A Measurement of the $^{12}C(n,2n)^{11}C$ Cross-Section Needed for an Inertial Confinement Fusion Diagnostic

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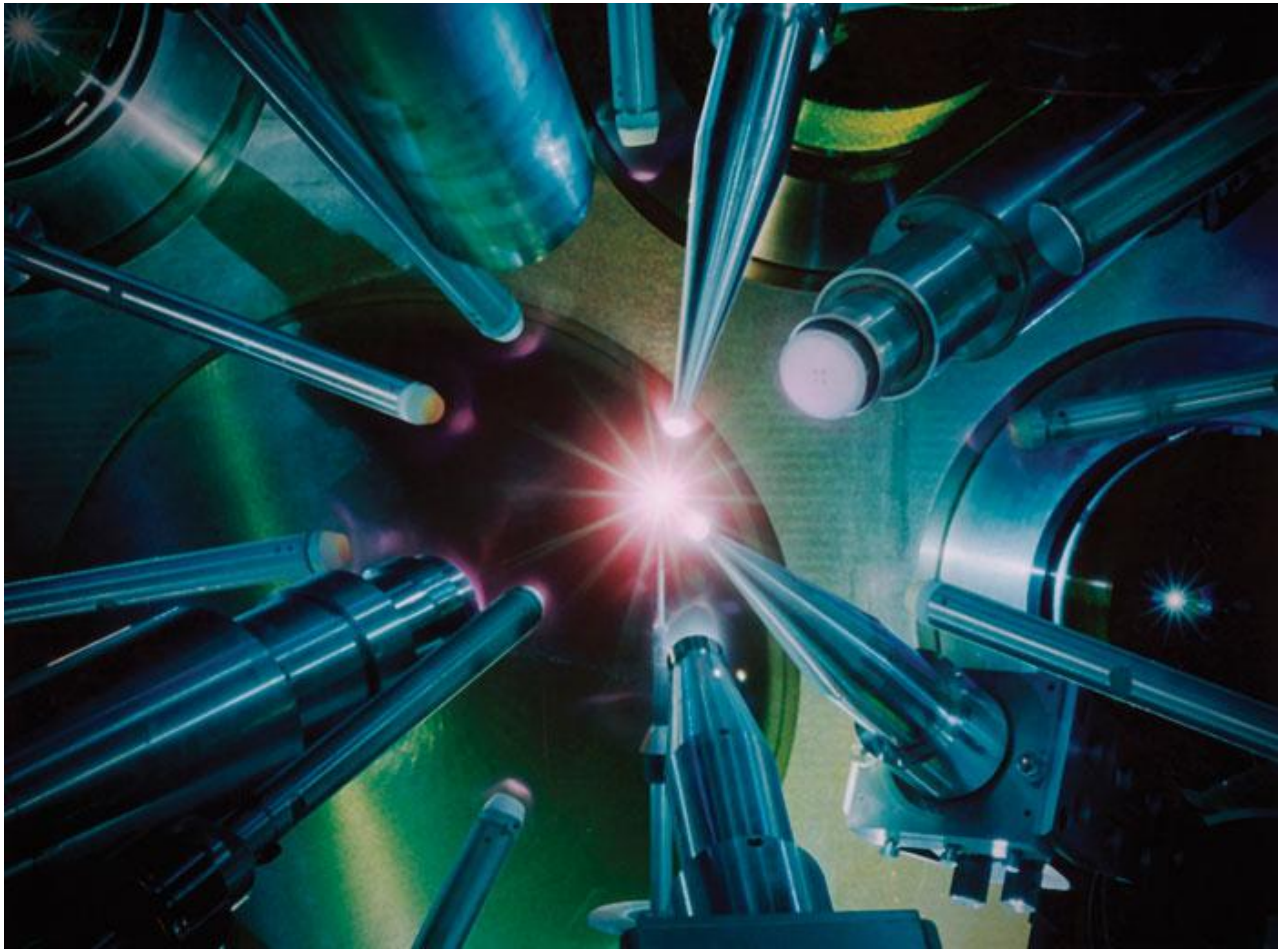
Inertial Confinement Fusion (ICF)

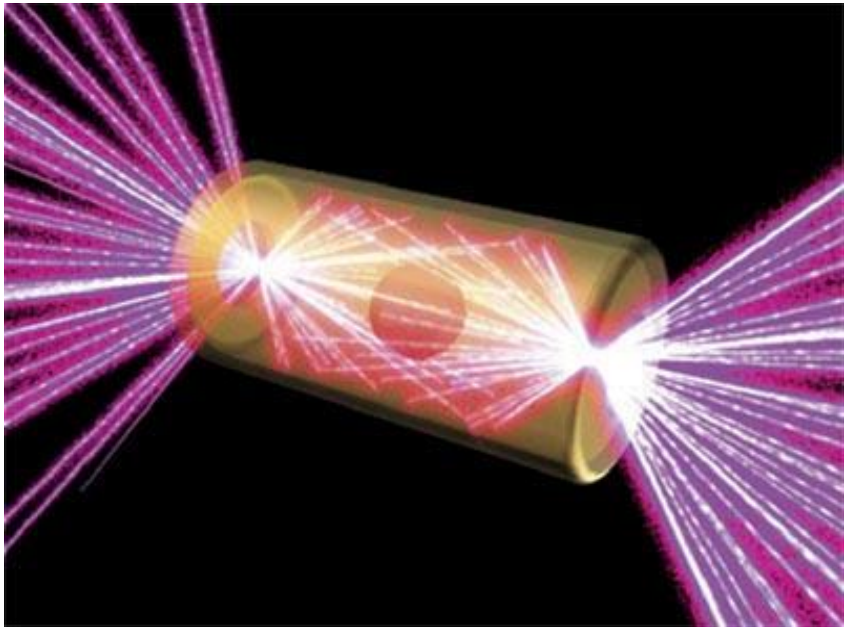


Credit:
Lawrence Livermore
National Laboratory

The ρR Parameter

Determine fraction of fuel burned, f_{b}

$$\rho R \propto \frac{f_{\mathrm{b}}}{1 - f_{\mathrm{b}}}$$



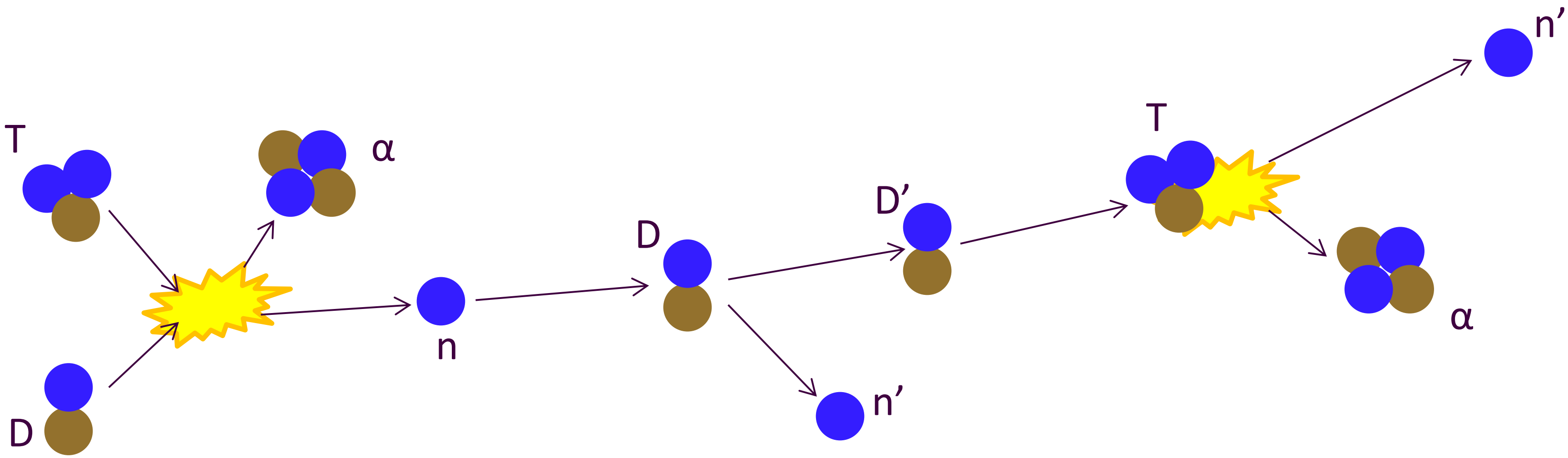
Credit: Lawrence Livermore National Laboratory

ICF Reactions

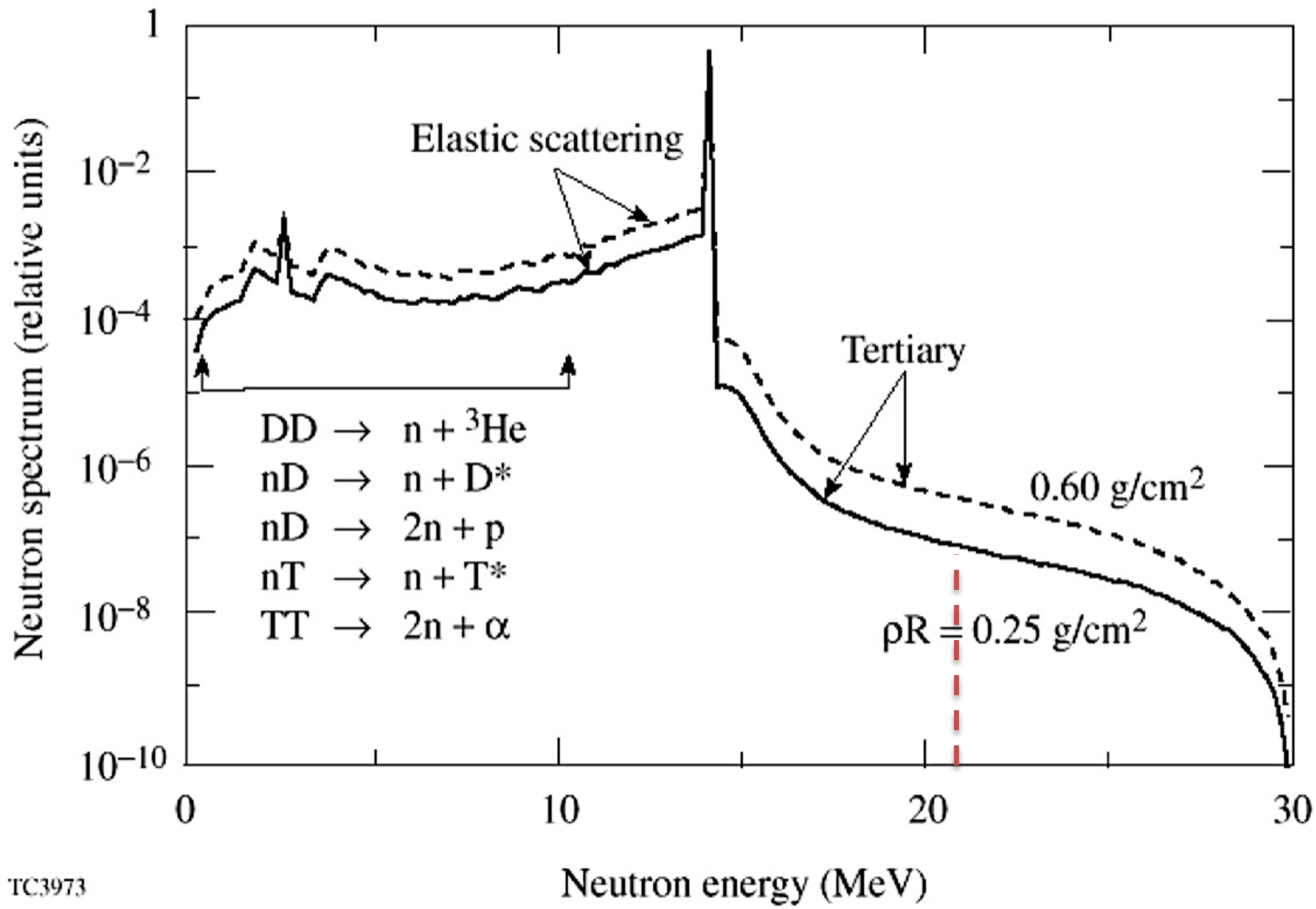
$$\mathrm{D} + \mathrm{T} \rightarrow \alpha + n(14.1\ \mathrm{MeV})$$

$$n + \mathrm{D}\ (\mathrm{or\ T}) \rightarrow n' + \mathrm{D}'(\mathrm{or\ T}')$$

$$\mathrm{D}' + \mathrm{T}\ (\mathrm{or\ D} + \mathrm{T}') \rightarrow \alpha + n''(12 - 30\ \mathrm{MeV})$$



Why Tertiary Neutrons

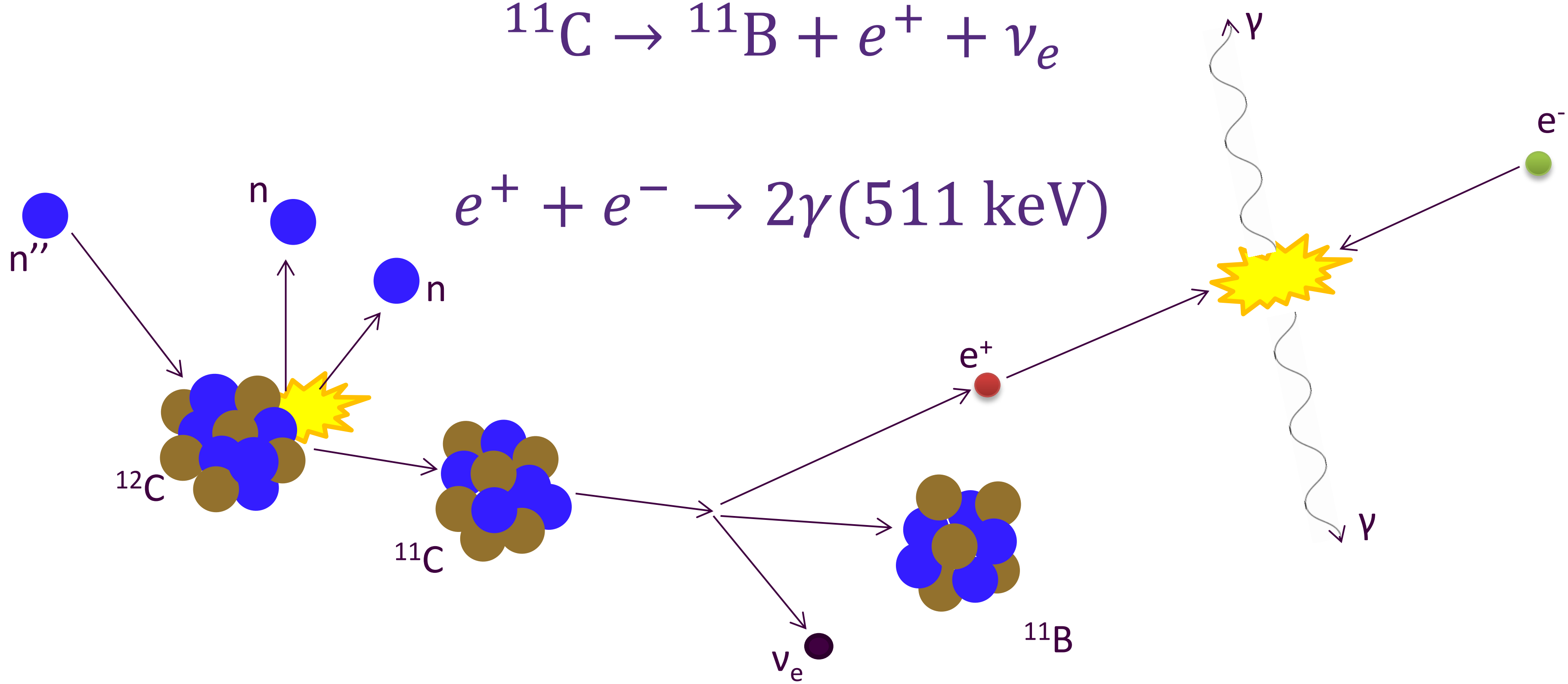


^{12}C(n,2n)^{11}C Reaction and Decay

$$n'' + {}^{12}\mathrm{C} \rightarrow 2n + {}^{11}\mathrm{C}$$

$$^{11}\mathrm{C} \rightarrow {}^{11}\mathrm{B} + e^{+} + \nu_e$$

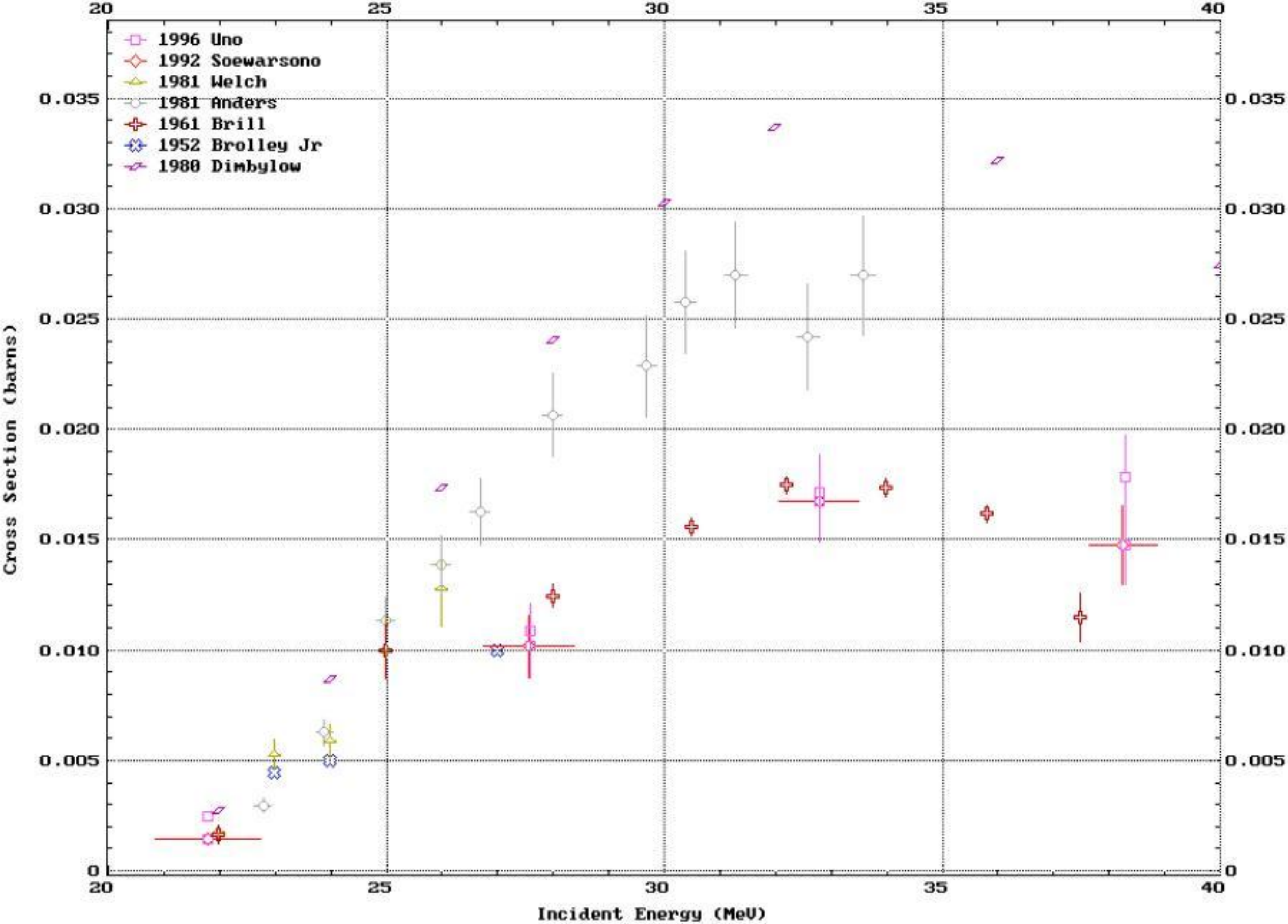
$$e^{+} + e^{-} \rightarrow 2\gamma(511\ \mathrm{keV})$$



Cross Sections

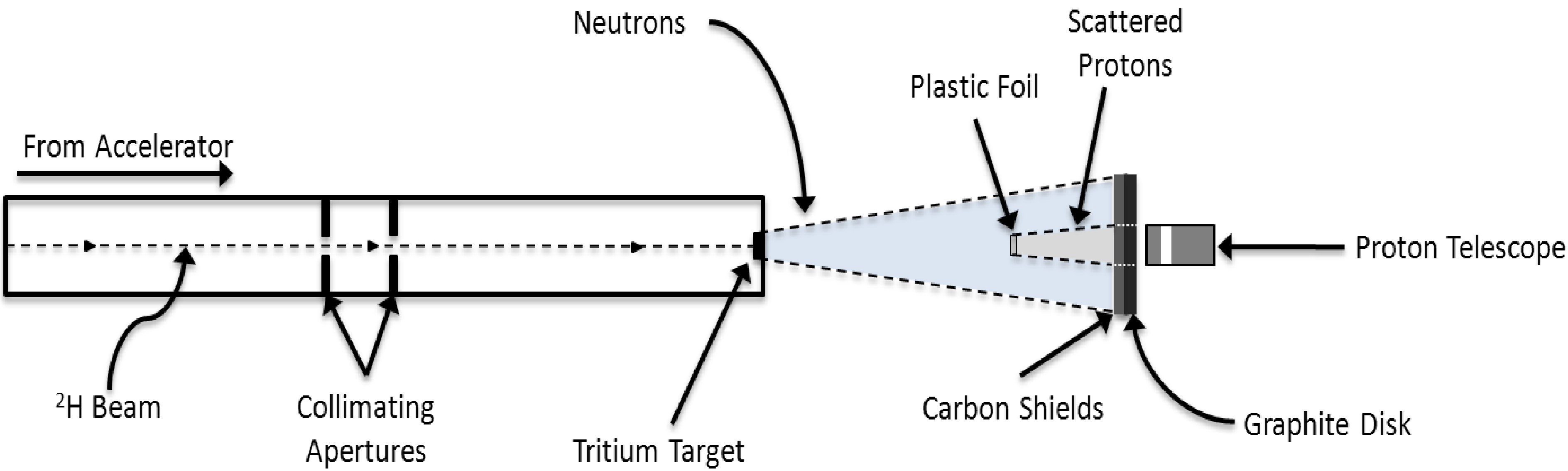
Likelihood of a reaction occurring

$$\sigma_{n,2n} \propto \frac{N_{^{11}C}}{N_{n''}}$$



1996 Uno
1992 Soewarsono
1981 Welch
1981 Anders
1961 Brill
1952 Brolley Jr
1980 Dimbylow
Cross Section (barns)
Incident Energy (MeV)
20
25
30
35
40
0
0.005
0.010
0.015
0.020
0.025
0.030
0.035

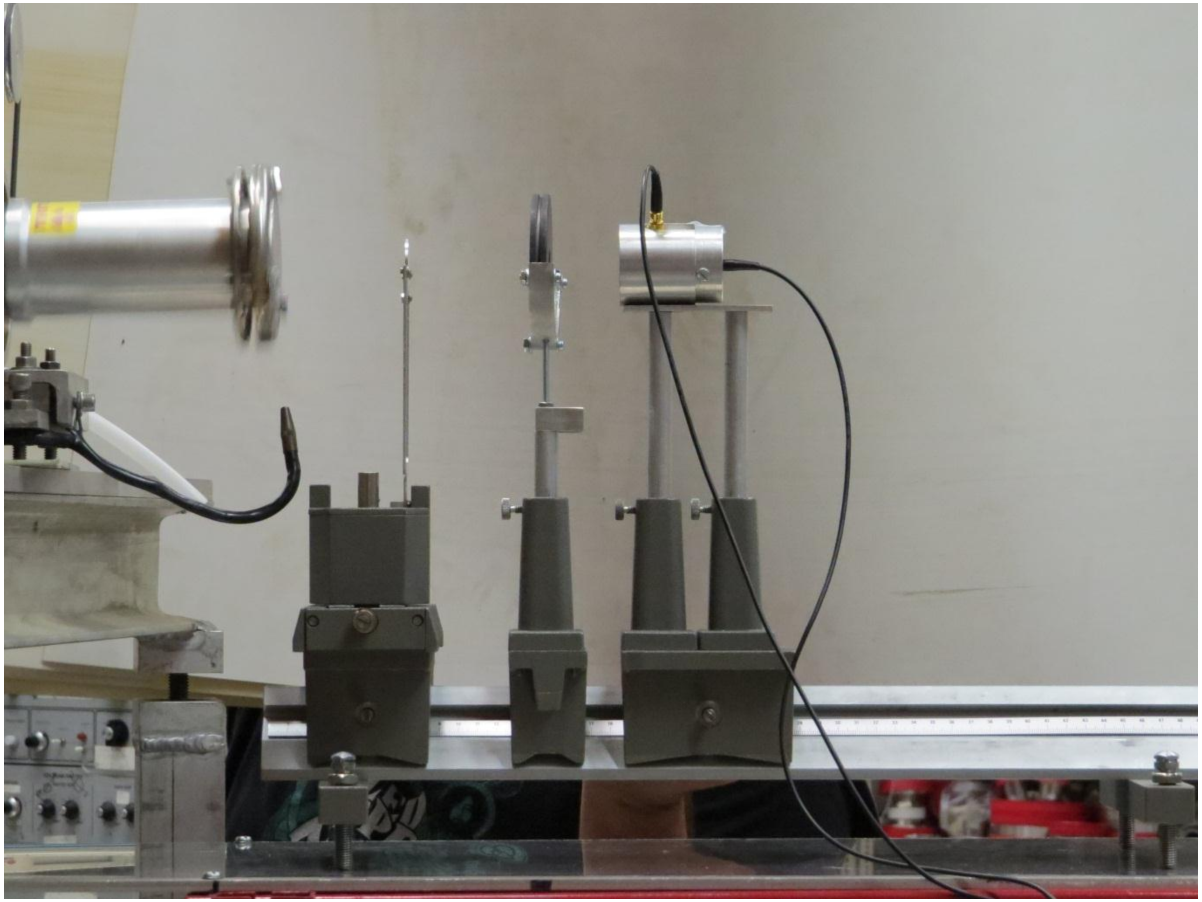
Measurements for Cross Section Determination



$$\sigma_{n,2n} \propto \frac{N_{^{11}C}}{N_{n''}}$$

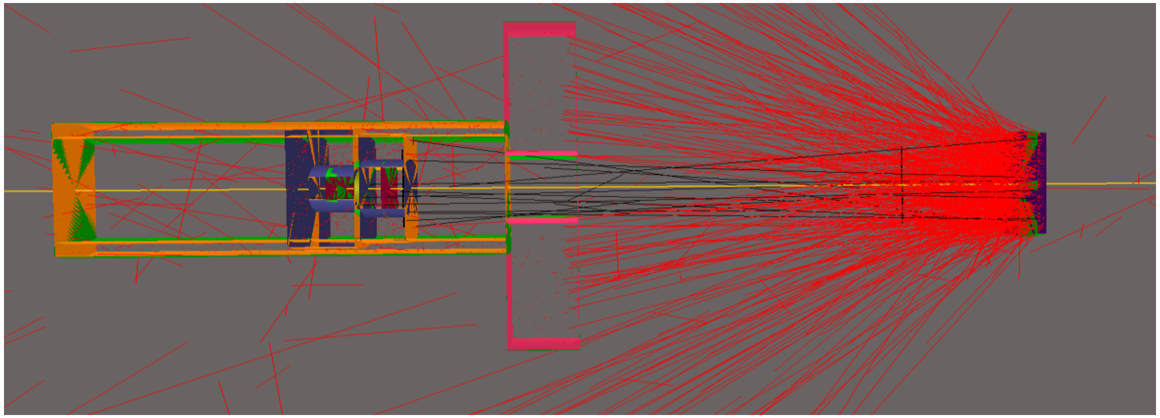
$$N_{n''} \propto N_p$$

Experiment at Ohio University



Improvements on prior experiments

- Ability to determine incident neutron flux
- Monoenergetic neutrons
- Proton identification
- Positron decay coincidence



SRI 2012 Experimental Design

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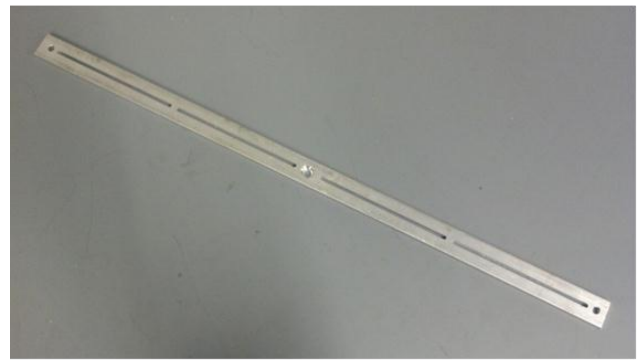
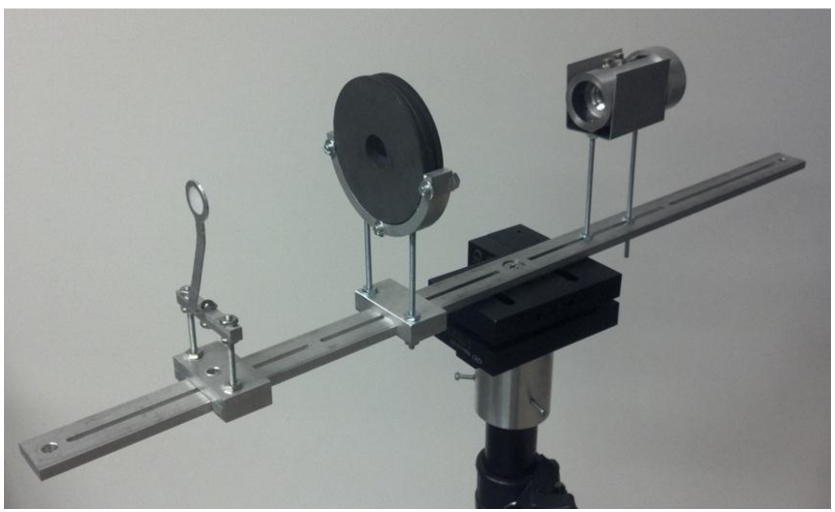
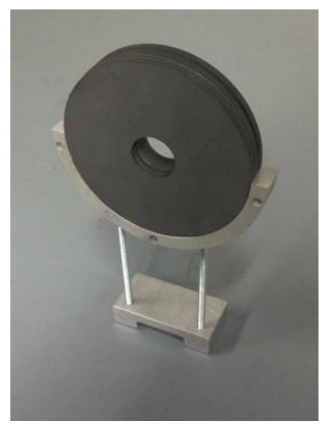
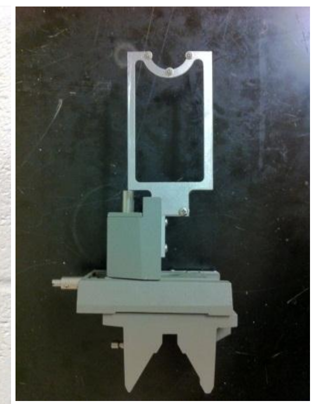
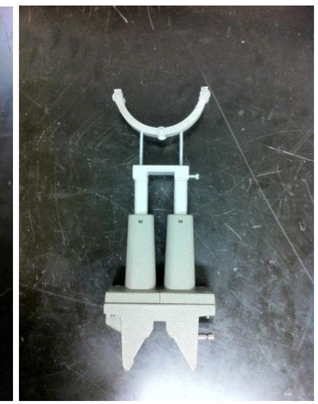
- Design focused on use of minimal material.
- 2000µm E detector utilized.

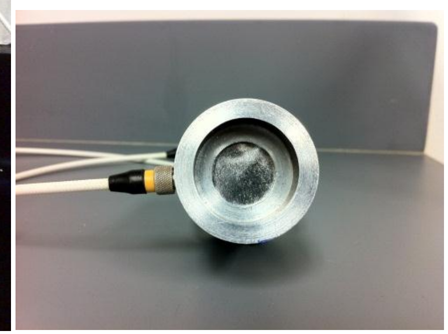




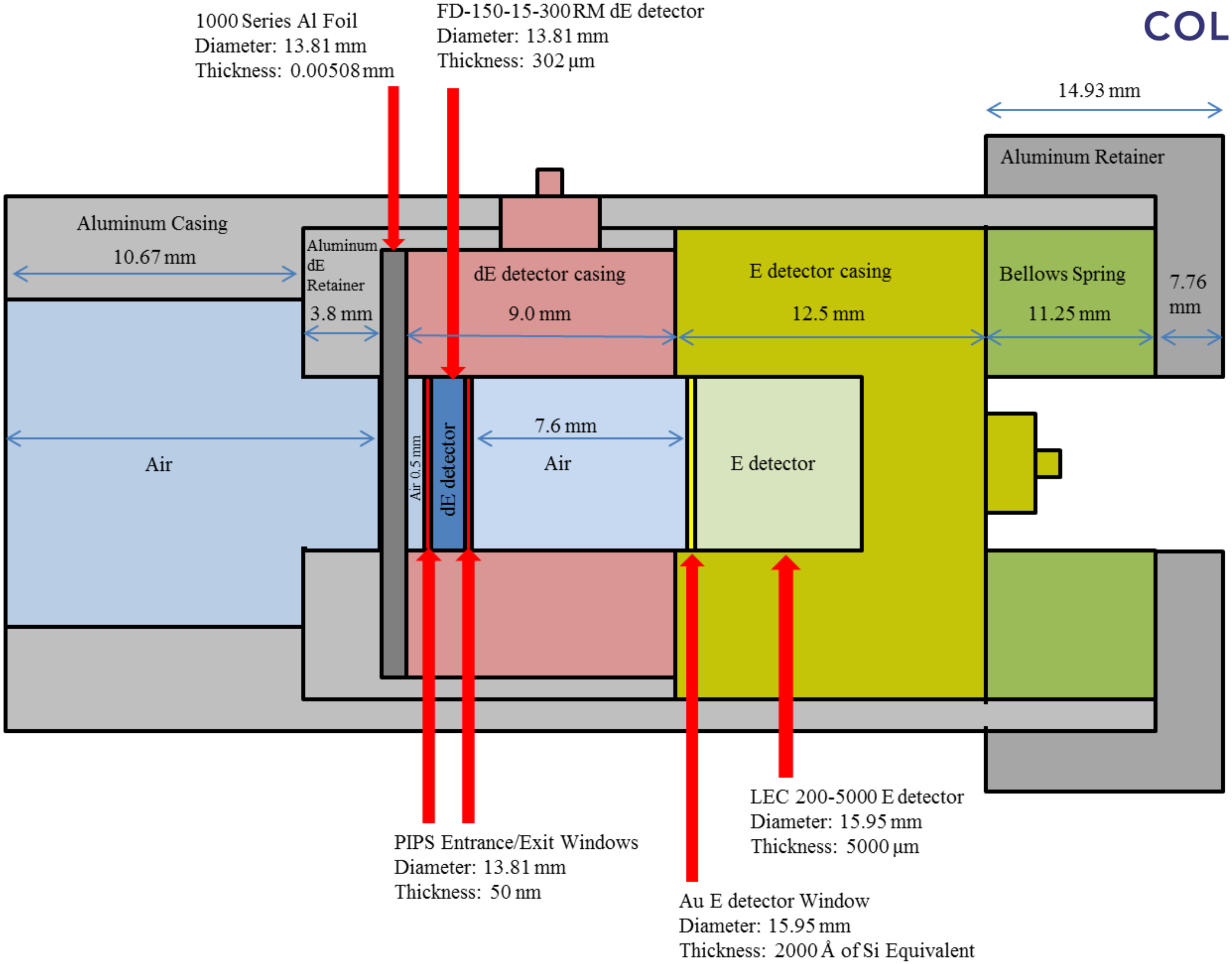


SRI 2013 Experimental Design

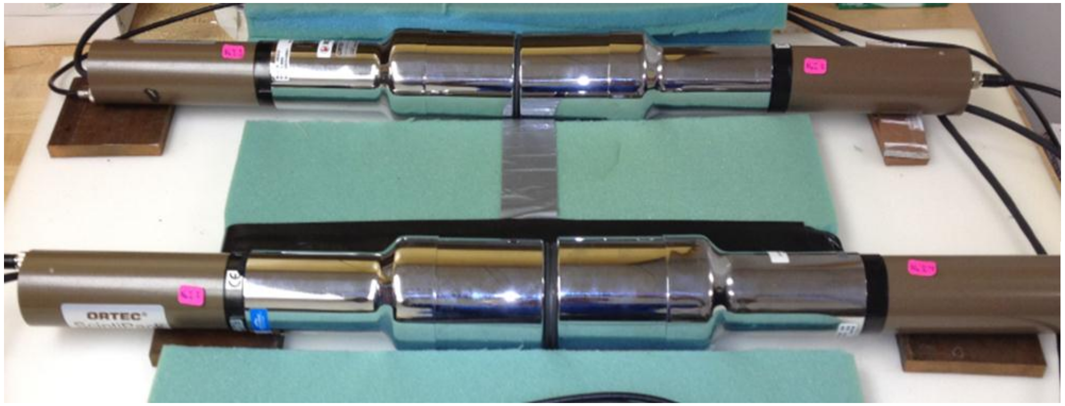






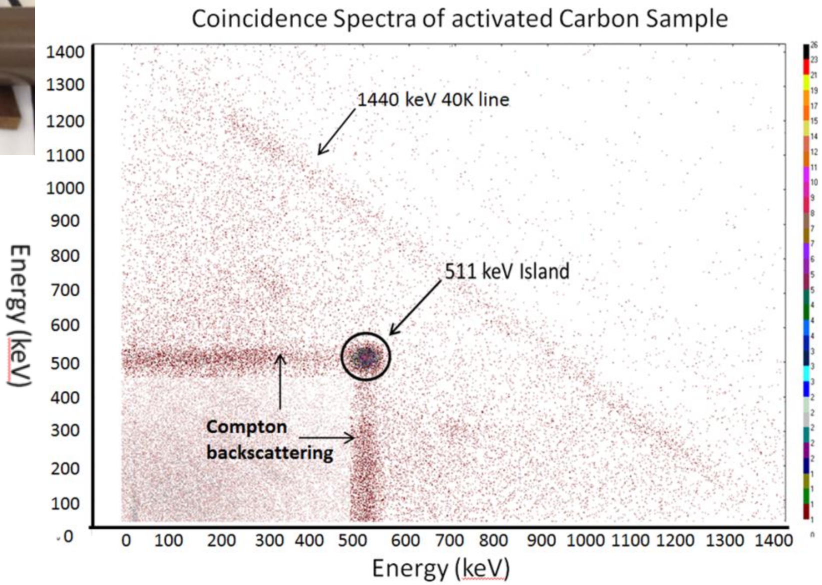

Proton Telescope



Counting Station



- Pairs of NaI detectors in coincidence are used to count ^{11}C decays in the target and shielding graphite.



NaI Efficiency Apparatus

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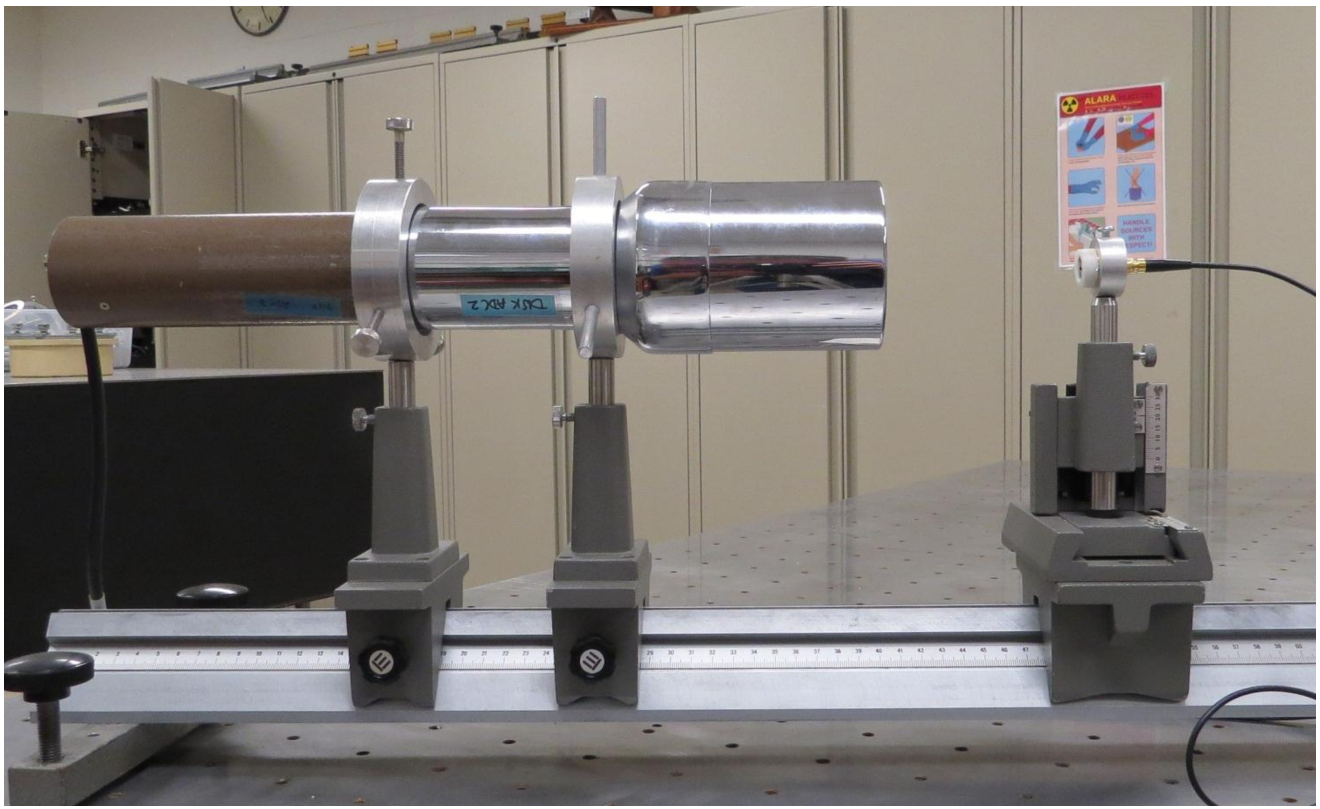
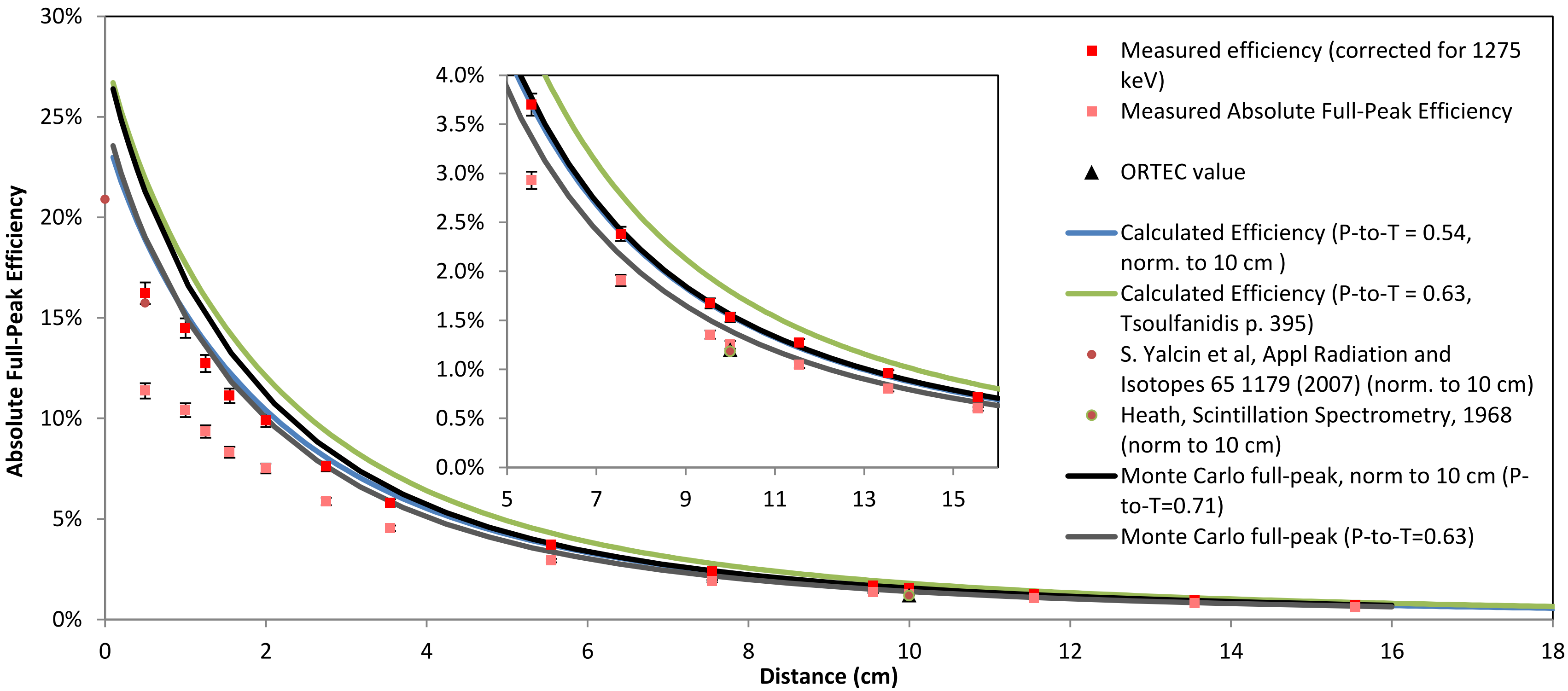


NaI Detector Efficiency



Cross-Section Calculation

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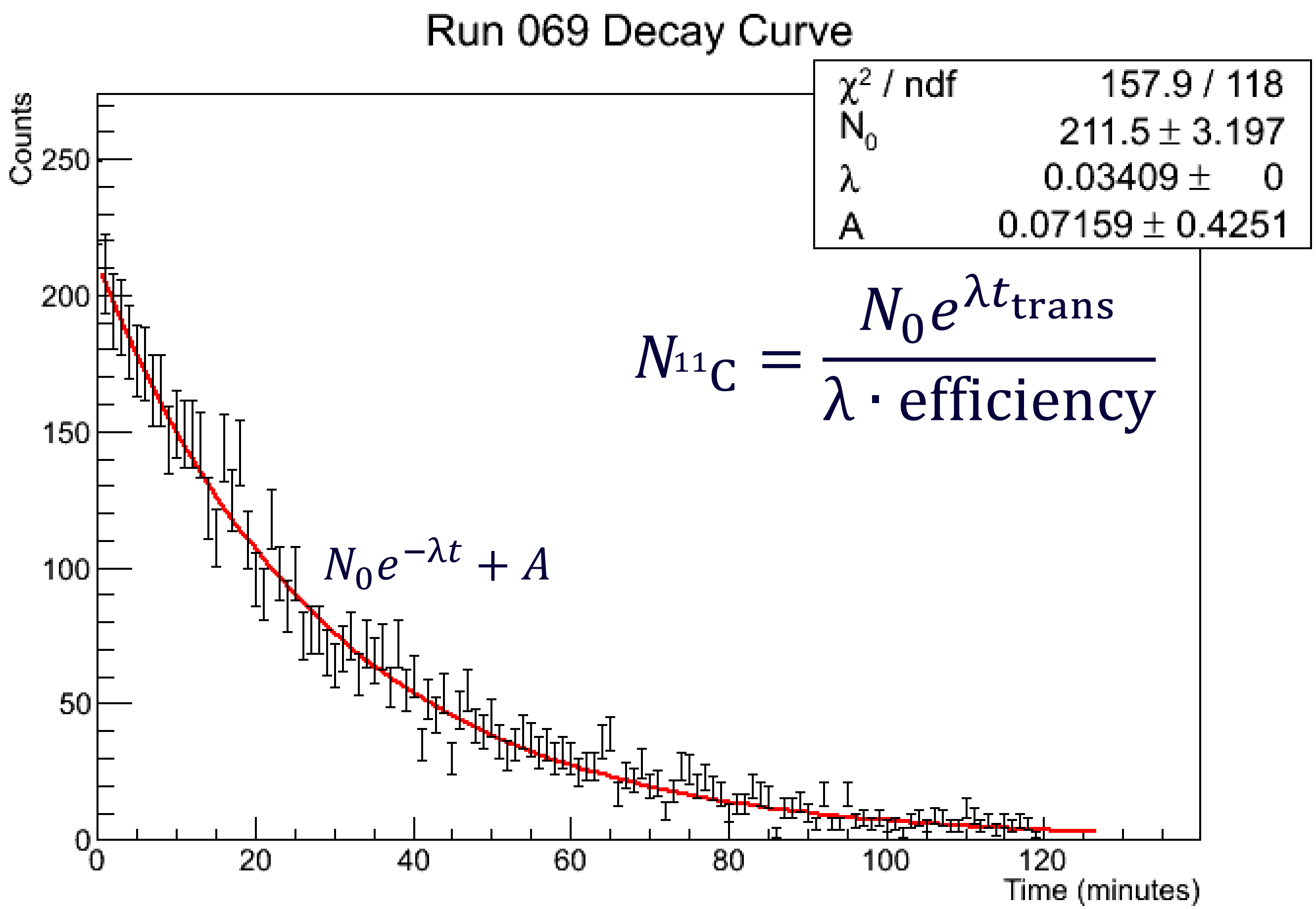
$$\frac{dN_{^{11}C}}{dt} = \sigma_{n2n} N_n T_C - \lambda N_{^{11}C}$$

$$\sigma_{n2n} = \frac{N_{^{11}C}\,\lambda}{N_n T_C (1 - e^{-\lambda\, t})} = \frac{N_{^{11}C}\,\lambda}{T_C (1 - e^{-\lambda\, t})} \left(\frac{N_p}{N_n}\right) \frac{1}{N_p}$$

^{11}C Activation Count, N_{C11}

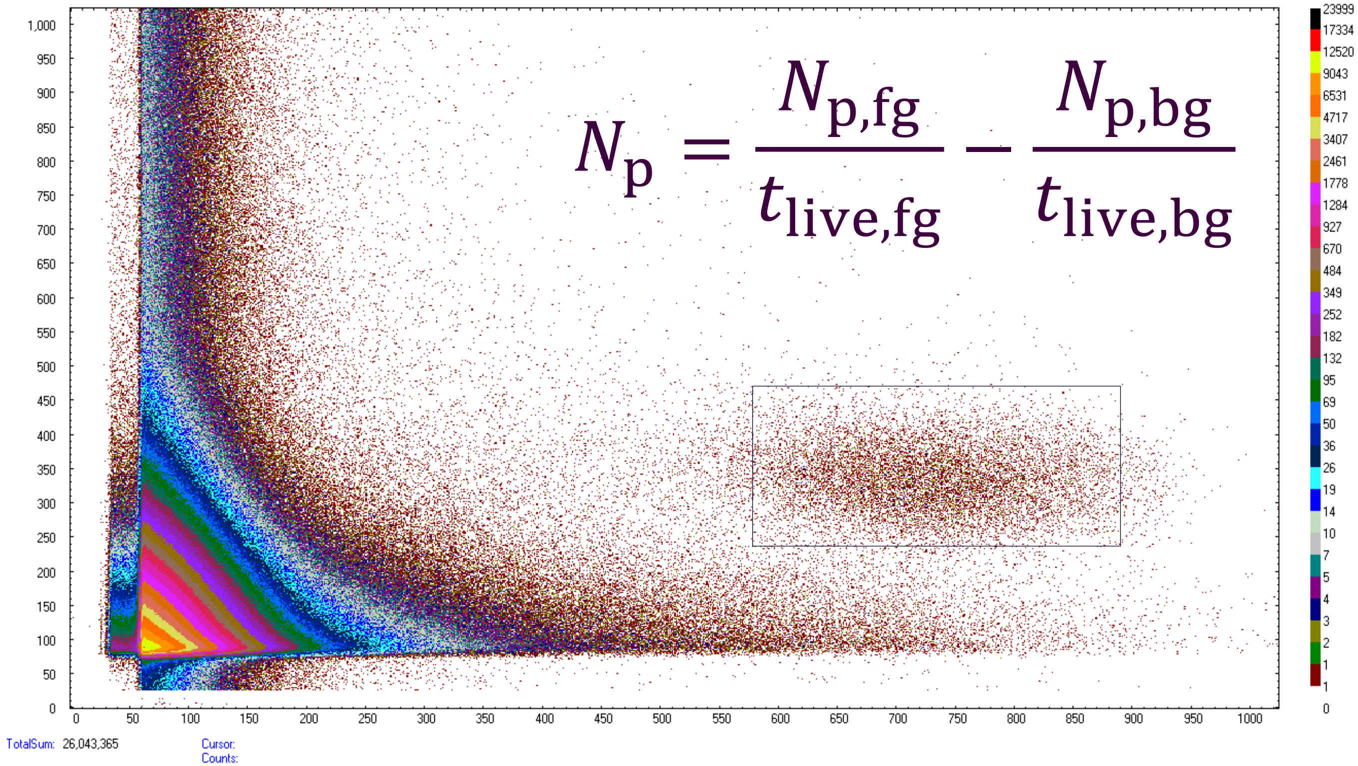


$$N_0 e^{-\lambda t} + A$$

$$N_{^{11}\mathrm{C}} = \frac{N_0 e^{\lambda t_{\mathrm{trans}}}}{\lambda \cdot \mathrm{efficiency}}$$

Proton Flux, N_p

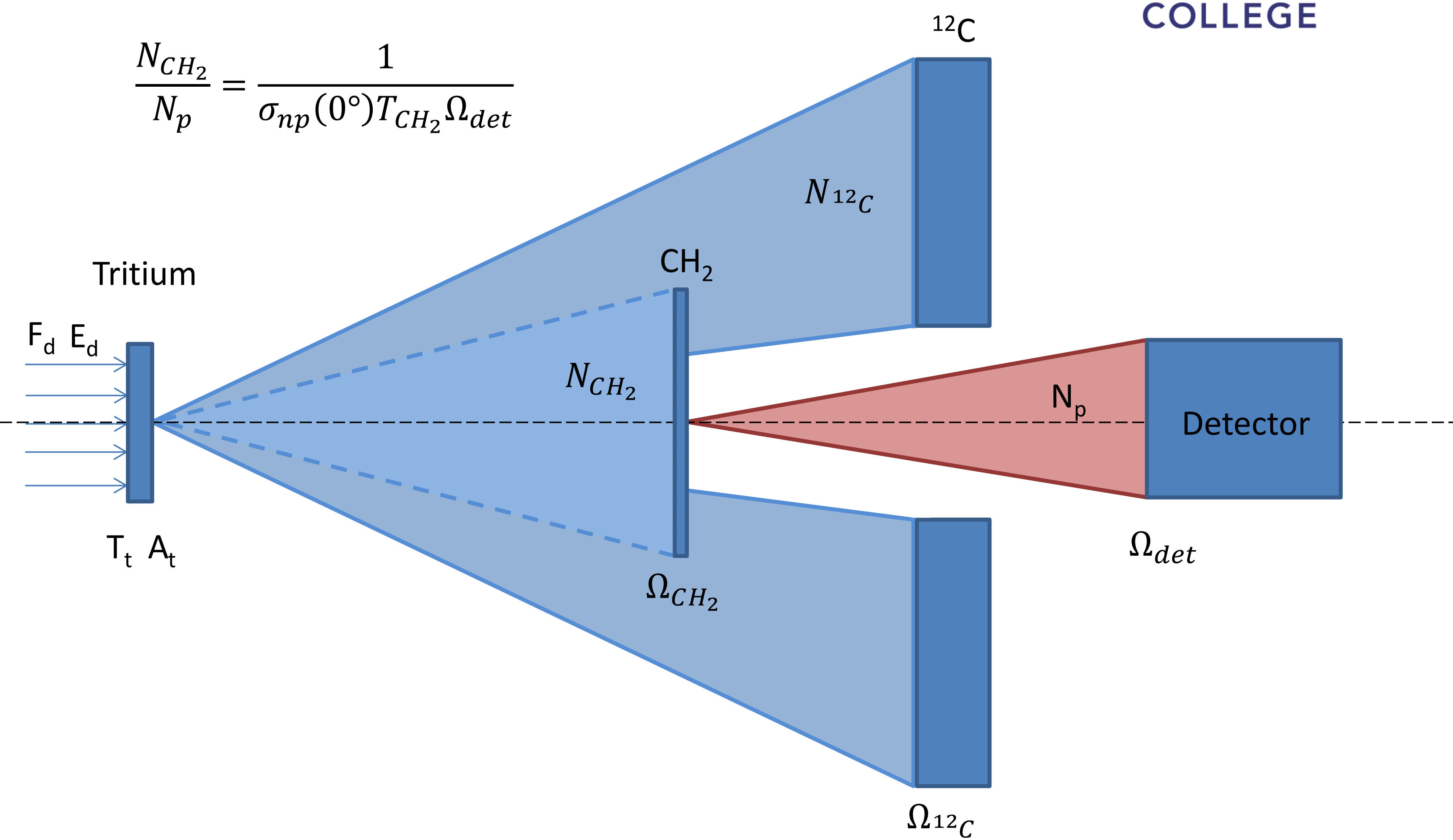
$$N_\mathrm{p} = \frac{N_\mathrm{p,fg}}{t_\mathrm{live,fg}} - \frac{N_\mathrm{p,bg}}{t_\mathrm{live,bg}}$$



Naïve Method

$$N_p = \sigma_{np}\,(0°) N_{CH_2} T_H\, \Omega_{det}$$

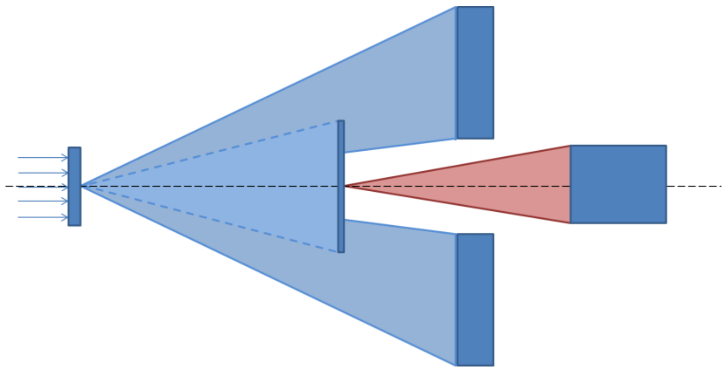
$$\frac{N_{CH_2}}{N_p} = \frac{1}{\sigma_{np}(0°) T_{CH_2} \Omega_{det}}$$



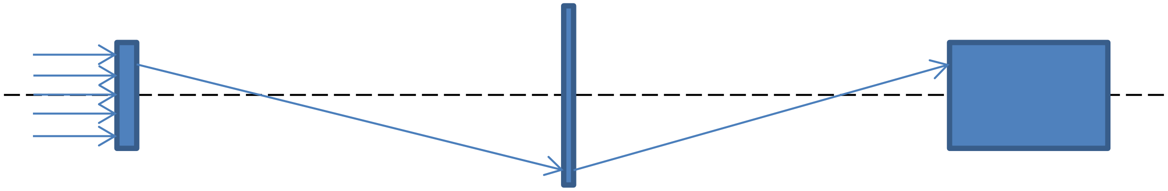
Analysis Goals

- Extended sources
- Cross-sections depend on energy and angle
- Collimation by graphite target

Correction 1 – Extended Targets



$$\frac{N_{CH_2}}{N_p} = \frac{1}{\sigma_{np}(0°)T_{CH_2}\Omega_{det}}$$



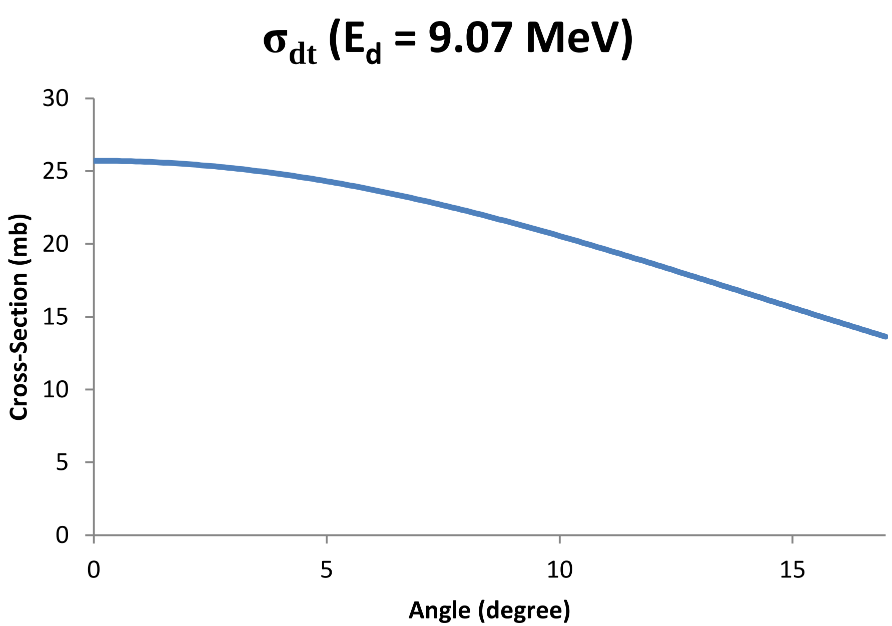
$$N_{CH_2} = \int_0^{2\pi}\int_0^{R_{CH_2}}\int_0^{2\pi}\int_0^{R_t} \sigma_{dt}(0°)\ F_d\ T_t\ r_1\,dr_1 d\theta_1 \frac{\cos\phi_1}{{R_1}^2} r_2\,dr_2 d\theta_2$$

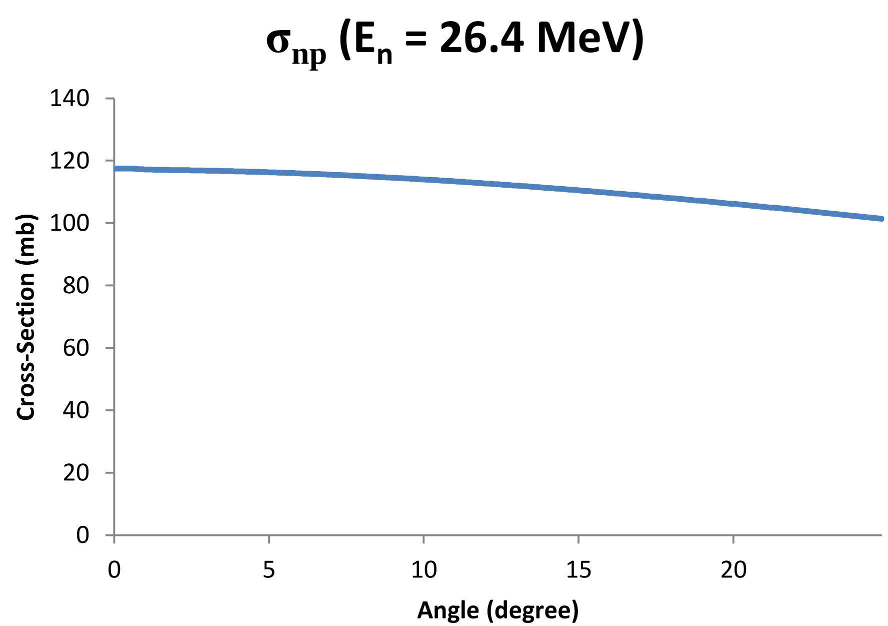
$$N_p = \int_0^{2\pi}\int_0^{R_d}\int_0^{2\pi}\int_0^{R_{CH_2}}\int_0^{2\pi}\int_0^{R_t} \sigma_{dt}(0°)\ \sigma_{np}(0°)\ F_d\ T_t\ \frac{T_H}{\cos\phi_1}\ r_1\,dr_1 d\theta_1 \frac{\cos\phi_1}{{R_1}^2} r_2\,dr_2 d\theta_2 \frac{\cos\phi_2}{{R_2}^2} r_3\,dr_3 d\theta_3$$

Correction 2 – Angular Dependence

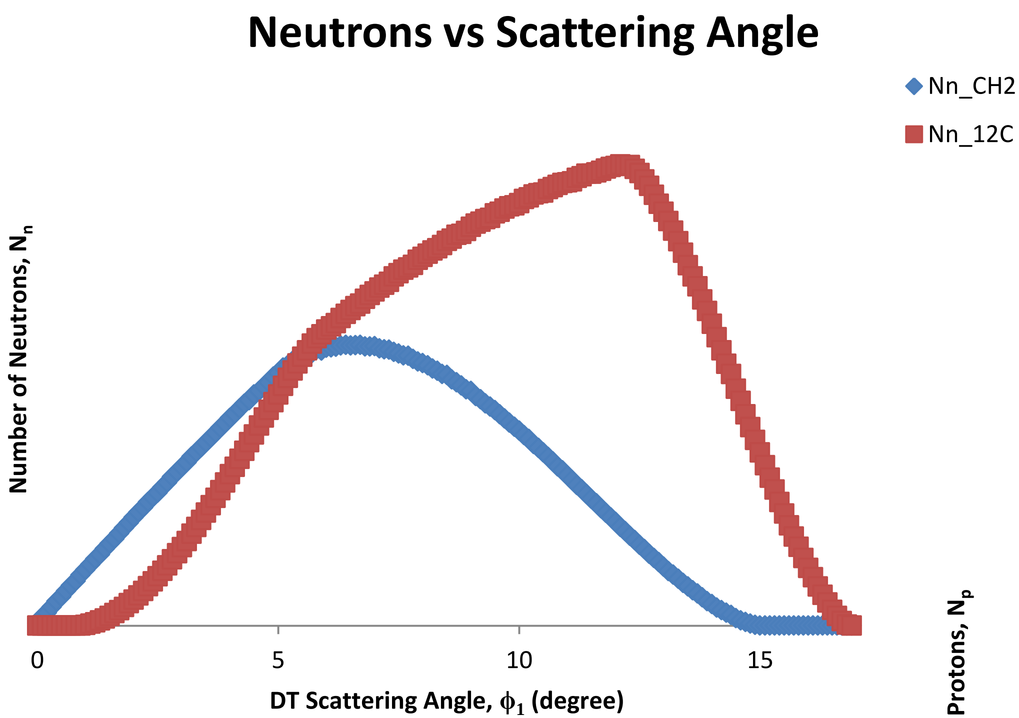
$$N_{CH_2} = \int_0^{2\pi} \int_0^{R_{CH_2}} \int_0^{2\pi} \int_0^{R_t} {\color{green}\sigma_{dt}(\phi_1)}\; F_d\, T_t\, r_1\, dr_1\, d\theta_1 \frac{\cos\phi_1}{{R_1}^2} r_2\, dr_2\, d\theta_2$$

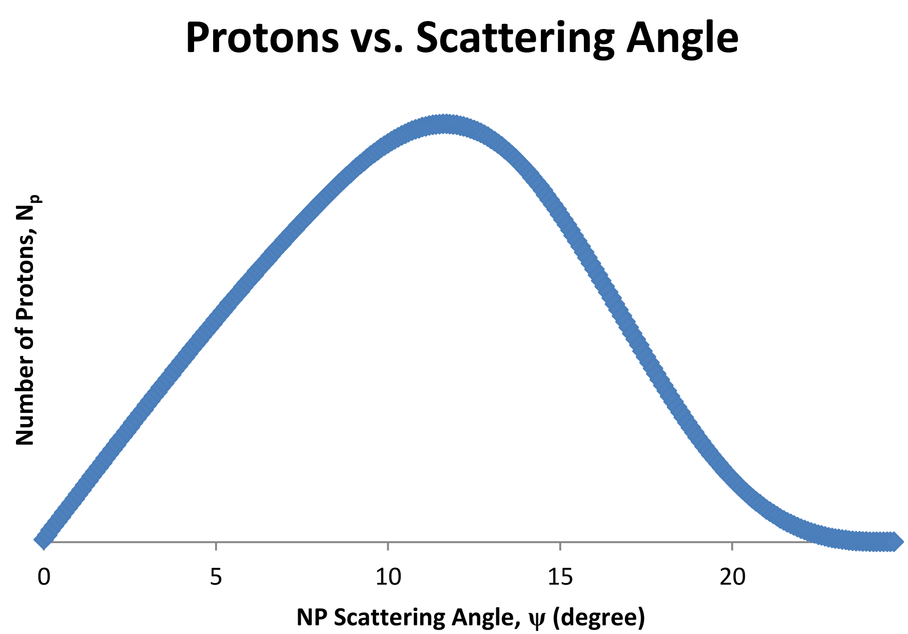
$$N_p = \int_0^{2\pi} \int_0^{R_d} \int_0^{2\pi} \int_0^{R_{CH_2}} \int_0^{2\pi} \int_0^{R_t} {\color{green}\sigma_{dt}(\phi_1)\; \sigma_{np}(\psi, E_n(\phi_1))}\; F_d\, T_t \frac{T_H}{\cos\phi_1}\; r_1\, dr_1\, d\theta_1 \frac{\cos\phi_1}{{R_1}^2} r_2\, dr_2\, d\theta_2 \frac{\cos\phi_2}{{R_2}^2} r_3\, dr_3\, d\theta_3$$





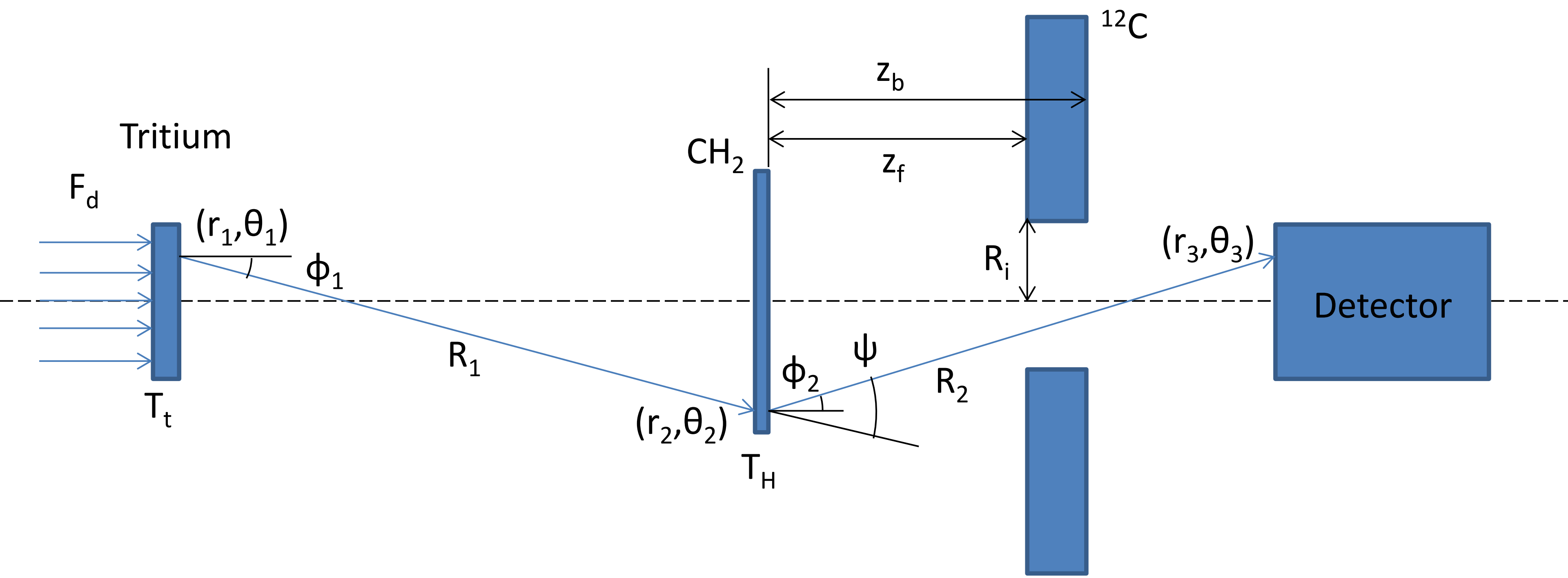
Correction 2 – Angular Dependence





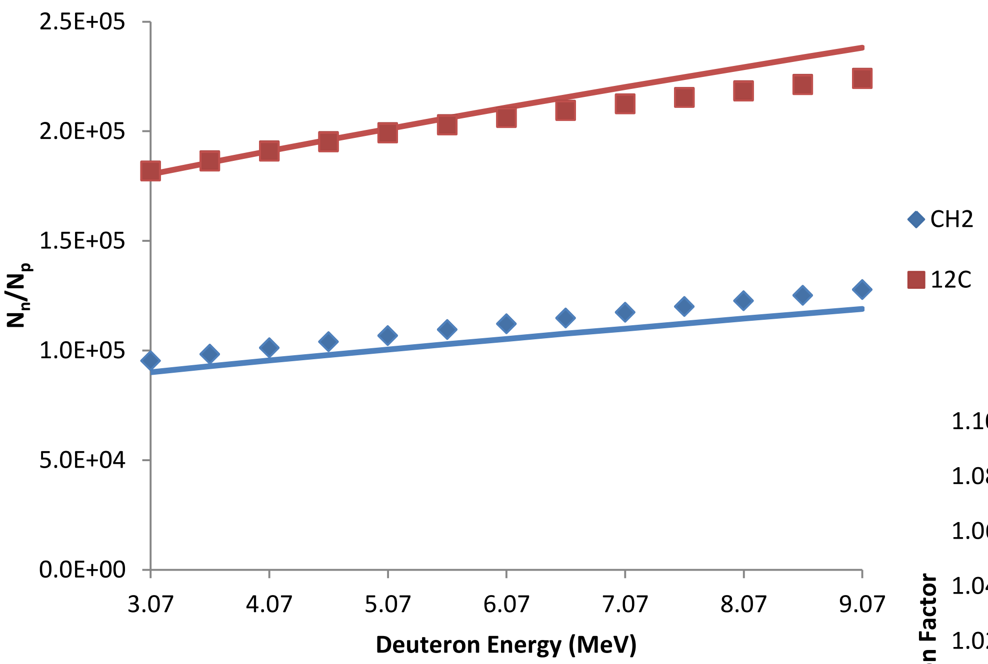
Correction 3 – Graphite Effects

$$N_p = \int_0^{2\pi}\int_0^{R_d}\int_0^{2\pi}\int_0^{R_{CH_2}}\int_0^{2\pi}\int_0^{R_t} \begin{Bmatrix} 0, & r(z_f) \geq R_i \; or \; r(z_b) \geq R_i \\ \sigma_{dt}(\phi_1)\,\sigma_{np}(\psi, E_n(\phi_1)) F_d T_t \dfrac{T_H}{\cos\phi_1} & \end{Bmatrix} r_1 dr_1 d\theta_1 \frac{\cos\phi_1}{{R_1}^2} r_2 dr_2 d\theta_2 \frac{\cos\phi_2}{{R_2}^2} r_3 dr_3 d\theta_3$$

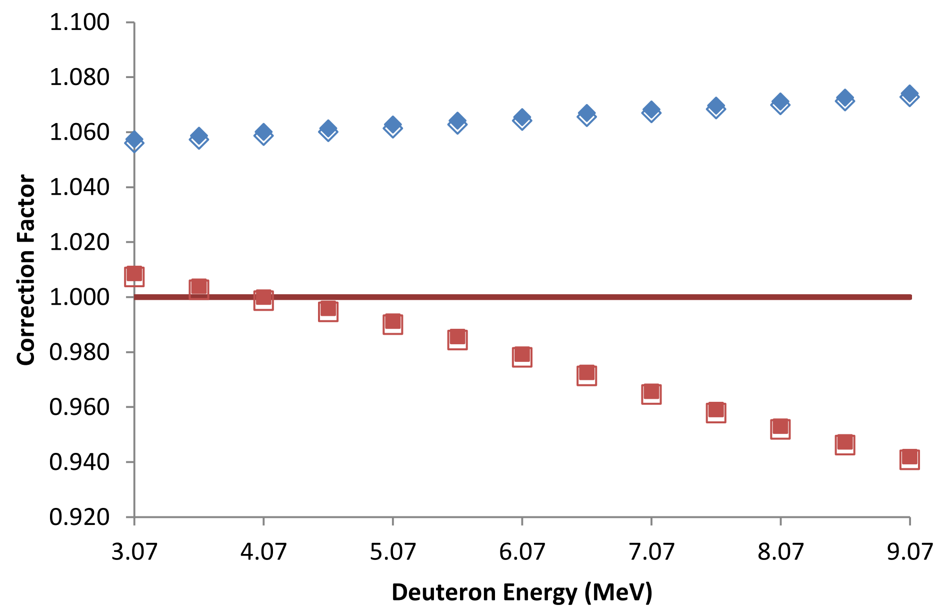


Correction 3 – Graphite Effects

Neutron to Proton Ratio



Comparison to Naïve Approach



Future Plans and Current Goals

- Continue work on NaI detector efficiency.
- Conduct experiment at energies beyond 26.4 MeV
- Additional corrections?

Collaborating Institutions

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The Research
Foundation for
The State University of New York

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Resources

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