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A Brief Primer for Simulating Photonuclear Interactions with MCNP(X)

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memorandum

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I. Introduction

The capability to include photonuclear physics in MCNP and MCNPX (hence fore taken as MCNP(X)) simulations via tabular data sampling has recently been introduced [1]. However, this new capability is limited by the availability of the data. This memo will walk through an example problem: how to calculate the neutron spectrum from a steel disk irradiated by a pencil beam of electrons. This problem was chosen as it demonstrates a number of features and concepts in as simple a manner as possible. However, it does not encompass the whole of what might be done using the photonuclear capability. This memorandum is written assuming the reader has already read the memorandum on the update to the user interface [1] and is reasonably familiar with the standard MCNP(X) interface [2,3].

II. Availability of Photonuclear Data

Evaluated photonuclear data files have become available from two sources. Mark Chadwick and Phil Young of T-16 have created the LA150 library [4] that includes complete descriptions of particle emission data for nuclear events from incident neutrons, protons and photons with energies up to 150 MeV. (See the Nuclear Information Website page on High Energy Data for Accelerator Applications http://t2.lanl.gov/data/he.html). The LA150 nuclear data library was created as part of the Accelerator Production of Tritium (APT) project for use in the MCNPX simulation code. The LA150 data include 12 photonuclear evaluations in the ENDF-6 format [5]. The 12 photonuclear evaluations in the LA150 library have been processed into class 'u' ACE files [6] with the library ID "24u" and released as LA150u ACE library [7].

The second source of evaluated photonuclear data files is the IAEA Coordinated Research Project for the creation of photonuclear data for applications [8]. The CRP was begun in 1996 with the goal of producing a comprehensive library of evaluated photonuclear data for the major isotopes of the structural, biological, shielding, transuranic and accelerator target materials. The final IAEA library contains 160 isotopic evaluations in the ENDF-6 format and their supporting documentation. An ACE library for use in MCNP(X) is forthcoming.

III. Example Problem

A. Input Deck

```
Example photonuclear simulation: find the n spectrum from a steel disk.
1    11    -7.9    -11   21 -22
2     0          ( 11 :-21: 22 ) -91
9     0                          91

11   cz     5.0
21   pz     0.0
22   pz     2.5
91   so   150.0

mode e p n
sdef pos=0 0 0 sur=21 vec=0 0 1 dir=1 par=3 erg=20
c     "Steel"  80 w/o Fe, 19 w/o Cr and 1 w/o Si
m11   plib=02p elib=01e nlib=24c pnlib=24u
        26054  0.045442
        26056  0.718611
        26057  0.017237
        24050  0.008659
        24052  0.166984
        24053  0.018935
        24054  0.004713
        14028  0.017910
        14029  0.000907
        14030  0.000602
mpn11
        26056  $ All three iron isotopes use table 26056.24u
        26056
        26056
        26056  $ All four chromium isotopes use table 26056.24u
        26056
        26056
        26056
        14028  $ All three silicon isotopes use table 14028.24u
        14028
        14028
fcl:p   1  0  0
phys:p 3j  1
cut:p   j  7.6142
cut:e   j  7.6142
wwp:e,p,n  5 3 5 0 0
wwe:e,p,n  20
wwn1:e,p   0.2     0.2     -1
wwn1:n     0.0001  0.0001  -1
e15     0.01 0.05 0.1 0.4 0.6 0.8 1
        1.25 1.5 1.75 2 2.5 3 3.5 4 5 6 7 8 9 10 12.3858
f15:n   0.0  100.0  1.25  0.0
e22     0.01 0.05 0.1 0.4 0.6 0.8 1
        1.25 1.5 1.75 2 2.5 3 3.5 4 5 6 7 8 9 10 12.3858
f22:n   11 21 22 (11 21 22)
nps     60000000
print
```

B. Simulation Goals

Simulations involving the photonuclear capability will typically fall into one of two categories: (1) situations where nuclear particles (i.e. neutrons, protons, etc.) are dominant and photonuclear interactions are desired for completeness or (2) situations where nuclear particles are rare and photonuclear interactions are the primary source of the particles. An example of the first situation is the core of a nuclear power reactor. In this example, neutrons are the dominant particle and photonuclear physics is brought about by neutrons producing high-energy photons producing photoneutrons. Photonuclear interactions in this situation are rare events that probably will have only minor effects on the overall problem results. The lessons from the example problem described here are still applicable, though maybe not as important.

To set the stage for the example problem (situation 2), consider the following. High-energy photons can undergo photonuclear interactions to produce neutrons or other nuclear particles, e.g. protons or alpha particles. Sometimes this is a desired feature, e.g. the use of high-energy photons to produce neutrons for materials studies. The Oak Ridge Electron Accelerator (ORELA) is an example of such a facility. Other times this is a detriment, e.g. neutron contamination and resultant personnel dose around electron accelerators. An example of this is any hospital using electron accelerators for radiotherapy. In either case, a rare event, i.e. photonuclear interaction, is driving the production of the particles of interest. The focus of this example problem is to discuss the issues associated with running simulations of this nature.

The sample input deck (given in section A) provides a simulation where photonuclear interactions are the primary source of neutrons. Specifically, a mono-energetic electron beam is perpendicularly incident on the center point of a steel disk. The steel may represent an electron target being used for the production of neutrons or it could represent an accident scenario where misdirected electrons interact with a steel magnet or support structure. For whichever case imagined, it is desired to determine the total neutron production in the steel per incident electron and the resulting neutron flux spectra one meter to the side (90 degrees off-axis from the incident beam). Remember as you read this that the input deck was contrived to illustrate a number of biasing techniques that can be employed when using the new photonuclear physics capability rather than to be an example of how any specific problem should be set-up.

C. Geometry

The geometry is composed of a simple steel disk. It is assumed that the remainder of the world has no influence on the problem. In a real problem, it would probably be necessary to include the full geometry of interest in the simulation. For example, the floor, ceiling and walls of a room may act as scatterers and affect the results of the spectrum calculation. Remember that neutrons are extremely penetrating in nature. Shielding problems should take extra care to include any potentially significant neutron scatterer or absorber in the area.

D. Radiation Source

Before discussion the radiation source, take a moment to think about the interaction mechanisms. The general shape of the photonuclear cross section is a rise from threshold (at an energy usually between 5 to 12 MeV) to a peak (at an energy usually between 12 to 23 MeV) followed by a long tail. The threshold is set by the amount of energy necessary to free a nucleon from the nucleus. The peak is from the giant dipole resonance (GDR) phenomenon and may actually be twin peaks in highly deformed nuclei. The tail is due to electro-magnetic interactions with quasi-deuterons (neutron-proton pairs). There is still other structure at higher energies, e.g. at 130 to 150 MeV when the pion production channel opens. For light isotopes, there may be structure at low energy where proton or other light particles are able to escape because of the lower potential barrier. Note that beryllium and deuterium have low neutron production thresholds, 1.57 and 2.22 MeV respectively, and that the fissionable isotopes have photo-fission components are lower energies as well. It is important in setting up the simulation to be knowledgeable of the interaction mechanisms.

The example source is a simple monoenergetic 20 MeV electron beam, perpendicularly incident on a point at the center of the disk. This was done for convenience but keep in mind that many applications use electron accelerators in this energy range. Real simulations should attempt to model their physical sources more closely. For thick (in the electron sense) targets, photonuclear calculations are relatively insensitive to minor variations in the position, spread or angular distribution of the electron beam. (This is due to the diffusive nature of electron transport and you should check this assumption for your particular problem.) However, the energy distribution can be important. The photonuclear events at medium energy are typically from giant dipole resonance interactions. This resonance peak can be as much as two orders of magnitude above the cross-section due to other interactions. Radiation sources with energies on the slope from the photonuclear threshold up to the peak may show significant changes from minor variations in source distributions.

E. Material Definition

"Steel" is chosen as the material of interest because it illustrates several issues. (This definition of "steel" has been simplified from an original composition of 70% Fe, 18% Cr, 9% Ni, 2% Mn and 1% Si.) The main concept presented here is that Monte Carlo sampling of tabular data is inherently limited by the availability of the tabular data. The question that must be answered is what to do when no data exist. For the purpose of this example, consider neutron and photonuclear transport data available only from the LA150 library.

Users desiring to run multi-particle simulations have typically approached material definitions first from the point-of-view of neutron collisions. Perusing the LA150N class 'c' tables, all four chromium and all three silicon isotopes have a neutron table available. However, only three of the four iron isotopes have a table available, ^{58}Fe being the exception. The lack of a desired table has traditionally been handled in one of two methods: lump the missing fraction into the major isotope or distribute the missing fraction among those isotopes with a table available. The example above illustrates the second method. Both methods do not faithfully represent the true material, but are assumptions commonly made to enable such a simulation to run.

"Steel"

Total Density (g/cc)	7.9	Isotope (ZA)	Atom Percent (Elemental)	Atom Percent (Adjusted)	Atom Fraction (To Input Deck)
Iron					
Weight Percent (%)	80	26054	5.8	5.82	0.045442
Partial Density (g/cc)	6.32	26056	91.72	91.98	0.718611
Atomic Weight	55.845	26057	2.2	2.21	0.017237
Atom Fraction	0.781289	26058	0.28		
Chromium					
Weight Percent (%)	19	24050	4.345	4.345	0.008659
Partial Density (g/cc)	1.501	24052	83.789	83.789	0.166984
Atomic Weight	51.9961	24053	9.501	9.501	0.018935
Atom Fraction	0.199292	24054	2.365	2.365	0.004713
Silicon					
Weight Percent (%)	1	14028	92.23	92.23	0.017910
Partial Density (g/cc)	0.079	14029	4.67	4.67	0.000907
Atomic Weight	28.0855	14030	3.1	3.1	0.000602
Atom Fraction	0.019419				

In a traditional simulation, photon (photoatomic only) and electron tables would then be chosen based on the element in question. The photoatomic and electron tables are distributed as libraries including all elements from hydrogen (Z=1) to plutonium (Z=94); additional tables exist for some higher Z elements. Isotopes listed by ZA are truncated to their base element Z. In the example material steel, photoatomic class 'p' and electron class 'e' tables would be selected for elemental iron (26000), chromium (24000) and silicon (14000).

With the addition of photonuclear physics, selection of photoatomic and electron tables will occur as it always has, by element. However, photonuclear data is tabulated by isotope and tables are chosen separately based on the true isotope (by ZA) requested. Since there is a limited selection of photonuclear evaluations and since neutron and photonuclear tables exist for different sets of isotopes, the photonuclear isotope override card (MPN) was introduced in MCNP(X) to allow a different isotope to be specified for photonuclear tables than that of the main material (see [1] for usage). This capability was added to enable the user to choose the best data available for neutron and photonuclear interactions independently.

In the definition of steel above, only the ^{56}Fe and ^{28}Si isotopes have a photonuclear table available in the LA150U library. Consequently, the best available representation of these two elements is to use the one available table for all other isotopes of that same element. Chromium presents a more difficult challenge because there is not a table available for any isotope of the element. The nearest tables are ^{40}Ca and ^{56}Fe. Trying to take the conservative route and overestimate the neutron production, ^{56}Fe is substituted for the chromium isotopes in this example problem.

Any time assumptions are made, the burden is on the user to understand the impact of their assumptions. Here are some suggestions and considerations for choosing substitute tables. If experimental data exist showing production cross-sections, try to match the missing isotope to a similar isotope that has a table available. Remember that the photonuclear cross section is generally larger for higher Z. Consider whether it is more important to match secondary particle production. If a conservative path is desired, e.g. in a neutron production and shielding calculation, chose a higher Z isotope for substitution over a lower one. If there is significant photon flux in the region of the photonuclear thresholds, remember that significant changes in particle production are possible. Remember that even-numbered isotopes may have significantly different absorption and emission characteristics than odd-numbered isotopes, e.g. ^{56}Fe versus ^{57}Fe. Use good judgment and try several different options to determine the sensitivity introduced by the assumptions. Remember that a zero (0) entry on the MPN card disables photonuclear production from that portion of the material; this may be helpful to determine sensitivity.

As a side note, the selection of materials will continue to get more confusing and difficult as more physics is added to these codes. The mixture of tabular and modular interaction sampling in MCNPX is one example of a further complication. It has been proposed to revamp the material interface to provide greater flexibility. One candidate solution is to have the base Mn card be the default definition; i.e. the most precise definition of the material. Overrides may then be accomplished by additional optional cards; e.g. Mn:pn might be the override for photonuclear interactions, Mn:n the override for neutron tables, etc. Override cards might even redefine component/fraction settings and might be made energy dependent to better enable mixing of tabular and modular methods. Suggestions are actively sought on this issue.

F. Biasing

A great many options are available to reduce the time necessary to perform simulations of this nature. Since photonuclear events are dependent on photon collisions, forced collisions [2] can be used to ensure collisions occur in the material of interest. In this example problem forced collisions are used in the steel disk. In a larger problem, forced collisions could be used to ensure enough collisions in, perhaps small or thin, cells of high-Z material that might be under sampled otherwise.

Photonuclear biasing, as described in the user interface memo [1], can also be used to ensure adequate sampling of photonuclear events. Analog sampling of photonuclear events would produce nuclear secondary particles only rarely. Biased sampling (set by the fourth entry on the PHYS:p card) reduces this burden by sampling a photonuclear event at every photon collision and producing particles of appropriately reduced weight. Note that biased photonuclear collisions are turned on in the example problem.

The primary information of interest is the neutron production and spectrum. Electrons and photons below the lowest photonuclear threshold do not contribute to these results. (If electron or photon information is also desired, the most efficient method will probably be to run separate simulations optimized for the information desired.) The cut card can be used to stop electron and photon transport below the lowest threshold energy. This can provide significant timesavings. Time-intensive, low-energy electron transport is ignored while still using the detailed electron physics necessary to provide accurate bremsstrahlung production. The savings for ignoring low-energy photon transport is not much but is done for the sake of symmetry between electron and photon transport. The energy cutoff for transport of electrons and photons in the example problem is 7.6142 MeV corresponding to the photonuclear threshold for ^{56}Fe. (Note that this number corresponds to the first energy point in the main grid, an easy number to look up. If you really want to get fancy, you might use 11.2 MeV corresponding to the threshold for neutron production.)

Weight windows can be used as a biasing method to produce more particles of interest and control populations of particles of less interest. The photonuclear particle production algorithm will attempt to produce the maximum number of particles, sampled independently, according to the current weight window boundary. In the example above, the very low neutron weight boundaries will force more photoneutrons to be sampled at lower weight. The higher photon weight boundary will force fewer photophotons to be sampled but with weights in the same range as other photons. Energy dependent weight windows can extend this to preferentially sample energy ranges of interest.

The biasing methods discussed above are the only ones currently recommended for use in photonuclear simulations. While other methods will work, those discussed above have been optimized to produce the best results.

G. Running the Simulation

This simulation shows a very simple set-up. Expect to spend a significant amount of time preparing a real deck. Brief, less than five minute, runs can be checked to ensure that everything is working as expected and may also help to optimize variance reduction techniques or binning for the tallies. This simulation was run out to 60 million starting particles and used 1017 CPU minutes (~17 hours) on a Sun Ultra10. This level of detail was done to get good statistics on the energy spectrum of the neutrons and is probably excessive for a normal problem. Still, it shows how quickly a large number of particles can be run when low-energy electron transport is not included.

H. Interpreting Output

The result of this simulation is a standard MCNP(X) output file with the information as requested; in this case a full print of all tables and the tallies requested. (Note that MCNP and MCNPX give slightly different answers. MCNP4C uses a newer electron transport package than MCNPX. Output shown below is from MCNPX 2.2.2.) Of particular interest here are Print Table 100, showing the cross section tables loaded; the problem summary tables; Print Table 130, showing the weight balance by particle by cell; Print Table 140, showing the photonuclear activity by nuclide by cell; and, the tally output. Each of these outputs is discussed below.

The material definition cards are the users requests for cross-section data. Input requests can be either exact requests that should retrieve specific tables or fuzzy matches that find an appropriate table. Print Table 100 shows exactly which tables were loaded for the specific output given. When reporting your results, it is very important to reference what data set you used. Table 1 shows the cross-section tables used for this example problem. Note that warnings were issued during the reading of the input deck for those photonuclear isotopes that did not match the corresponding material isotope.

The problem summary is printed in every output deck. It presents overall averages about the creation and loss of the particles transported in the simulation (see Table 2 for the neutron summary, Table 3 for the photon summary and Table 4 for the electron summary). In addition to the previously available output, new entries describe the photonuclear contributions.

Table 2 shows that approximately two neutrons are created for every 10,000 electron source particles. Given a 25 μA current (1.56E14 electrons/second), a 0.82 Ci (3.1E10 neutrons/second) neutron source strength is implied. The neutrons will have a distribution of energies but the average energy can be found by dividing the weighted energy created (3.4161E-4 MeV) by the total weight produced (1.9524E-4) for photoneutrons to obtain 1.75 MeV. The average neutron emission energy for all reactions is shown later in Print Table 140 and agrees with this value. The transmission of neutrons out of the steel disk can be determined by dividing the weight that escapes (1.9391E-4) by the weight produced (1.9524E-4) to obtain the result that 99.3% of the neutrons escape the steel disk. Normally these values would be obtained from the weight balance by cell (Print Table 130) to determine the quantities for the cell of interest; however, the example problem has only one cell and the number from the summary is identically that of the cell.

Table 3 provides several interesting pieces of information. The average number of neutrons produced per photonuclear absorption can be determined by dividing the weight of photoneutrons created (1.9524E-4) by the weight of photons lost to photonuclear absorption (2.5305E-4) to obtain 0.77 neutrons per absorption. The average number of photophotons produced, 1.06, and their average energy, 2.14 MeV, can be found in a manner similar to that shown for neutrons. The average energy of photons born from bremsstrahlung is 10.7 MeV. The average photon energy lost to photonuclear absorption can be determined by dividing the weighted energy (3.6293E-3) by the weight lost (2.5305E-4) to obtain 14.3 MeV. As expected, this number lays within the GDR region despite the greater number of lower energy photons.

Note that MCNP and MCNPX use slightly different methods in accounting for particles produced below their energy cutoff. MCNPX notes that a particle was born below its energy cutoff by accounting for its production, accounting for its loss due to the energy cutoff and discarding the particle. MCNP discards particles born below without noting them in the summaries.

Table 4, the electron summary table, shows that 60 million source particles were simulated. (Note that no new information is in the electron summary. Electro-nuclear interaction data still is not included. However, since it is two orders of magnitude less likely than photonuclear interaction, this is probably not a significant issue.) Print Table 130 (not shown here; see an example in [1]) provides information similar to the problem summary except by cell. This information is of greater use when simulating multi-cell geometries.

Table 5 shows the photonuclear activity by nuclide, by cell. Obviously, the "by cell" portion of this information would be more useful in a more complicated geometry. Even though there are only two tables used for collisions in the cell, each material fraction has been maintained and is listed along with the average event information. **Given other information, such as multiple runs using different substitute tables, this may be helpful in determining the influence/sensitivity of a certain isotope.** The weight production by isotope by cell may also be useful for locating the largest neutron source term. The average emission energy is also available.

Figure 1 shows a plot of the normalized flux at the point of interest (one meter off-axis), through the three surfaces and averaged over the entire surface. The plot has been normalized such that the peak flux is unity. Several things stand out. First, the curves show too distinct peaks, one just below 1 MeV and one just above. These correspond to the average emission energy for silicon and iron, 0.82

and 1.75 MeV respectively. Next note the high-energy tail; neutrons are born with energies up to 9 MeV (source energy – neutron production threshold). The last item of note is the influence of geometry. There is a significantly higher low-energy flux through the front and back faces of the disk. Remember that the electron beam is incident on the center of the disk and that photon production is highly forward peaked. Thus, most of the neutrons are born along the centerline of the disk and those downscattered will more easily escape through the front or back face. The radial thickness of the disk shields the off-axis area. It cannot be stressed enough that accurate simulations will require accurate modeling.

With the end goal now reached, any of several possible uses could be made of the information. The spectrum might be compared to a measurement made at the point of interest. The spectrum may be folded with a damage curve or a flux-to-dose conversion factor to look at damage or dose information (note that this would be better done with a flux multiplier within the calculation). Remember that the area around the disk, e.g. the concrete walls/floor of a room, might greatly alter the spectrum due to scatter.

IV. Conclusions

This example has shown a number of new features and their use within MCNP(X). Most noteworthy are (1) how to make use of the MPN card to select both the best neutron and the best photonuclear cross-section tables available; (2) how to make use of forced photonuclear collisions to produce particles of interest; (3) how to use weight windows to keep the different particle populations in appropriate weight regions to prevent spurious tally hits; (4) how to use the electron/photon energy cutoffs to avoid unnecessary time spent tracking time-expensive low-energy electron transport; and (5) what new information is available in the output for understanding the photonuclear processes in the simulation.

V. References

1. White, M.C. *User Interface for Photonuclear Physics in MCNP(X).* X-5:MCW-00-88(U). Los Alamos National Laboratory: Los Alamos, NM, 2000.

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3. Waters, L. S., ed. *MCNPX User's Guide*. LA-UR-99-6058. Los Alamos National Laboratory: Los Alamos, NM, 1999.

4. Chadwick, M.B., Young, P.G., Chiba, S., Frankle, S.C., Hale, G.M., Hughes, H.G., Koning, A.J., Little, R.C., MacFarlane, R.E., Prael, R.E., and Waters, L.S. “Cross-Section Evaluations to 150 MeV for Accelerator-Driven Systems and Implementation in MCNPX,” *Nuclear Science and Engineerin*g. Vol. 131, No. 3, pp. 293-328, 1999.

5. McLane, V., Dunford, C.L. and Rose, P.F., eds. *ENDF-102 Data Formats and Procedures for the Evaluated Nuclear Data File ENDF-6*. BNL-NCS-44945. Brookhaven National Laboratory: Upton, NY, 1997.

6. White, M.C. *Class 'u' ACE Format – Photonuclear Data.* X-5:MCW-00-86(U). Los Alamos National Laboratory: Los Alamos, NM, 2000.

7. White, M.C. *Release of the LA150U Photonuclear Data Library*. X-5:MCW-00-87(U). Los Alamos National Laboratory: Los Alamos, NM, 2000.

8. *Handbook on photonuclear data for applications: Cross-sections and spectra.* IAEA-TECDOC-1178. International Atomic Energy Agency: Vienna, Austria, October 2000.

Table 1. Isotope mismatch warnings and photonuclear table information.

```
 warning.  m   11:photonuclear event sees ZA= 26056 in place of ZA= 26054

 warning.  m   11:photonuclear event sees ZA= 26056 in place of ZA= 26057

 warning.  m   11:photonuclear event sees ZA= 26056 in place of ZA= 24050

 warning.  m   11:photonuclear event sees ZA= 26056 in place of ZA= 24052

 warning.  m   11:photonuclear event sees ZA= 26056 in place of ZA= 24053

 warning.  m   11:photonuclear event sees ZA= 26056 in place of ZA= 24054

 warning.  m   11:photonuclear event sees ZA= 14028 in place of ZA= 14029

 warning.  m   11:photonuclear event sees ZA= 14028 in place of ZA= 14030

[lines cut]

                      tables from file la150u
  14028.24u   70693  LA150 Photonuclear Data Library Si-28                                      mat1425     07/26/00
  26056.24u   64043  LA150 Photonuclear Data Library Fe-56                                      mat2631     07/26/00
```

Table 2. Neutron creation and loss table from the problem summary.

neutron creation	tracks	weight (per source particle)	energy (per source particle)	neutron loss	tracks	weight (per source particle)	energy (per source particle)
source	0	0.	0.	escape	21128109	**1.9391E-04**	2.9999E-04
nucl. interaction	0	0.	0.	energy cutoff	0	0.	0.
particle decay	0	0.	0.	time cutoff	0	0.	0.
weight window	8126674	1.7594E-07	2.1618E-11	weight window	194054	1.7473E-07	3.3166E-11
cell importance	0	0.	0.	cell importance	0	0.	0.
weight cutoff	0	0.	0.	weight cutoff	0	0.	0.
energy importance	0	0.	0.	energy importance	0	0.	0.
dxtran	0	0.	0.	dxtran	0	0.	0.
forced collisions	0	0.	0.	forced collisions	0	0.	0.
exp. transform	0	0.	0.	exp. transform	0	0.	0.
upscattering	0	0.	1.5118E-15	downscattering	0	0.	4.0929E-05
				capture	0	1.3309E-06	6.8828E-07
(n,xn)	0	0.	0.	loss to (n,xn)	0	0.	0.
fission	0	0.	0.	loss to fission	0	0.	0.
				nucl. interaction	0	0.	0.
tabular boundary	0	0.	0.	tabular boundary	0	0.	0.
(gamma,xn)	13195489	**1.9524E-04**	**3.4161E-04**				
total	21322163	1.9542E-04	3.4161E-04	total	21322163	1.9542E-04	3.4161E-04

		average time of (shakes)		cutoffs	
number of neutrons banked	17952506				
neutron tracks per source particle	3.5537E-01	escape	3.1195E+02	tco	1.0000E+34
neutron collisions per source particle	3.1672E-01	capture	2.3610E+03	eco	0.0000E+00
total neutron collisions	19003377	capture or escape	3.2592E+02	wc1	-5.0000E-01
net multiplication	0.0000E+00 0.0000	any termination	3.2896E+02	wc2	-2.5000E-01

Table 3. Photon creation and loss table from the problem summary.

photon creation	tracks	weight (per source particle)	energy (per source particle)
source	0	0.	0.
nucl. interaction	0	0.	0.
particle decay	0	0.	0.
weight window	0	3.0807E-04	9.3096E-04
cell importance	0	0.	0.
weight cutoff	0	0.	0.
energy importance	0	0.	0.
dxtran	0	0.	0.
forced collisions	8695526	0.	0.
exp. transform	0	0.	0.
from neutrons	867	5.4201E-07	4.3992E-06
bremsstrahlung	7944494	**1.3218E-01**	**1.4169E+00**
p-annihilation	0	0.	0.
electron x-rays	0	0.	0.
1st fluorescence	0	0.	0.
2nd fluorescence	0	0.	0.
(gamma,xgamma)	1575881	**2.6739E-04**	**5.7138E-04**
total	18216768	1.3276E-01	1.4185E+00

photon loss	tracks	weight (per source particle)	energy (per source particle)
escape	8695526	7.6067E-02	8.1123E-01
energy cutoff	4689862	2.5214E-02	6.0775E-02
time cutoff	0	0.	0.
weight window	313845	3.0878E-04	9.3206E-04
cell importance	0	0.	0.
weight cutoff	0	0.	0.
energy importance	0	0.	0.
dxtran	0	0.	0.
forced collisions	0	0.	0.
exp. transform	0	0.	0.
compton scatter	0	0.	1.9872E-01
capture	3036	2.0449E-05	2.0823E-04
pair production	4514499	3.0895E-02	3.4295E-01
loss to pn. abs.	0	**2.5305E-04**	**3.6293E-03**
total	18216768	1.3276E-01	1.4185E+00

number of photons banked	16959857
photon tracks per source particle	3.0361E-01
photon collisions per source particle	1.4493E-01
total photon collisions	8695526

average time of (shakes)		cutoffs	
escape	5.1101E-01	tco	1.0000E+34
capture	5.7579E-03	eco	7.6142E+00
capture or escape	5.0920E-01	wc1	-5.0000E-01
any termination	3.0200E-01	wc2	-2.5000E-01

Table 4. Electron creation and loss table from the problem summary.

electron creation	tracks	weight (per source particle)	energy (per source particle)	electron loss	tracks	weight (per source particle)	energy (per source particle)
source	**60000000**	1.0000E+00	2.0000E+01	escape	258912	2.5921E-03	2.8116E-02
nucl. interaction	0	0.	0.	energy cutoff	63502269	1.0280E+00	7.1276E+00
particle decay	0	0.	0.	time cutoff	0	0.	0.
weight window	0	1.2252E-04	1.1164E-03	weight window	90770	1.2400E-04	1.1292E-03
cell importance	0	0.	0.	cell importance	0	0.	0.
weight cutoff	0	0.	0.	weight cutoff	0	0.	0.
energy importance	0	0.	0.	energy importance	0	0.	0.
pair production	1630025	1.1708E-02	1.1451E-01	scattering	0	0.	8.5987E+00
compton recoil	1857610	1.2825E-02	1.2889E-01	bremsstrahlung	0	0.	4.5408E+00
photo-electric	3035	2.0449E-05	2.0819E-04				
photon auger	0	0.	0.				
electron auger	0	0.	0.				
knock-on	361281	6.0209E-03	5.1643E-02	interact or decay	0	0.	0.
total	63851951	1.0307E+00	2.0296E+01	total	63851951	1.0307E+00	2.0296E+01

number of electrons banked	3851951
electron tracks per source particle	1.0642E+00
electron sub-steps per source particle	7.1824E+01
total electron sub-steps	4309423656

cutoffs	
tco	1.0000E+34
eco	7.6142E+00
wc1	0.0000E+00
wc2	0.0000E+00

Table 5. Photonuclear activity of each nuclide in each cell (Print Table 140).

1photonuclear activity of each nuclide in each cell, per source particle print table 140

cell index	cell name	nuclides	atom fraction	total collisions	collisions * weight	tot p produced	wgt. of p produced	avg p energy	tot n produced	wgt. of n produced	avg n energy
1	1	26056.24u	4.54E-02	401305	1.1665E-05	72799	1.2265E-05	2.1400E+00	608753	9.0220E-06	1.7529E+00
		26056.24u	7.19E-01	6356408	1.8480E-04	1152601	1.9586E-04	2.1320E+00	9670346	1.4309E-04	1.7495E+00
		26056.24u	1.72E-02	152580	4.4342E-06	27855	4.6885E-06	2.1461E+00	231974	3.4305E-06	1.7475E+00
		26056.24u	8.66E-03	76600	2.2206E-06	13790	2.3319E-06	2.1822E+00	116270	1.7152E-06	1.7562E+00
		26056.24u	1.67E-01	1477979	4.2894E-05	267807	4.5239E-05	2.1342E+00	2247426	3.3195E-05	1.7498E+00
		26056.24u	1.89E-02	167816	4.9059E-06	30494	5.2321E-06	2.1613E+00	256684	3.8107E-06	1.7554E+00
		26056.24u	4.71E-03	41857	1.2140E-06	7587	1.2845E-06	2.1321E+00	63011	9.3325E-07	1.7529E+00
		14028.24u	1.79E-02	19347	8.5226E-07	2701	4.4563E-07	3.7080E+00	970	4.4273E-08	8.3288E-01
		14028.24u	9.07E-04	970	3.8671E-08	166	3.1234E-08	2.9465E+00	45	2.0483E-09	6.0427E-01
		14028.24u	6.02E-04	664	2.9684E-08	81	1.3691E-08	3.6841E+00	10	4.5596E-10	8.4949E-01
	total			8695526	2.5305E-04	1575881	2.6739E-04	2.1368E+00	13195489	1.9524E-04	**1.7496E+00**

total over all cells by nuclide	total collisions	collisions * weight	tot p produced	wgt. of p produced	avg p energy	tot n produced	wgt. of n produced	avg n energy
14028.24u	20981	9.2062E-07	2948	4.9055E-07	3.6589E+00	1025	4.6777E-08	8.2303E-01
26056.24u	8674545	2.5213E-04	1572933	2.6690E-04	2.1340E+00	13194464	1.9520E-04	1.7499E+00

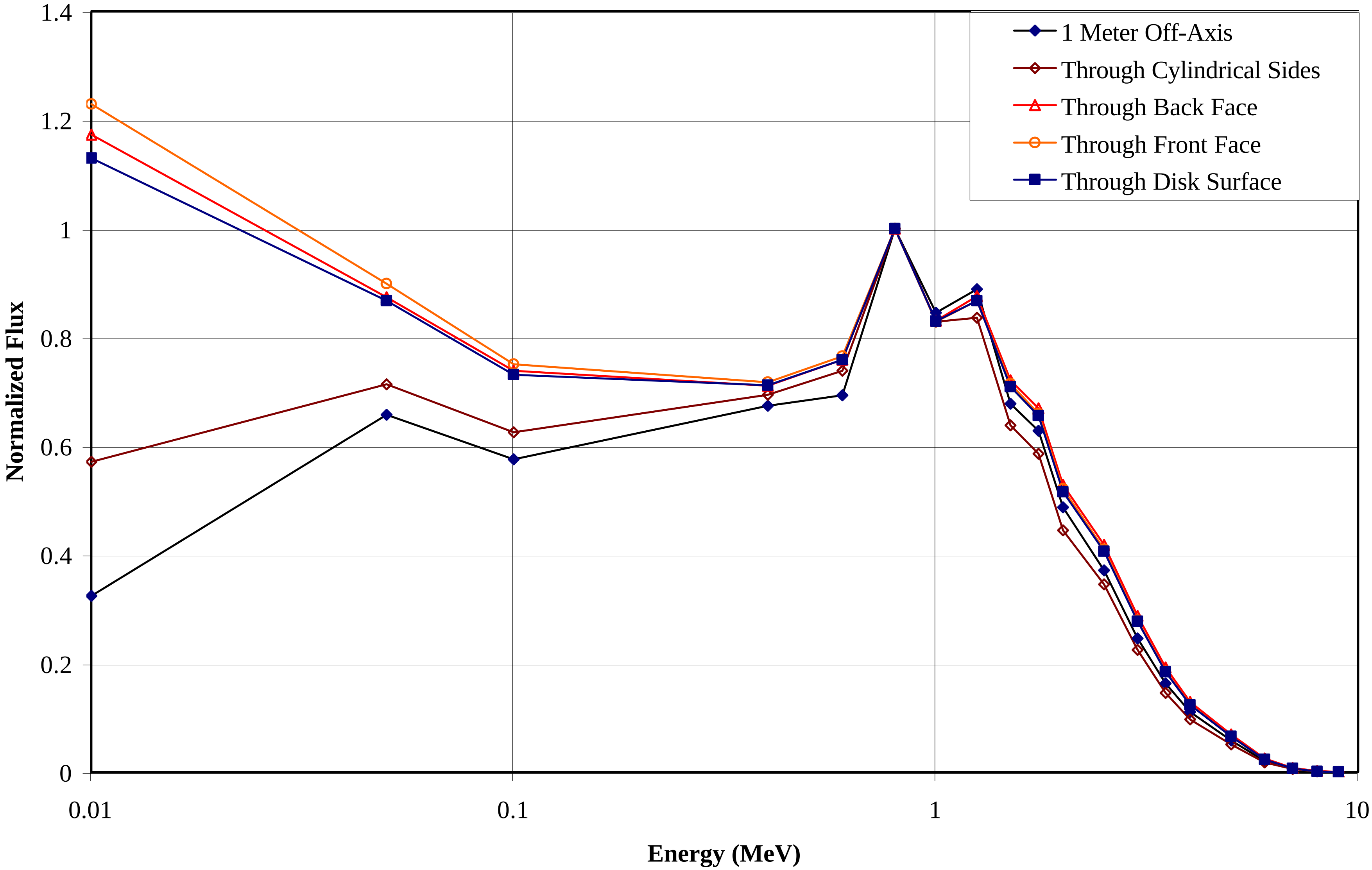

Figure 1. Normalized neutron flux at the surfaces and at a point of interest near the steel disk.