *E*_{j1} *f*₂ *E*_{i2} *E*_{j2} ... *f*_k *E*_{ik} *E*_{jk} (optional)

B = bias option invoked

*f*_k = multiplicative bias factor on line intensities in energy range *E*_{ik} – *E*_{jk}

Example: SI17 F 92237 TAPE11L 0 94241
 SB17 B 100 .1 .3 10 1.0 1.5

In this example, the source isotope is ²³⁷U and the line data for it are obtained from file TAPE11L. Uranium-237 is a daughter of ²⁴¹Pu and, therefore, a positive daughter/parent concentration ratio must be input on the appropriate SPn N card. The SB17 card specifies that the photons in the energy ranges 0.1–0.3 MeV and 1.0–1.5 MeV be biased by factors of 100 and 10, respectively.

Special Cases: Bremsstrahlung and Spontaneous Fission Sources

Since the Bremsstrahlung from the ²³⁸U decay chain and the photons from ²⁴⁰Pu spontaneous fission are continuous rather than discrete (line) distributions, they must be treated somewhat differently. Nuclide ZAIDs of –92238 and –94240 were chosen for these “isotopes.” They exist in file SFBREM and are called into a problem on an SIn card like any other nuclide as follows:

SI15 F -92238 SFBREM 0 0

See also Sec. II.A.(3). for further discussion on the input for these special cases.

2. Source Cell Input

Form: SIn *S* *I*₁ *I*₂ ... *I*_i

S = “spectra” option (that is, the *I*_i entries are distributions, not data entries)

*I*_i = distribution number for isotope *i* – refers to a distribution on an SIn card with the *F* option (see Sec. IV.A.1 above)

Form: SPn *N* ρ_c *W*_c ± *W*_{c1} ± *W*_{c2} ... ± *W*_{ci}

- N = number density calculation option invoked
 ρ_c = mass density of cell c (g/cm^3)
 W_c = weight fraction of all source isotopes in cell c
 $-W_{ci}$ = weight fraction of source isotope i in all source isotopes of cell c (if $\sum_i W_{ci} \neq 1$, the code will normalize)
 $+W_{ci}$ = atoms of daughter isotope i per parent isotope (valid only for daughter isotopes—see below)

Form: SBn $b_1 \ b_2 \cdots b_i$ (optional)

b_i = biased weight fractions of isotope i in all source isotopes

Some clarification of the SPn N card input are in order. All W_{ci} entries except those for ^{241}Am and any daughter nuclides should be negative, and the units should be relative weight fraction, not atom fraction. The following sections define the ^{241}Am and daughter isotope inputs:

Special Case: ^{241}Am Time Dependence

For ^{241}Am , three input possibilities are allowed:

- $W_{ci}(^{241}\text{Am}) < 0$ — ^{241}Am is treated as any other parent nuclide.
- $W_{ci}(^{241}\text{Am}) > 0$ — ^{241}Am is treated as any other daughter nuclide (see below).
- $W_{ci}(^{241}\text{Am}) = 0$ and the AMn card present—the initial ^{241}Am concentration (ppm) and decay time is taken from the AMn card and used with the ^{241}Pu concentration in Eq. (8) to calculate the appropriate ^{241}Am concentration at the decay time.

Special Case: Daughter Nuclide Input

For daughter nuclides, $W_{ci} > 0$ and

W_{ci} = ratio of daughter isotope atom density at some time of interest to the initial parent isotope atom density.

This quantity is multiplied times the parent nuclide concentration calculated by the code to obtain the daughter nuclide concentration.

Special Case: Bremsstrahlung and Spontaneous Fission

The special treatment of the Bremsstrahlung and spontaneous fission photons calls for some explanation of the input on the SPn N card. Here, the W_{ci} for both “isotopes” (-92238 and -94240) should equal that of their companion nuclides (92238 and 94240), respectively. Their concentration is used to calculate the photon activity (γ/sec) resulting from these processes, but is not added to the total material concentration because this would constitute a duplication of matter.

Example: SC5 NATURAL URANIUM

```

SI5  S   6   7   8
SP5  N  18.9  1.0  -.0072  -.9928  1R
SB5  b6  b7  b8
SI6  F   92235  TAPE11L  0   0
SI7  F   92238  TAPE11L  0   0
SI8  F  -92238  SFBREM   0   0

```

3. Problem Source Definition

Although this portion of the input for a typical problem is identical to that for MCNP Version 3A, some discussion of it is given here for completeness.

Form: SDEF CEL=Dn₁ ERG FCEL Dn₂ ...
SCn₁ MCNP CELLS THAT ARE SOURCES
SIn₁ L C₁ C₂ ... C_m (C_m=problem source cell numbers)
SPn₁ V
SBn₁ optional
SCn₂ ENERGY DISTRIBUTIONS ASSOCIATED WITH CELLS
DSn₂ S S₁ S₂ ... S_m (S_m=isotope distribution number for cell m—see cell input distribution in Section IV.A.2). See Ref. 1 for DS card definition.

Note that the V on the SPn₁ card causes the cell volumes to be used in calculations of total photon source strength (photons/sec) for the problem.

Example: See Fig. 1 and Table IV for an example of input for natural uranium and thorium in two different cells.

4. Bremsstrahlung Normalization

Form: RDUM f

f = empirically determined factor to scale the Bremsstrahlung (-92238) source strength so that better agreement with experiment is obtained.

5. Warnock Uniform Sampling Scheme

The line spectra source distributions can be sampled uniformly using a quasi-random number scheme²³ of Tony Warnock instead of the pseudorandom numbers of MCNP. Best results are obtained when the distributions are sampled from the first "Warnock Recipe" (*k* = 1 below). For comparisons, a χ^2 is calculated for each distribution.

Form: IDUM *k*

- k* = 0 No uniform sampling (default)
- k* = 1 All distributions use a single counter advanced with NPS. The Warnock recipe number is the source distribution program number.
- k* = 2 Each distribution has a separate counter. Warnock recipe #1 is used for all distributions except those having the *S* option, which use recipe #2.

6. MCPLLOT

The MCPLLOT²⁴ code, which will be integrated into MCNP at a later date, has been incorporated into this version of the code. To execute the MCPLLOT options described in Ref. 24, the user must first generate a RUNTPE file from a MCNPIR3A run, then execute a separate MCNP run to get into the MCPLLOT overlay as follows:

MCNPIR3A Z RUNTPE=filename

B. Detector Resolution Broadening

Form: DET type unit *A* *B*

- type = detector type (1=NaI, 2=BGO)
- unit = detector # (different detectors of same type may have different *A*, *B*)
- A*, *B* = empirically determined constants as defined below:
- type = 1: $\sigma(E) = A + B\sqrt{E(\text{keV})}$
- type = 2: $FWHM(E) = A + B/\sqrt{E(\text{keV})}$ $FWHM(E) = 2\sigma(E)\sqrt{2 \ln 2}$ for a Gaussian distribution.¹¹

It should be noted that the form of the equations for type=1 and type=2 are not invariant. They derive historically from the availability of calibration data from two different experimenters. One could invoke type=1 but use appropriately derived constants *A* and *B* for BGO or HPGe.

C. First-Principles Detector Response Tally

At present, this type of tally is “hard-wired” into the code patch as tally 94. As discussed in Sec. II, it is felt that this tally is not mature enough for a unique tally since it has only been thought out and tested for NaI, BGO, and HPGe photon spectrometers. It probably works for other detector types if total energy deposition is of interest and if charged-particle reaction products have a small range compared with the dimensions of the detector active volume.

TABLE IV

MCNP INPUT FOR
PHOTON SOURCE FROM RADIOACTIVE DECAY
OF NATURAL URANIUM AND THORIUM
(without explicit daughter nuclides)

SDEF CEL D1 ERG FCEL D2 ...

Level 1

SC1	SOURCE CELLS		
SI1	L	C ₁	C ₂
SP1	D	P ₁	P ₂
SC2	SOURCE "SPECTRA"		
DS2	S	3	4

Level 2

SC3	URANIUM NUCLIDES					
SI3	S	5	6	8		
SP3	N	18.9	1.0	-.0072	-.9928	1R
SC4	THORIUM NUCLIDE					
SI4	S	7				
SP4	N	11.7	1.0	-1.0		

Level 3

SC5	U235 PHOTON LINES				
SI5	F	92235	TAPE11L	0	0
SC6	U238 PHOTON LINES				
SI6	F	92238	TAPE11L	0	0
SC7	TH232 PHOTON LINES				
SI7	F	90232	TAPE11E	0	0
SC8	BREMSSTRAHLUNG FROM PA234M BETA IN URANIUM METAL				
SI8	F	-92238	SFBREM	0	0

Simple Form: F94:P C₁ ... C_i
 SD94 1 (tally must be normed by 1 rather than by
 volume)

Complex Form: F94:P C_1 $(C_2 \cdots C_3)$ $(C_4 \cdots C_5)$ C_6 $C_7 \cdots$
SD94 1 (K-1)R (tally must be normed by 1 rather than by volume)

C_i = cell numbers in which deposited energy is to be tallied.

This tally accumulates the energy deposited in a set of tally cells, then registers a tally (that is, 1 count) in the energy bin corresponding to the energy deposited. It is recommended that variance reduction not be done in the vicinity of the detector. If a particle enters a tally cell, but does not deposit any energy in it, then it is “counted” in the first bin for bookkeeping purposes.

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