# Proposal for PhD topic: Two Neutron Correlation Study On Photofission of Actinides

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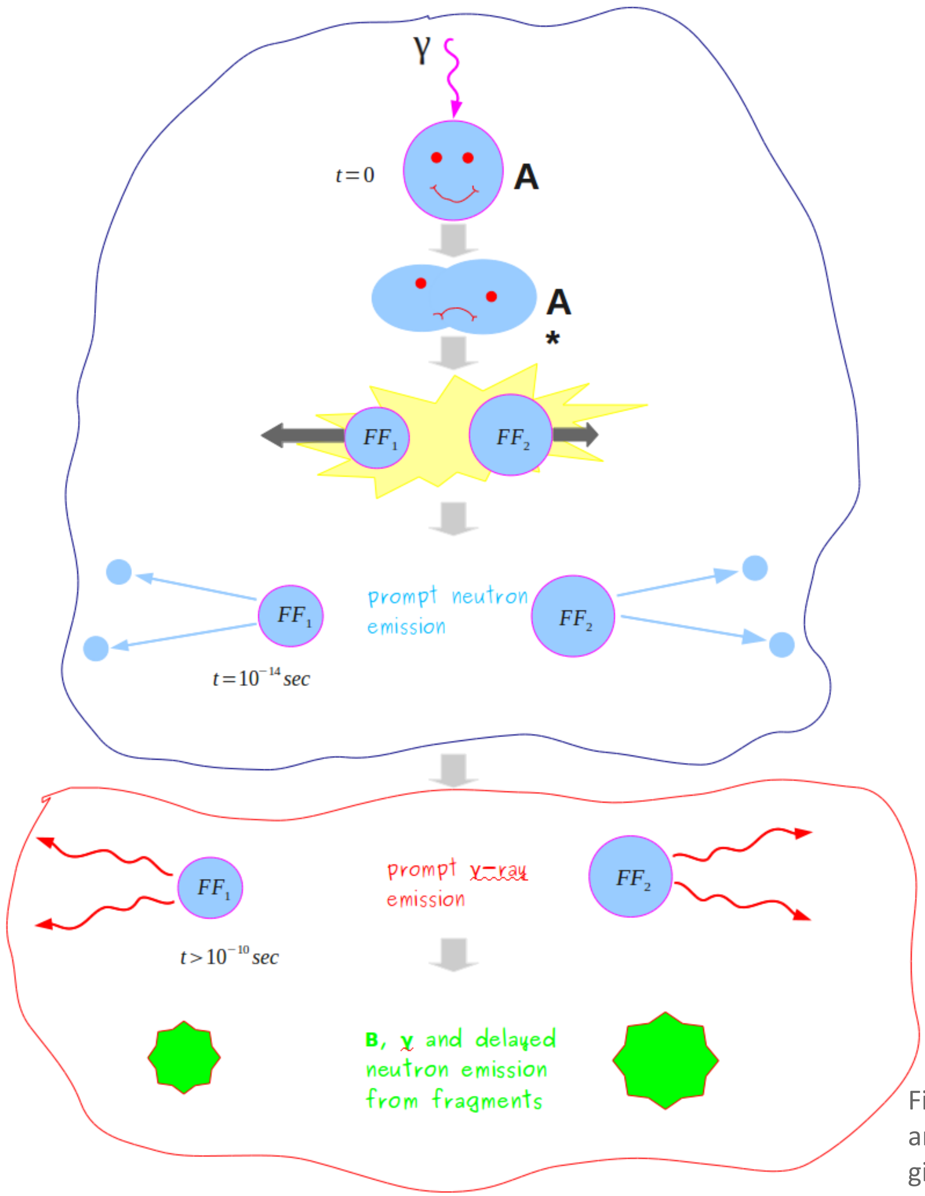
# Abstract

It is well known that two fission fragments (FF’s) are emitted essentially back to back in the laboratory frame. That can be used widely in many applications as a unique signature of fissionable materials. However, such fission fragments are difficult to detect. The energy and angular distributions of neutrons, on the other hand, are easy to measure, and that distribution will carry information about the fission fragment’s energy and angular spectra, as well as the neutron spectra in the fission fragment rest frame.

We propose to investigate the two neutron correlation yield resulting from two FF’s as a function of different targets, the angle between the two neutrons and the neutron energies. The preliminary calculation of the two neutron correlation shows a huge asymmetry effect: many more neutrons are emitted anti-parallel to each other than parallel to each other. That asymmetry becomes even more if the energy cut on each neutron is done. This study will potentially permit a new technique for actinide detection for homeland security and safeguards applications as well as improve our knowledge of correlated neutron emission.

# Outline

# Simple summary of Fission Physics (1)




**Discuss:**

- up to the time scale of about $10^{-14} - 10^{-13}$ sec, when the prompt neutrons are emitted from the fully accelerated fragments

**Assume:**

- no "scission" neutrons
- all neutrons are emitted from fully accelerated fragments

**Ignore:**

- Time scale greater then $t > 10^{-10}$ sec, when prompt gammas and delayed β, γ and n are emitted

Figure 1.1: Schematic representation of the fission process. Neutrons are emitted from fully accelerated fission fragments. The time scale gives the orders of magnitude only [26].

# Simple summary of Fission Physics (2)

It has long been known that the photofission reaction with a heavy nucleus in the energy range of the giant dipole resonance goes through the intermediate compound nucleus. That intermediate nucleus is in an excited state followed by the emission of two fission fragments:

$$\boldsymbol{\gamma + A \rightarrow A^* \rightarrow FF_1 + FF_2 + TKE}$$

$$\text{TKE} = T_1 + T_2 = 165\ \text{MeV}$$

$$\frac{T_1}{T_2} = \frac{m_2}{m_1}$$

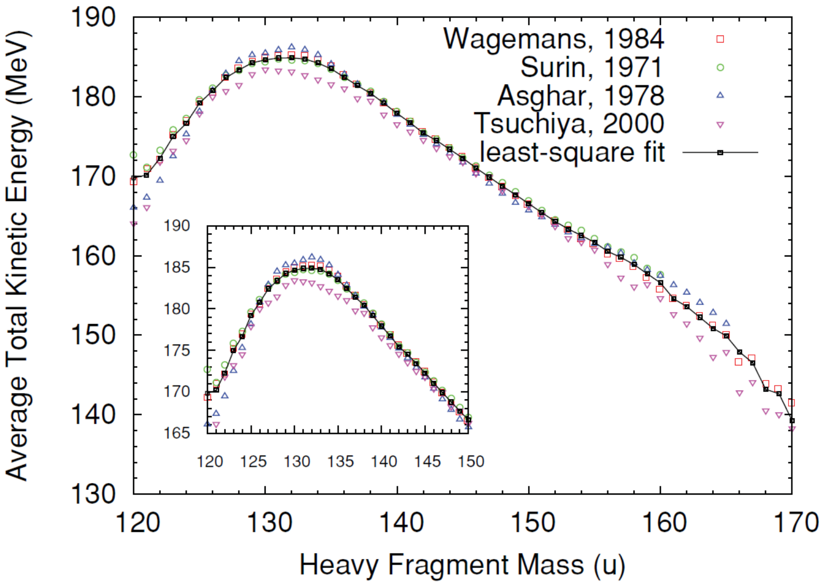
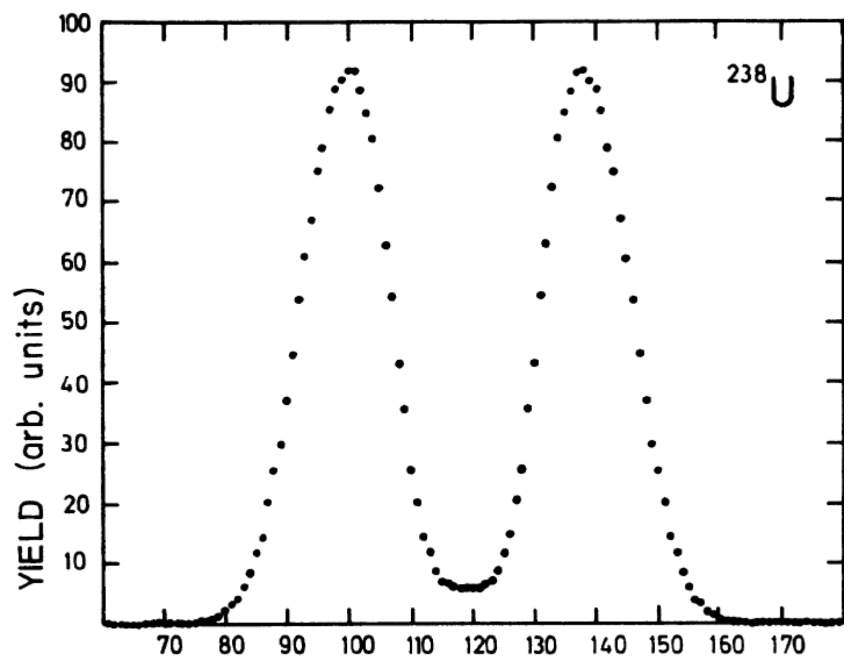



Figure 1.2: The average TKE as a function of the heavy fragment mass. The solid line is the result of a least-square fitting of the experimental data sets [17].



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# Simple summary of Fission Physics (3)

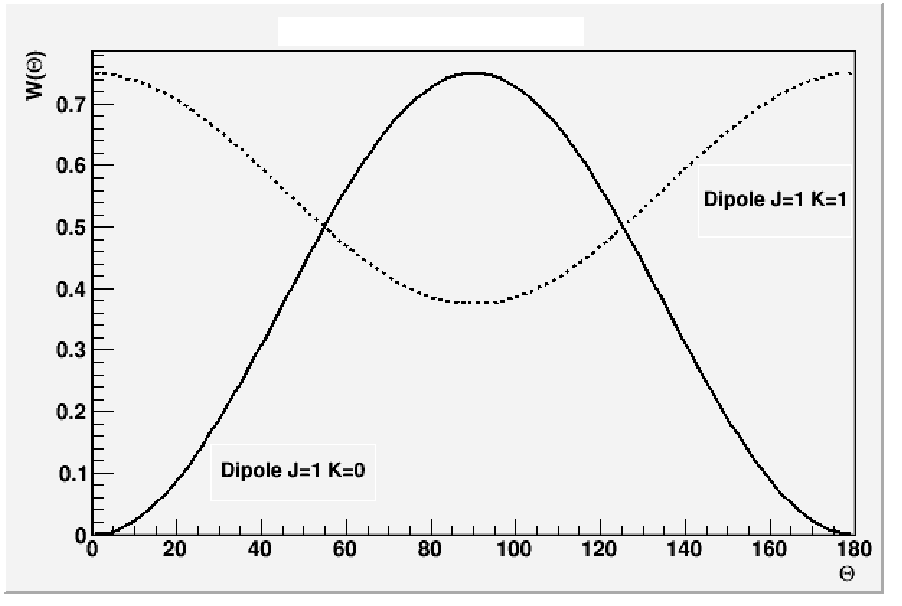
**The angular distribution of individual FF's:**

- can be explained according to A.Bohr's fission channel concept [5]
- briefly described by R.Ratzek et al. [11] with regards to photoinduced reactions
- For even-even nucleus ($J^{\pi} = 0^{+}$ , such as $^{238}U$ ) and consider only electric dipole (E1) transactions [11]:

$$W(\Theta) = A_0 + A_2 P_2(\cos(\Theta))$$

where

- $A_0$ and $A_2$ depend on the transition state (J,K)
- K is the projection of the total spin J on the symmetry axis of the deformed nucleus
- For J=1, K=0, we have $A_0 = \frac{1}{2},\ A_2 = -\frac{1}{2}$
- For J=1, K=1, we have $A_0 = \frac{1}{2},\ A_2 = \frac{1}{4}$
- $P_2(\cos(\Theta)) = \frac{1}{2}(2 - 3\sin^2(\Theta))$



# Simple summary of Fission Physics (4)

## 1) Simple kinematics of reaction

- If $E_\gamma$< 20 MeV -> the excited nucleus A* is almost in rest
- FF1 and FF2 are flying in opposite direction in LAB

## 2) After about $10^{-14}$ -$10^{-13}$ sec the fission fragments will emit neutrons.

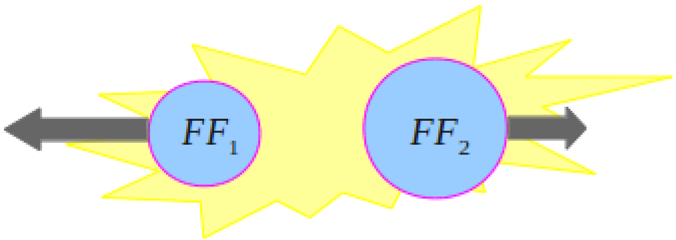
- All prompt neutrons are emitted from fully accelerated fragments
- There are no so called "scission" neutrons emitted at the time of fission
- The total excitation energy (TXE) will be shared among light and heavy fragments
- When the excitation energy is relatively low the light fragments will acquire the larger part of that shared energy [23, 24]
- Assume that the initial energy release is completely due to the neutron emission [17]
- The statistical model to analyze the neutron emission spectrum can be applied [3]
- The angular distribution of prompt neutrons is isotropic in the center-of-mass frame of the FF

$$\rho(\varepsilon_n) = \varepsilon_n \exp\left(\frac{\varepsilon_n}{T}\right) \qquad (1.4)$$

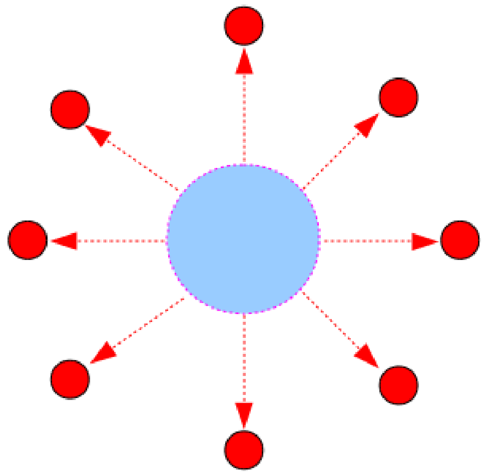
- After the first neutron is emitted the second one will be emitted and so on until the excitation energy of the fragments becomes less then the neutron separation energy

**Below is a short summary of the photossion reaction mechanisms discussed above which will be used in the following to discuss the idea of the proposed two neutron correlation:**

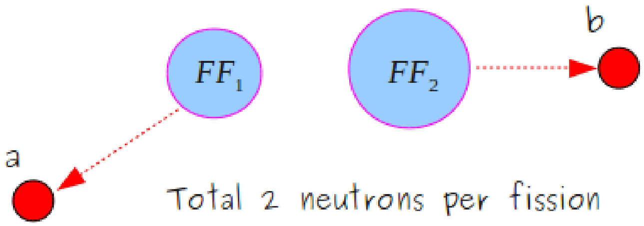
- two fission fragments recoil essentially back to back.




- the angular distribution of the prompt neutrons is isotropic in the center-of-mass frame of the FF's with a statistical energy distribution.



- each fully accelerated FF emits only one neutron.



# Idea of 2n correlation (1)

Let's start to count how many FF's pairs are going antiparallel and how many FF's pairs are going parallel to each other.

$$A_{FF} = \frac{\text{FF}'\text{s antiparallel}}{\text{FF}'\text{s parallel}} = \infty$$

FF’s antiparallel -- the # of FF’s pairs going in antiparallel direction
FF’s parallel -- the # of FF’s pairs going in parallel direction

But:

- The fission fragments are very difficult to detect.
- Neutrons emitted by FF’s will fly outside of the target and could be easily detected.
- The question here is whether or not the angular asymmetry of fission fragments $A_{FF}$ is manifest in the angular distribution of prompt neutrons.

In order to answer this question, we propose to measure the two neutron angular and energy distributions with the ultimate goal of calculation the two neutron asymmetry:

$$A_{2n} = \frac{2n\prime\text{s antiparallel}}{2n\prime\text{s parallel}}$$

2n’s antiparallel -- the # of 2n’s pairs going in antiparallel direction
2n’s parallel -- the # of 2ns pairs going in parallel direction

# Idea of 2n correlation (2)

1) Take a typical 1 MeV neutron in the center-of-mass frame of the fission fragment:

$$T = \frac{mc^2\beta^2}{2} \qquad \beta = \sqrt{\frac{2*1\ \mathrm{MeV}}{939\ \mathrm{MeV}}} = 4.6\%$$

2) Take two fission fragments with typical mass numbers $A_1$ = 95 and $A_2$ = 143

$$\frac{T_1}{T_2} = \frac{m_2}{m_1} = 1.51 \qquad T_1 + T_2 = 165\ \mathrm{MeV}$$

$$\Longrightarrow \quad T_1 = 99\ \mathrm{MeV} \qquad T_2 = 99\ \mathrm{MeV} \quad \Longrightarrow$$

$$\beta_1 = \sqrt{\frac{2*99\ \mathrm{MeV}}{95{,}000\ \mathrm{MeV}}} = 4.6\% \qquad \beta_2 = \sqrt{\frac{2*66\ \mathrm{MeV}}{143{,}000\ \mathrm{MeV}}} = 3.0\%$$

3) The expected 2n correlation asymmetry could be thought of as:

$$A_{2n} = A_{FF} \times W_n \times W_{scat}$$

- $A_{FF}$ - asymmetry of two fission fragments
- $W_n$ - washing effect due to isotropic angular distribution of neutrons in the fission fragment rest frame
- $W_{scat}$ - washing effect due to neutron multiple scattering effect inside the target and surrounding materials

4) Because $A_{FF} = \infty$, the total two neutrons asymmetry as measured in laboratory frame would be the sufficient to observe

# Review of what has been done (1)

- 1956, Winhold and Halpern [9].

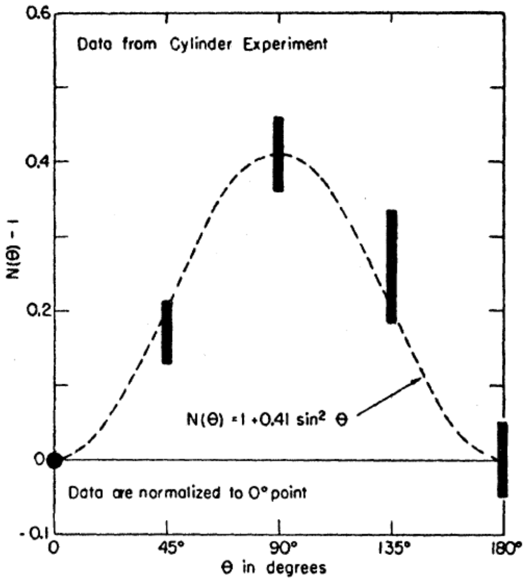



Figure 2.1: The angular distribution, N(θ), of fission fragments from $Th^{232}$ caught at the angles θ to the x-ray beam. The x-ray beam was produced in a thick lead target by an electron beam whose spectrum was centered at 13 MeV and was about 5 MeV wide [9].

- **Angular distribution has the form**

$$a + b\sin^2\theta$$

- **$b/a$ depends on:**

1. Energy of the photons
2. Fissionable target
3. Fission fragment observed

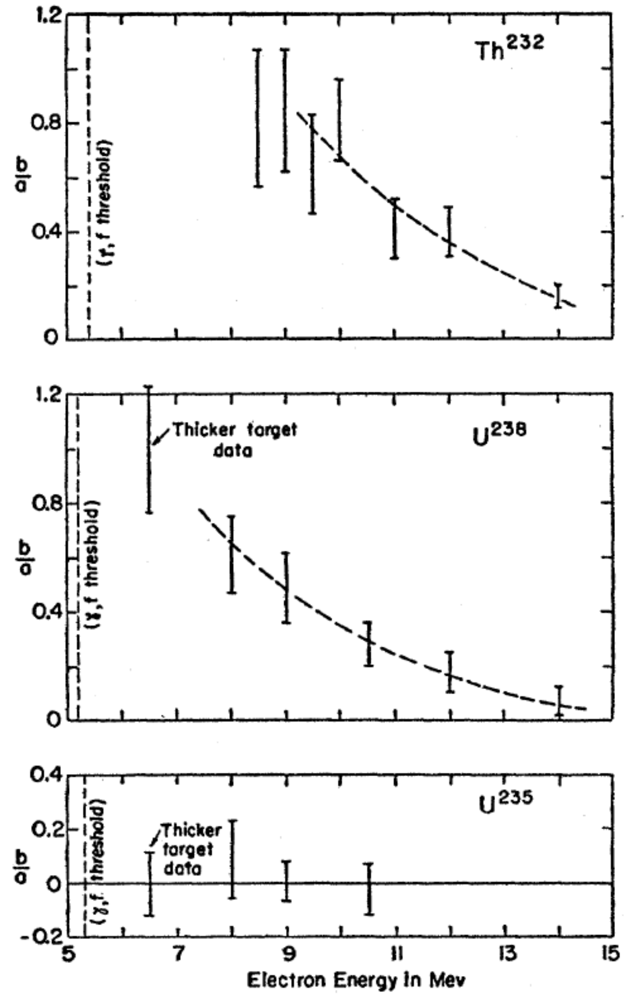



Figure 2.2: The anisotropy in the photofission of three targets. The angular distributions were all assumed to be the form a + b sin2 [9].

# Review of what has been done (2)

- 1962, Bowman *et al.* [10].

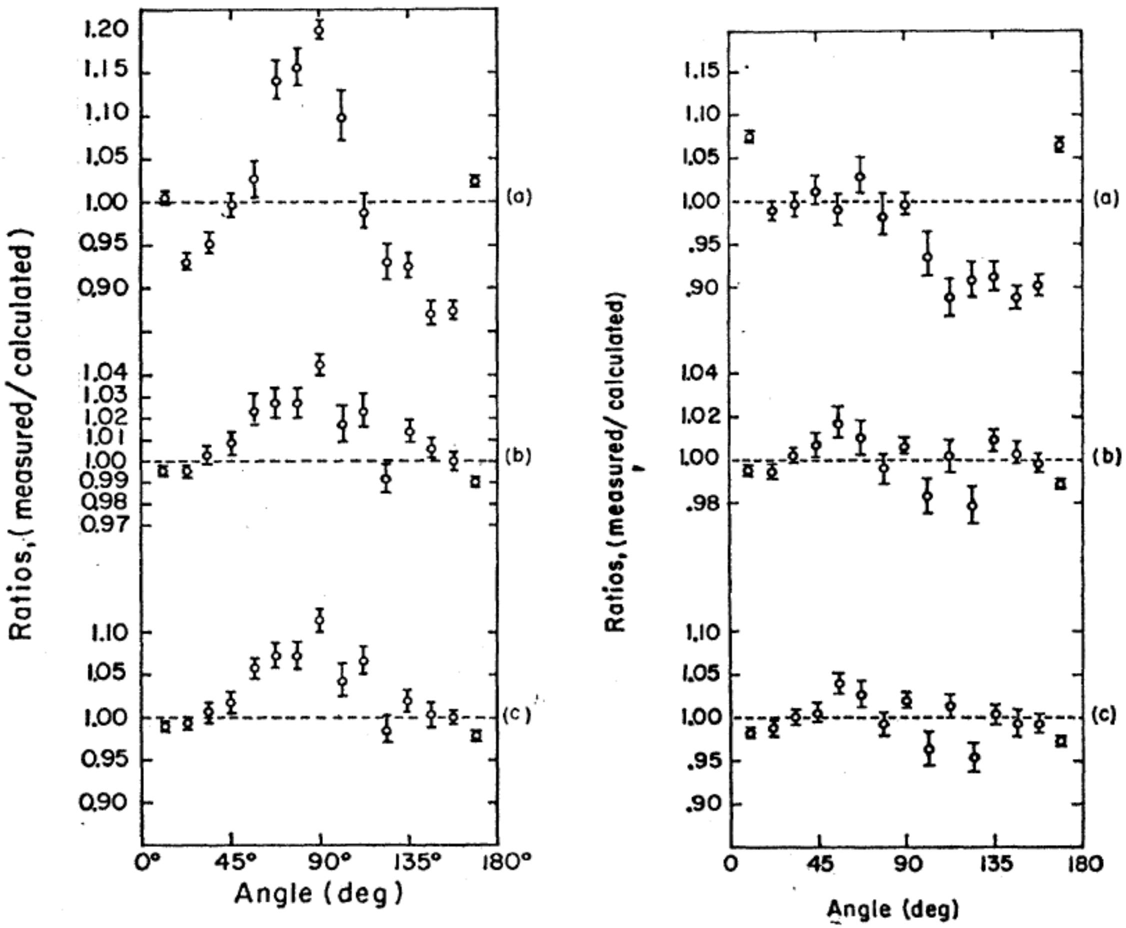



Figure 2.3: The ratio of measured to calculated values for (a) numbers of neutrons (b) average velocities, and (c) average energies as a function of angles.

**Experiment:**

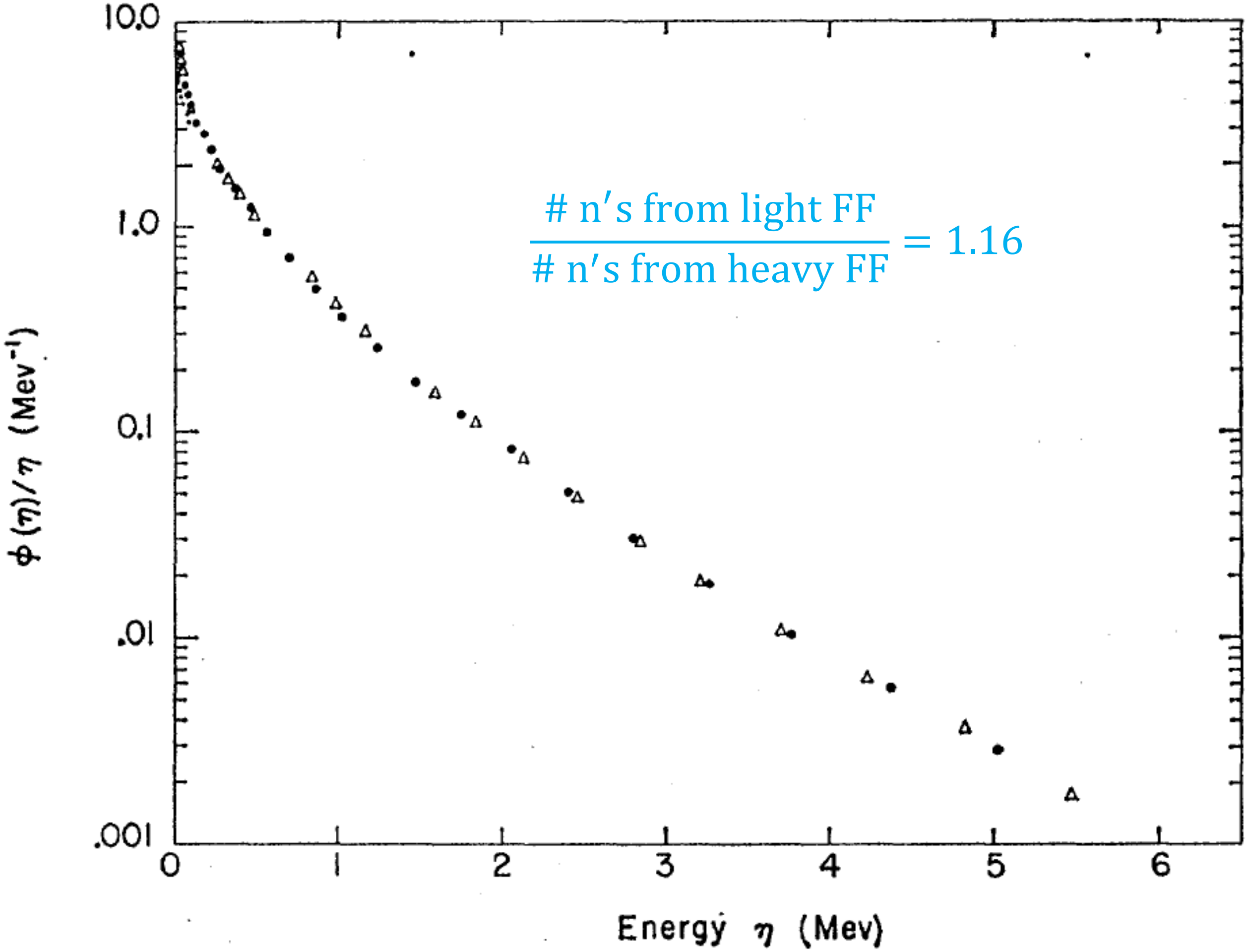
- $^{252}Cf$ spontaneous fission
- TOF techniques to measure neutrons in coincidence with FFs

**Analyze:**

- No "scission" neutrons – left figure
- 10% of "scission" neutrons – right figure

# Review of what has been done (3)

- Bowman *et al.* [10]. Continue…



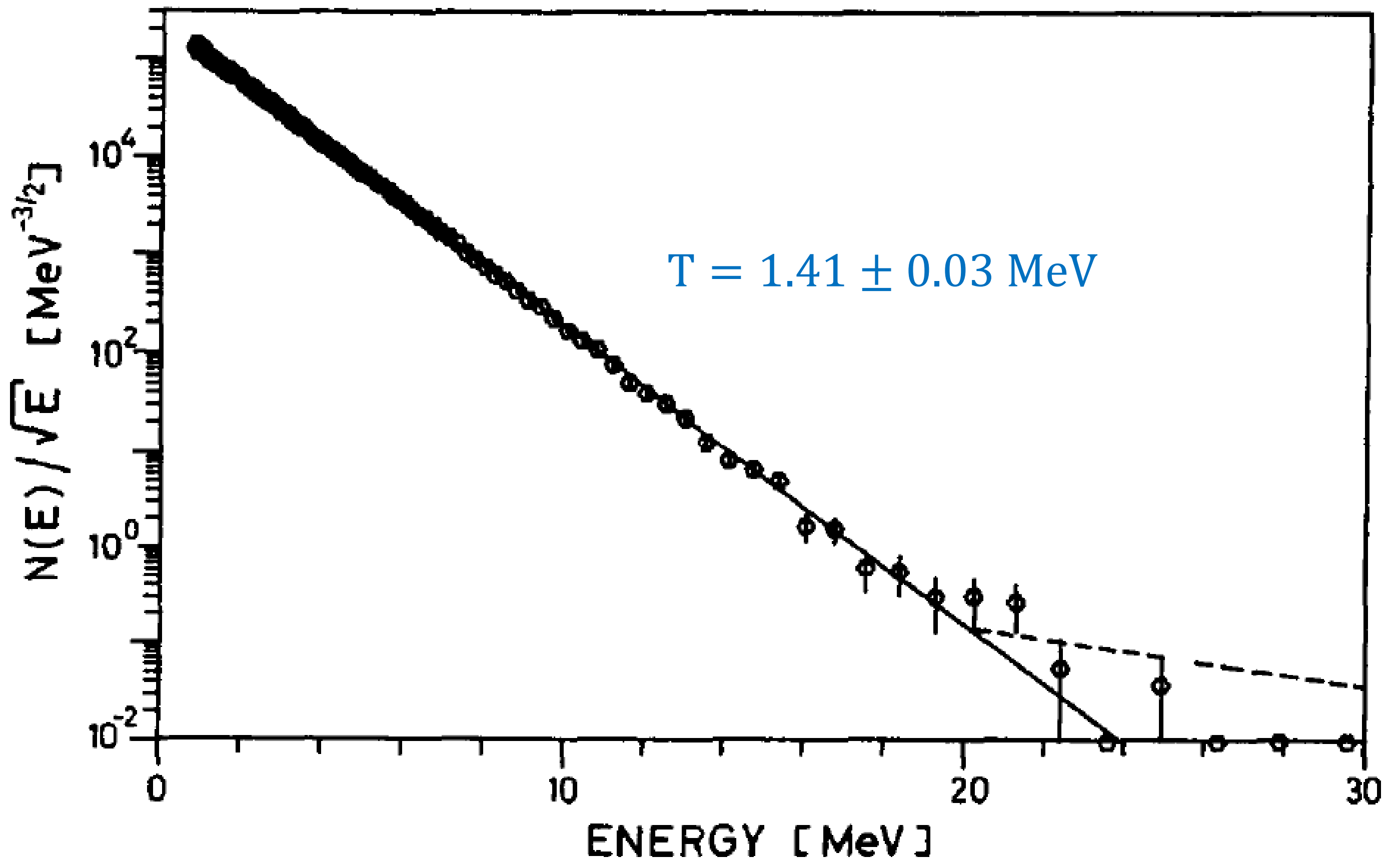

$$\frac{\#\ n's\ \text{from light FF}}{\#\ n's\ \text{from heavy FF}} = 1.16$$

The results can be explained well by assumption of isotropic evaporation of neutrons from the fully accelerated fragments.

Figure 2.4: The center-of-mass neutron energy spectrum Φ(η) (CM) divided by η. The large dots - the neutrons emitted in the direction of the light fragments and the triangles - the neutrons emitted in the direction of the heavy fragments. The curve for light fragments was reduced by the factor 1.16

# Review of what has been done (4)

- 1988, Budtz-Jorgensen and Knitter [12]




**Experiment:**

- $^{252}Cf$ spontaneous fission
- TOF techniques

**Analyze:**

- Maxwell bellow 20 MeV

Figure 2.5: Fission neutron energy spectrum divided by the square root of the neutron energy versus the neutron energy. The solid line is Maxwell energy distribution.

# Review of what has been done (5)

- Budtz-Jorgensen and Knitter [12]. Continue…

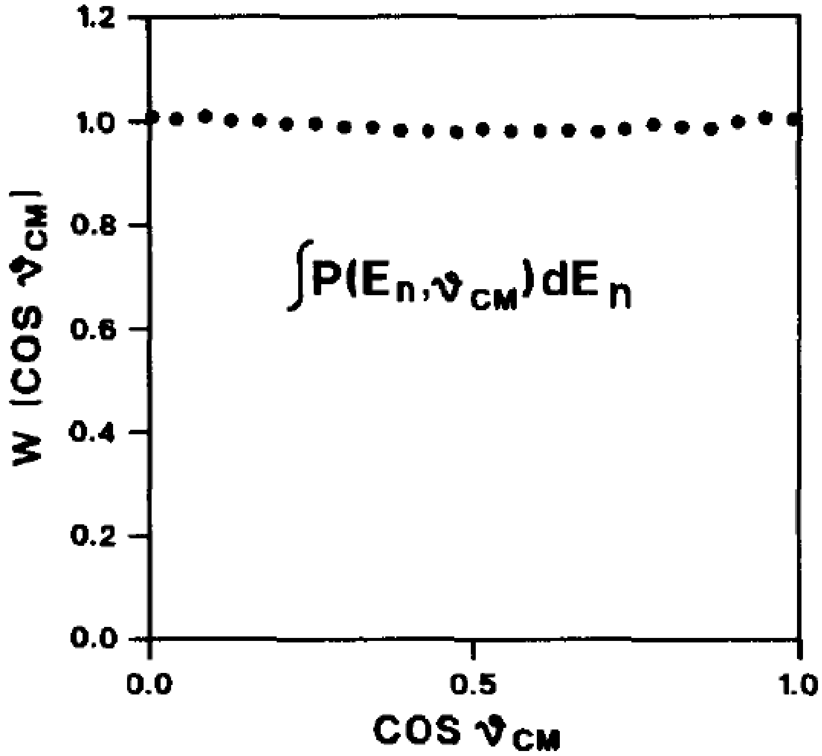



Figure 2.6: Fission neutron angular distribution in the fragment center-of-mass system integrated over all neutron energies

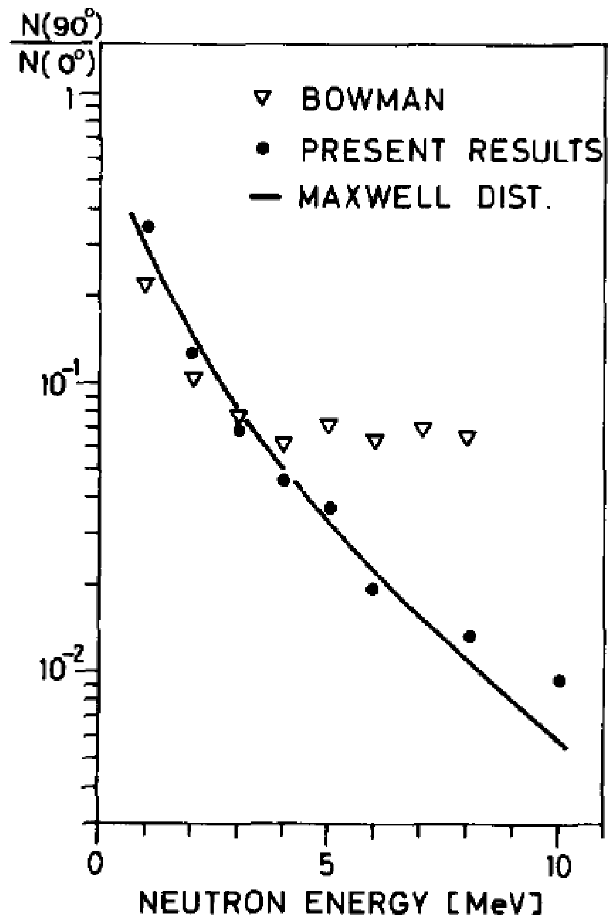


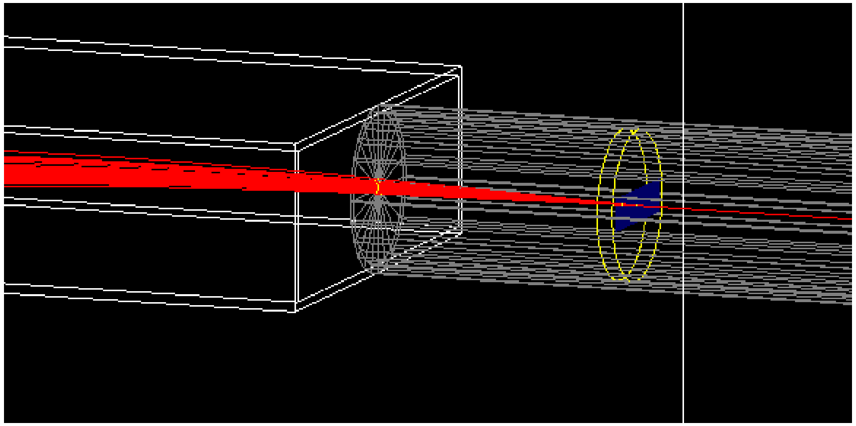

Figure 2.7: Fission neutron intensity ratio N(90°)/N(0°) is plotted versus the fission neutron energy. The solid line is a theoretical line calculated with the assumption that there are no 'scission' neutrons and is in good agreement with the Budtz-Jorgensen measurements.

# Experimental set-up (1)

We plan to use the HRRL LINAC to construct the beamline to produce the bremsstrahlung photons:

- 20 ns pulse width
- 10-80 mA peak current
- hopefully 1000 Hz beam pulse repetition rate

When electrons strike the radiator, that results in the bremsstrahlung radiation in the forward with respect to the beam direction. The typical energy spectrum of bremsstrahlung photons for the 7 MeV endpoint energy is shown in Fig 4.6.



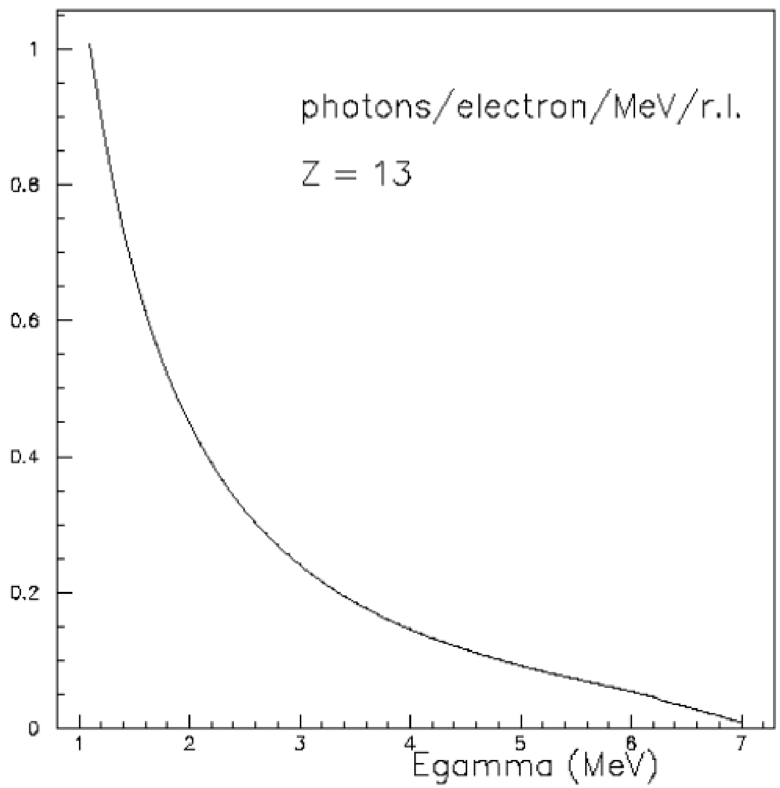



Figure 4.6: Bremsstrahlung spectrum of photons produced by 7 MeV electrons hitting the Al radiator

# Experimental set-up (2)

- A beam of unpolarized photons will be used to measure the two neutron correlation yield as a function of different targets, the angle between the two neutrons and the neutron energy.
- The time of flight (TOF) technique will be used to identify neutrons and to measure their energy, with the start signal coming from the accelerator beam pulse.

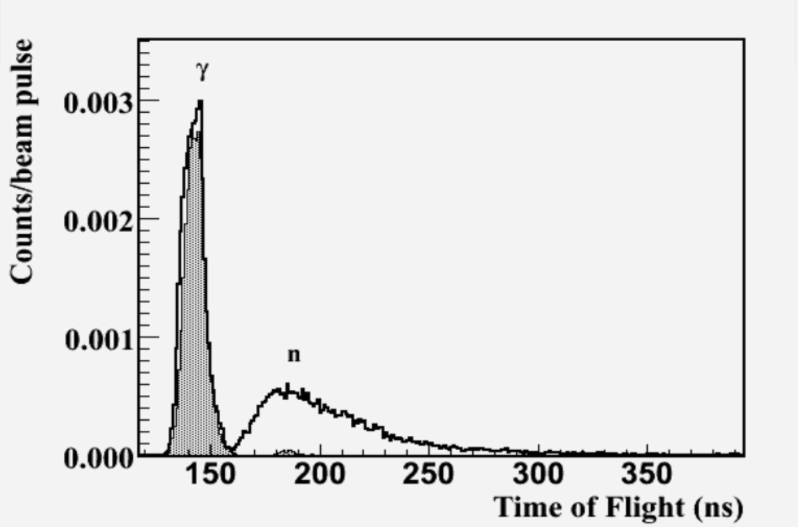



Figure 3.1: Typical TOF spectrum from photodisintegration of deuteron measured from previous HRRL runs. The distance from target to detector is about 2 m. The spectrum illustrate the ability to distinguish gammas peak from neutrons one.

Take a typical 1 MeV neutron located 1 m away from target:

$$\mathrm{TOF(n's)} = \frac{1\ \mathrm{m}}{0.05\times 3\cdot 10^{8}\ \mathrm{m/s}} \approx 67\ \mathrm{ns} \qquad (1)$$

$$\mathrm{TOF}(\gamma'\mathrm{s}) \approx 3.3\ \mathrm{ns} \qquad (2)$$

$\mathrm{TOF(n's)} \ll \mathrm{TOF}(\gamma')$ so we can distinguish n's from γ's

Error in n energy will depend on the LINAC pulse width

$$\frac{\delta E}{E} = \frac{\delta t}{t} = \frac{20\ \mathrm{ns}}{67\ \mathrm{ns}} \approx 30\%$$

# Experimental set-up (3)

There are 16 plastic scintillators with area of $15\ \text{cm} \times 75.8\ \text{cm} = 0.114\ \text{m}^2$

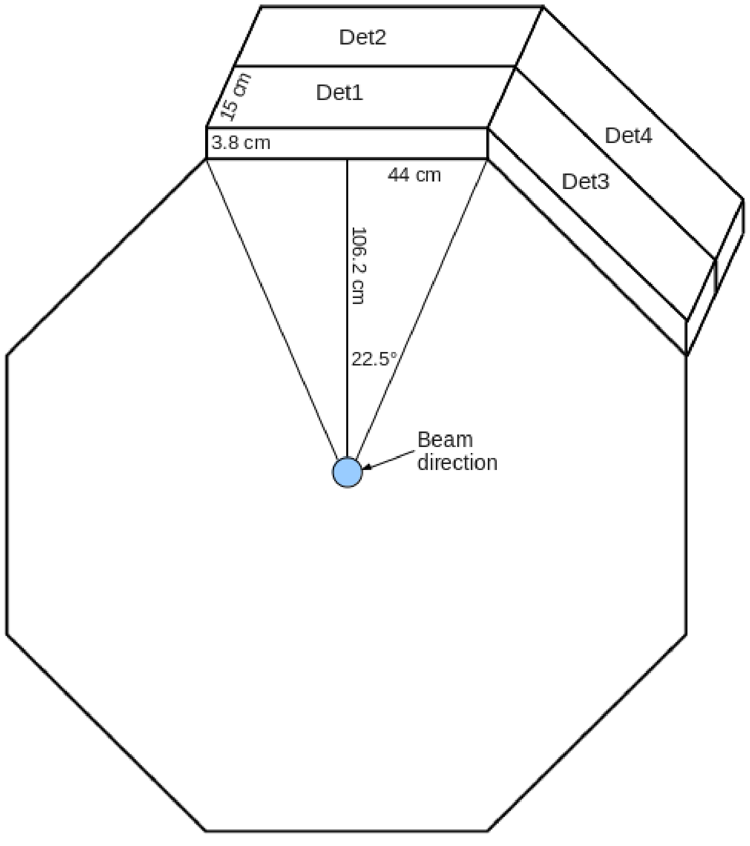
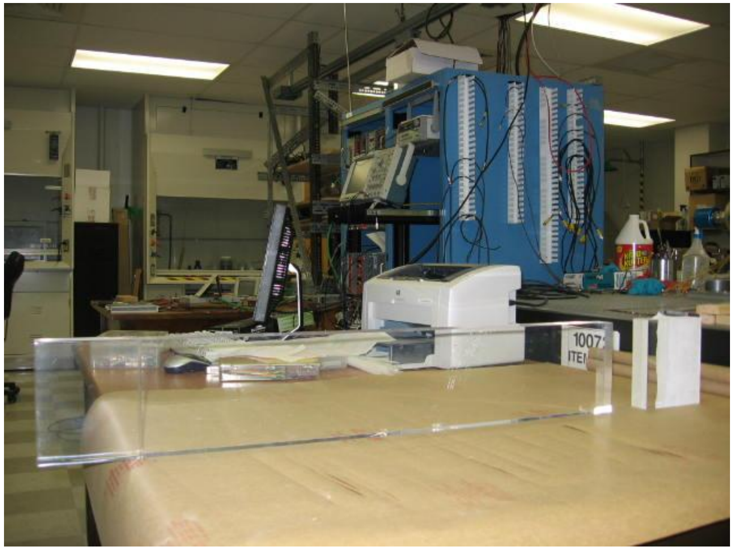



Figure 3.2: Possible detector geometry to measure the two neutron correlation yield. Total 16 neutron detectors are placed at the angle of 90 degree with respect to the beam. The detector size is 15 cm × 75.8 cm × 3.8 cm.



To maximize the 2n correlation yield such plastic scintillators will be placed at the angle of 90 degree with respect to the beam surrounding the target. Further thinking and calculation about the detector location should be done but, in principal, that will allow almost 2π cover as can be seen from Fig 3.2.

# Experimental set-up (4)

**To find the angle between two neutrons we need to find the position y where the neutron hits the detector**

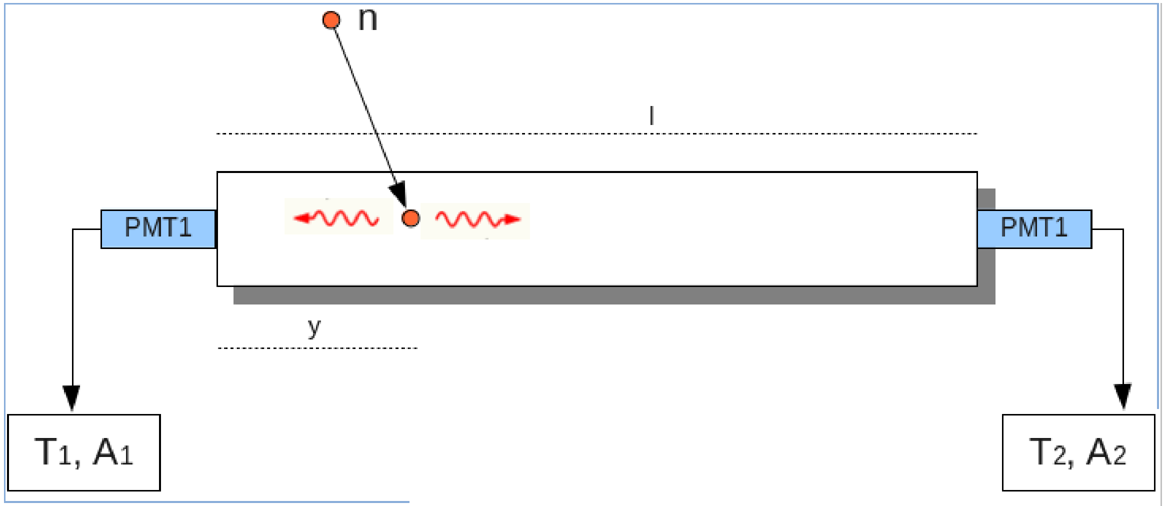



Figure 3.3: Neutron detector with two PMT's attached to both each end. Neutron n hits the detector at distance y from rst PMT. The amplitude signals A1, A2 and TOF signals T1, T2 are measured from PMT1 and PMT2 correspondingly.

Amplitude method:

$$A_1 = I_0 e^{-\alpha y} \qquad A_2 = I_0 e^{-\alpha(l-y)}$$

$$y = \frac{l}{2} - \frac{1}{2\alpha} \ln \frac{A_1}{A_2}$$

TOF method:

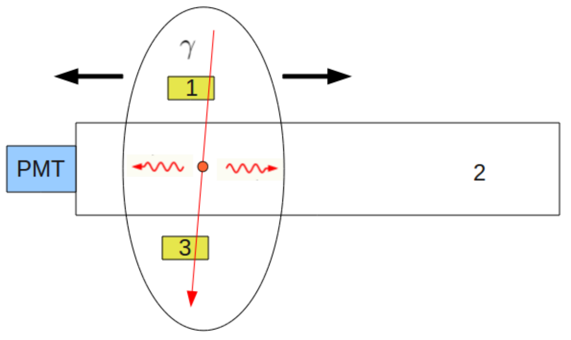
$$T_1 = \frac{L}{c} + \frac{yn}{c} \qquad T_2 = \frac{L}{c} + \frac{(l-y)v}{c}$$

$$y = \frac{c}{2n}(T_1 - T_2) + \frac{l}{2}$$

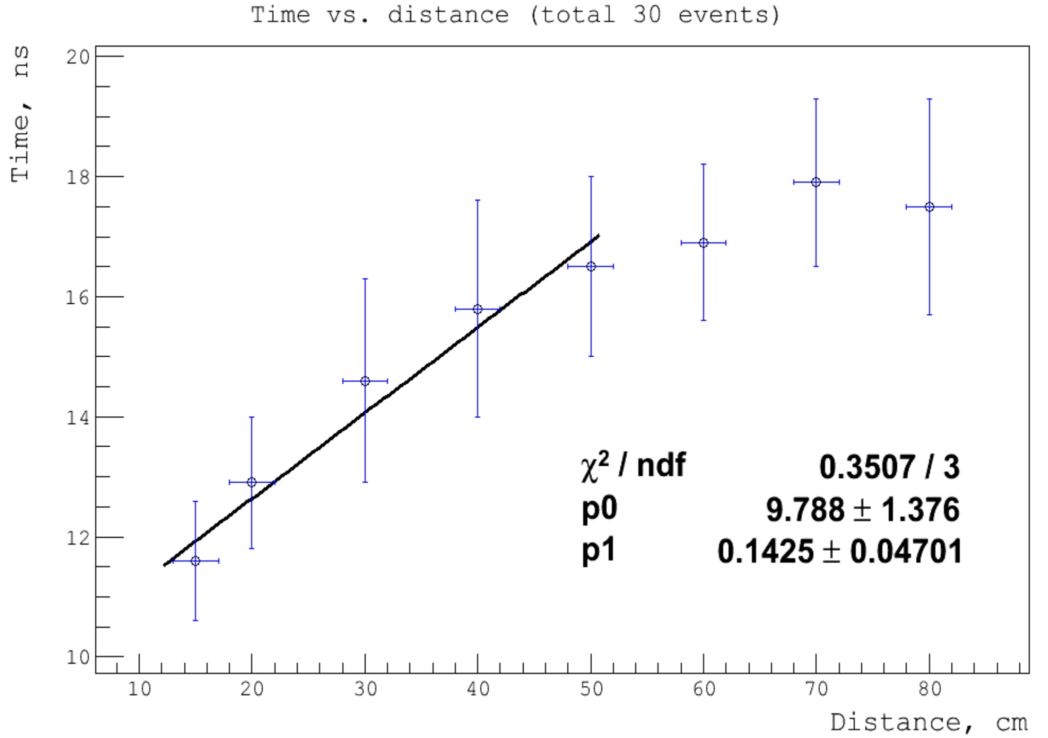
- Both techniques can be used to calculate the position where the neutron hits the detector.
- However the last method looks more simple and preferable

# Experimental set-up (5)

## Preliminary TOF measurements with 1 PMT attached to the end of the detector




Two small plastic detectors 1 and 2 were placed above and under the "big" plastic detector and were moved along the "big" one. The triple coincidence between detectors 1, 2 and 3 from the cosmic ray was used as a start signal to measure the time as a function of distance.




- The results show the ability to identify the source position as a function of measured TOF.
- The calculated average speed of light inside the scintillator is about 7 cm/nsec

Figure 3.5: TOF measurements with 1 PMT attached to the end of detector.

# Expected results. Asymmetry calculation (1)

**To estimate the expected asymmetry in 2n correlations, a Monte-Carlo simulation was performed:**

- 10 million fission events
- each neutron was sampled up to 10 MeV in the fission fragment rest frame.

**Assumption:**

- The $^{238}U$ with J = 1 and K = 0 is used as the fissionable target
- The fission fragment mass distribution is sampled uniformly between 85 < A < 105 and 130 < A < 150
- A fixed amount of total kinetic energy of 165 MeV is given to the two fission fragments and is distributed between them proportional to their mass ratio
- Each fission fragments emit one neutron. Neutrons are emitted isotropically in the center-of-mass of fully accelerated FF's with the energy distribution given by:

$$N(E) = \sqrt{E}\exp\left(-\frac{E}{0.75}\right)$$

- Two recoiled fission fragment are emitted back to back. The fission fragment angular distribution is sampled according to:

$$W(\Theta) = \frac{1}{2} - \frac{1}{2}\left(\frac{1}{2}(2 - 3\sin^2\Theta)\right) = \frac{3}{4}\sin^2\Theta$$

# Expected results. Asymmetry calculation (2)

After both angular and energy distributions of neutrons and FF's were sampled using the assumptions above, neutrons were boosted from the fission fragments rest frame into the laboratory frame

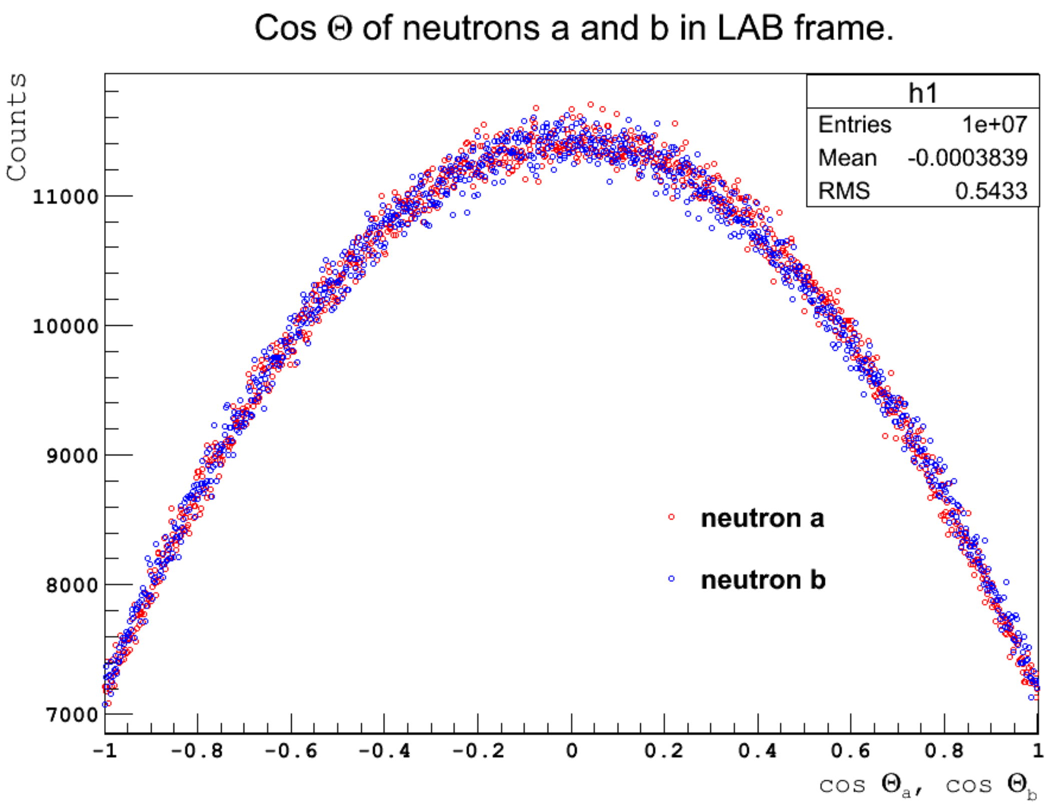
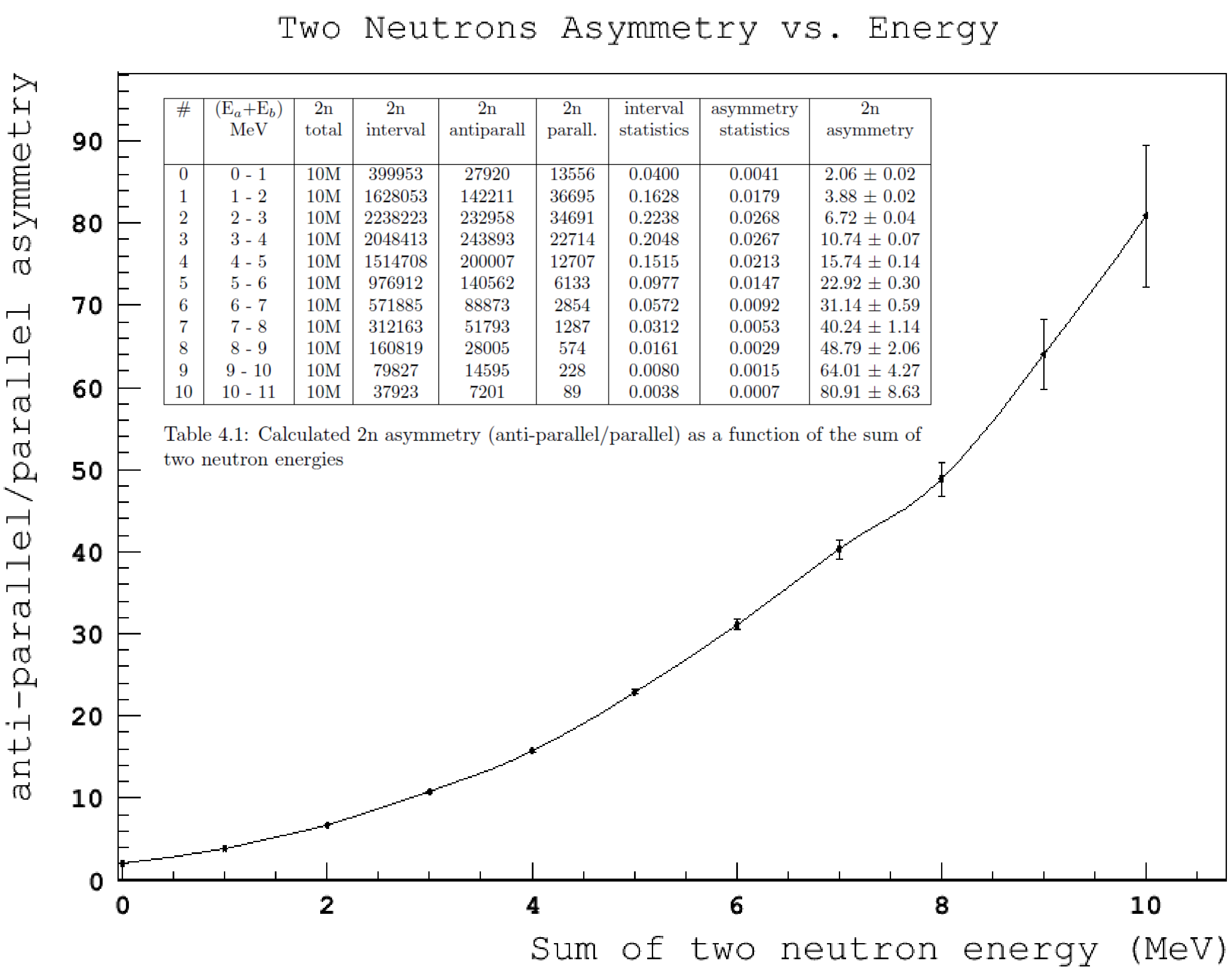



Figure 4.1: The energy distribution of sum of kinetic energy of two neutrons a and b emitted by fully accelerated fission fragments as seen in laboratory frame

- angular distributions of both neutrons a and b look statistically similar
- angular distribution is strongly anisotropic
- the angular distribution of the FF's is strongly manifested in the angular distribution of prompt neutrons in laboratory frame.

# Expected results. Asymmetry calculation (3)




| # | $(E_a+E_b)$ MeV | 2n total | 2n interval | 2n antiparall | 2n parall. | interval statistics | asymmetry statistics | 2n asymmetry |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 - 1 | 10M | 399953 | 27920 | 13556 | 0.0400 | 0.0041 | $2.06 \pm 0.02$ |
| 1 | 1 - 2 | 10M | 1628053 | 142211 | 36695 | 0.1628 | 0.0179 | $3.88 \pm 0.02$ |
| 2 | 2 - 3 | 10M | 2238223 | 232958 | 34691 | 0.2238 | 0.0268 | $6.72 \pm 0.04$ |
| 3 | 3 - 4 | 10M | 2048413 | 243893 | 22714 | 0.2048 | 0.0267 | $10.74 \pm 0.07$ |
| 4 | 4 - 5 | 10M | 1514708 | 200007 | 12707 | 0.1515 | 0.0213 | $15.74 \pm 0.14$ |
| 5 | 5 - 6 | 10M | 976912 | 140562 | 6133 | 0.0977 | 0.0147 | $22.92 \pm 0.30$ |
| 6 | 6 - 7 | 10M | 571885 | 88873 | 2854 | 0.0572 | 0.0092 | $31.14 \pm 0.59$ |
| 7 | 7 - 8 | 10M | 312163 | 51793 | 1287 | 0.0312 | 0.0053 | $40.24 \pm 1.14$ |
| 8 | 8 - 9 | 10M | 160819 | 28005 | 574 | 0.0161 | 0.0029 | $48.79 \pm 2.06$ |
| 9 | 9 - 10 | 10M | 79827 | 14595 | 228 | 0.0080 | 0.0015 | $64.01 \pm 4.27$ |
| 10 | 10 - 11 | 10M | 37923 | 7201 | 89 | 0.0038 | 0.0007 | $80.91 \pm 8.63$ |

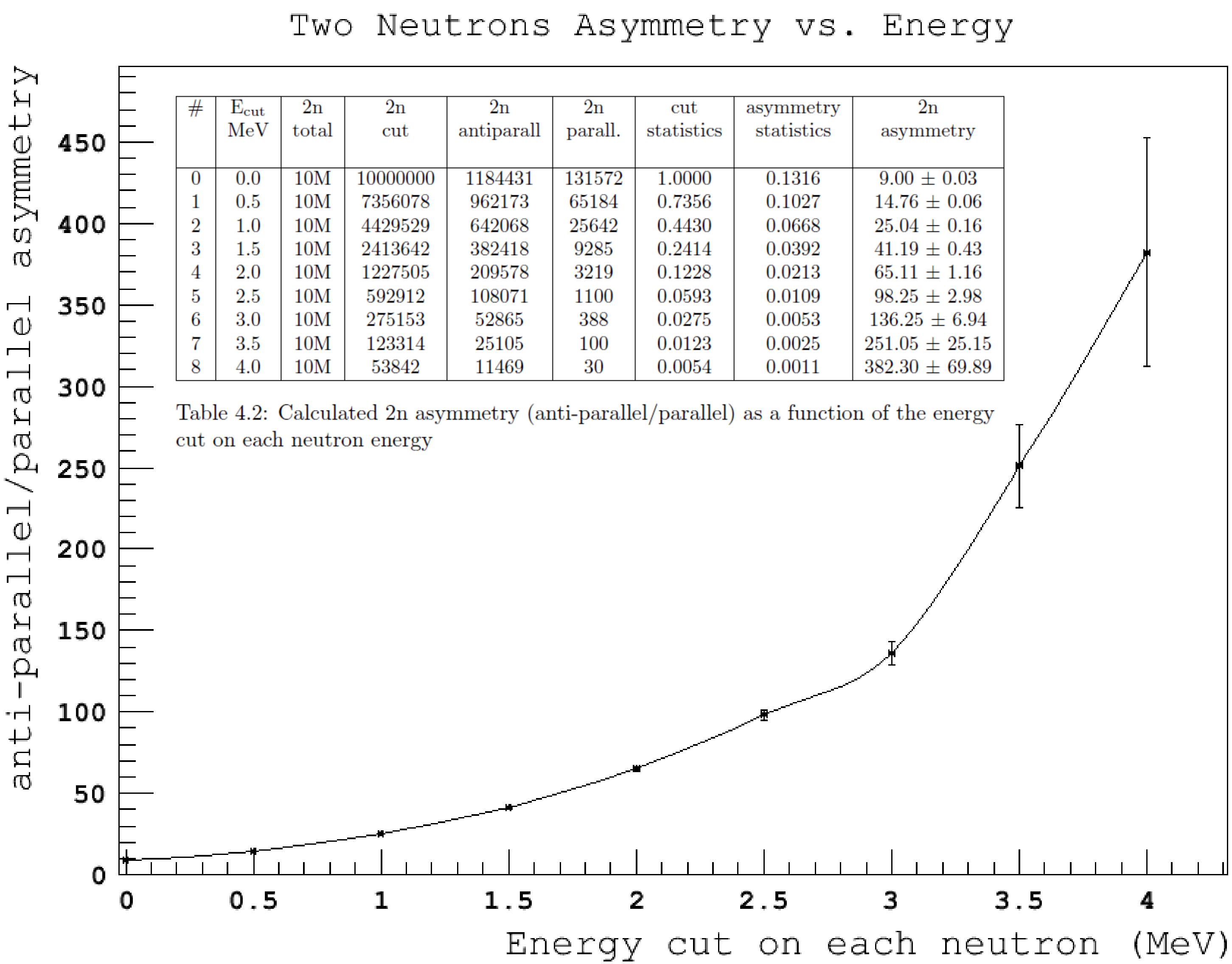
Table 4.1: Calculated 2n asymmetry (anti-parallel/parallel) as a function of the sum of two neutron energies

Antiparallel:
$\cos\theta_{2n} < -0.9$

Parallel:
$\cos\theta_{2n} > 0.9$

Figure 4.3: Calculated 2n asymmetry (antiparallel/parallel) as a function of the sum of two neutron energies

# Expected results. Asymmetry calculation (4)




| # | $E_{cut}$ MeV | 2n total | 2n cut | 2n antiparall | 2n parall. | cut statistics | asymmetry statistics | 2n asymmetry |
|---|---|---|---|---|---|---|---|---|
| 0 | 0.0 | 10M | 10000000 | 1184431 | 131572 | 1.0000 | 0.1316 | $9.00 \pm 0.03$ |
| 1 | 0.5 | 10M | 7356078 | 962173 | 65184 | 0.7356 | 0.1027 | $14.76 \pm 0.06$ |
| 2 | 1.0 | 10M | 4429529 | 642068 | 25642 | 0.4430 | 0.0668 | $25.04 \pm 0.16$ |
| 3 | 1.5 | 10M | 2413642 | 382418 | 9285 | 0.2414 | 0.0392 | $41.19 \pm 0.43$ |
| 4 | 2.0 | 10M | 1227505 | 209578 | 3219 | 0.1228 | 0.0213 | $65.11 \pm 1.16$ |
| 5 | 2.5 | 10M | 592912 | 108071 | 1100 | 0.0593 | 0.0109 | $98.25 \pm 2.98$ |
| 6 | 3.0 | 10M | 275153 | 52865 | 388 | 0.0275 | 0.0053 | $136.25 \pm 6.94$ |
| 7 | 3.5 | 10M | 123314 | 25105 | 100 | 0.0123 | 0.0025 | $251.05 \pm 25.15$ |
| 8 | 4.0 | 10M | 53842 | 11469 | 30 | 0.0054 | 0.0011 | $382.30 \pm 69.89$ |

Table 4.2: Calculated 2n asymmetry (anti-parallel/parallel) as a function of the energy cut on each neutron energy

Antiparallel:
$\cos\theta_{2n} < -0.9$

Parallel:
$\cos\theta_{2n} > 0.9$

Figure 4.4: Calculated 2n asymmetry (antiparallel/parallel) as a function of the energy cut on each neutron energy

# Expected results. Asymmetry calculation (5)

**What can be done extra to improve calculation:**

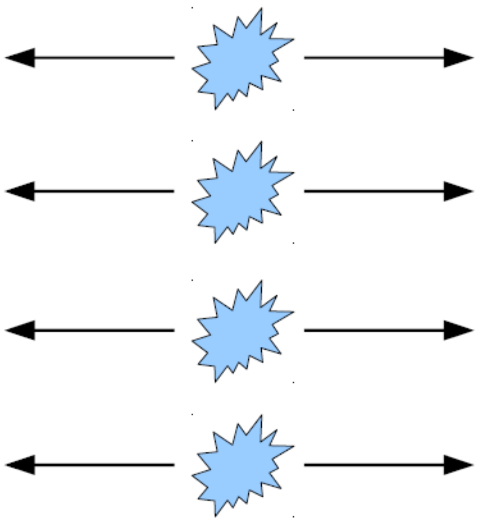
- Use realistic FF's mass distribution
- Use realistic multiplicity value
- Use separate nuclear temperature for each FF
- Use realistic total kinetic energy value of FFs
- Estimate the neutron multiple scattering effect inside the target.

- That all can be done later, however, the results of simulation show the huge asymmetry effect in 2n correlation. That will potentially permit a new technique for actinide detection for homeland security and safeguards applications.
- The very interesting physics can be done here.

# Expected results. Count rate calculation (1)

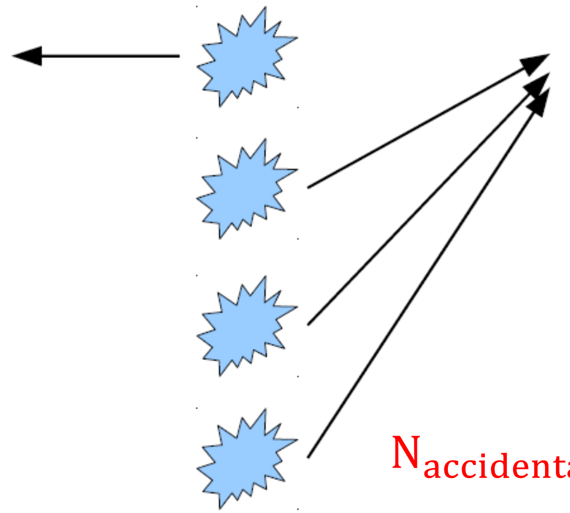
**Assume we have N fission events per beam pulse.**

True coincidence - between two neutrons
Coming from the same fission event



$$N_{true} = N$$

Accidental coincidence - between two neutrons
coming from the different fission events



$$N_{accidental} = N(N-1)$$

$$\frac{N_{true}}{N_{accidental} + N_{true}} = \frac{N}{N(N-1) + N} = \frac{1}{N}$$

We need to design the experiment in such a way
that the following condition is satisfied:

$$N = \frac{1 \text{ fission}}{\text{pulse}}$$

# Expected results. Count rate calculation (2)

Beam parameter:

- pulse width  τ = 20 ns
- Peak current I = 20 mA

$$N_{e^-} = 20 \cdot 10^{-3}\frac{\mathrm{C}}{\mathrm{sec}} \times \frac{1\ e^-}{1.6 \cdot 10^{-19}\mathrm{C}} \times 20\ \mathrm{ns} = 2.5 \cdot 10^{9}\frac{e^-}{\mathrm{pulse}}$$

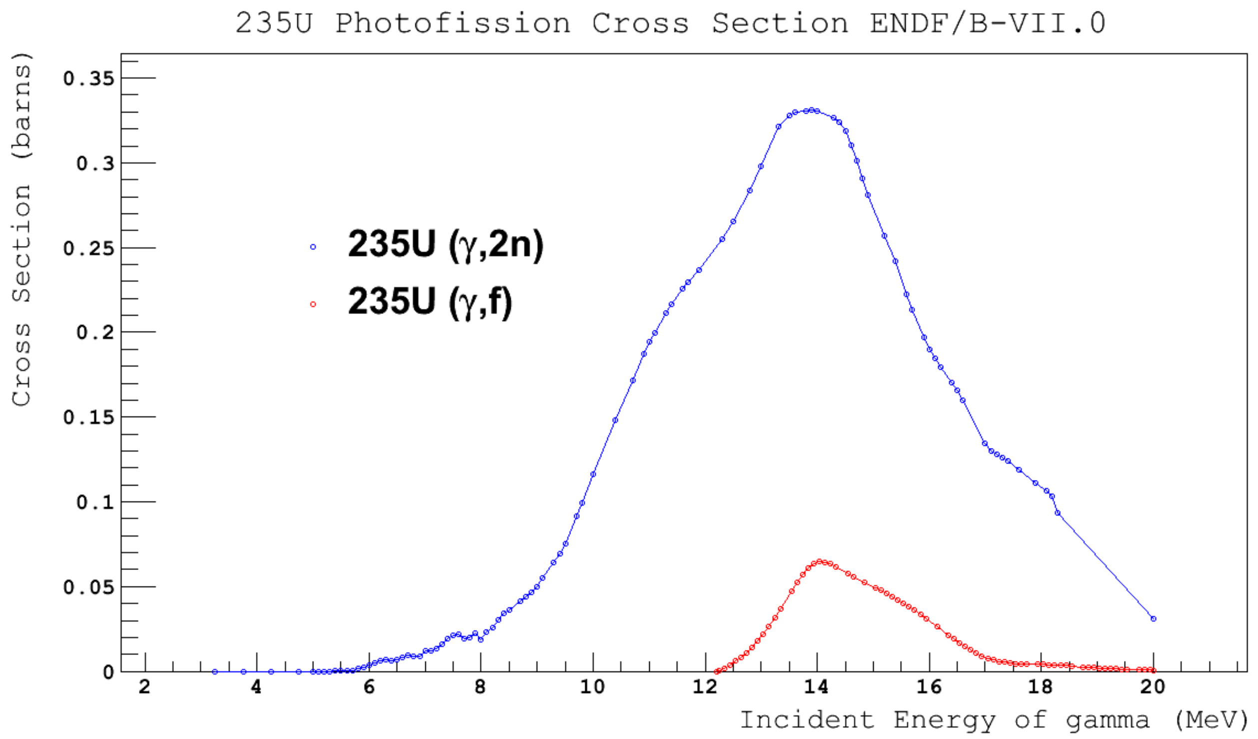



Figure 4.5: $^{235}$U photofission cross section taken from ENDF/B-VII.0

Optimal energy of incident gammas would be about 6-7 MeV:

- $(\gamma, \mathrm{f})$ cross-section is low
- no “2n knockout”
- study the pure $(\gamma, \mathrm{f})$

# Expected results. Count rate calculation (3)

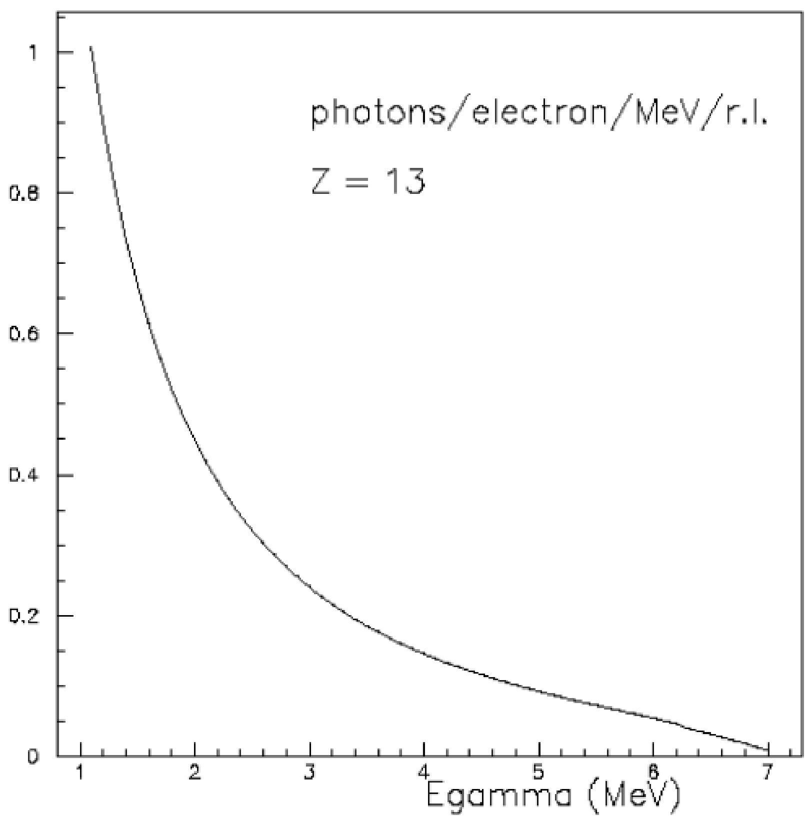



Figure 4.6: Bremsstrahlung spectrum of photons produced by 7 MeV electrons hitting the Al radiator

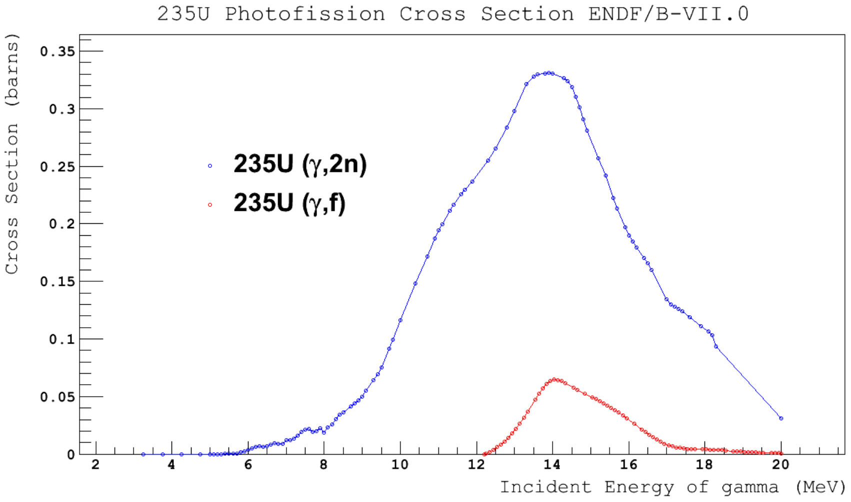
- 0.05 photons/$e^-$/MeV/r.l . in the 6-7 MeV region
- Al radiator $10^{-3}$ radiation length

$$N_{\gamma'} = 2.5 \cdot 10^9 \frac{e^-}{\text{pulse}} \times 0.05 \frac{\text{photons}}{e^- \text{ MeV r.l.}} \times 1 \text{ MeV} \times 10^{-3} \text{r.l.} = 1.25 \cdot 10^5 \frac{\gamma' s}{\text{pulse}}$$

# Expected results. Count rate calculation (4)

Assume collimation factor 50%:

$$N_{\gamma'} = 1.25 \cdot 10^5 \frac{\gamma' s}{pulse} \times 50\% = 6.25 \cdot 10^4 \frac{\gamma' s}{pulse}$$



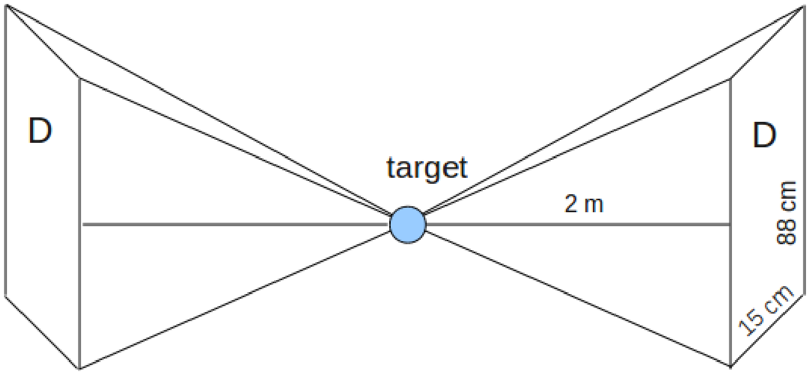

We want one fission per pulse:

$$\frac{1 \text{ fission}}{\text{pulse}} = N_\gamma \times t \times \sigma$$

Solve for $t = 2.29 \cdot 10^{21} \frac{atoms}{cm^2}$ or $t = 470\ \mu m$

- By varying t, we were able to satisfy the desired situation of having the 1 fission/pulse
- Also can vary: the thickness of radiator, the collimation hole.
- Also finally can vary: I and τ

# Expected results. Beam time calculation




$$\Omega = \frac{S}{r^2} = 2.6 \cdot 10^{-3} \text{rad}$$

Figure 4.7: Two detector geometry located 2 m away from target

The count rate for two neutron detectors, located 2 m away from the target

$$N\left[\frac{\text{coinc}}{\text{sec}}\right] = \frac{1 \text{ fission}}{\text{pulse}} \times N_G^2 \times N_{intr}^2 \times N_{cut} \times 2.2 \frac{\text{neutrons}}{\text{pulse}} \times 10^3 \text{Hz} = 4 \cdot 10^{-4} \frac{\text{coin}}{\text{sec}}$$

- $N_G$ is the geometrical detector efficiency, Ω
- $N_{intr}$ is the absolute intrinsic detector efficiency, assume 25%
- 2.2 is the average number neutron per pulse
- $10^3$ Hz is HRRL repetition rate

Total of 16 neutron detectors available: $N_{16\ det} = N \times 64 = 2.6 \cdot 10^{-2} \frac{\text{coin}}{\text{day}}$

**Run 1 day:** $\mathbf{N_{day} = N_{16\ det} \times 60\ sec \times 60\ min \times 8\ hours \approx 750 \frac{coin}{day}}$

# Summary, conclusion

- There is a need for in experimental data of two neutron correlation measurements in photossion of different materials.

- The preliminary calculation of the two neutron correlation shows a huge asymmetry effect: many more neutrons are emitted anti-parallel to each other than parallel to each other. That asymmetry becomes even more if the energy cut on each neutron is done. There are some factors, neutron multiple scattering effect, for example, that will reduce the calculated asymmetry and that could be calculated later. But that will not reduce the expected asymmetry significantly.

- We propose to measure and analyze the two neutron correlation yield resulting from two FF's as a function of different targets, the angle between the two neutrons and the neutron energies. There are a total of 16 “big” plastic detectors available at the present time, which can be used for neutron detection. With the High Repetition Rate Linac we can get about 750 coincidences per day.

- This study will potentially permit a new technique for actinide detection for homeland security and safeguards applications as well as improve our knowledge of correlated neutron emission.

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# Expected results. Asymmetry calculation

| # | $(E_a+E_b)$ MeV | 2n total | 2n interval | 2n antiparall | 2n parall. | interval statistics | asymmetry statistics | 2n asymmetry |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 - 1 | 10M | 399953 | 27920 | 13556 | 0.0400 | 0.0041 | $2.06 \pm 0.02$ |
| 1 | 1 - 2 | 10M | 1628053 | 142211 | 36695 | 0.1628 | 0.0179 | $3.88 \pm 0.02$ |
| 2 | 2 - 3 | 10M | 2238223 | 232958 | 34691 | 0.2238 | 0.0268 | $6.72 \pm 0.04$ |
| 3 | 3 - 4 | 10M | 2048413 | 243893 | 22714 | 0.2048 | 0.0267 | $10.74 \pm 0.07$ |
| 4 | 4 - 5 | 10M | 1514708 | 200007 | 12707 | 0.1515 | 0.0213 | $15.74 \pm 0.14$ |
| 5 | 5 - 6 | 10M | 976912 | 140562 | 6133 | 0.0977 | 0.0147 | $22.92 \pm 0.30$ |
| 6 | 6 - 7 | 10M | 571885 | 88873 | 2854 | 0.0572 | 0.0092 | $31.14 \pm 0.59$ |
| 7 | 7 - 8 | 10M | 312163 | 51793 | 1287 | 0.0312 | 0.0053 | $40.24 \pm 1.14$ |
| 8 | 8 - 9 | 10M | 160819 | 28005 | 574 | 0.0161 | 0.0029 | $48.79 \pm 2.06$ |
| 9 | 9 - 10 | 10M | 79827 | 14595 | 228 | 0.0080 | 0.0015 | $64.01 \pm 4.27$ |
| 10 | 10 - 11 | 10M | 37923 | 7201 | 89 | 0.0038 | 0.0007 | $80.91 \pm 8.63$ |

Table 4.1: Calculated 2n asymmetry (anti-parallel/parallel) as a function of the sum of two neutron energies

| # | $E_{cut}$ MeV | 2n total | 2n cut | 2n antiparall | 2n parall. | cut statistics | asymmetry statistics | 2n asymmetry |
|---|---|---|---|---|---|---|---|---|
| 0 | 0.0 | 10M | 10000000 | 1184431 | 131572 | 1.0000 | 0.1316 | $9.00 \pm 0.03$ |
| 1 | 0.5 | 10M | 7356078 | 962173 | 65184 | 0.7356 | 0.1027 | $14.76 \pm 0.06$ |
| 2 | 1.0 | 10M | 4429529 | 642068 | 25642 | 0.4430 | 0.0668 | $25.04 \pm 0.16$ |
| 3 | 1.5 | 10M | 2413642 | 382418 | 9285 | 0.2414 | 0.0392 | $41.19 \pm 0.43$ |
| 4 | 2.0 | 10M | 1227505 | 209578 | 3219 | 0.1228 | 0.0213 | $65.11 \pm 1.16$ |
| 5 | 2.5 | 10M | 592912 | 108071 | 1100 | 0.0593 | 0.0109 | $98.25 \pm 2.98$ |
| 6 | 3.0 | 10M | 275153 | 52865 | 388 | 0.0275 | 0.0053 | $136.25 \pm 6.94$ |
| 7 | 3.5 | 10M | 123314 | 25105 | 100 | 0.0123 | 0.0025 | $251.05 \pm 25.15$ |
| 8 | 4.0 | 10M | 53842 | 11469 | 30 | 0.0054 | 0.0011 | $382.30 \pm 69.89$ |

Table 4.2: Calculated 2n asymmetry (anti-parallel/parallel) as a function of the energy cut on each neutron energy