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Geant4 Beta Delayed Neutron Working Document

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Chapter 1

Introduction

Geant4, MCNPX, and actual theory will be compared to understand the capabilities of Geant4 for the fission process and the decay of resulting products. The overall objective will be to implement a working model of fission in Geant4 for cosmic muons. In the course of this work, neutrons will be investigated in order to create a criticality calculation of an HEU test object and the decays of its actinides. Afterwards, the final step will be the implementation of muon fission, and product decay.

The general geometry of the simulations is quite simple including a sphere of nearly prompt critical HEU. A sub-prompt critical sphere is used with a 93 percent U-235 enrichment at 18.95 g/cc density. This sphere will be bombarded by a beam of neutrons, muons, etc.

Chapter 2

Prompt Neutron Fission in Geant4 and MCNPX

Thermal (.025 eV neutrons) were projected on the HEU sphere in Geant4 which resulted in several fissions via the nFission process.

An example of this output is shown below:

```
*******************************************************************************************
* G4Track Information:   Particle = neutron,   Track ID = 1,   Parent ID = 0
*******************************************************************************************

Step#     X         Y         Z        KineE    dEStep   StepLeng  TrakLeng    Volume     Process
   0      0 fm      0 fm    -50 cm  0.025 eV      0 eV      0 fm      0 fm      expHall    initStep
   1      0 fm      0 fm   -6.8 cm  0.025 eV      0 eV   43.2 cm   43.2 cm      expHall  Transportation
setting leaves
   2      0 fm      0 fm  -6.79 cm      0 eV      0 eV    123 um   43.2 cm    thesphere    nFission
   :----- List of 2ndaries - #SpawnInStep=  5(Rest= 0,Along= 0,Post= 5), #SpawnTotal=  5 ---------------
   :      0 fm      0 fm  -6.79 cm   4.11 MeV   neutron
   :      0 fm      0 fm  -6.79 cm   2.02 MeV   neutron
   :      0 fm      0 fm  -6.79 cm   1.51 MeV   neutron
   :      0 fm      0 fm  -6.79 cm   1.27 MeV   neutron
   :      0 fm      0 fm  -6.79 cm   1.34 MeV     gamma
   :------------------------------------------------------------------ EndOf2ndaries Info ---------------
```

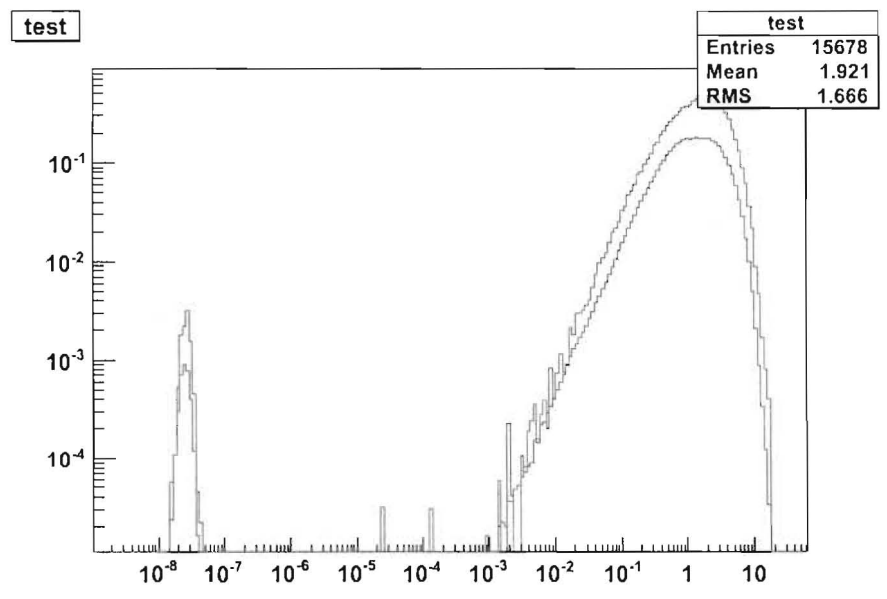
A few points can be derived from this output alone. First, fission occurred (as expected so it is important to confirm how Geant4 decided to perform this process (i.e. investigate cross-section and that the cross-section library was being called), second the residuals of the fission process include not only gamma and neutron but also a 1/3, 2/3 product residual. These fission products are no where to be found and must be instated if appropriate delayed decay processes are to be simulated correctly.

When using the QGSP BERT HP physics list the fission products are absent (though high precision neutron physics are used).

2.0.1 MCNPX and GEANT4 comparison of prompt neutron energy spectrum

The sub-critical test sphere was used to obtain the 4 pi distribution of the prompt neutron energy spectrum in both GEANT4 and MCNPX for thermal fission. The geant4 program was run with 10 million particles while the mcnpx program ran with 284971 particles (the large order decrease in events is due to delay and daughter processes which are computationally expensive).

The following plot shows that there is a small departure in agreement for the thermal and fast neutrons as a result of the fission process with Geant4+HP Fission and MCNPX using thermal neutrons. Geant4 is in red and MCNPX is in blue.

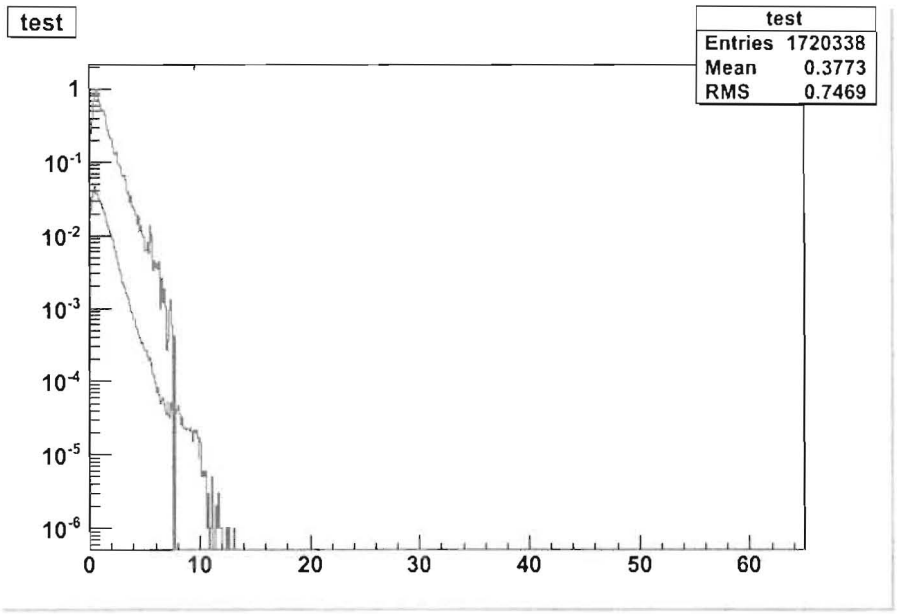


2.0.2 MCNPX and GEANT4 comparison of prompt gamma energy spectrum

The sub-critical test sphere was used to obtain the 4 pi distribution of the prompt gamma energy spectrum in both GEANT4 and MCNPX for thermal fission. All other parameters are identical to the previous subsection.

The prompt gamma emission spectrum has more deviation than the neutrons output from the fission done in Geant4 vs. MCNPX. Geant4 is in red

and MCNPX is in blue.



2.0.3 Analysis of Prompt Differences between G4 and MCNPX

As shown from the above graphs, there is a difference with both the neutron and gamma interactions (though the difference is less than an order of magnitude. It is important to understand why the results are that far off though considering the geometry and incident particle are identical. It is probable that differences exist in each code but these differences should be better understood.

The first data point of comparison will be to generate the aforeshown plots with a small change in the simulation. The incident neutron source will be moved to the center of the test object in both MCNPX and Geant4. This point source will then be emitted isotropically from the center of that object. Other Geant4 models will be investigated for comparing fission simulations in Geant4 to MCNPX.

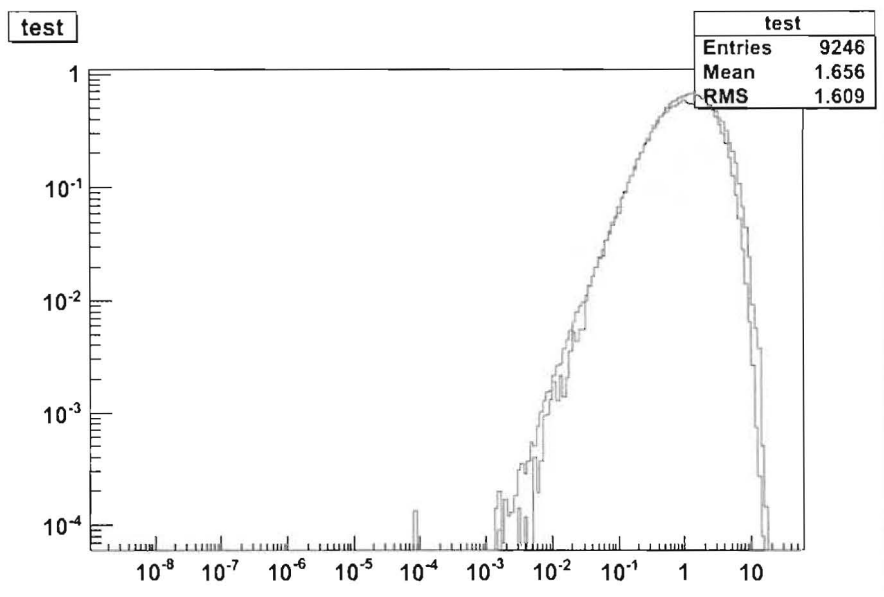
2.0.4 Parafission Model for a Better Agreement between Geant4 and MCNPX

After investigating the fission and other neutron behaviour in Geant4 I dropped the usage of QGSP BERT HP in light of using a more comprehensive customized physics list. This list will include the standard electromagnetics and so forth along with the high precision neutrons and other hadronics. Most importantly the parafission model was invoked to analyze fission fragments and the impact of the model on the prompt output of neutrons and gamma. The result to say the least was satisfying showing a very nice agreement with MCNPX.

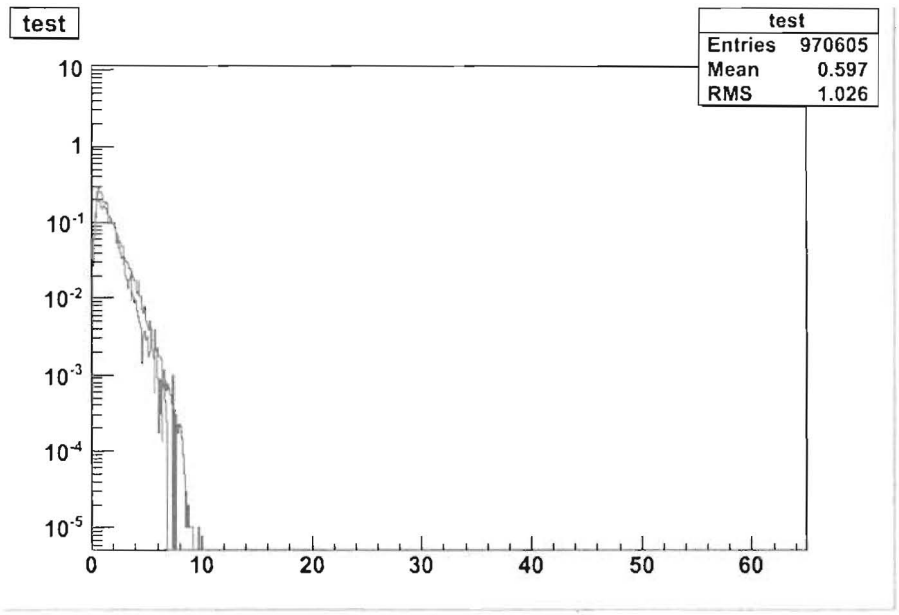
The first two plots are for prompt gamma and neutron emissions from the sphere with an isotropic point source in the middle of the sphere. The Geant4 simulation ran for 100000 particles while MCNPX ran for 8852 particles.

In the following plots Geant4 is red, MCNPX is blue.

NEUTRON:



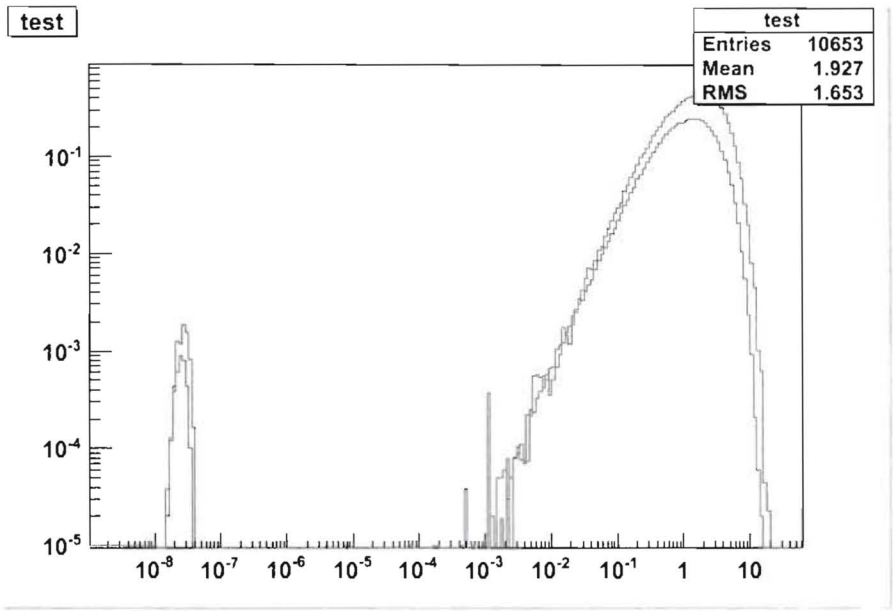
GAMMA:



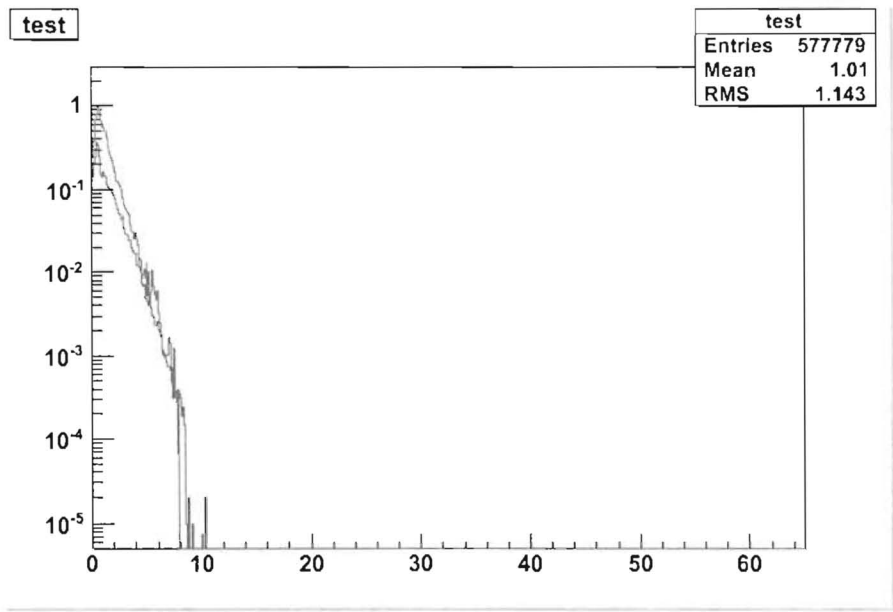
The next two plots are for prompt gamma and neutron emissions from the sphere with a point source 4 cm away from the sphere and directed towards its center. Geant4 was run for 100000 particles and MCNPX was run for 68030 particles. The neutrons both traveled through vacuum.

In the following plots Geant4 is red, MCNPX is blue.

NEUTRON:



GAMMA:



The above simulations may indicated that there is a small difference between the treatment of fission and its competing reactions. When the source

particle originates inside the sphere of HEU fission has an extremely high probability of occurrence and both Geant4 and MCNPX are in agreement. When the source particle must first travel to the sphere and possibly interact with another process such as scattering or capture, there is a slight difference. This can be investigated further in the future. For now, the results are definitely close and the next step of analysis is on fission fragments.

Chapter 3

Fission fragments in Literature, Geant4, and MCNPX

This chapter is the next process of analysis for studying the fission fragment distribution from U-235. Three sources will be used for the comparison, literature, Geant4 with the Parafission model+HP neutron physics, and MCNPX.

3.0.5 Fission fragments from literature

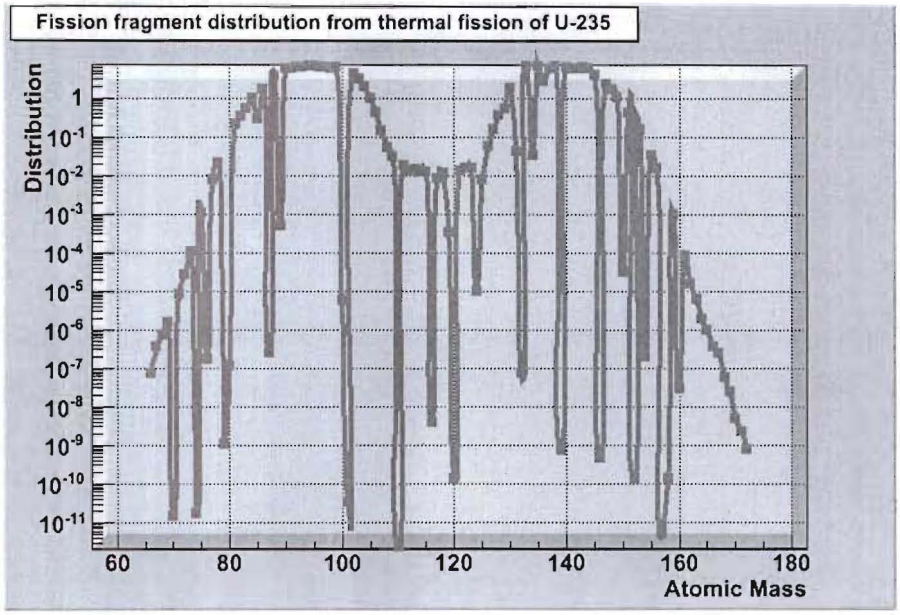
The distribution of thermal fission fragments for U-235 is referenced from the work done at Los Alamos in 1993. The table is attached in appendix: A.

The table can be found here (as well as other materials):

`http://ie.lbl.gov/fission.html`

Fission Product Yields per 100 Fissions for 235U Thermal Neutron Induced Fission Decay, T.R. England and B.F. Rider, LA-UR-94-3106, ENDF-349.

The fission fragment list shown in the appendix will be parsed with a python script and then plotted to show the distribution of fission fragments as a function of atomic mass.

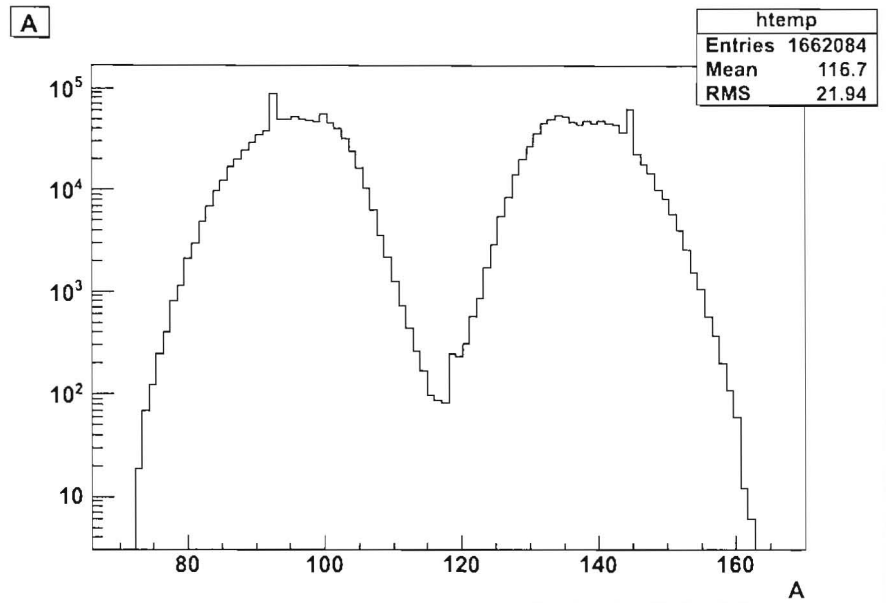


3.0.6 Fission fragments using Geant4+Parafission

An isotropic point source in the center of a sphere will be used for the study of the fission producs that are emitted from Geant4. The neutron source will be 0.025 eV (thermal). The objective will be to compare the output of Geant4 to literature. Additionally, the parafission model is used to sample the fission products in tandem with other physics packages (especially high precision neutron scattering, capture models).

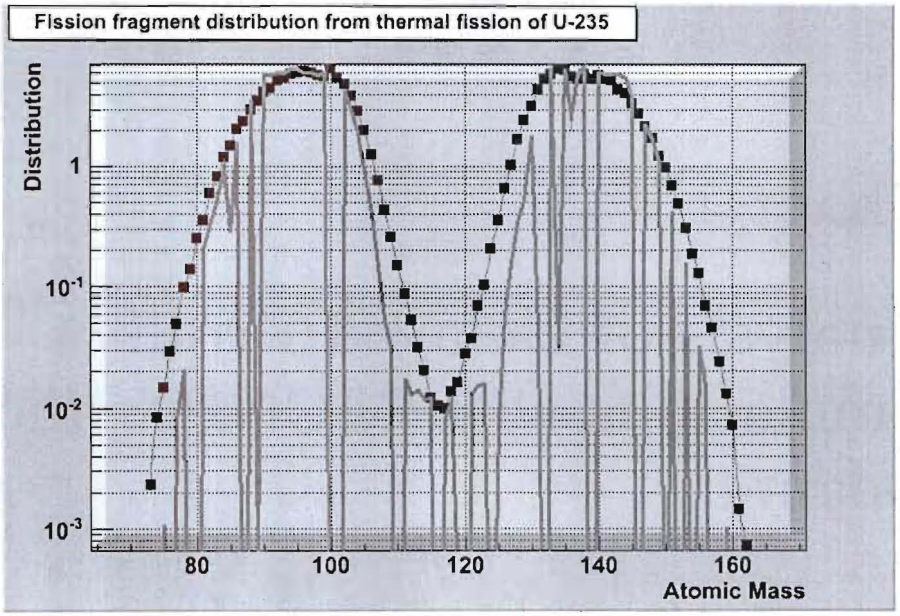
A side note for comparison is that my target is mostly u-235 while I believe the LANL literature source is full U-235 (or at least mostly U-235 compared to U-238 as well). The impact on the results should be minor as the thermal fission cross-section is very large for U-235 and the data is normalized per fission event.

Geant4 was run for 100000 incident thermal neutrons.



3.0.7 Comparison between literature and Geant4

When the two graphs are merged, we can see good agreement between the distribution of the most likely fission fragments. The red line with black markers is from the Geant4 results. The blue line is from the literature results. There is a slight difference between the results for the less likely fission products which is fine enough for now but can be investigated in the future. The most likely fission products have excellent agreement. Additionally, both the literature and simulation results are normalized per 100 fissions.


Fission fragment distribution from thermal fission of U-235
Distribution
1
10-1
10-2
10-3
80
100
120
140
160
Atomic Mass

Chapter 4

Analysis of Delayed Product simulations with MCNPX and Geant4

The next logical step in analyzing the fission simulation process is investigating time and energy distributions (and in some cases angular distribution), of the delayed gammas and neutrons that result from the decay of the fission products. This is of paramount importance to control of nuclear reactors, DHS applications, and so forth.

This chapter will take a stepwise approach in investigating the delayed contributions of fission fragments in our sphere of HEU case with the isotropic thermal neutron source located in the center of the sphere. The treatment of delayed products can be extremely different between codes depending on if they employ tabular or model based algorithms for determining the resulting delayed gamma/neutron. For example in MCNPX there are a variety of flags that control delayed gamma production based upon 25 multigroup analysis or some combination of multigroup assisted with line emission (which has a significant cost computationally). I would assume that Geant4 has other subtle nuances that might affect these results as well.

4.0.8 MCNPX Delayed Production of Gamma/Neutron

The first 2 plots are of the time distribution of neutrons and gammas that result from fission inside the U-235 sphere. Pertinent flags in MCNPX for decayed gammas and neutrons are:

```
phys:n j j j -1001 j 1        $ delayed analog sampling models and libraries, correct sample nu
phys:p j j j -1 j -101        $ analog photonuclear & high fidelity delayed gamma
```

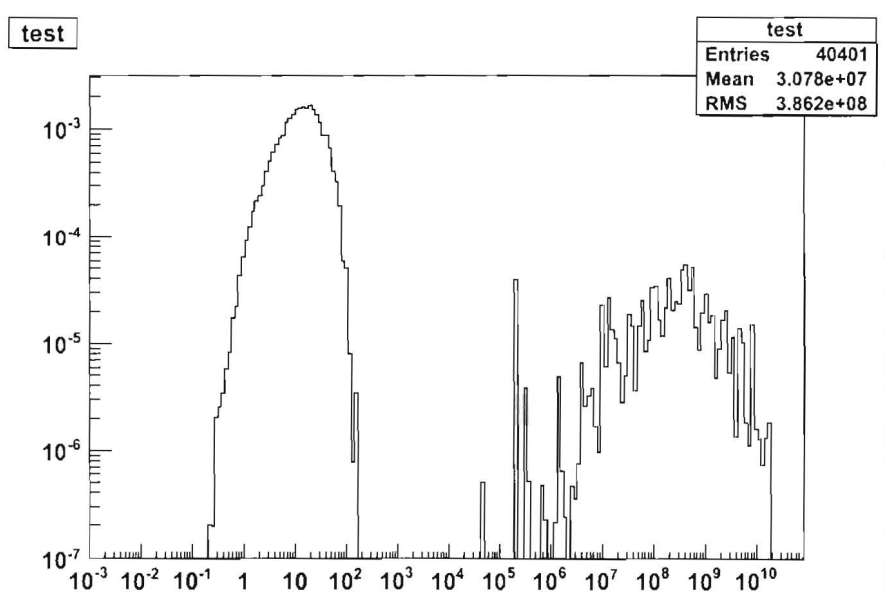
First, the phys:n card -1001 entry means that the delayed neutron production is a function based upon models when libraries are absent. There are other options that force delayed neutron production to only occur based upon just libraries, models, or other algorithms.

Second, the phys:p card has a few important controls for delayed gamma production. The first -1 value enables analog photonuclear interactions. The last flag is critical to the production of delayed gammas. If the value is 0, no delayed gammas are produced, if the value is -101 multigroup-25 emission data is used and sampled, finally if the value is -102 the multigroup is augmented by line emission sampling for 1000 nuclides (where the multigroup represents the other 3400 nuclides from the CINDER90 database).

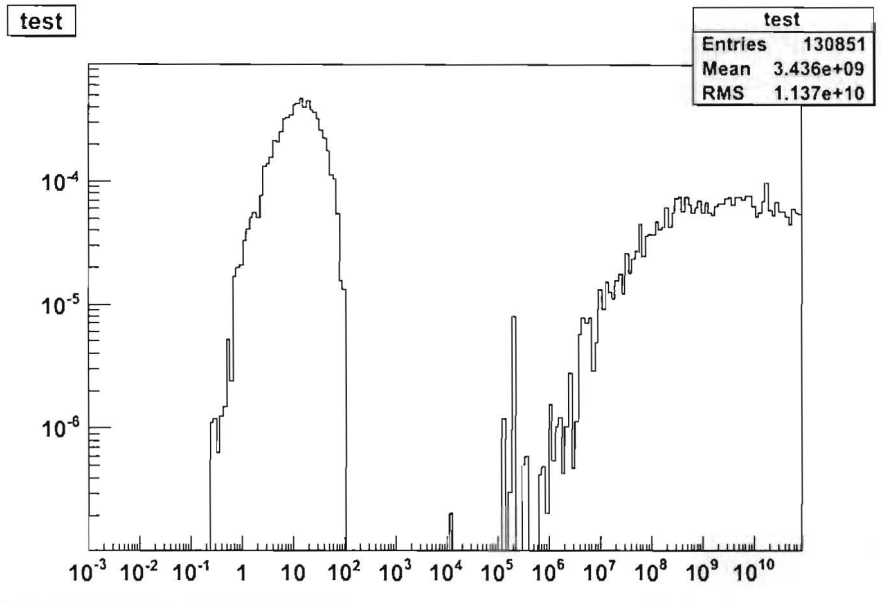
The following simulation was run for 8852 histories (more can be done though the fidelity of information is fine for our current analysis as the source was inside the sphere and has a great probability of interacting). Higher fidelity runs can be done in the near future if necessary.

Note that the x-axis is in shakes where 1 shake = 10 ns. As can be seen, the delayed products occur at approximately 100000 shakes/1 millisecond and greater.

NEUTRON:



GAMMA:



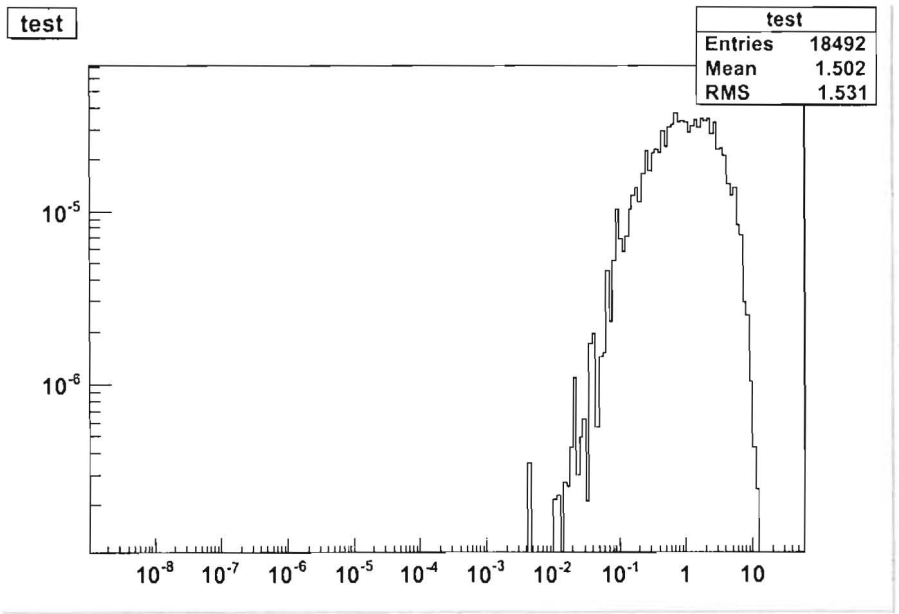
Next are the energy spectrums of the delayed products for all times greater than 1 millisecond a.k.a.

$$10^5$$

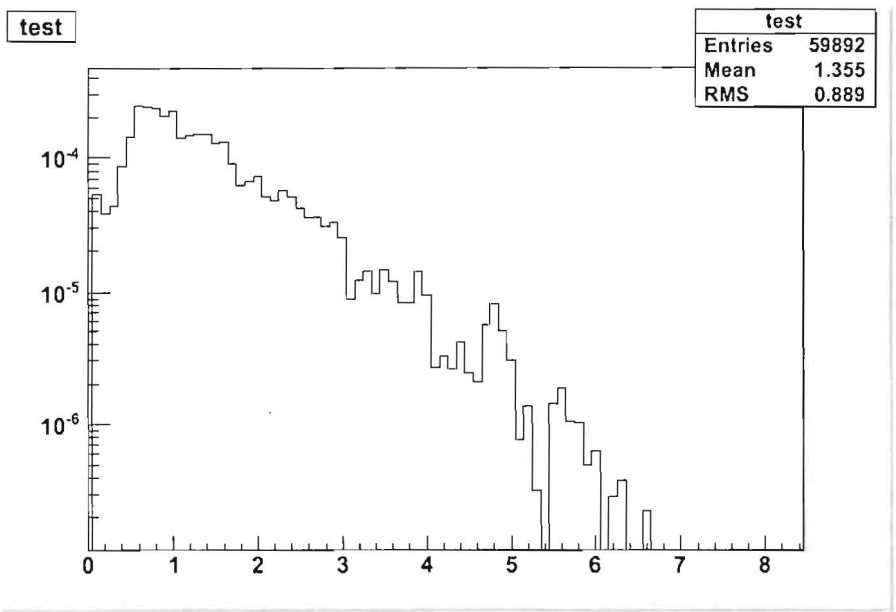
shakes and greater.

Note that x-axis is in units of MeV.

NEUTRON:


test
test
Entries 18492
Mean 1.502
RMS 1.531
10^-5
10^-6
10^-8 10^-7 10^-6 10^-5 10^-4 10^-3 10^-2 10^-1 1 10

GAMMA:


test
test
Entries 59892
Mean 1.355
RMS 0.889
10^-4
10^-5
10^-6
0 1 2 3 4 5 6 7 8

4.0.9 Delayed products in Geant4

The delayed fission products in Geant4 are handled by invoking the G4Decay module and decaying each of the daughters. Appendix B contains elements explaining the G4Decay process, how it does the decays, lookup tables, etc. In summary G4Decay interfaces with a process controller and table lookup for handling decays of most particles (excluding massless particles and so forth) for both in-flight and at rest. Of course, we are mostly interested in the decay of fission daughters which should be covered. Additonal decay modes can be adjusted by and injected by the user into the physics list.

Another critical element for simulating the decay modes is to kill the decay chain from continuing, in this case we would want to terminate after an hours worth of decay chain (i.e. dont decay Cs, as there is no point in looking at residuals at that duration, approx 30 years for Cs-137).

Thus we kill certain particles such as Cs-137 (or just ignore their decay and let them ionize). In fact the best way to do this is to run a time filter in the stepping manager in order to kill the long lived decays. I.e. if the decay time is greater than 7200 seconds as shown below for G4.

```
if (theTrack->GetGlobalTime()/s > 7200){//time killer
theTrack->SetTrackStatus(fKillTrackAndSecondaries);}
```

We also include the following code in the user physics list (includes the ion decay element as well).

```
//include decay elements
#include "G4Decay.hh"
#include "G4RadioactiveDecay.hh"
#include "G4GenericIon.hh"
```

```
// Add Decay Process
G4Decay* fDecayProcess = new G4Decay();
G4RadioactiveDecay*  theRadioactiveDecay = new G4RadioactiveDecay();
G4GenericIon* ion = G4GenericIon::GenericIon();
```

```
theParticleIterator->reset();
while( (*theParticleIterator)() ){
  G4ParticleDefinition* particle = theParticleIterator->value();
  G4ProcessManager* pmanager = particle->GetProcessManager();

  if (particle == ion) {
    pmanager->AddProcess(theRadioactiveDecay, 0, -1, 3);

  } else if (fDecayProcess->IsApplicable(*particle)) {

    pmanager ->AddProcess(fDecayProcess);

    // set ordering for PostStepDoIt and AtRestDoIt
    pmanager ->SetProcessOrdering(fDecayProcess, idxPostStep);
    pmanager ->SetProcessOrdering(fDecayProcess, idxAtRest);

  }
}
```

An example of the decayed output is shown:

```
*******************************************************************************************
* G4Track Information:   Particle = Bi214[0.0],   Track ID = 366,   Parent ID = 364
*******************************************************************************************

Step#    X         Y         Z        KineE    dEStep   StepLeng  TrakLeng   Volume     Process
    0  -2.34 cm   1.65 mm   2.35 mm   1.49 eV     0 eV      0 fm      0 fm    thesphere   initStep
    1  -2.34 cm   1.65 mm   2.35 mm     0 eV   1.49 eV   5.38 Ang  5.38 Ang   thesphere    ionIoni
    2  -2.34 cm   1.65 mm   2.35 mm     0 eV     0 eV      0 fm   5.38 Ang   thesphere  RadioactiveDecay
    :----- List of 2ndaries - #SpawnInStep=  5(Rest= 5,Along= 0,Post= 0), #SpawnTotal=  5 ---------------
    :  -2.34 cm   1.65 mm   2.35 mm   4.38 eV Po214[0.0]
    :  -2.34 cm   1.65 mm   2.35 mm    609 keV     gamma
    :  -2.34 cm   1.65 mm   2.35 mm   1.24 MeV     gamma
    :  -2.34 cm   1.65 mm   2.35 mm    661 keV anti_nu_e
    :  -2.34 cm   1.65 mm   2.35 mm    764 keV        e-
    :------------------------------------------------------------------ EndOf2ndaries Info ---------------
```

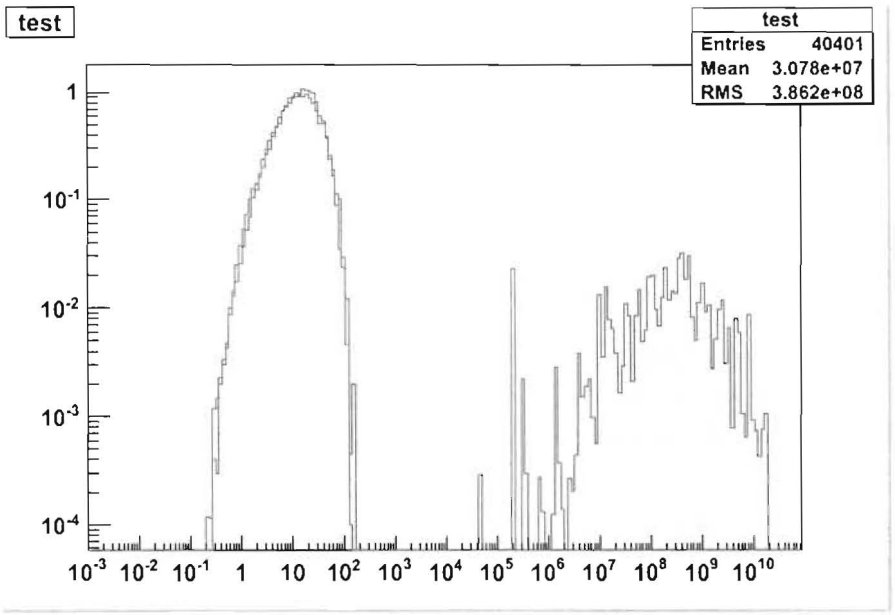
Another imporant element to avoid segmentation faults in Geant4 is the following conditional statement that needs to be filtered.

```
(theStep->GetPostStepPoint()->GetProcessDefinedStep() !=0)
```

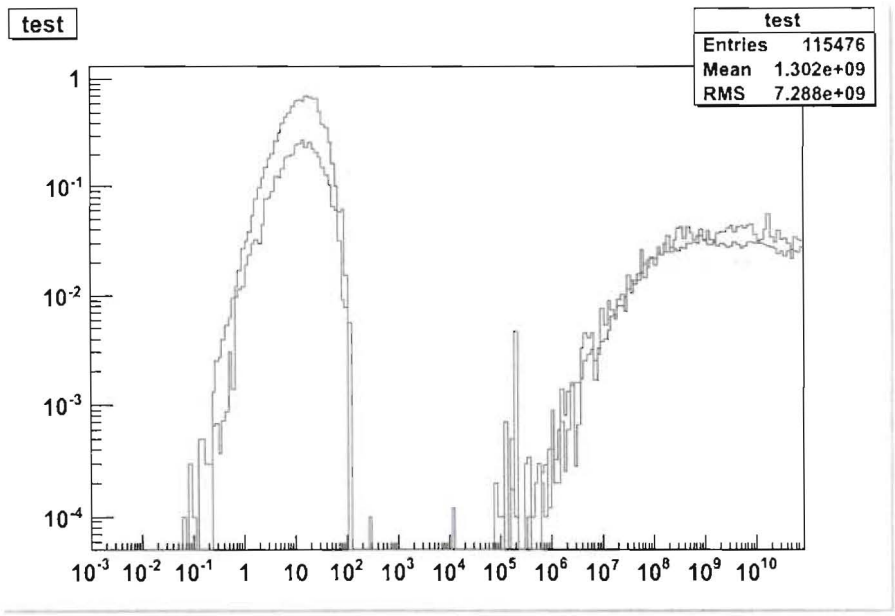
The following is a time distribution of photons and neutrons as a result of prompt and delayed neutron fission in Geant4. The gamma delay and neutron prompt matches perfectly. The gamma prompt is within an order

of magnitude which can be investigated. The main problem now is that the neutron precursors are not decaying for the delayed neutron contribution.

NEUTRON:



GAMMA:



After investigating the decay tables included with Geant4 it is apparent that the neutrons created by precursors such as I-137 are not included! One possible solution is to modify the decay tables to include the I-137 in the physics list. Specifically, delayed neutrons are created as a residual from Beta minus decay where the resulting excited daughter has enough energy that it exceeds the neutron seperation energy band. Thus when I-137 neutron converts to a proton and makes Xe-137, Xe-137 sometimes has so much energy that an additional neutron can escape causing Xe-136.

4.0.10 Delayed Neutrons in Geant4

In order to produce delayed neutrons in Geant4 the excited nucleus must relax and emit the appropriate ratio of gammas and neutrons. Geant4 handles the relaxation of excited atomic nuclei with the G4PhotonEvaporation, thus to handle other isomers of beta delayed neutron emitters, the G4Radioactivedecay database will have to be adjusted.

There are 5 important high Z isotopes that will potentially result in the release of a beta and neutron provided that the neutron seperation energy is met. These isotopes in question are:

- I-137 which beta decays to Xe-137 which has a neutron seperation energy of 4.02546 MeV to release a free neutron and Xe-136
- Rb-95 which beta decays to Sr-95 which has a neutron seperation energy of 4.346878 MeV to release a free neutron and Sr-94
- Rb-94 which beta decays to Sr-94 which has a neutron seperation energy of 6.8255 MeV to release a free neutron and Sr-93
- Br-88 which beta decays to Kr-88 which has a neutron seperation energy of 7.05348 MeV to release a free neutron and Kr-87
- Br-87 which beta decays to Kr-87 which has a neutron seperation energy of 5.51361 MeV to release a free neutron and Kr-86

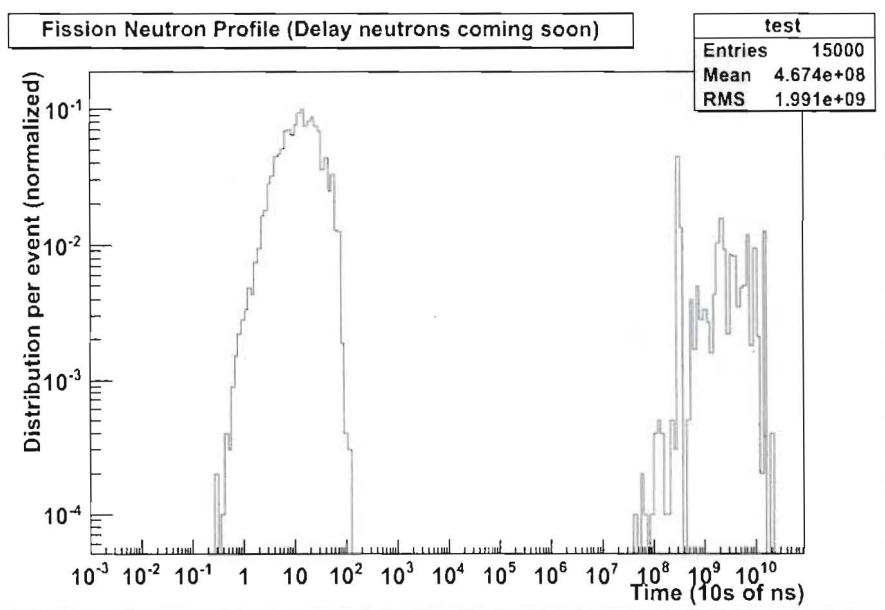
A potential route to including the beta minus decay is by adjusting the G4RadioactiveDecay to include Beta - and neutron reaction. These cross-sections can be found easily in ENDF and can be incorporated in the G4RadioactiveDecay library. Then the last element is to write additional code to support the additional branching physics.

4.0.11 Process for Including Beta- and Free Neutron in G4

The following is a brief summary of code that has been modified to include the effects of free neutrons in Geant4 from beta- decays. A simpler method is to hijack the already existing beta decay and make a similar, competing reaction that will spit out the beta- and free neutron with appropriate cross-sections and formula.

This involves customizing the G4BetaMinusDecayChannel, G4DecayChannel, G4Radioactive decay and other modules. The ultimate goal will be to provide a surrogate physics reaction that is called BetaMinusN.

The first iteration of this has now been implemented and the time profile of neutron production from fission daughters is shown below. Now only I-137 is undergoing Beta- + n but the other precursors will be added shortly.



Chapter 5

Appendix A: Thermal neutron fission products in U-235

Fission Product Yields per 100 Fissions for
235U Thermal Neutron Induced Fission Decay,
T.R. England and B.F. Rider, LA-UR-94-3106,
ENDF-349

Nuclide	t1/2	Ind. Yield	Cum. Yield
66Cr		2.41E-12	2.41E-12
66Mn		7.20E-10	7.22E-10
66Fe		3.76E-08	3.83E-08
66Co	0.23s	2.81E-08	6.64E-08
66Ni	54.6 h	5.78E-09	7.21E-08
66Cu	5.10 m	1.43E-11	7.22E-08
67Mn		5.38E-10	5.38E-10
67Fe		6.87E-08	6.92E-08
67Co		2.00E-07	2.70E-07
67Ni	21 s	9.04E-08	3.60E-07
67Cu	2.580d	9.68E-10	3.61E-07
68Mn		6.66E-11	6.66E-11
68Fe		3.92E-08	3.92E-08

68Co		2.47E-07	2.86E-07
68Ni	19 s	4.19E-07	7.05E-07
68Cu-m	3.79m	7.36E-09	7.36E-09
68Cu	31 s	3.15E-09	7.12E-07
68Zn	stable	4.74E-11	7.16E-07
69Mn		8.03E-12	8.03E-12
69Fe		1.22E-08	1.22E-08
69Co		3.25E-07	3.37E-07
69Ni	10 s	1.12E-06	1.46E-06
69Cu	2.8 m	1.14E-07	1.57E-06
69Zn-m	13.76h	1.06E-09	1.06E-09
69Zn	56 m	2.48E-10	1.57E-06
70Fe		3.24E-09	3.24E-09
70Co		2.09E-07	2.13E-07
70Ni		2.78E-06	3.00E-06
70Cu-m	47 s	4.46E-07	1.94E-06
70Cu	5 s	1.49E-07	1.65E-06
70Zn	stable	3.03E-08	3.62E-06
70Ga	21.1 m	1.47E-11	1.47E-11
71Fe		4.92E-10	4.92E-10
71Co		1.48E-07	1.49E-07
71Ni		4.35E-06	4.50E-06
71Cu	20 s	3.48E-06	7.97E-06
71Zn-m	3.97 h	3.29E-07	3.29E-07
71Zn	2.4 m	7.71E-08	8.05E-06
71Ga	stable	9.39E-10	8.38E-06
72Fe		7.15E-11	7.15E-11
72Co	0.124s	5.80E-08	5.81E-08
72Ni	3.83 s	7.60E-06	7.66E-06
72Cu	6.6 s	1.27E-05	2.04E-05
72Zn	46.5 h	6.10E-06	2.65E-05
72Ga	14.10h	3.86E-08	2.65E-05
72Ge	stable	3.64E-11	2.65E-05

73Fe		5.54E-12	5.54E-12
73Co	0.129s	2.21E-08	2.21E-08
73Ni	0.491s	7.13E-06	7.16E-06
73Cu	3.9 s	4.71E-05	5.42E-05
73Zn	24 s	4.63E-05	1.01E-04
73Ga	4.87 h	1.21E-06	1.02E-04
73Ge-m	0.53 s	5.59E-10	1.02E-04
73Ge	stable	2.38E-09	1.02E-04
74Co	0.092s	3.00E-09	3.00E-09
74Ni	0.900s	4.58E-06	4.58E-06
74Cu	0.648s	6.82E-05	7.28E-05
74Zn	1.60 m	2.51E-04	3.24E-04
74Ga	8.1 m	1.46E-05	3.38E-04
74Ge	stable	1.67E-07	3.39E-04
74As-m	8.0 s	1.16E-11	1.16E-11
74As	17.76d	4.99E-12	1.66E-11
75Co	0.082s	3.81E-10	3.81E-10
75Ni	0.231s	1.53E-06	1.53E-06
75Cu	1.3 s	1.01E-04	1.02E-04
75Zn	10.2 s	7.67E-04	8.69E-04
75Ga	2.10 m	1.93E-04	1.06E-03
75Ge-m	48.9 s	4.56E-06	4.70E-05
75Ge	1.380h	6.81E-07	1.07E-03
75As	stable	2.56E-09	1.07E-03
76Co		2.53E-11	2.53E-11
76Ni	0.305s	5.02E-07	5.02E-07
76Cu	0.6 s	8.28E-05	8.33E-05
76Zn	5.7 s	1.84E-03	1.92E-03
76Ga	29 s	1.05E-03	2.97E-03
76Ge	stable	1.30E-04	3.10E-03
76As	26.3 h	1.65E-07	1.65E-07
76Se	stable	3.04E-11	1.65E-07
77Ni	0.103s	5.64E-08	5.64E-08
77Cu	0.305s	4.45E-05	4.46E-05

77Zn	2.1 s	3.14E-03	3.19E-03
77Ga	13.0 s	4.08E-03	7.27E-03
77Ge-m	53 s	8.91E-05	6.49E-03
77Ge	11.30h	5.96E-04	2.83E-03
77As	38.8 h	4.31E-06	7.96E-03
77Se-m	17.45s	1.84E-09	2.39E-05
77Se	stable	2.75E-10	7.96E-03
78Ni	0.132s	5.03E-09	5.03E-09
78Cu	0.118s	1.09E-05	1.09E-05
78Zn	1.5 s	3.56E-03	3.58E-03
78Ga	5.09 s	1.03E-02	1.39E-02
78Ge	1.45 h	6.94E-03	2.08E-02
78As	1.512h	1.30E-04	2.10E-02
78Se	stable	2.47E-07	2.10E-02
79Zn	1.0 s	1.64E-03	1.64E-03
79Ga	2.85 s	1.71E-02	1.87E-02
79Ge	19.1s	2.33E-02	4.21E-02
79As	9.0 m	2.66E-03	4.47E-02
79Se-m	3.89 m	1.65E-06	4.47E-02
79Se	6.5e4y	1.10E-05	4.47E-02
79Br-m	4.86 s	1.04E-09	1.04E-09
80Ni		1.56E-12	1.56E-12
80Cu	0.090s	5.25E-08	5.25E-08
80Zn	0.55 s	2.42E-04	2.42E-04
80Ga	1.68 s	1.17E-02	1.19E-02
80Ge	29.5 s	1.02E-01	1.15E-01
80As	16.0 s	1.37E-02	1.28E-01
80Se	stable	4.89E-04	1.29E-01
80Br-m	4.42 h	1.11E-07	1.11E-07
81Ga	1.22 s	8.18E-03	8.18E-03
81Ge	7.6 s	1.26E-01	1.35E-01
81As	33 s	6.09E-02	1.96E-01
81Se-m	57.3 m	6.93E-03	6.93E-03
81Se	18.5 m	1.04E-03	2.04E-01

81Br	stable	8.86E-06	2.04E-01
82Cu		1.48E-10	1.48E-10
82Zn	0.127s	1.08E-05	1.08E-05
82Ga	0.607s	6.26E-03	6.27E-03
82Ge	4.6 s	1.26E-01	1.32E-01
82As-m	13.7 s	2.71E-02	2.71E-02
82As	19 s	1.29E-01	2.60E-01
82Se	stable	3.71E-02	3.25E-01
83Zn	0.084s	6.32E-08	6.32E-08
83Ga	0.31s	1.92E-04	1.92E-04
83Ge	1.9 s	4.79E-02	4.80E-02
83As	13.4 s	2.91E-01	3.40E-01
83Se-m	1.17m	3.35E-02	2.51E-01
83Se	22.3m	1.43E-01	2.65E-01
83Br	2.40h	1.95E-02	5.36E-01
83Kr-m	1.83 h	1.55E-06	5.36E-01
84Zn		1.22E-06	1.22E-06
84Ga	0.098s	1.11E-02	1.11E-02
84Ge	1.2 s	1.90E-02	3.01E-02
84As	5.5 s	1.97E-01	2.26E-01
84Se	3.3 m	6.31E-01	9.66E-01
84Br-m	6.0 m	1.67E-02	1.67E-02
84Br	31.8 m	1.86E-02	9.85E-01
85Ga	0.087s	5.88E-07	5.88E-07
85Ge	0.250s	2.13E-03	2.13E-03
85As	2.03 s	1.21E-01	2.19E-01
85Se-m	19 s	4.47E-01	4.94E-01
85Se	39 s	4.47E-01	5.56E-01
85Br	2.87m	2.35E-01	1.28E+00
85Kr-m	4.48 h	5.89E-03	1.29E+00
85Kr	10.73y	2.55E-02	2.83E-01
86Zn		2.28E-10	2.28E-10
86Ga		3.28E-05	3.28E-05

86Ge	0.247s	6.29E-01	6.29E-01
86As	0.9 s	1.99E-02	5.53E-01
86Se	15.0 s	8.36E-01	1.37E+00
86Br-m	4.5 s	2.30E-01	2.31E-01
86Br	55.5 s	2.30E-01	1.60E+00
87Ge	0.134s	2.20E-03	2.20E-03
87As	0.8 s	5.05E-02	5.27E-02
87Se	5.6 s	7.31E-01	7.60E-01
87Br	55.9 s	1.27E+00	2.03E+00
87Kr	1.27 h	4.63E-01	2.56E+00
87Rb	10.67l	2.50E-03	2.56E+00
87Sr-m	2.81 h	2.51E-07	2.51E-07
88Ge	0.129s	5.20E-05	5.20E-05
88As	0.135s	1.24E-01	1.24E-01
88Se	1.50 s	2.68E-01	3.92E-01
88Br	16.4 s	1.39E+00	1.78E+00
88Kr	2.84 h	1.73E+00	3.55E+00
88Rb	17.7 m	2.23E-02	3.57E+00
88Sr	stable	7.68E-05	3.58E+00
89As	0.121s	1.54E-04	1.54E-04
89Se	0.41 s	4.86E-02	4.87E-02
89Br	4.37 s	1.04E+00	1.09E+00
89Kr	3.15 m	3.44E+00	4.51E+00
89Rb	15.4 m	2.05E-01	4.72E+00
89Sr	50.52d	1.75E-02	4.73E+00
89Y -m	15.7 s	1.88E-07	4.73E-04
90Se	0.427s	1.27E-02	1.27E-02
90Br	1.9 s	5.53E-01	5.64E-01
90Kr	32.3 s	4.40E+00	4.86E+00
90Rb-m	4.3 m	7.07E-01	1.24E+00
90Rb	2.6 m	1.39E-01	4.50E+00
90Sr	29.1 y	7.37E-02	5.78E+00
90Y	2.67 d	8.97E-06	5.78E+00

91Se	0.27s	6.66E-04	6.66E-04
91Br	0.54 s	2.24E-01	2.24E-01
91Kr	8.6 s	3.16E+00	3.35E+00
91Rb	58.0 s	2.23E+00	5.58E+00
91Sr	9.5 h	2.51E-01	5.83E+00
91Y	58.5 d	3.30E-04	5.83E+00
92Se	0.168s	4.17E-05	4.17E-05
92Br	0.34 s	2.68E-02	2.68E-02
92Kr	1.84 s	1.66E+00	1.67E+00
92Rb	4.48 s	3.13E+00	4.82E+00
92Sr	2.71 h	1.08E+00	5.94E+00
92Y	3.54 h	7.15E-02	6.01E+00
93Br	0.176s	3.09E-03	3.09E-03
93Kr	1.29 s	4.86E-01	4.89E-01
93Rb	5.85 s	3.07E+00	3.55E+00
93Sr	7.4 m	2.57E+00	6.24E+00
93Y	10.2 h	1.09E-01	6.35E+00
93Zr	1.5e6y	1.37E-04	6.35E+00
93Nb-m	12 y	8.49E-10	6.03E+00
94Se		1.71E-08	1.71E-08
94Br	0.111s	1.66E-04	1.66E-04
94Kr	0.21 s	8.68E-02	8.70E-02
94Rb	2.73 s	1.57E+00	1.65E+00
94Sr	1.25 m	4.51E+00	6.06E+00
94Y	18.7 m	3.90E-01	6.45E+00
94Zr	stable	1.95E-02	6.47E+00
95Kr	0.78 s	7.19E-03	7.19E-03
95Rb	0.377s	7.64E-01	7.70E-01
95Sr	25.1s	4.54E+00	5.27E+00
95Y	10.3 m	1.11E+00	6.38E+00
95Zr	64.02d	1.27E-01	6.50E+00
95Nb-m	3.61 d	2.48E-05	6.51E-02
95Nb	34.97d	1.06E-04	6.50E+00
95Mo	stable	4.94E-10	6.50E+00

96Se		1.28E-11	1.28E-11
96Br	0.089s	1.91E-06	1.91E-06
96Kr	0.293s	3.78E-02	3.78E-02
96Rb	0.199s	1.68E-01	2.06E-01
96Sr	1.06 s	3.57E+00	3.76E+00
96Y -m	9.6 s	2.02E+00	2.02E+00
96Y	6.2 s	2.24E-01	6.00E+00
97Kr	0.1 s	2.97E-05	2.97E-05
97Rb	0.169s	3.79E-02	3.80E-02
97Sr	0.42 s	1.72E+00	1.75E+00
97Y	3.76 s	3.14E+00	4.89E+00
97Zr	16.8 h	1.09E+00	5.98E+00
97Nb-m	58.1 s	2.45E-03	5.63E+00
97Nb	1.23 h	1.08E-02	6.00E+00
98Kr	0.160s	1.63E-03	1.63E-03
98Rb	0.107s	2.36E-03	3.99E-03
98Sr	0.65 s	8.08E-01	8.12E-01
98Y -m	2.1 s	1.11E+00	1.11E+00
98Y	0.59 s	1.11E+00	1.92E+00
98Zr	30.7 s	2.57E+00	5.64E+00
98Nb-m	51 m	3.86E-02	3.86E-02
98Nb	2.9 s	1.16E-01	5.75E+00
99Sr	0.269s	1.33E-01	1.33E-01
99Y	1.47 s	1.95E+00	2.08E+00
99Zr	2.2 s	3.58E+00	5.63E+00
99Nb-m	2.6 m	4.07E-01	2.10E+00
99Nb	15.0 s	3.00E-02	3.97E+00
99Mo	2.748d	4.28E-02	6.11E+00
99Tc-m	6.01 h	2.89E-08	5.38E+00
99Tc	2.1e5y	1.23E-07	6.11E+00
100Kr		1.15E-06	1.15E-06
100Rb	0.053s	3.48E-02	3.48E-02
100Sr	0.201s	8.15E-03	4.29E-02

100Y	0.73 s	5.67E-01	6.10E-01
100Zr	7.1 s	4.98E+00	5.58E+00
100Nb-m	3.0 s	3.19E-01	3.11E+00
100Nb	1.5 s	3.19E-01	3.11E+00
100Mo	stable	7.30E-02	6.29E+00
100Tc	16 s	5.59E-06	5.59E-06
101Sr	0.115s	4.49E-03	4.49E-03
101Y	0.43 s	2.78E-01	2.83E-01
101Zr	2.1 s	2.79E+00	3.07E+00
101Nb	7.1 s	1.92E+00	4.99E+00
101Mo	14.6 m	1.86E-01	5.17E+00
101Tc	14.2 m	1.61E-04	5.17E+00
101Ru	stable	1.62E-08	5.17E+00
101Rh	3 y	3.26E-11	3.26E-11
102Sr	0.068s	1.73E-04	1.73E-04
102Y	0.36 s	2.68E-01	2.68E-01
102Zr	2.9 s	1.78E+00	2.05E+00
102Nb	1.3 s	1.58E+00	3.63E+00
102Mo	11.3 m	6.51E-01	4.28E+00
102Tc-m	4.4 m	9.55E-03	4.29E+00
102Tc	5.3 s	9.55E-03	2.24E-01
102Ru	stable	9.76E-07	4.30E+00
103Y	0.260s	2.58E-03	2.58E-03
103Zr	1.3 s	4.99E-01	5.01E-01
103Nb	1.5 s	1.41E+00	1.91E+00
103Mo	1.13 m	1.04E+00	2.95E+00
103Tc	54 s	8.22E-02	3.03E+00
103Ru	39.27d	2.36E-05	3.03E+00
103Rh-m	56.12m	4.27E-10	3.00E+00
104Sr	0.163s	1.31E-07	1.31E-07
104Y	0.128s	5.68E-04	5.68E-04
104Zr	1.2 s	8.28E-02	8.34E-02
104Nb	4.8 s	5.70E-01	6.55E-01
104Mo	60 s	1.13E+00	1.79E+00

104Tc	18.2 m	9.26E-02	1.88E+00
104Ru	stable	3.27E-04	1.88E+00
105Zr	0.493s	1.16E-01	1.16E-01
105Nb	3.0 s	1.39E-01	2.53E-01
105Mo	36 s	6.68E-01	9.16E-01
105Tc	7.6 m	4.85E-02	9.64E-01
105Ru	4.44 h	1.11E-07	9.64E-01
106Zr	0.907s	1.68E-06	1.68E-06
106Nb	1.0 s	1.57E-02	1.57E-02
106Mo	8.4 s	3.59E-01	3.75E-01
106Tc	36 s	2.68E-02	4.02E-01
106Ru	1.020y	9.07E-07	4.02E-01
107Nb	0.766s	2.31E-03	2.31E-03
107Mo	3.5 s	1.21E-01	1.24E-01
107Tc	21.2 s	2.24E-02	1.46E-01
107Ru	3.8 m	4.94E-06	1.46E-01
108Zr	0.378s	3.10E-10	3.10E-10
108Nb	0.242s	9.00E-05	9.00E-05
108Mo	1.5 s	3.02E-02	3.03E-02
108Tc	5.1 s	2.38E-02	5.41E-02
108Ru	4.5 m	1.67E-05	5.41E-02
109Nb	0.315s	4.84E-04	4.84E-04
109Mo	1.41 s	1.55E-02	1.60E-02
109Tc	1.4 s	1.34E-02	2.94E-02
109Ru	34.5 s	1.71E-03	3.12E-02
109Rh-m	50 s	2.06E-06	1.56E-02
109Rh	1.34 m	2.06E-06	3.12E-02
109Pd-m	4.69 m	5.46E-10	5.46E-10
109Pd	13.5 h	2.94E-10	3.12E-02
110Zr		9.29E-09	9.29E-09
110Nb	0.130s	1.53E-05	1.53E-05
110Mo	2.77 s	3.89E-03	3.90E-03

110Tc	0.83 s	1.16E-02	1.55E-02
110Ru	15 s	9.89E-03	2.53E-02
110Rh-m	29 s	5.65E-05	5.65E-05
110Rh	3.1 s	5.65E-05	2.54E-02
110Pd	stable	2.15E-07	2.54E-02
110Ag-m	252 d	2.28E-12	2.28E-12
111Mo	0.466s	2.28E-04	2.28E-04
111Tc	1.98 s	4.49E-03	4.72E-03
111Ru	1.5 s	1.18E-02	1.65E-02
111Rh	11 s	8.80E-04	1.74E-02
111Pd-m	5.5 h	4.72E-06	7.97E-05
111Pd	23.4 m	2.54E-06	1.74E-02
111Ag-m	1.08 m	8.28E-10	1.73E-02
111Ag	7.47 d	1.24E-10	1.74E-02
112Mo	0.975s	9.65E-06	9.65E-06
112Tc	0.431s	6.86E-04	6.95E-04
112Ru	4.5 s	9.92E-03	1.06E-02
112Rh	4 s	2.30E-03	1.29E-02
112Pd	20.04h	1.28E-04	1.30E-02
112Ag	3.13 h	8.29E-07	1.30E-02
112Cd	stable	1.06E-09	1.30E-02
113Tc	0.652s	1.40E-04	1.40E-04
113Ru	2.7 s	6.05E-03	6.19E-03
113Rh	0.9 s	6.84E-03	1.30E-02
113Pd	1.64 m	1.16E-03	1.42E-02
113Ag-m	1.14 m	3.62E-06	1.42E-03
113Ag	5.3 h	5.42E-07	1.28E-02
113Cd-m	14.6 y	8.68E-10	1.66E-04
113Cd	9.e15y	2.59E-10	1.40E-02
114Mo	0.377s	4.40E-09	4.40E-09
114Tc	0.202s	7.01E-06	7.01E-06
114Ru	8.14 s	1.73E-03	1.73E-03
114Rh	1.8 s	5.03E-03	6.76E-03
114Pd	2.48 m	4.16E-03	1.09E-02

114Ag	4.6 s	9.17E-04	1.18E-02
114Cd	stable	7.65E-08	1.18E-02
115Ru	0.878s	2.57E-04	2.57E-04
115Rh	0.99 s	3.63E-03	3.89E-03
115Pd	47 s	7.13E-03	1.10E-02
115Ag-m	18.7 s	1.37E-03	4.34E-03
115Ag	20 m	1.93E-04	8.23E-03
115Cd-m	44.6 d	5.53E-06	1.00E-03
115Cd	2.228d	9.00E-07	1.16E-02
115In-m	4.486h	3.82E-11	1.16E-02
115In	5.e14y	1.63E-10	1.22E-02
116Tc	0.115s	6.31E-09	6.31E-09
116Ru	1.70 s	2.46E-05	2.46E-05
116Rh	0.7 s	8.69E-04	8.93E-04
116Pd	12.7 s	6.82E-03	7.71E-03
116Ag-m	10.5 s	7.65E-04	4.62E-03
116Ag	2.68 m	4.74E-03	8.60E-03
116Cd	stable	3.00E-05	1.32E-02
116In-m	54.2 m	3.85E-09	3.85E-09
117Ru	0.343s	2.52E-06	2.52E-06
117Rh	1.22 s	4.65E-04	4.67E-04
117Pd	5 s	8.77E-03	9.24E-03
117Ag-m	5.3 s	1.52E-03	6.14E-03
117Ag	1.22 m	1.52E-03	6.14E-03
117Cd-m	3.4 h	3.73E-04	3.44E-03
117Cd	2.49 h	1.12E-04	9.32E-03
117In-m	1.94 h	8.59E-08	8.61E-03
117In	44 m	3.66E-07	8.20E-03
118Ru	0.662s	6.92E-08	6.92E-08
118Rh	0.316s	3.63E-05	3.64E-05
118Pd	2.4 s	3.18E-03	3.22E-03
118Ag-m	2.4 s	2.99E-03	4.60E-03
118Ag	4.0 s	3.42E-03	7.14E-03
118Cd	50.3 m	1.72E-03	1.13E-02

118In-m	4.4 m	1.69E-06	1.69E-06
118In	5.0 s	5.06E-06	1.13E-02
118Sn	stable	4.10E-09	1.13E-02
119Ru	0.195s	6.55E-10	6.55E-10
119Rh	0.465s	1.86E-06	1.86E-06
119Pd	1.76 s	4.35E-04	4.37E-04
119Ag	2.1s	7.25E-03	7.69E-03
119Cd-m	2.20 m	2.25E-03	6.09E-03
119Cd	2.69 m	2.45E-03	6.29E-03
119In-m	17.9 m	1.59E-05	6.31E-03
119In	2.3 m	4.72E-04	6.88E-03
119Sn-m	293 d	1.14E-07	3.44E-04
120Ru	0.350s	3.03E-10	3.03E-10
120Rh	0.172s	2.39E-06	2.39E-06
120Pd	3.91 s	2.71E-03	2.71E-03
120Ag	1.23 s	8.75E-04	3.59E-03
120Cd	50.8 s	8.39E-03	1.20E-02
120In-m	46 s	3.15E-04	6.30E-03
120In	3.1 s	3.15E-04	6.30E-03
120Sn	stable	3.00E-06	1.26E-02
120Sb-m	5.76 d	1.30E-10	1.30E-10
121Rh	0.250s	1.44E-08	1.44E-08
121Pd	0.644s	4.73E-05	4.73E-05
121Ag	0.78 s	2.58E-03	2.62E-03
121Cd	13.5 s	7.24E-03	9.86E-03
121In-m	3.8 m	3.24E-04	2.10E-03
121In	23 s	2.47E-03	1.06E-02
121Sn-m	55 y	2.79E-05	2.79E-05
121Sn	1.128d	3.58E-04	1.30E-02
122Rh	0.107s	2.85E-10	2.85E-10
122Pd	1.41 s	4.77E-06	4.77E-06
122Ag	0.56 s	6.68E-04	6.73E-04
122Cd	5.3 s	1.19E-02	1.26E-02
122In-m	10 s	1.26E-03	1.26E-03

122In	1.5 s	1.26E-03	1.39E-02
122Sn	stable	3.65E-04	1.55E-02
123Rh	0.134s	8.52E-12	8.52E-12
123Pd	0.300s	3.99E-07	3.99E-07
123Ag	0.31 s	2.75E-04	2.76E-04
123Cd	2.09 s	1.01E-02	1.04E-02
123In-m	47 s	2.51E-04	2.64E-03
123In	6.0 s	3.91E-03	1.19E-02
123Sn-m	40.1 m	3.10E-04	1.48E-02
123Sn	129.2d	8.04E-04	8.04E-04
123Sb	stable	5.17E-06	1.57E-02
124Rh		1.04E-12	1.04E-12
124Pd	0.514s	2.73E-07	2.73E-07
124Ag	0.22 s	5.52E-04	5.52E-04
124Cd	1.24 s	1.21E-02	1.27E-02
124In	3.18 s	3.39E-03	1.61E-02
124Sn	stable	1.07E-02	2.68E-02
124Sb-m	20.2 m	2.42E-06	2.42E-06
124Sb	60.20d	7.61E-06	1.00E-05
125Ag	0.334s	1.66E-09	1.66E-09
125Cd	0.68 s	5.55E-03	5.55E-03
125In-m	12.2 s	4.72E-03	6.39E-03
125In	2.36 s	4.72E-03	8.61E-03
125Sn-m	9.5 m	1.05E-02	1.80E-02
125Sn	9.63 d	8.54E-03	1.60E-02
125Sb	2.758y	2.74E-05	3.40E-02
125Te-m	58 d	2.30E-11	7.65E-03
126Ag	0.140s	4.75E-10	4.75E-10
126Cd	0.52 s	8.08E-03	8.08E-03
126In	1.63 s	3.30E-03	1.14E-02
126Sn	1.e5y	4.45E-02	5.61E-02
126Sb-m	19.0 m	1.72E-03	5.79E-02
126Sb	12.4 d	6.51E-04	8.75E-03
126Te	stable	8.25E-10	5.85E-02

127Ag	0.175s	1.58E-10	1.58E-10
127Cd	0.4 s	8.16E-03	8.16E-03
127In-m	3.73 s	6.25E-03	1.03E-02
127In	1.14 s	4.12E-02	4.52E-02
127Sn-m	4.15 m	7.92E-03	3.04E-02
127Sn	2.12 h	8.67E-02	1.19E-01
127Sb	3.84 d	7.09E-03	1.57E-01
127Te-m	109 d	2.43E-08	2.51E-02
127Te	9.4 h	9.92E-09	1.56E-01
128Pd		1.34E-12	1.34E-12
128Ag	0.094s	1.12E-11	1.25E-11
128Cd	0.28 s	3.55E-03	3.55E-03
128In	0.80 s	2.63E-02	2.98E-02
128Sn	59.1 m	3.01E-01	3.32E-01
128Sb-m	10.1 m	6.37E-03	3.37E-01
128Sb	9.1 h	1.07E-02	1.13E-02
128Te	stable	1.72E-04	3.49E-01
129Cd	0.27 s	7.24E-07	7.24E-07
129In-m	1.23 s	2.53E-02	2.53E-02
129In	0.63s	2.75E-02	2.75E-02
129Sn-m	6.9 m	1.96E-01	1.97E-01
129Sn	2.4 m	2.30E-01	2.82E-01
129Sb	4.40 h	6.41E-02	5.43E-01
129Te-m	33.6 d	1.40E-05	9.02E-02
129Te	1.16 h	5.73E-06	5.11E-01
130Pd		6.79E-11	6.79E-11
130Ag		6.66E-06	6.66E-06
130Cd	0.20 s	8.78E-02	8.78E-02
130In	0.29 s	9.42E-03	9.72E-02
130Sn	3.7 m	1.08E+00	1.18E+00
130Sb-m	6.5 m	3.57E-01	1.42E+00
130Sb	38.4 m	2.15E-01	3.33E-01
130Te	stable	5.79E-02	1.81E+00

131Cd	0.106s	1.38E-02	1.38E-02
131In	0.28 s	1.11E-02	2.49E-02
131Sn	39 s	8.81E-01	9.06E-01
131Sb	23.0 m	1.65E+00	2.56E+00
131Te-m	1.35 d	2.33E-01	4.12E-01
131Te	25.0 m	9.70E-02	2.55E+00
131I	8.040d	3.92E-03	2.89E+00
131Xe-m	11.9 d	3.48E-07	4.05E-02
132In	0.20 s	6.23E-03	6.23E-03
132Sn	40 s	5.92E-01	5.98E-01
132Sb-m	2.8 m	8.63E-01	1.16E+00
132Sb	4.2 m	1.30E+00	1.60E+00
132Te	3.26 d	1.53E+00	4.30E+00
132I	2.28 h	1.83E-02	4.31E+00
132Xe	stable	4.22E-05	4.31E+00
132Cs	6.475d	7.38E-08	7.38E-08
133In	0.18 s	1.71E-04	1.71E-04
133Sn	1.44 s	1.38E-01	1.38E-01
133Sb	2.5 m	2.26E+00	2.40E+00
133Te-m	55.4 m	2.99E+00	3.99E+00
133Te	12.4 m	1.15E+00	3.06E+00
133I	20.8 h	1.65E-01	6.70E+00
133Xe-m	2.19 d	1.89E-03	1.89E-01
133Xe	5.243d	6.66E-04	6.70E+00
134Cd		9.33E-11	9.33E-11
134In	0.081s	3.47E-06	3.47E-06
134Sn	1.04 s	1.77E-02	1.77E-02
134Sb	0.8 s	7.17E-01	7.31E-01
134Te	42 m	6.22E+00	6.97E+00
134I -m	3.7 m	3.64E-01	3.64E-01
134I	52.6 m	5.00E-01	7.83E+00
134Xe-m	0.29 s	2.46E-02	3.19E-02
135Sn	0.418s	6.27E-04	6.27E-04
135Sb	1.71 s	1.45E-01	1.46E-01

135Te	19.0 s	3.22E+00	3.34E+00
135I	6.57 h	2.93E+00	6.28E+00
135Xe-m	15.3 m	1.78E-01	1.10E+00
135Xe	9.10 h	7.85E-02	6.54E+00
135Cs	2.3e6y	4.91E-04	6.54E+00
136In		1.68E-10	1.68E-10
136Sn	0.717s	1.57E-05	1.57E-05
136Sb	0.82 s	1.15E-02	1.15E-02
136Te	17.5 s	1.32E+00	1.34E+00
136I -m	47 s	1.25E+00	1.26E+00
136I	1.39 m	1.32E+00	2.64E+00
137Sn		1.86E-05	1.86E-05
137Sb	0.478s	7.43E-02	7.44E-02
137Te	2.5 s	3.92E-01	4.53E-01
137I	24.5 s	2.62E+00	3.07E+00
137Xe	3.82 m	3.19E+00	6.13E+00
137Cs	30.17y	6.00E-02	6.19E+00
137Ba-m	2.552m	1.33E-04	5.85E+00
138Sn		3.29E-09	3.29E-09
138Sb	0.173s	3.92E-05	3.92E-05
138Te	1.4 s	6.62E-02	6.62E-02
138I	6.5 s	1.42E+00	1.49E+00
138Xe	14.1 m	4.81E+00	6.30E+00
138Cs-m	2.9 m	2.23E-01	2.23E-01
138Cs	32.2 m	2.43E-01	6.71E+00
139Sb	0.218s	1.40E-06	1.40E-06
139Te	0.580s	6.66E-03	6.67E-03
139I	2.30 s	7.71E-01	7.78E-01
139Xe	39.7 s	4.32E+00	5.04E+00
139Cs	9.3 m	1.31E+00	6.35E+00
139Ba	1.396h	6.88E-02	6.41E+00
139La	stable	2.27E-05	6.41E+00
139Ce-m	56 s	7.03E-10	7.03E-10

140Te	0.894s	1.69E-02	1.69E-02
140I	0.86 s	1.37E-01	1.54E-01
140Xe	13.6 s	3.51E+00	3.65E+00
140Cs	1.06 m	2.07E+00	5.72E+00
140Ba	12.75d	4.88E-01	6.21E+00
140La	1.678d	5.22E-03	6.22E+00
141I	0.45s	4.07E-02	4.07E-02
141Xe	1.72 s	1.22E+00	1.25E+00
141Cs	24.9 s	2.92E+00	4.17E+00
141Ba	18.3 m	1.66E+00	5.83E+00
141La	3.90 h	1.85E-02	5.85E+00
141Ce	32.50d	4.99E-06	5.85E+00
142Te	0.590s	2.07E-06	2.07E-06
142I	0.2 s	5.86E-03	5.86E-03
142Xe	1.22 s	4.34E-01	4.39E-01
142Cs	1.8 s	2.28E+00	2.72E+00
142Ba	10.7 m	3.01E+00	5.75E+00
142La	1.54 h	9.65E-02	5.85E+00
142Ce	5.e16y	1.76E-04	5.85E+00
143Xe	0.30 s	5.30E-02	5.30E-02
143Cs	1.78 s	1.40E+00	1.45E+00
143Ba	14.3 s	4.10E+00	5.55E+00
143La	14.1 m	3.80E-01	5.92E+00
143Ce	1.38 d	3.13E-02	5.96E+00
143Pr	13.57d	4.50E-07	5.96E+00
143Nd	stable	4.80E-12	5.96E+00
144Xe	1.2 s	6.05E-03	6.05E-03
144Cs	1.01 s	4.18E-01	4.23E-01
144Ba	11.4 s	3.98E+00	4.40E+00
144La	40.7 s	1.07E+00	5.47E+00
144Ce	284.6d	3.45E-02	5.50E+00
144Pr-m	7.2 m	1.28E-05	2.75E-02
144Pr	17.28m	1.43E-06	5.50E+00
144Nd	15.32l	9.57E-09	5.50E+00

145Xe	0.9 s	7.16E-05	7.16E-05
145Cs	0.59 s	7.56E-02	7.57E-02
145Ba	4.0 s	1.87E+00	1.93E+00
145La	24 s	1.92E+00	3.85E+00
145Ce	3.00 m	8.54E-02	3.93E+00
145Pr	5.98 h	3.33E-04	3.93E+00
145Nd	stable	5.55E-08	3.93E+00
146Xe	0.563s	1.06E-05	1.06E-05
146Cs	0.322s	7.64E-03	7.65E-03
146Ba	2.20 s	9.14E-01	9.21E-01
146La	6.3 s	1.49E+00	2.41E+00
146Ce	13.5 m	5.83E-01	2.99E+00
146Pr	24.2 m	3.62E-03	3.00E+00
146Nd	stable	3.19E-06	3.00E+00
146Pm	5.53 y	4.50E-10	4.50E-10
147Ba	0.892s	2.46E-01	2.46E-01
147La	4.02 s	6.43E-01	8.89E-01
147Ce	56 s	9.98E-01	1.89E+00
147Pr	13.4 m	3.60E-01	2.25E+00
147Nd	10.98d	6.72E-05	2.25E+00
147Pm	2.623y	2.49E-09	2.25E+00
148Xe		1.10E-09	1.10E-09
148Cs	0.15 s	1.31E-05	1.31E-05
148Ba	0.64 s	2.22E-02	2.22E-02
148La	1.1 s	3.36E-01	3.59E-01
148Ce	56 s	1.24E+00	1.59E+00
148Pr	2.27 m	7.77E-02	1.67E+00
148Nd	stable	9.93E-04	1.67E+00
149Ba	0.36 s	1.03E-03	1.03E-03
149La	1.10 s	7.99E-02	8.09E-02
149Ce	5.2 s	6.98E-01	7.78E-01
149Pr	2.3 m	2.97E-01	1.07E+00
149Nd	1.72 h	6.81E-03	1.08E+00

149Pm	2.212d	3.87E-06	1.08E+00
149Sm	1.e16y	1.71E-10	1.08E+00
150Cs	0.124s	1.99E-09	1.99E-09
150Ba	0.962s	5.02E-05	5.02E-05
150La	0.608s	1.04E-02	1.05E-02
150Ce	4.4 s	3.92E-01	4.02E-01
150Pr	6.2 s	2.18E-01	6.21E-01
150Nd	stable	3.27E-02	6.53E-01
150Pm	2.68 h	3.00E-05	3.00E-05
150Sm	stable	1.22E-08	3.00E-05
151La	0.719s	1.03E-03	1.03E-03
151Ce	1.0 s	9.90E-02	1.00E-01
151Pr	22.4 s	2.39E-01	3.39E-01
151Nd	12.4 m	7.95E-02	4.18E-01
151Pm	1.183d	6.42E-04	4.19E-01
151Sm	90 y	4.75E-07	4.19E-01
151Eu	stable	2.49E-10	4.19E-01
152Ba	0.420s	1.49E-08	1.49E-08
152La	0.285s	4.53E-05	4.53E-05
152Ce	3.1 s	2.05E-02	2.06E-02
152Pr	3.2 s	1.03E-01	1.23E-01
152Nd	11.4 m	1.41E-01	2.64E-01
152Pm-m	7.5 m	1.39E-03	1.39E-03
152Pm	4.1 m	1.39E-03	2.66E-01
152Sm	stable	9.65E-06	2.67E-01
152Eu-m	9.3 h	1.36E-10	1.36E-10
153La	0.326s	1.42E-06	1.42E-06
153Ce	1.47 s	1.70E-03	1.71E-03
153Pr	4.3 s	3.67E-02	3.85E-02
153Nd	28.9 s	1.11E-01	1.49E-01
153Pm	5.4 m	8.80E-03	1.58E-01
153Sm	1.929d	8.01E-05	1.58E-01
153Eu	stable	2.33E-07	1.58E-01

154La	0.149s	1.46E-08	1.46E-08
154Ce	2.02 s	9.12E-05	9.12E-05
154Pr	2.3 s	5.02E-03	5.11E-03
154Nd	25.9 s	5.80E-02	6.31E-02
154Pm-m	2.7 m	5.41E-03	5.41E-03
154Pm	1.7 m	5.41E-03	6.86E-02
154Sm	stable	4.73E-04	7.44E-02
154Eu	8.8 y	1.94E-07	1.94E-07
155Ce	0.528s	2.55E-06	2.55E-06
155Pr	1.12 s	6.73E-04	6.76E-04
155Nd	8.9 s	1.75E-02	1.82E-02
155Pm	48 s	1.26E-02	3.08E-02
155Sm	22.2 m	1.31E-03	3.21E-02
155Eu	4.71 y	2.63E-06	3.21E-02
155Gd	stable	4.08E-10	3.21E-02
156Ce	0.596s	5.73E-08	5.73E-08
156Pr	0.379s	4.07E-05	4.07E-05
156Nd	5.5 s	4.70E-03	4.74E-03
156Pm	26.7 s	7.06E-03	1.18E-02
156Sm	9.4 h	3.03E-03	1.48E-02
156Eu	15.2 d	1.62E-05	1.49E-02
156Gd	stable	1.43E-08	1.49E-02
157Ce	0.214s	4.59E-10	4.59E-10
157Pr	0.380s	1.65E-06	1.65E-06
157Nd	2.48 s	4.85E-04	4.86E-04
157Pm	10.9 s	2.93E-03	3.42E-03
157Sm	8.0 m	2.67E-03	6.09E-03
157Eu	15.13h	6.35E-05	6.15E-03
157Gd	stable	1.48E-07	6.15E-03
157Tb	160 y	4.93E-12	4.93E-12
158Ce		3.87E-12	3.87E-12
158Pr	0.169s	3.75E-08	3.75E-08
158Nd	2.69 s	5.19E-05	5.19E-05
158Pm	4.8 s	7.06E-04	7.58E-04

158Sm	5.5 m	2.40E-03	3.16E-03
158Eu	45.9 m	1.28E-04	3.29E-03
158Gd	stable	1.48E-06	3.29E-03
158Tb-m	10.9 s	1.33E-11	1.33E-11
158Tb	150 y	1.20E-10	1.33E-10
159Pr	0.181s	4.88E-10	4.88E-10
159Nd	0.642s	1.77E-06	1.77E-06
159Pm	3.0 s	1.06E-04	1.08E-04
159Sm	11.3 s	7.42E-04	8.50E-04
159Eu	18.1 m	1.56E-04	1.00E-03
159Gd	18.6 h	3.71E-06	1.01E-03
159Tb	stable	1.70E-09	1.01E-03
160Pr		2.82E-12	2.82E-12
160Nd	0.789s	5.04E-08	5.05E-08
160Pm	0.729s	7.55E-06	7.60E-06
160Sm	9.6 s	2.11E-04	2.19E-04
160Eu	38 s	9.03E-05	3.09E-04
160Gd	stable	1.01E-05	3.19E-04
160Tb	72.3 d	2.84E-08	2.84E-08
160Dy	stable	1.93E-12	2.84E-08
161Nd	0.311s	6.16E-10	6.16E-10
161Pm	0.790s	4.40E-07	4.41E-07
161Sm	4.78 s	2.83E-05	2.88E-05
161Eu	27 s	4.54E-05	7.41E-05
161Gd	3.66 m	1.11E-05	8.52E-05
161Tb	6.91 d	5.96E-08	8.53E-05
161Dy	stable	2.51E-11	8.53E-05
162Nd		3.48E-12	3.48E-12
162Pm	0.324s	6.80E-09	6.80E-09
162Sm	5.26 s	2.03E-06	2.03E-06
162Eu	11 s	6.99E-06	9.02E-06
162Gd	8.4 m	6.79E-06	1.58E-05
162Tb-m	2.23 h	4.52E-08	3.61E-07
162Tb	7.6 m	4.52E-08	1.55E-05

162Dy	stable	2.03E-10	1.59E-05
163Pm		1.82E-10	1.82E-10
163Sm	1.27 s	1.37E-07	1.38E-07
163Eu	7.60 s	1.94E-06	2.08E-06
163Gd	1.13 m	3.81E-06	5.89E-06
163Tb	19.5 m	2.14E-07	6.11E-06
163Dy	stable	1.24E-09	6.11E-06
164Pm		1.66E-12	1.66E-12
164Sm	1.39 s	6.04E-09	6.04E-09
164Eu	1.58 s	2.01E-07	2.07E-07
164Gd	45 s	1.49E-06	1.70E-06
164Tb	3.0 m	1.80E-07	1.88E-06
164Dy	stable	4.78E-09	1.88E-06
165Sm	0.454s	2.55E-10	2.55E-10
165Eu	1.35 s	3.87E-08	3.90E-08
165Gd	0.705m	6.14E-07	6.53E-07
165Tb	2.1 m	2.81E-07	9.34E-07
165Dy-m	1.26 m	2.29E-09	4.69E-07
165Dy	2.33 h	1.53E-08	9.40E-07
165Ho	stable	2.05E-11	9.52E-07
166Sm		6.43E-12	6.43E-12
166Eu		2.50E-09	2.51E-09
166Gd		1.66E-07	1.69E-07
166Tb		1.54E-07	3.23E-07
166Dy	3.400d	3.98E-08	3.63E-07
166Ho-m	1.2e3y	9.41E-11	9.41E-11
166Ho	1.117d	4.03E-11	3.63E-07
167Eu		2.24E-10	2.24E-10
167Gd		3.68E-08	3.70E-08
167Tb		1.34E-07	1.71E-07
167Dy	6.2 m	7.51E-08	2.46E-07
167Ho	3.1 h	1.03E-09	2.47E-07
167Er	stable	1.10E-12	2.47E-07

168Eu		2.85E-12	2.85E-12
168Gd		2.18E-09	2.18E-09
168Tb		1.73E-08	1.95E-08
168Dy	8.5 m	3.64E-08	5.59E-08
168Ho	3.0 m	1.16E-09	5.71E-08
168Er	stable	6.79E-12	5.71E-08
169Gd		1.19E-10	1.19E-10
169Tb		4.07E-09	4.19E-09
169Dy		1.74E-08	2.16E-08
169Ho	4.7 m	2.23E-09	2.38E-08
169Er	9.40 d	3.27E-11	2.38E-08
170Gd		2.68E-12	2.68E-12
170Tb		2.24E-10	2.26E-10
170Dy		3.73E-09	3.95E-09
170Ho-m	43 s	4.93E-10	4.93E-10
170Ho	2.8 m	4.93E-10	4.45E-09
170Er	stable	6.42E-11	5.01E-09
171Tb		2.92E-11	2.92E-11
171Dy		1.09E-09	1.12E-09
171Ho		1.07E-09	2.19E-09
171Er	7.52 h	1.58E-10	2.35E-09
172Tb		1.05E-12	1.05E-12
172Dy		1.77E-10	1.78E-10
172Ho		3.69E-10	5.47E-10
172Er	2.05 d	2.20E-10	7.68E-10
172Tm	2.65 d	1.68E-12	7.69E-10

Chapter 6

Appendix B: Geant4 decay process

5.2.3. Particle Decay Process

This section briefly introduces decay processes installed in Geant4. For details of the implementation of particle decays, please refer to the Physics Reference Manual. 5.2.3.1. Particle Decay Class

Geant4 provides a G4Decay class for both ''at rest'' and ''in flight'' particle decays. G4Decay can be applied to all particles except:

massless particles, i.e.,
    G4ParticleDefinition::thePDGMass <= 0
particles with ''negative'' life time, i.e.,
    G4ParticleDefinition::thePDGLifeTime < 0
shortlived particles, i.e.,
    G4ParticleDefinition::fShortLivedFlag = True

Decay for some particles may be switched on or off by using G4ParticleDefinition::SetPDGStable() as well as ActivateProcess() and InActivateProcess() methods of G4ProcessManager.

G4Decay proposes the step length (or step time for AtRest) according to the lifetime of the particle unless PreAssignedDecayProperTime is defined in G4DynamicParticle.

The G4Decay class itself does not define decay modes of the particle. Geant4 provides two ways of doing this:

*

using G4DecayChannel in G4DecayTable, and

*

using thePreAssignedDecayProducts of G4DynamicParticle

The G4Decay class calculates the PhysicalInteractionLength and boosts decay products created by G4VDecayChannel or event generators. See below for information on the determination of the decay modes.

An object of G4Decay can be shared by particles. Registration of the decay process to particles in the ConstructPhysics method of PhysicsList (see Section2.5.3) is shown in Example5.2.

Example5.2. Registration of the decay process to particles in the ConstructPhysics method of PhysicsList.

```
#include "G4Decay.hh"
void ExN02PhysicsList::ConstructGeneral()
{
  // Add Decay Process
  G4Decay* theDecayProcess = new G4Decay();
  theParticleIterator->reset();
  while( (*theParticleIterator)() ){
    G4ParticleDefinition* particle = theParticleIterator->value();
    G4ProcessManager* pmanager = particle->GetProcessManager();
    if (theDecayProcess->IsApplicable(*particle)) {
```

```
      pmanager ->AddProcess(theDecayProcess);
      // set ordering for PostStepDoIt and AtRestDoIt
      pmanager ->SetProcessOrdering(theDecayProcess, idxPostStep);
      pmanager ->SetProcessOrdering(theDecayProcess, idxAtRest);
    }
  }
}
```

5.2.3.2. Decay Table

Each particle has its G4DecayTable, which stores information on the decay modes of the particle. Each decay mode, with its branching ratio, corresponds to an object of various ''decay channel'' classes derived from G4VDecayChannel. Default decay modes are created in the constructors of particle classes. For example, the decay table of the neutral pion has G4PhaseSpaceDecayChannel and G4DalitzDecayChannel as follows:

```
// create a decay channel
G4VDecayChannel* mode;
// pi0 -> gamma + gamma
mode = new G4PhaseSpaceDecayChannel("pi0",0.988,2,"gamma","gamma");
table->Insert(mode);
// pi0 -> gamma + e+ + e-
mode = new G4DalitzDecayChannel("pi0",0.012,"e-","e+");
table->Insert(mode);
```

Decay modes and branching ratios defined in Geant4 are listed in Section5.3.2.

Branching ratios and life time can be set in tracking time.

```
// set lifetime
G4Neutron::Neutron()->SetPDGLifeTime(885.7*second);
// allow neutron decay
G4Neutron::Neutron()->SetPDGStable(false);
```

Branching ratios and life time can be modified by using user commands, also.

Example: Set 100% br for dalitz decay of pi0

```
Idle> /particle/select pi0
Idle> /particle/property/decay/select 0
Idle> /particle/property/decay/br 0
Idle> /particle/property/decay/select 1
Idle> /particle/property/decay/br 1
Idle> /particle/property/decay/dump
      G4DecayTable:  pi0
         0:  BR:  0  [Phase Space]    :   gamma gamma
         1:  BR:  1  [Dalitz Decay]   :   gamma e- e+
```