Comparison of IAC and HRRL n's count rate using the Monte-Carlo package GEANT4

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Abstract

The study of photofission reaction $\gamma(\mathrm{U,f})$ using the polarized Bremsstrahlung photons is under the investigation at Idaho State University now. The 44 MeV IAC LINAC and 16 MeV HRRL were used at different time. The experimental data shows the huge difference in neutron's count rates production [1]. The geant4 calculation was performed to understand the results.

1 The Experiment

The photofission experiment using the High Repetition Rate Linac (HRRL) was initially performed at ISU in October 2008. The electron beam energy was 14 MeV and the repetition rate was between 900-1000 Hz [1]. Polarized bremsstrahlung photons were produced using 1 mil Ti radiator and were collimated at the critical angle 2.09^{o} using off-axis collimator with respect to incident electron beam line. The DU plate was used as target and three plastic scintillator detectors were placed at 90^{o} to collect neutrons.

Later, to increase the polarization of the bremsstrahlung photons, the 44 MeV LINAC machine was used at the IAC in September 2011. The electron beam energy was 25 MeV and the repetition rate was 180 Hz [1]. 1 mil Al radiator was used to produce the polarized bremsstrahlung photons and the critical angle was 1.17^{o}. A DU cylinder target was used instead of a DU plate and neutrons were collected using an array of plastic scintillators located at 90^{o} with respect to the beam line.

The general experimental setup is shown in Figure 1. The conditions of two experiments and n's count rate measurements are summarized in Table 1. As can be seen the HRRL experiment was better in neutron rate production and the ratio with the IAC experiment is as follow:

$$\left(\frac{\mathrm{R}^{\mathrm{HRRL}}}{\mathrm{R}^{\mathrm{IAC}}}\right)_{\mathrm{n}} = \frac{46\ \mathrm{n/s}}{0.113\ \mathrm{n/s}} = 407.08 \tag{1}$$

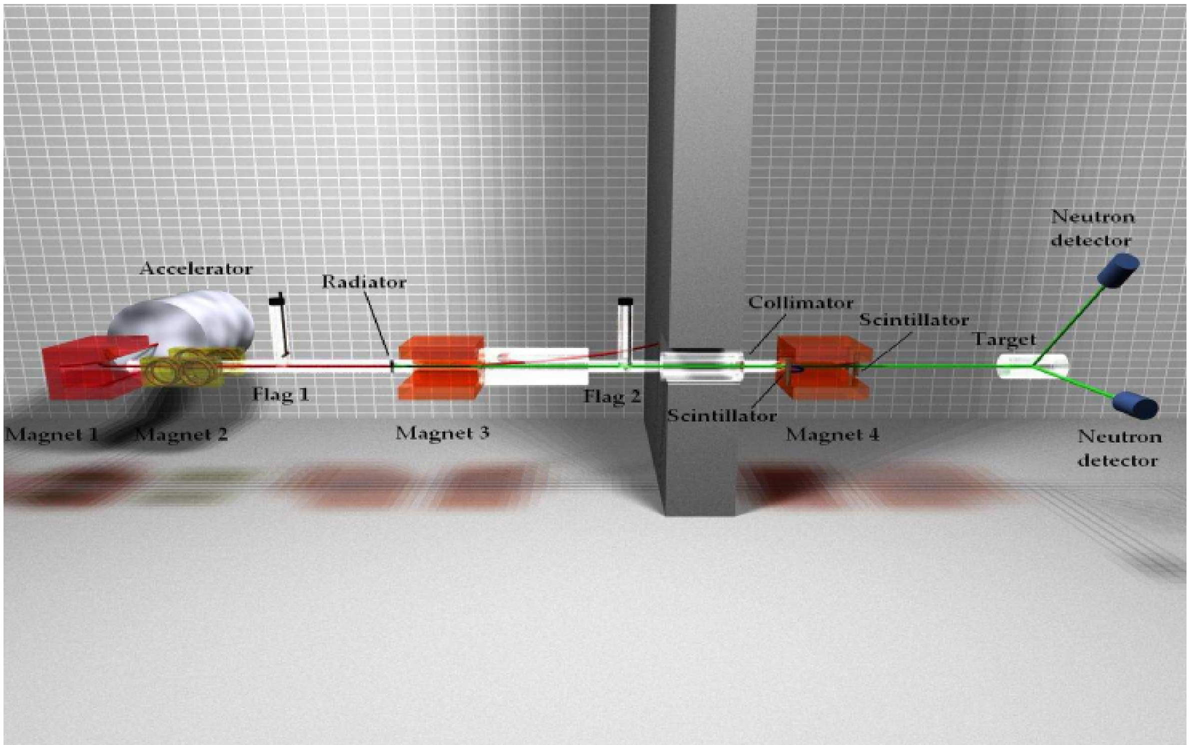

Figure 1: The general experimental setup.

	HRRL	IAC
Electron energy	14 MeV	25 MeV
Radiator	1 mil Ti	1 mil Al
Repetition Rate	900-1000 Hz	180 Hz
Current	~ 100 mA (??)	~ 120 mA
Pulse width	~ 25 ns	~ 2 ns
Target	DU plate	DU cylinder
Collimation angle (m/E)	2.09^{o}	1.17^{o}
Target to detector distance	88 inch	129.5 cm
Neutron's statistics	155,000	119
Neutron's production rate	46 n/s, 51 n/s	0.113 n/s

Table 1: Summary of experimental conditions

2 GEANT4 Simulation

The general setup used in geant4 simulations are shown in Figure 2 and the geometry is summarized in Table 2. The material of the upstream/downstream collimator, vacuum pipe and box pipe was Fe. The material of concrete wall was `G4_CONCRETE` from geant4 material database. The surrounding matter was Air consisting from 70% of N and 30% of O. Inside the vacuum pipe and vacuum box was vacuum.

Two separate simulations for HRRL and IAC setup were performed. The total number of 100M events was simulated for each run. Bremsstrahlung photons were generated using the 14 MeV(25 MeV) electron beam impinged on 1 mil of Ti(Al) radiator for HRRL(IAC)

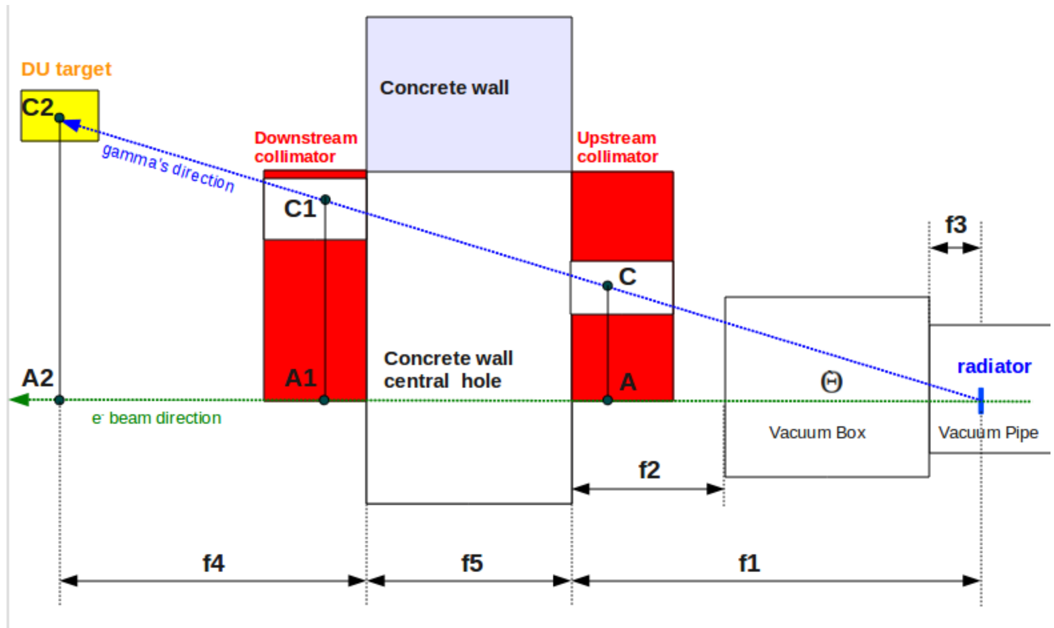

Figure 2: The experimental setup used in geant4 simulation.

	HRRL	IAC
Electron beam energy	14 MeV	25 MeV
Θ_{critical}	2.09^o	1.17^o
f1	182.9 cm	280.6
f2	55 cm	55 cm
f3	17.25 cm	17.25 cm
f4	116.8 cm	238.6 cm
f5	121.9 cm	183 cm
AC	6.46 cm	5.61 cm
A1C1	11.35 cm	9.60 cm
A2C2	15.39 cm	14.35 cm
Upstream collimator hole diameter	1 cm	(1/4) inch
Downstream collimator hole diameter	2 cm	(1/2) inch
DU target	3.5x3.5 inch plate	2 cm ⊘

Table 2: Summary of geometry used in geant4 simulation

runs correspondingly. Magnetic field of 0.1 Tesla was created inside the Vacuum Box in Y directions to bent the electrons horizontally as can been seen in Table 3(left up).

Initially all materials as described above were used in simulation. But doing some initial pre-runs it was found that only photons produced inside the radiator and collimated by downstream/upstream collimator were coming into detector. Table 3(right up) shows how the precise collimation was done and Table 3(left down) shows how all secondary particles are stopped inside the concrete wall. Table 3(right down) shows the rear event when the

Bremsstrahlung photon are going through the collimator system into the detector location.

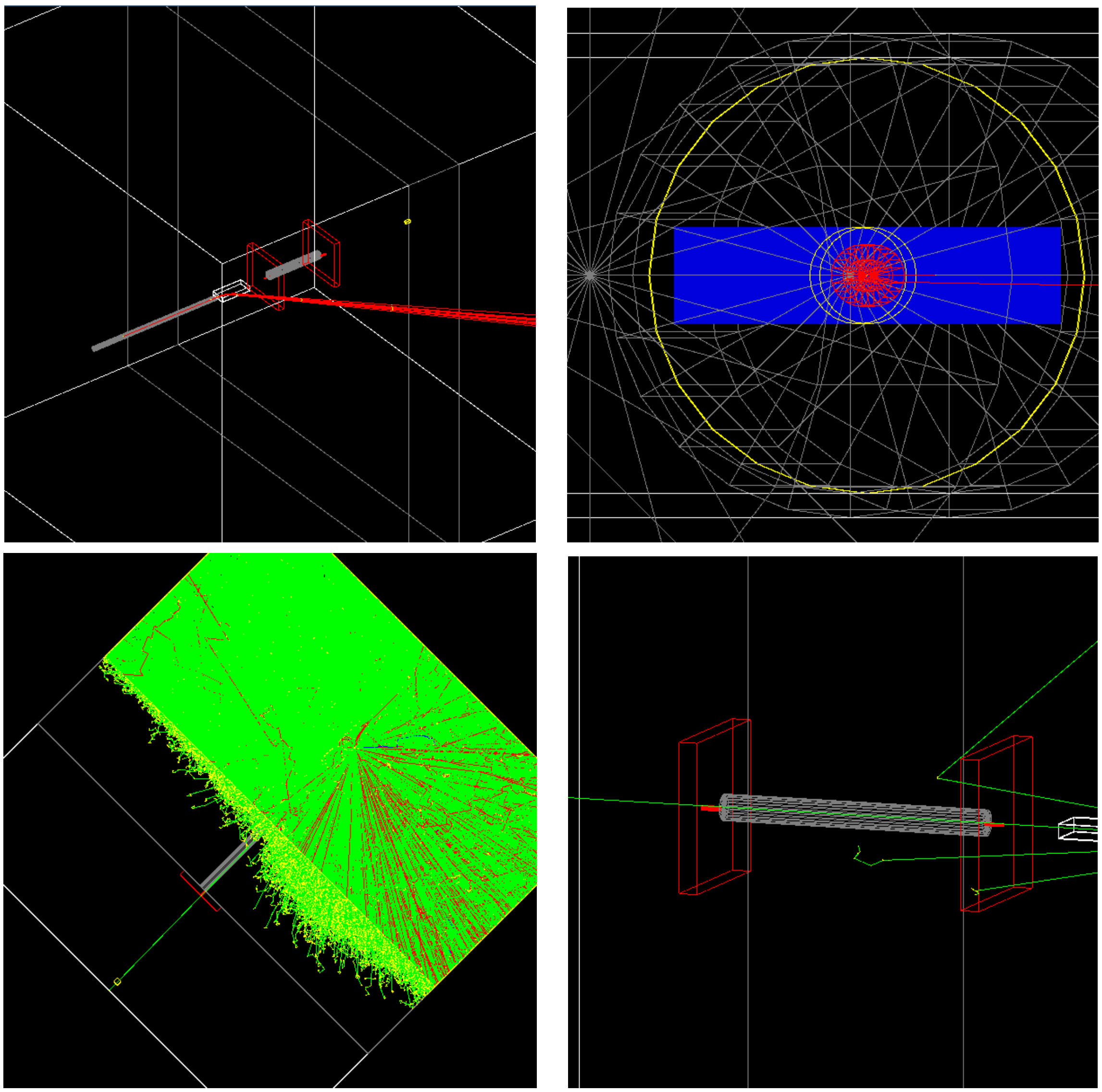

Table 3: gent4 general setup shows the deflection of electrons by magnetic field (left up); the collimator alignments (right up); all secondary particles are stopped by concrete wall (left down); the passage of bremsstrahlung photon through collimator (right down).

So, because there are no any other photons created outside the radiator were found inside the detector, to increase the computational time, the vacuum pipe, vacuum box, concrete wall and air material were replaced by vacuum. That will not change the flux detected by target material.

The energy and angular spectra of bremsstrahlung photons at radiator and at target locations were printed out and saved into the ascii files for later analysis. The comparison of bremsstrahlung energy and angular spectra produced by thin 1 mil radiator for HRRL/IAC runs are shown in Figure 3 and 4. It could be seen that the number of bremsstrahlung photons produced from Ti radiator is 557653/265270 = 2.1 times more than the number of photons produced by the Al radiator. That is simply because the difference in radiation length of radiator materials used. Also the Θ angular distribution is more directed in forward direction for the low Z Al material as expected. The Φ distribution is uniform in both cases. There are small sharp peak in 90^o in Φ distribution and that is probably explained by the geometry of radiator used for simulation. It was the plane 8 cm long in X direction and 2 cm long in Y direction.

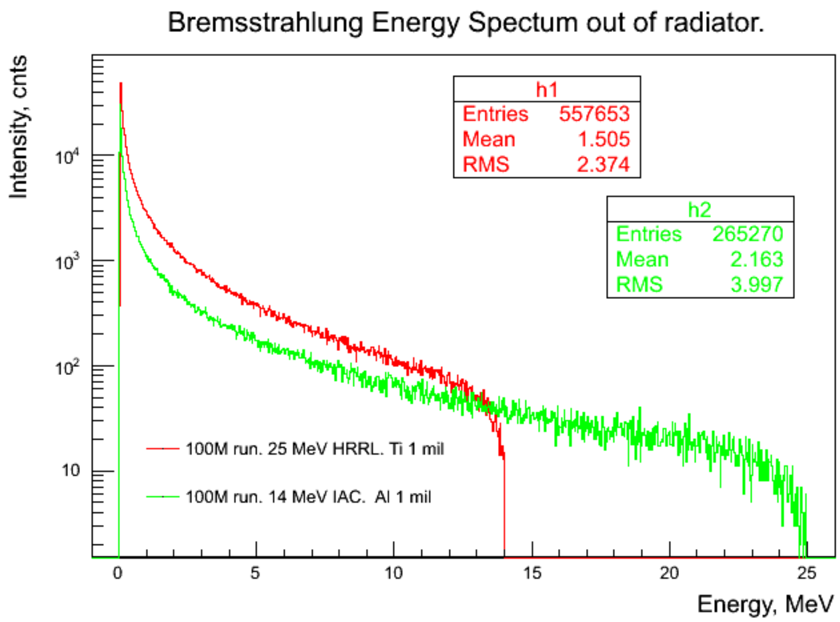

Figure 3: The GEANT4 simulation of the bremsstrahlung energy spectra from 1 mil of Ti (red line) and 1 mil of Al (green line) radiators.

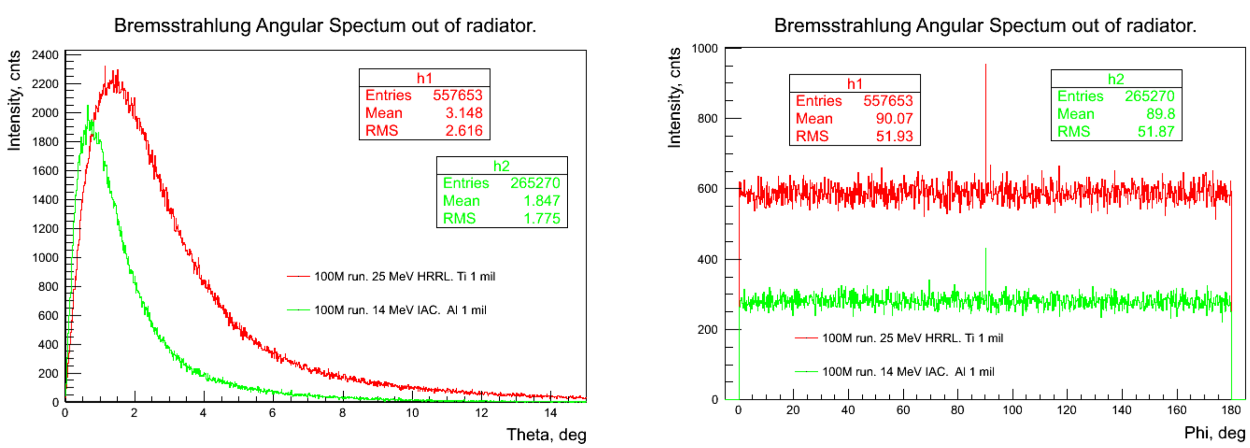

Figure 4: The GEANT4 simulation of the bremsstrahlung angular spectra from 1 mil of Ti (red line) and 1 mil of Al (green line) radiators. Left Figure shows the Theta distribution and right Figure shows the Phi distribution.

The energy and angular spectra as seen at DU target location are shown in Figure 5 and 6 correspondingly. Although the statistics for observed gammas is low here, the effect of collimation is obvious. It could be seen how precisely the collimation is in $\Theta_c = 2.09^o$ and in $\Theta_c = 1.17^o$ directions for HRRL and IAC experiments correspondingly.

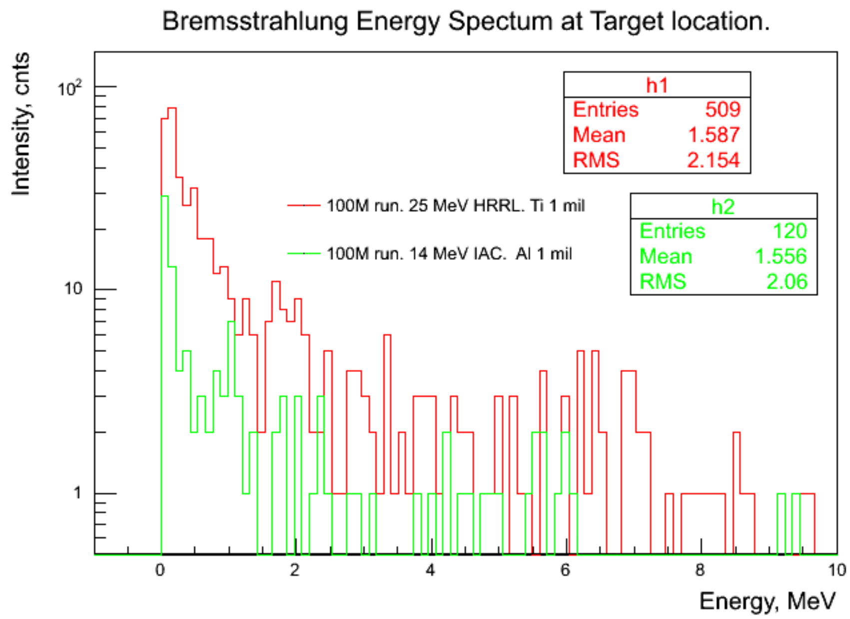

Figure 5: The GEANT4 simulation of the bremsstrahlung energy spectra from 1 mil of Ti (red line) and 1 mil of Al (green line) radiators as seen by DU target.

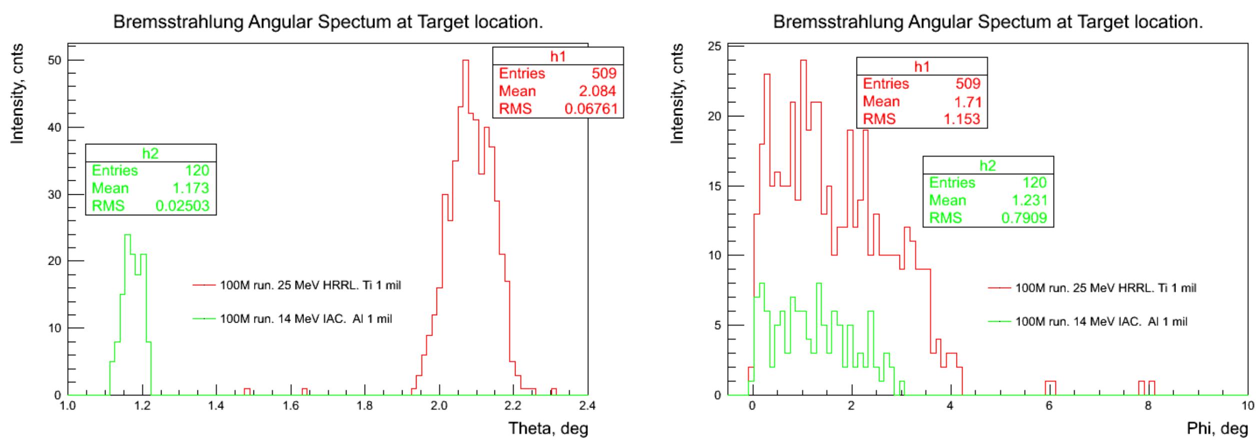

Figure 6: The GEANT4 simulation of the bremsstrahlung angular spectra from 1 mil of Ti (red line) and 1 mil of Al (green line) radiators as seen by DU target. Left Figure shows the Theta distribution and right Figure shows the Phi distribution.

The HRRL experiment gives more flux than IAC experiment and the ratio is as follow:

$$\frac{\mathrm{Bremss_{HRRL}}}{\mathrm{Bremss_{IAC}}}\frac{\mathrm{Collim_{HRRL}}}{\mathrm{Collim_{IAC}}} = \frac{509}{120} = 4.24 \tag{2}$$

That factor is due to the difference in the bremsstrahlung photon production rate in radiator and due to the different collimation geometry for HRRL and IAC runs.

3 Analyse of n's count rate ratio observed at HRRL and IAC experiments

The experimental results presented earlier can be analyzed as follow. The neutron's count rate ratio can be thought as the product of several terms: the ratio of electron flux impinged on the target, the ratio of the bremsstrahlung photons production rate and the ratio of the collimation factor, the ratio of the neutron's production rate in target and the ratio of detector geometrical efficiency:

$$\left(\frac{\mathrm{R}^{\mathrm{HRRL}}}{\mathrm{R}^{\mathrm{IAC}}}\right)_{\mathrm{n}} = \left(\frac{\Phi^{\mathrm{HRRL}}}{\Phi^{\mathrm{IAC}}}\right)_{\mathrm{e}^-} \times \left(\frac{\mathrm{Bremss}^{\mathrm{HRRL}}}{\mathrm{Bremss}^{\mathrm{IAC}}} \times \frac{\mathrm{Collim}^{\mathrm{HRRL}}}{\mathrm{Collim}^{\mathrm{IAC}}}\right) \times \left(\frac{\sigma^{\mathrm{HRRL}}}{\sigma^{\mathrm{IAC}}}\right)_{\mathrm{n}} \times \left(\frac{\mathrm{G}^{\mathrm{HRRL}}}{\mathrm{G}^{\mathrm{IAC}}}\right) \quad (3)$$

Because the same neutron detector was used in both case there is no ratio of absolute detector efficiency here. The first terms can be calculated using the electron beam parameter from Table 1:

$$\left(\frac{\Phi^{\mathrm{HRRL}}}{\Phi^{\mathrm{IAC}}}\right)_{\mathrm{e}^-} = \frac{1000\ \mathrm{Hz} \cdot 100\ \mathrm{mA} \cdot 25\ \mathrm{ns}}{180\ \mathrm{Hz} \cdot 120\ \mathrm{mA} \cdot 2\ \mathrm{ns}} = 57.87 \quad (4)$$

The ratio of the bremsstrahlung photons production rate and the ratio of the collimation factor is that what the geant4 simulation result is, and according to 2 equals to:

$$\left(\frac{\mathrm{Bremss}^{\mathrm{HRRL}}}{\mathrm{Bremss}^{\mathrm{IAC}}} \times \frac{\mathrm{Collim}^{\mathrm{HRRL}}}{\mathrm{Collim}^{\mathrm{IAC}}}\right) = 4.24 \quad (5)$$

The third term, the ratio of the neutron production rate in target can be estimated by integrating the photo-nuclear cross section weighed over incident gamma energy flux. The photo-nuclear cross sections data for ^{238}U target were taken from National Nuclear Data Center [2] and are plotted in left Figure 7. The right Figure represents the cross-section data weighted over the $1/\mathrm{E}_\gamma$ gamma flux.

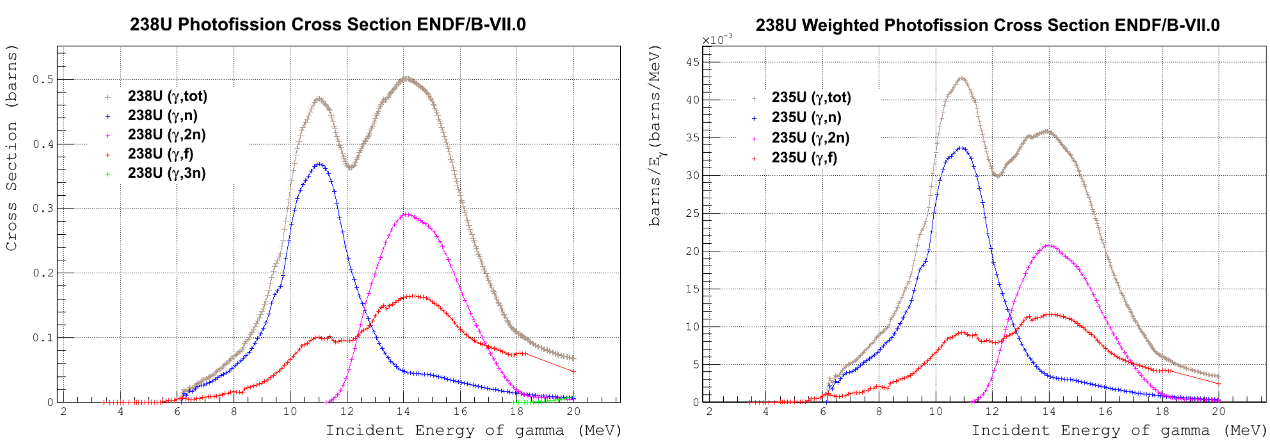

Figure 7: The photo-nuclear cross section for ^{238}U target. Left picture represent the cross-section data taken from [2]. Right Figure represents the cross-section data weighted over the $1/\mathrm{E}_\gamma$ gamma flux.

Because the all neutrons from all channels were detected in experiment, the total cross section was used for integration. For HRRL experiment the integral was evaluated in (0,14)

MeV energy range and for IAC experiment in (0,25) MeV energy range. The result is as follow:

$$\left(\frac{\sigma^{\mathrm{HRRL}}}{\sigma^{\mathrm{IAC}}}\right)_{\mathrm{n}} = \frac{\int_{0\ \mathrm{MeV}}^{14\ \mathrm{MeV}} \left(\frac{\sigma_{\mathrm{tot}}}{\mathrm{E}_\gamma}\right) \mathrm{dE}_\gamma}{\int_{0\ \mathrm{MeV}}^{25\ \mathrm{MeV}} \left(\frac{\sigma_{\mathrm{tot}}}{\mathrm{E}_\gamma}\right) \mathrm{dE}_\gamma} = \frac{0.1880}{0.2804} = 0.67 \tag{6}$$

The last, term, the ratio of geometrical efficiency, can be estimated as follow. In general, the geometrical detector efficiency can be thought as the solid angle subtended by detectors and weighted over the angular distribution of neutrons. Assuming the isotropic angular distribution, or saying that n's detectors were located in the place with the similar angular distribution for both experiments, the ratio of geometrical efficiency will be proportional just the solid angles and can be calculated as follow:

$$\left(\frac{\mathrm{G}^{\mathrm{HRRL}}}{\mathrm{G}^{\mathrm{IAC}}}\right) = \left(\frac{\Omega^{\mathrm{HRRL}}}{\Omega^{\mathrm{IAC}}}\right)_{\mathrm{det}} = \left(\frac{\mathrm{r}^{\mathrm{IAC}}}{\mathrm{r}^{\mathrm{HRRL}}}\right)^2 = \left(\frac{129.5\ \mathrm{cm}}{88 \cdot 2.54\ \mathrm{cm}}\right)^2 = 0.34 \tag{7}$$

Combining together the terms 4, 5, 6 and 7 the total ratio of neutrons count rates is:

$$\left(\frac{\mathrm{R}^{\mathrm{HRRL}}}{\mathrm{R}^{\mathrm{IAC}}}\right)_{\mathrm{n}} = 57.87 \times 4.24 \times 0.67 \times 0.34 = 55.89 \tag{8}$$

4 Discussion of results

There is a huge difference between the measured n's rate ratio 1 and calculated one 8:

$$\frac{\left(\frac{\mathrm{R}^{\mathrm{HRRL}}}{\mathrm{R}^{\mathrm{IAC}}}\right)_{\mathrm{n}}^{\mathrm{experiment}}}{\left(\frac{\mathrm{R}^{\mathrm{HRRL}}}{\mathrm{R}^{\mathrm{IAC}}}\right)_{\mathrm{n}}^{\mathrm{calculation}}} = \frac{407.08}{55.89} = 7.3\ \mathrm{times} \tag{9}$$

To understand the possible sources of such a kind of discrepancy, some study were done as described below.

There are some factors, pointing out that the maximum beam current at HRRL experiment was between 50 and 80 mA. That can give to as the error of about (100-50)/100 = 50% with respect to electron beam flux calculated in 4. But that is even worse result because the total calculated ratio 9 becomes smaller.

In calculation of geometrical neutron efficiency the isotropic angular distribution was assumed (or the similar anisotropic neutron flux in detector location). The violation of this assumption can easily give to us the error of about 50%. The other factors, like shielding in front of n's detector, the photon hardeners placed in front of collimator, can give to us the other extra factor of 50% error.

Combining the all factors mentioned above, the maximum possible error are of about:

$$\mathrm{Error} = \sqrt{0.5^2 + 0.5^2 + 0.5^2 + 0.5^2} = 100\% \tag{10}$$

That is obviously not enough to explain the huge difference 9 between the experimental and calculated results.

The other kind of errors are the possible misalignments of collimation elements, like downstream/upstream collimator and target. The series of gent4 test simulations were done to estimate the effect of possible misalignments. Firstly, the downstream IAC collimator was shifted by (1/8) inch and by (1/4) inch in positive X directions with respect to initial location. There were total 10M events for each test run. Because the observed statistics of photons were small here, to make the test is more accurate, more simulations were performed for HRRL model as follow:

test01: the downstream collimator was shifted by 0.5 cm in positive X direction

test02: the upstream collimator was shifted by 1 cm in negative X direction

test03: the target was shifted by 2 cm in positive X direction

test04: all tree elements were shifted as described in test01, test02 and test03.

The views of collimation system from the target location from critical angle for HRRL setup for different test runs are shown in the Table 4. It can bee seen how the different elements of collimation system (upstream/downstream collimator, target) are shifted with respect to each other for different test runs.

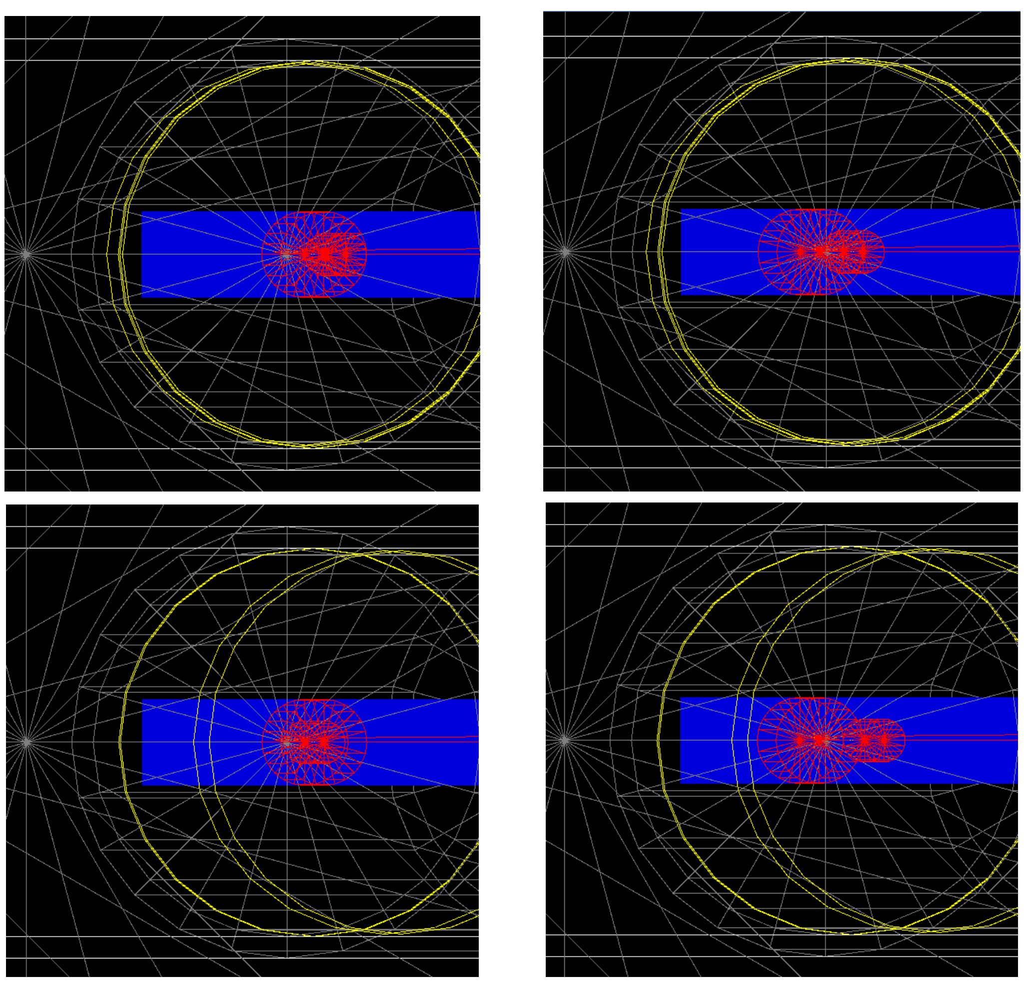

Table 4: geant4 view of collimation system for different test runs: test01 (left up); test02 (right up); test03 (left down); test04 (right down).

The results of test simulations are summarized in table 5. As can be seen the most sensitive elements of alignments is the downstream collimator and the most worst scenario is the test04 where the all tree elements were shifted simultaneously. To estimate the effect of misalignments more precisely, the long run of 100M events was performed for the test01 and test04 conditions.

#	test	condition of run	N_{events}(total)	$N_{\gamma's}$(detector)
1	IAC initial setup	as in table 2	10M	15
2	IAC test01	A1C1 = A1C1 + (1/8) inch	10M	13
3	IAC test02	A1C1 = A1C1 + (1/4) inch	10M	6
4	HRRL initial setup	as in table 2	10M	45
5	HRRL test01	AC = AC + 0.5 cm	10M	13
6	HRRL test02	A1C1 = A1C1 - 1.0 cm	10M	19
7	HRRL test03	A2C2 = A2C2 + 2 cm	10M	43
8	HRRL test04	HRRL (01+02+03) all together	10M	1
9	HRRL initial setup	as in table 2	100M	509
10	HRRL test01A	same as HRRL test01	100M	159
11	HRRL test04A	same as HRRL test04	100M	25

Table 5: geant4 study of possible collimator's and detector's misalignment effects.

It can be seen from the result of test01A, that by misalignment of the downstream collimator in horizontal direction by 0.5 cm, the flux could be decreased by the factor 3.2, and from the result of test04A, that in the most bad scenario of misalignments of all elements simultaneously, the flux could be cut out by the factor of about 25. That is more than enough to explain the observed discrepancy 1 between the IAC and HRRL experiment. If we assume that the misalignments was done during the IAC experiment, that will reduce the measured n's count rates a lot with respect to ideal alignment case. Also note that for the IAC experiment the critical angle was smaller, so it is easily to make the misalignments error as compared to the HRRL experiment.

It is interesting topic and the more detailed study of misalignments effect can be done in future. To increase the simulated statistics of photons at target, the bremsstrahlung photons spectrum simulated from radiator (Figure 4) can be sampled and used as the geant4 general particle source (gps). That will gives to us the possibility to increase the bremsstrahlung gamma flux a lot, and, as a consequence, to increase the statistics of the whole simulation results.

References

[1] A. Kosinov, HRRL vs. IAC, Presentation at Physics Department at Dan's group meeting, December 1, 2011

[2] *National Nuclear Data Center*, (`http://www.nndc.bnl.gov/`)