Comparison of Incident and Modulated Neutron Flux Inside a High Flux Neutron Generator in the Presence of a Polyethylene Shield.

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INTRODUCTION

Deuteron and tritium based neutron generators are becoming ubiquitous in research labs, particularly university research labs, due to the following reasons, among others: (1) They are relatively of low cost and easy to acquire or build. (2) They are easy to operate than the conventional research reactor making it easy to operate. (3) They produce far less radiation and radioactive waste than a conventional research reactor used as neutron source. In this paper the discussion is only on fusion of two deuteron atoms to produce neutrons.

When two deuterons undergo nuclear fusion, the process proceed with two reaction channels according to the following:

$$ {}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + {}^{1}_{0}n \quad (1) $$

$$ {}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{1}H + {}^{1}_{1}p \quad (2) $$

with equal probability owing to the fact that the nuclear force is charge symmetric, hence the probability of ejecting either neutron in the case of (1) or proton in the case of (2) are equal [1]. The energy and yield of neutrons produced by the HFNG shows an angular dependence.

The department of Nuclear Engineering, University of California Berkeley built a deuteron-deuteron neutron generator known as High Flux Neutron Generator (HFNG), that is currently used for fundamental research. Figure 1 shows a CAD drawing of the HFNG [2]. In the design, there are two ion sources. The target is at the center and has changed a lot in design from angled to flat shape. The deuteron is accelerated at a voltage of between 100 – 125 keV with plan to push the voltage up a bite.

A Monte Carlo simulation, using MCNP5 [3], and its default ENDF/B-VII.1 data, is used to find the relationship between the incident and modulated neutron fluxes when the HFNG is surrounded with polyethylene. There are situations that require the use of modulated neutrons. Thus, it becomes inevitable to find how the two fluxes relate to each other. However, before the simulation can be done, the angular dependence of energy and yield of neutrons need to be determined.

Energy distribution of neutrons

Energy of the produced neutrons varies with the incident deuteron energy and shows angular dependence. This angular dependence can be approximated very well by fitting experimental data with Legendre polynomials. Reference [4] gives this distribution at 100 keV as a least square fit of data from [5]. This polynomial is given in equation (3).

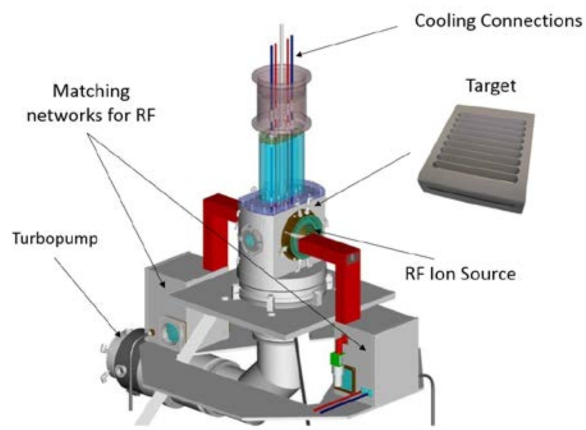

Fig. 1. CAD drawing of the HFNG. (Source: Ref. [2].)

$$ E_n(E_d, \theta) = E_0 + \sum_{i=1}^{n} E_i Cos^i \theta \quad (3) $$

where E_d is the deuteron energy, E_n is the neutron energy and $E_i s$ are constants that depends on the incident deuteron energy. At incident deuteron energy of 100 keV the angular distribution of the energy of produced neutrons is shown in table 1.

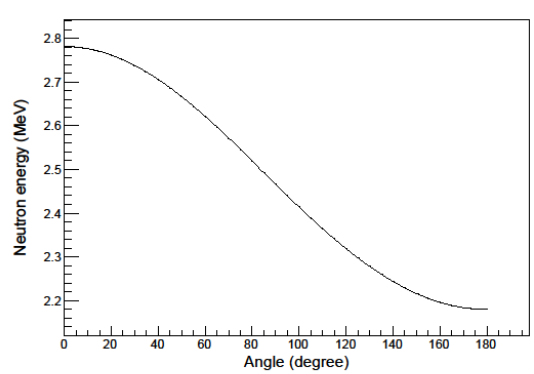

Fig. 2. Angular distribution of neutron energy.

Angular distribution of neutron yield.

As well as showing angular dependence in energy, neutrons produced in D(d, n)^{3}He also shows angular dependency in yield. This angular dependence is given by Ref. [4] as a least square fit to experimental data in Ref. [5] and is given in equation (4)

$$Y(\theta) = Y(90^o) \times \left(1 + \sum_{i=1}^{n} A_i cos^i\theta\right) \qquad (4)$$

where $Y(90^o)$ is the yield at 90°. The parameters A_i, for i greater than 1 refers to the anisotropy in the yield of neutrons. This anisotropy depends on the bombarding deuteron energy [4]. Multiplying (4) by the differential cross section at 90^0 1.02 mb/sr [5] gives the differential cross section at other angle θ:

$$\frac{d\sigma}{d\Omega} = \sigma(\theta) = \sigma(90^0)Y(\theta) \qquad (5)$$

A plot of (5) is shown in figure 3. It shows that the differential cross-section, and hence yield, is forward peaked.

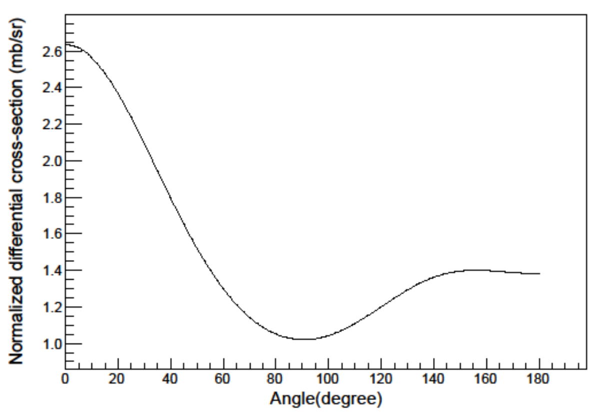

Fig. 3. Differential cross section for D(d, n)^{3}He at deuteron energy of 100 keV.

The cross section as a function of angle, $\sigma(\theta)$ is given by:

$$\sigma(\theta) = \int \frac{d\sigma(\theta)}{d\Omega} d\Omega \qquad (6)$$

Where $d\Omega$ is the solid angle subtended by a detector that detects one of the products. $d\Omega = \sin\theta d\theta d\phi$.
Therefore, (6) becomes

$$\sigma(\Delta\theta) = \int_0^{2\pi} d\phi \int_{\theta_i}^{\theta_{i+1}} \frac{d\sigma(\theta)}{d\Omega} \sin\theta d\theta = 2\pi \int_{\theta_i}^{\theta_{i+1}} \frac{d\sigma(\theta)}{d\Omega} \sin\theta d\theta$$

The above is for thin target. HFNG uses thick target, so a thick target parameter was incorporated. The thick target yield, $dY(E_d, \theta)$ was used to normalize $\sigma(\Delta\theta)$. $dY(E_d,\theta)$ was calculated using Simulation of Range of Ion in Matter (SRIM) [6] and implemented in [2]. Thus, probability of producing neutrons at azimuthal angle θ is given by:

$$f(\theta) = \sigma(\theta) \frac{Y(\theta)}{\sum_{\theta=0}^{\pi} Y(\theta)} \qquad (7)$$

THE SIMULATION

Using equations (3), (4) and (8), a source input was generated for use in the input file of MCNP. The angle from 0 to 180 degree was divided into 180 cosine bins for the purpose of tabulating the angular dependency of energy and yield. The simulation was divided into two: the first one with polyethene covering the top and sides of the HFNG. It was not practical covering the bottom of the HFNG. More so, the bottom contains mazes of cables and support. The second simulation was done without any polyethylene cover. MCNP plot of the two geometries are shown in figures 4 and 5.

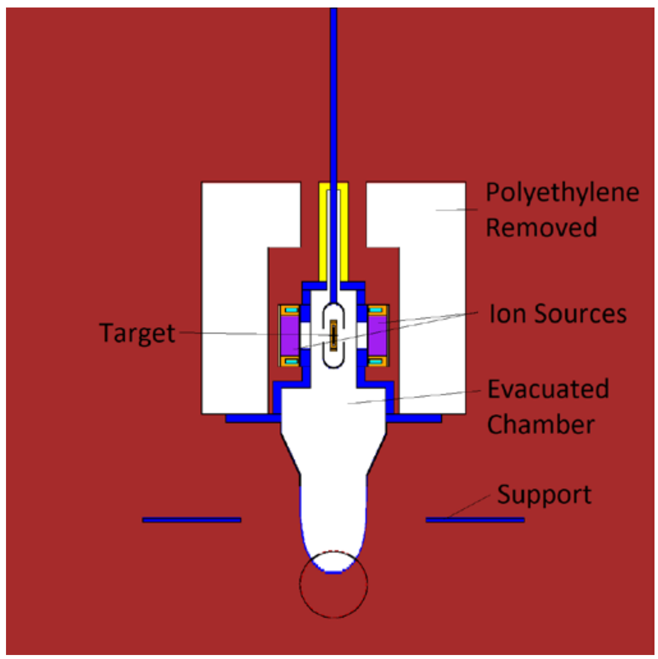

Fig. 4. MCNP geometry of the HFNG without polyethylene surrounding it.

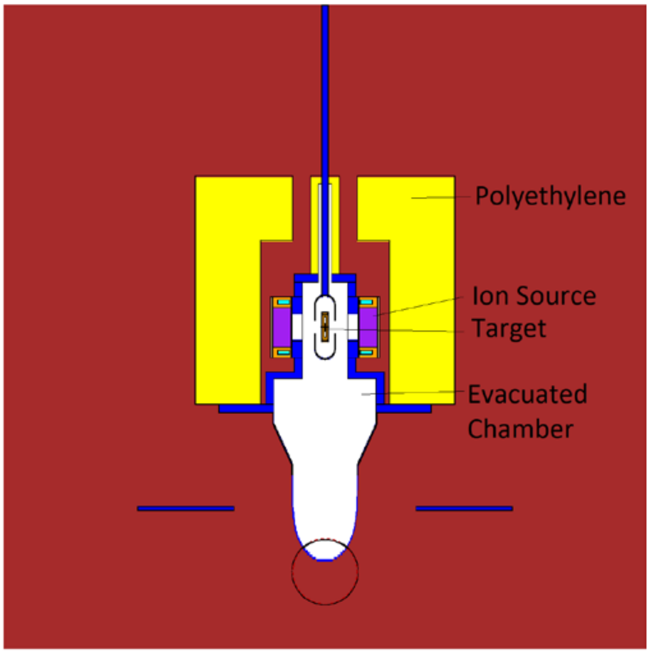

Fig. 5. MCNP geometry of the HFNG with polyethylene surrounding it. The polyethylene is 20 cm thick.

Superimposed FMESH tally was used to tally the number of ${}^{115m}_{49}In$ and ${}^{116m}_{49}In$ produced, in each case, at the center, according to the reactions

$$ {}^{115}_{49}In + \mathrm{n} \rightarrow {}^{115m}_{49}In + n^{*} \quad (8)$$

$$ {}^{115}_{49}In + \mathrm{n} \rightarrow {}^{116m}_{49}In + \gamma \quad (9)$$

The FMESH represents an indium disc of radius 0.495 cm and thickness of 0.05 cm, positioned 0.696cm from the point where neutrons are produced. A billion neutrons were simulated using one of the Berkeley High Performance Computer clusters.

RESULTS

A table of production rate of the two products of interest, and are shown in table 1. As could be seen from the table, the production of ${}^{115m}_{49}In$ is practically unaffected by presence of the polyethene. This is because the first reaction (8) is a threshold reaction with threshold of about 336 keV and the scattering of neutrons by carbon and hydrogen atoms either reduces their energy below threshold or lowers it to such a value where the reaction cross-section is practically zero. (See figure 6).

Table I. Rates of reaction for production of ${}^{115m}_{49}In$ and ${}^{115m}_{49}In$ normalized by the number of incident neutrons.

Reaction	Poly		No Poly	
	Rate(/neutron/s)	Fractional error	Rate(/neutron/s)	Fractional error
${}^{116m}_{49}In$	7.087E-05	1.861E-02	2.987E-05	1.360E-02
${}^{115m}_{49}In$	9.254E-05	8.522E-05	9.253E-05	8.434E-05
${}^{115m}_{49}In/{}^{116m}_{49}In$	1.306	0.019	3.098	0.014

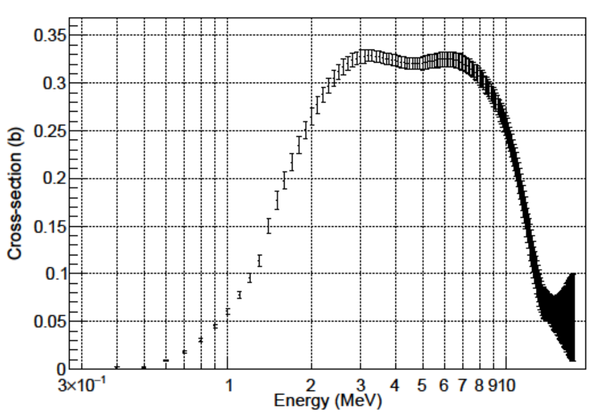

Fig. 6. Cross section for formation of ${}^{115m}_{49}In$ [7].

Thus, in an experiment involving thermal neutrons in which a deuteron-deuteron neutron generator is surrounded with polyethylene, the incident neutron flux produced by the generator could be monitored using reaction (8) without worrying of the effect of modulated neutrons.

Relating incident and modulated flux.

The ratio $\frac{N_{In-115m}}{N_{In-116m}}$ for presence of polyethylene shield, tabulated in table 1 as ${}^{115m}_{49}In/{}^{116m}_{49}In$ is given by:

$$R_{Poly} = \frac{\left(N\sum\left(\phi_{inc}(E)\sigma_{inc}(E)\right)_{115m}\right)_{poly}}{\left(N\left(\sum\left(\phi_{mod}(E)\sigma_{mod}(E)\right)+\sum\left(\phi_{inc}(E)\sigma_{inc}(E)\right)\right)_{116m1}\right)_{poly}}$$

$$= \left[\left(\frac{N\sum\left(\phi_{mod}(E)\sigma_{mod}(E)\right)_{116m}}{N\sum\left(\phi_{inc}(E)\sigma_{inc}(E)\right)_{115m}}\right)_{poly} + \left(\frac{N\sum\left(\phi_{inc}(E)\sigma_{inc}(E)\right)_{116m}}{N\sum\left(\phi_{inc}(E)\sigma_{inc}(E)\right)_{115m}}\right)_{poly}\right]^{-1}$$

where ϕ_{inc} = flux of incident neutrons, ϕ_{mod} = flux of modulated neutrons.

Since capture without polyethylene cover is dominated by capture in the incident neutron flux region, as stated earlier, due to $^{115m}_{49}In$ having relatively very small cross-section in moderated neutron region, one can write.

$$\left(\frac{N\sum\left(\phi_{inc}(E)\sigma_{inc}(E)\right)_{116m}}{N\sum\left(\phi_{inc}(E)\sigma_{inc}(E)\right)_{115m}}\right)_{poly} \approx \left(\frac{N\sum\left(\phi_{inc}(E)\sigma_{inc}(E)\right)_{116m}}{N\sum\left(\phi_{inc}(E)\sigma_{inc}(E)\right)_{115m}}\right)_{no\ poly} \approx R^{-1}_{No\ Poly}$$

where $R_{No\ Poly}$ is the ratio $\frac{N_{In-115m}}{N_{In-116m}}$ in the absence of polyethylene and tabulated in table 1 as $^{115m}_{49}In/^{116m}_{49}In$.

$$\therefore R_{Poly} \approx \left(x + R^{-1}_{No\ Poly}\right)^{-1}$$

Where

$$x = \left(\frac{\sum\left(\phi_{mod}(E)\sigma_{mod}(E)\right)_{116m}}{\sum\phi_{inc}(E)\sigma_{inc}(E)_{115m}}\right)_{poly}$$

Or $x = \left(\frac{\sum\left(\phi_{mod}(E)\sigma_{mod}(E)\right)_{116m}}{\sum\phi_{inc}(E)\sigma_{inc}(E)_{115m}}\right)_{poly} \approx {R_{Poly}}^{-1} - R^{-1}_{No\ Poly}$

$= 0.443.$

Using average modulated neutron cross section of 153.2 barns taken from ENDF/B-VI.1, and cross section at 2.78 MeV (320 mb) for the reaction (8) gotten from [7]. Thus:

$$\phi^{avg}_{mod} = 9.2 \times 10^{-4}\phi^{avg}_{inc}$$

Conclusion

Thus, with polyethylene shield, the modulated flux is still insignificant compared to the flux of D-D neutron at the center. The flux of neutron inside can be taken as that of fast incident flux. Since polyethylene has more moderating power than all surrounding structures such as the concrete wall, it implies that those surrounding structures doesn't practically degrade the incident neutron spectrum.

Acknowledgements

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