The $^{12}C(n,2n)^{11}C$ Cross Section from 20-27 MeV

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Carl Brune, Thomas Massey. Ohio University, Ohio University.

Ryan Fitzgerald, Mollie Bienstock, National Institute of Standards and Technology.

Craig Sangster, Sean Regan. Laboratory for Laser Energetics.

Locations

LLE
SUNY Geneseo
Houghton College
Ohio University
NIST
NIF

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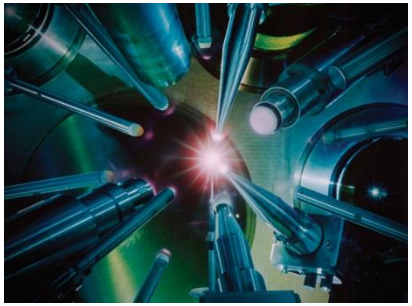
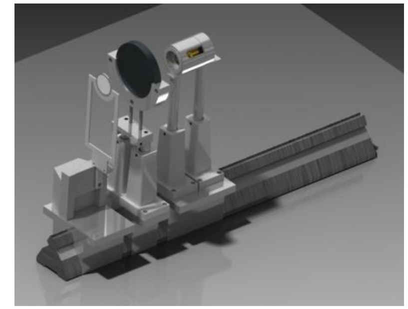
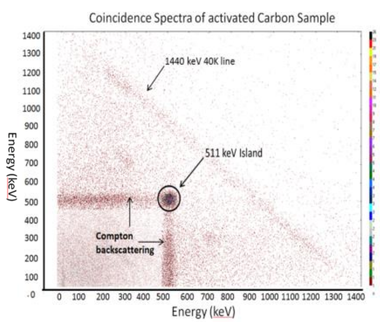


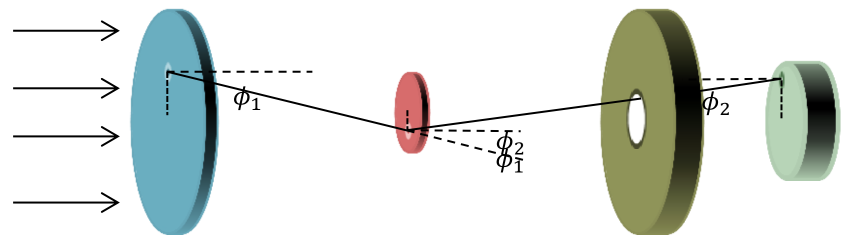
What does this have to do with ICF?

How does the experiment work?

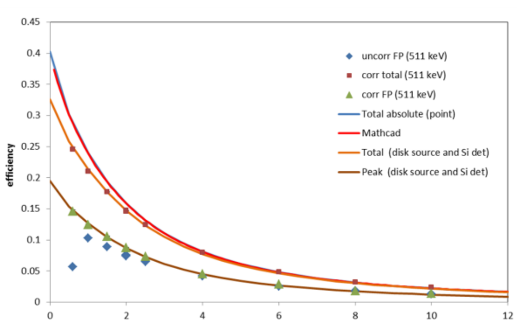




How do you extract the $^{12}C(n,2n)^{11}C$ cross section?



What about geometry?



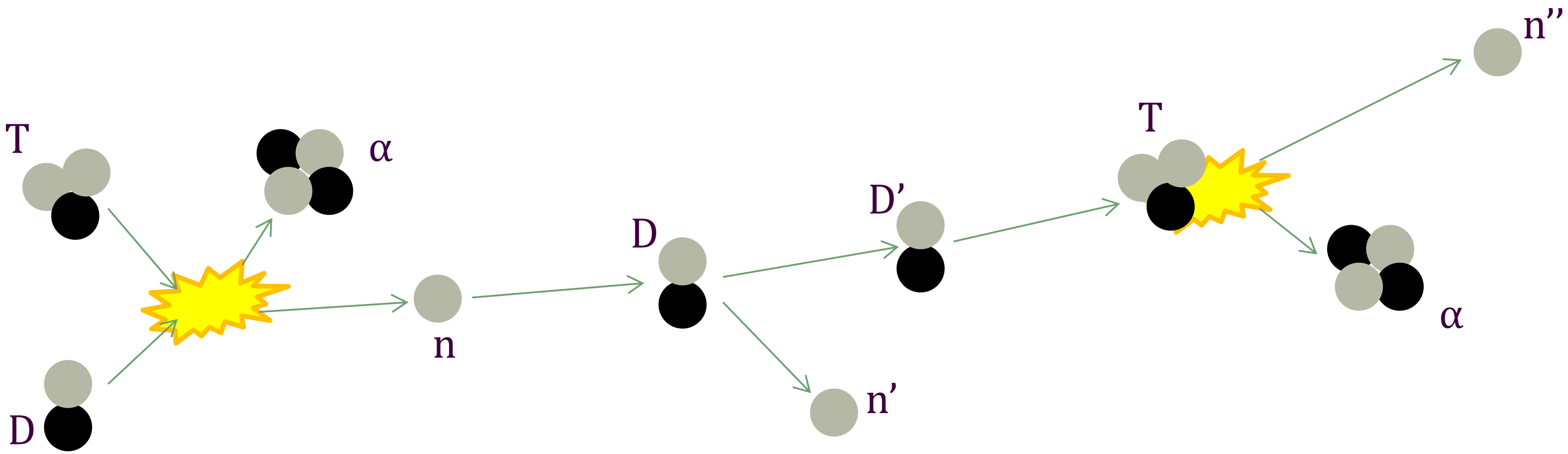
Why aren't you finished yet?

What does this have to do with ICF?

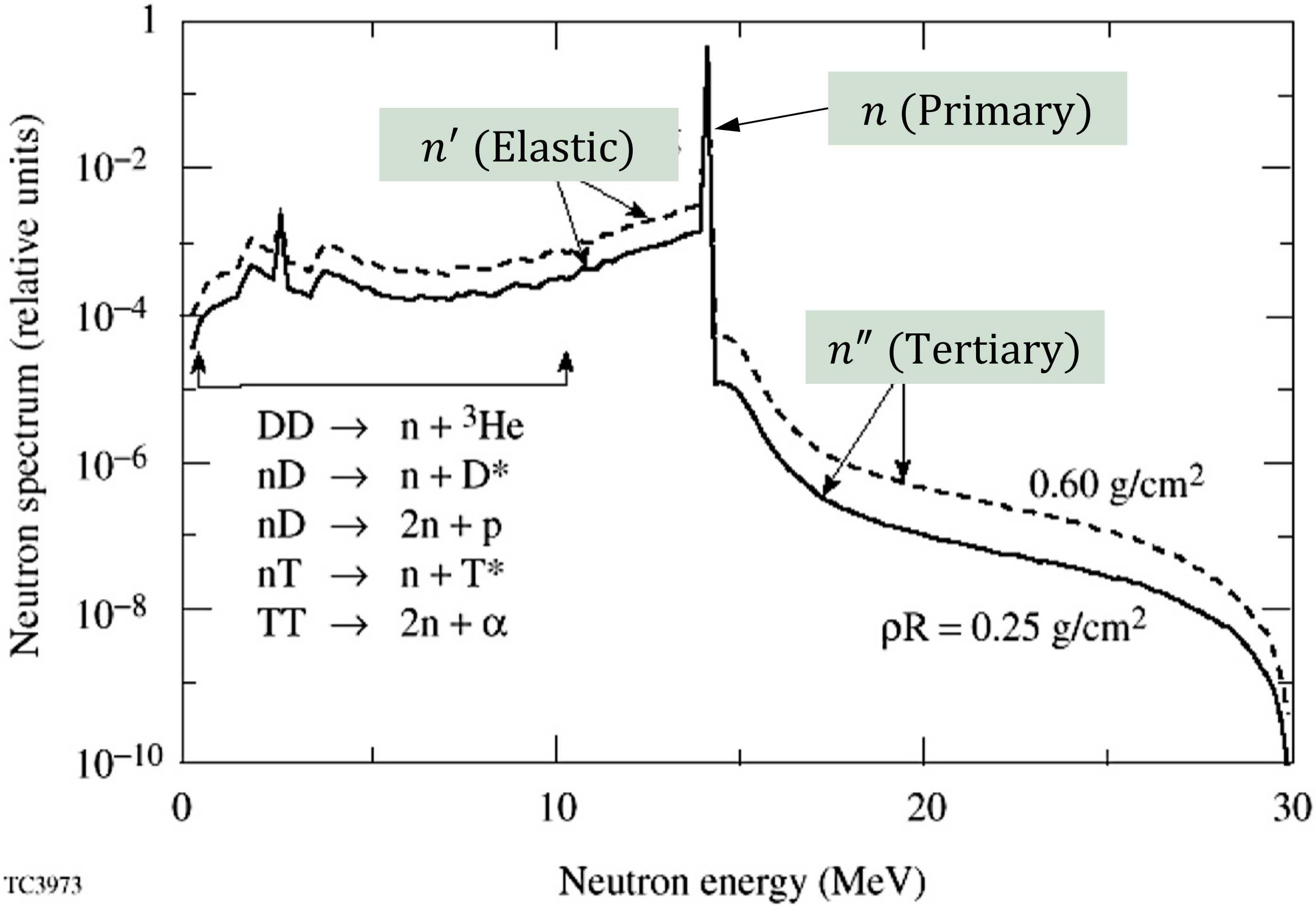
$$\mathrm{D} + \mathrm{T} \rightarrow \alpha + n\ (14.1\ \mathrm{MeV})$$

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

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



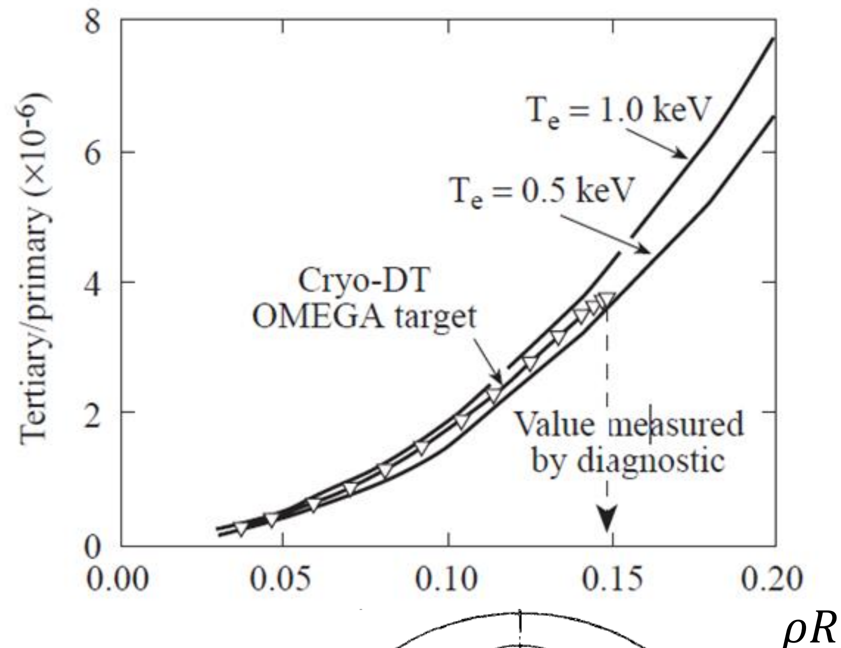
Calculated neutron spectrum



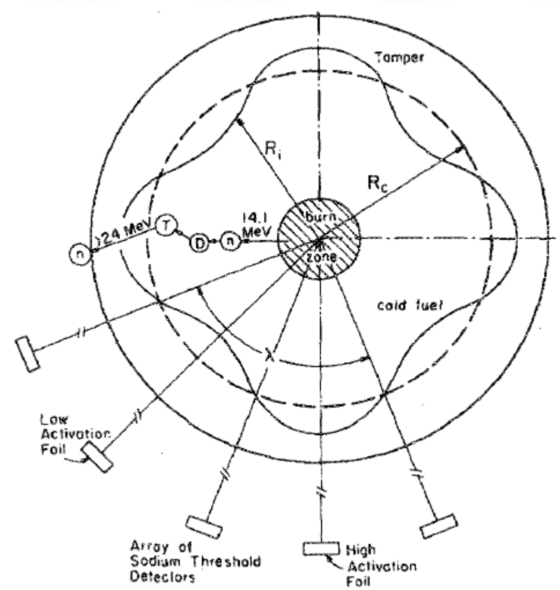
R. Town, LLE Review, **69**, pp. 46 (1996)

Tertiary neutrons (n'')

$$\frac{N_{n''}}{N_n} = \frac{\text{Tertiary}}{\text{Primary}} \sim (\rho R)^2$$



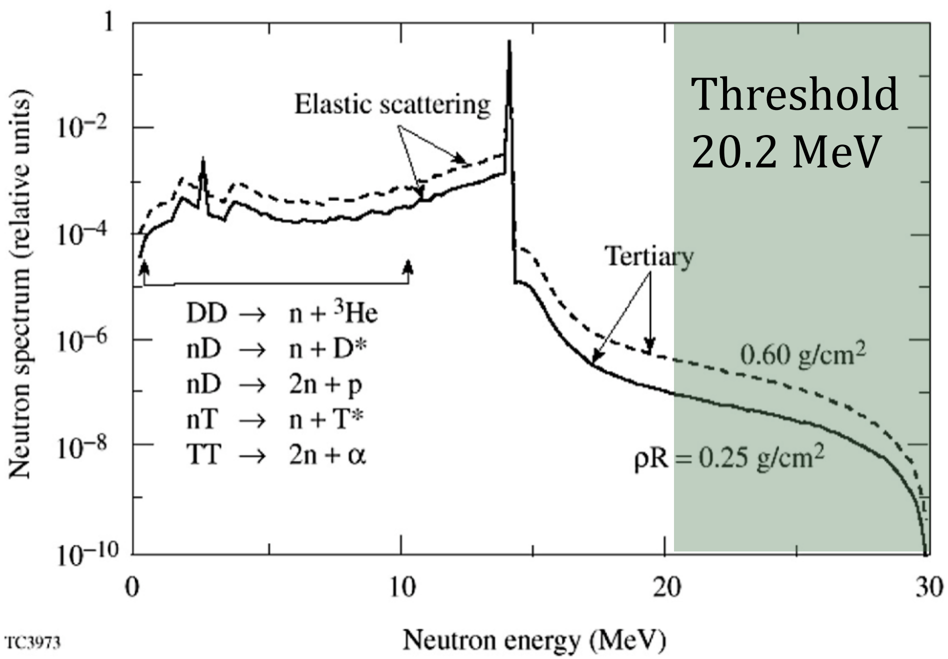
Hydrodynamic stability – angular variation of tertiary neutrons



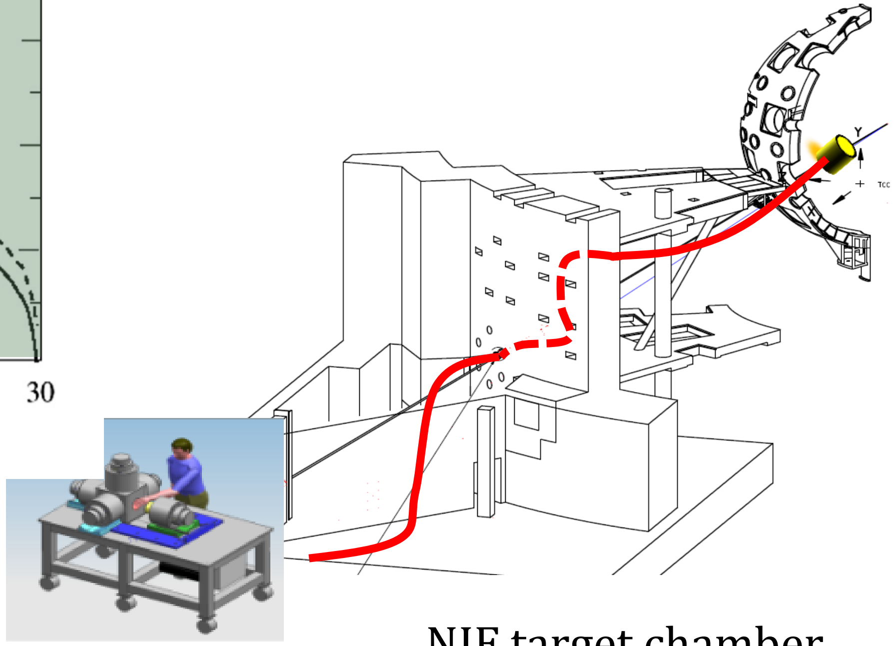
R. Town, LLE Review, **69**, pp. 46 (1996)
D.R. Welch, H. Kislev, and G.H. Miley, Rev. Sci. Intrum. **59**, 4 pp. 612 (1988).

Carbon activation

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



Graphite target developed at SUNY Geneseo

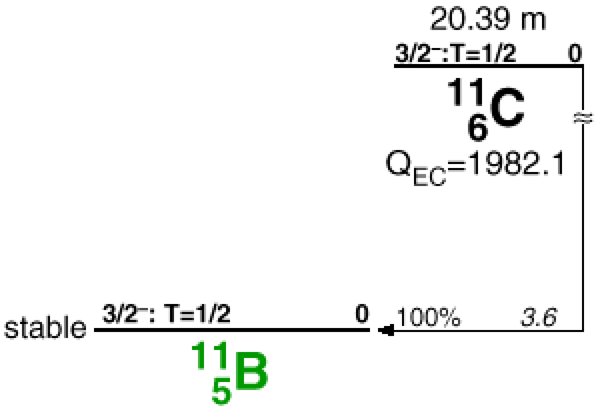


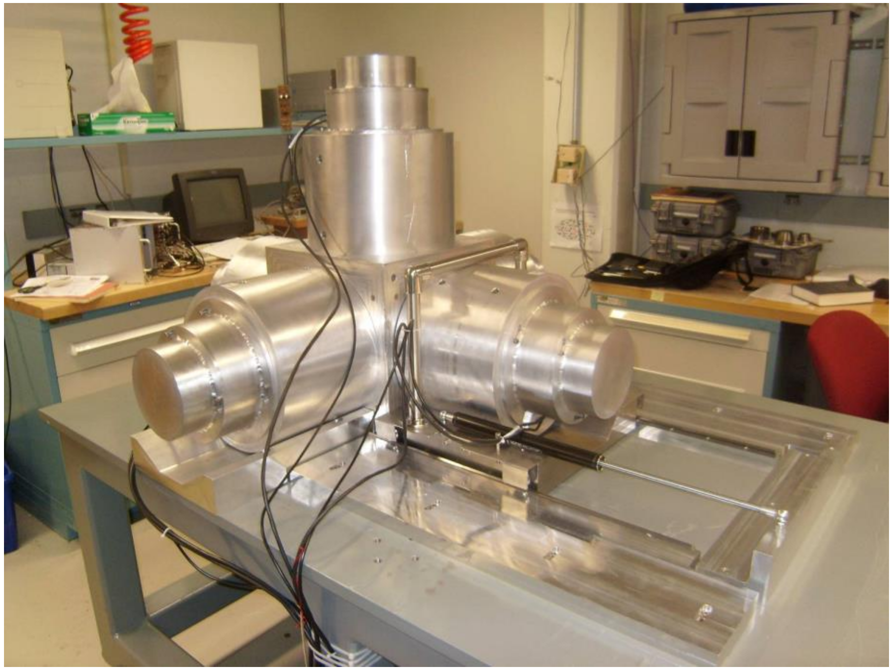
NIF target chamber

^{11}C decay

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

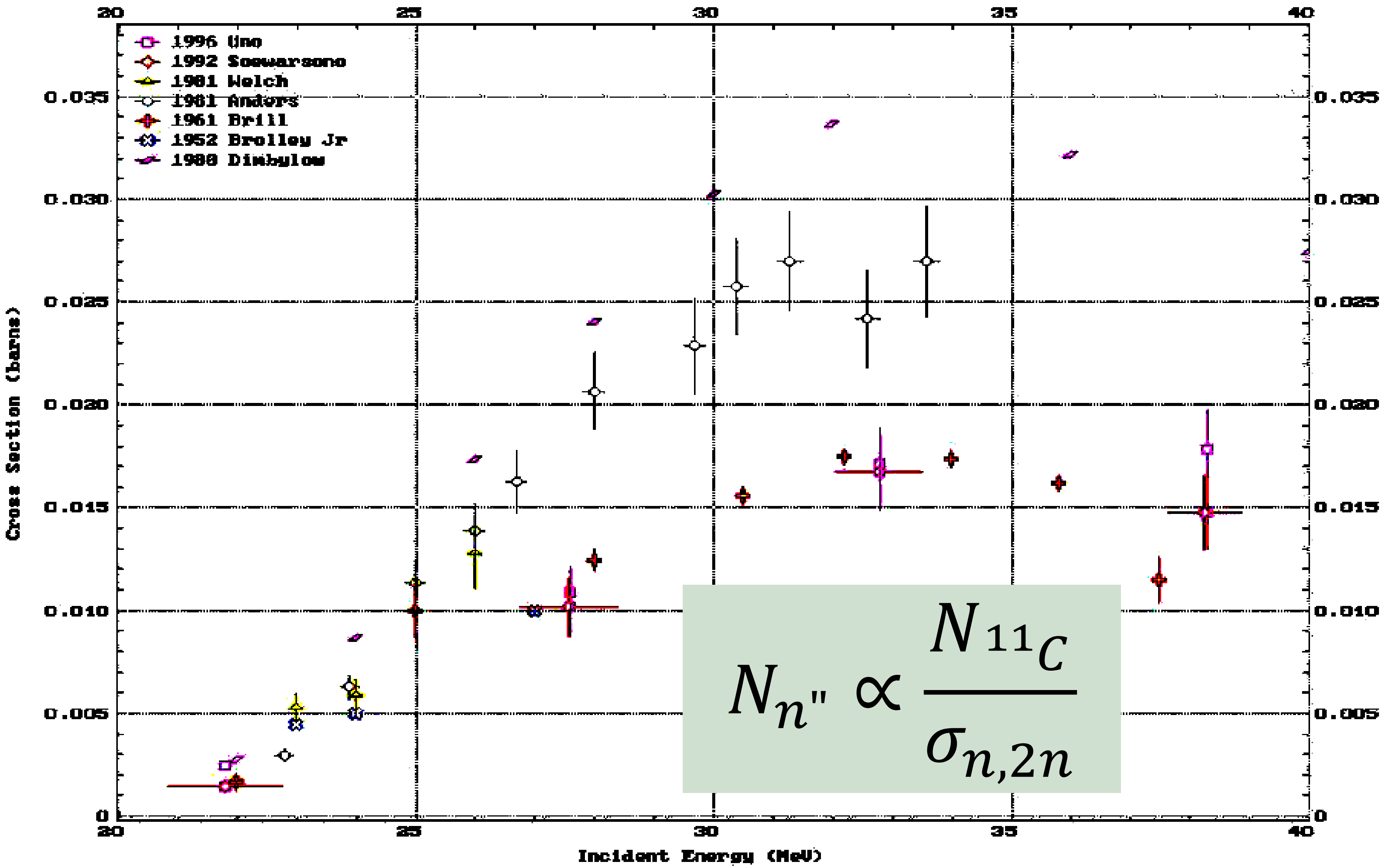
$$e^{+} + e^{-} \rightarrow 2\gamma \ (511\ \mathrm{keV})$$





Counting station at LLE

$^{12}C(n,2n)^{11}C$ Cross section



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

Weaknesses of previous measurements:

1. Neutron Source

a) Fixed energy cyclotron
   1) DT, change energy using energy degraders or by changing angle
   2) $^{7}Li(p,n)$, not monoenergetic

b) Only non-cyclotron measurement was done at Ohio University

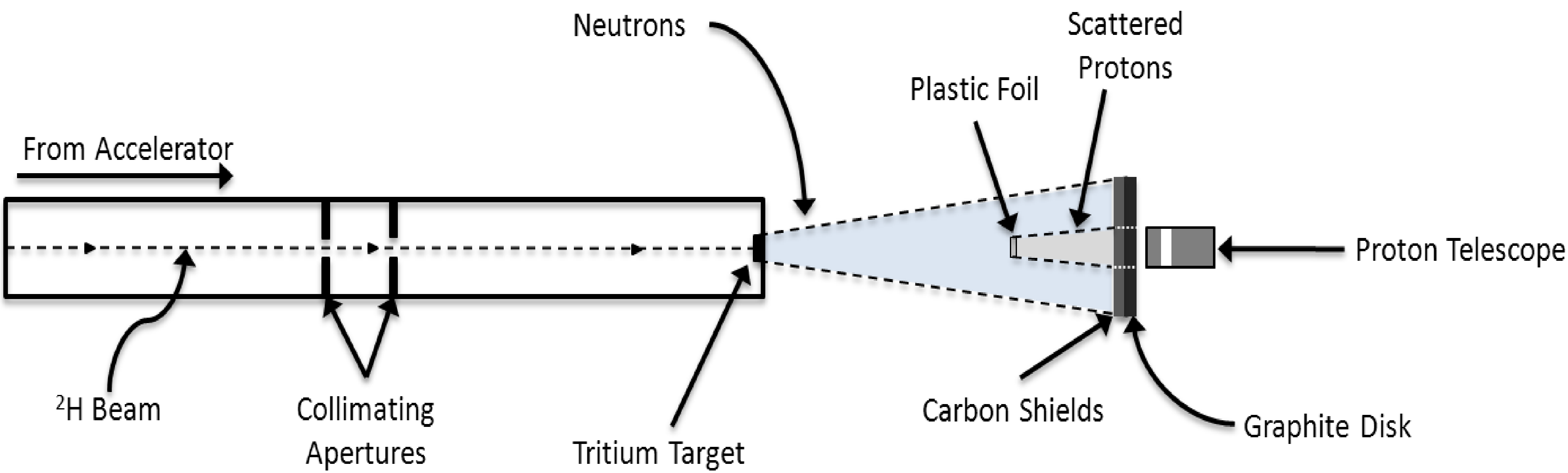
2. Neutron flux

a) calculated from DT cross sections
b) measured using TOF to plastic or liquid scintillators
c) recoil spectrometer
d) Li target activation
e) No particle ID, No measurement at target

3. Activation

a) Geiger counter (no energy)
b) Single Germanium detector
c) One experiment used coincidence in NaI
d) Efficiencies!

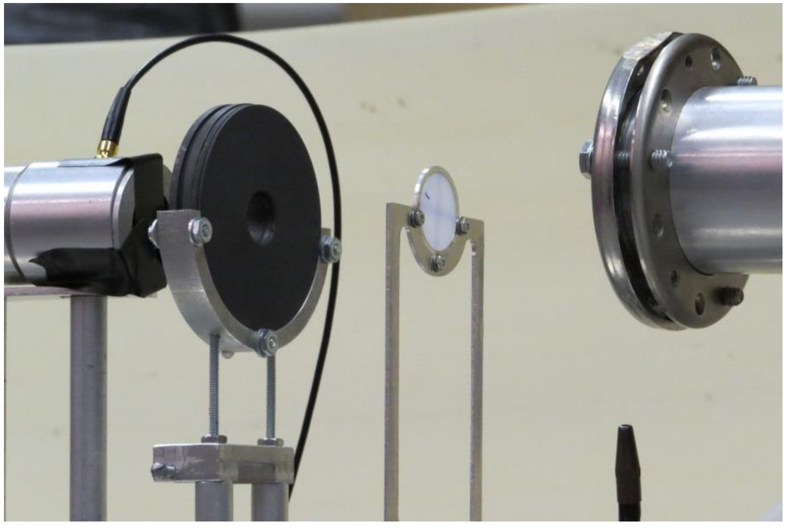
How does the experiment work?



Advantages:

1. Neutron Source

a) Monoenergetic
   a) Tandem van de Graff, DT
   b) Energy spread < 0.5 MeV



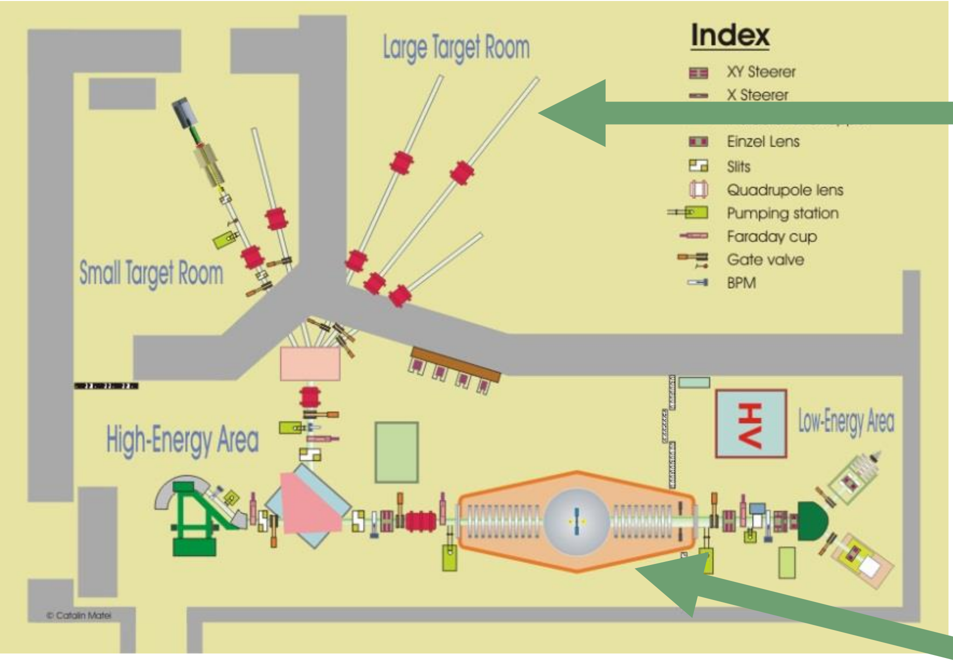
2. Neutron flux

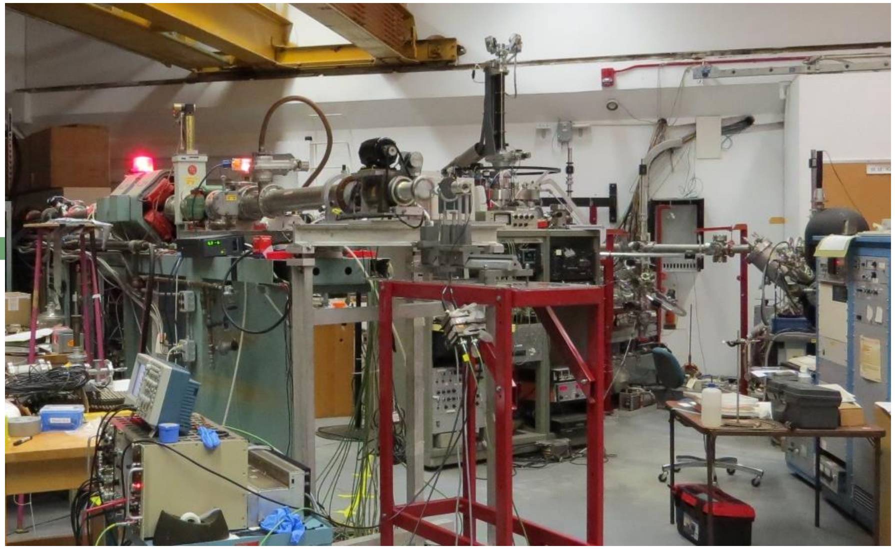
a) Proton recoil telescope
b) Proton ID
c) Flux measured on target

3. Activation

a) Coincidence
b) Energy
c) Careful efficiency measurement

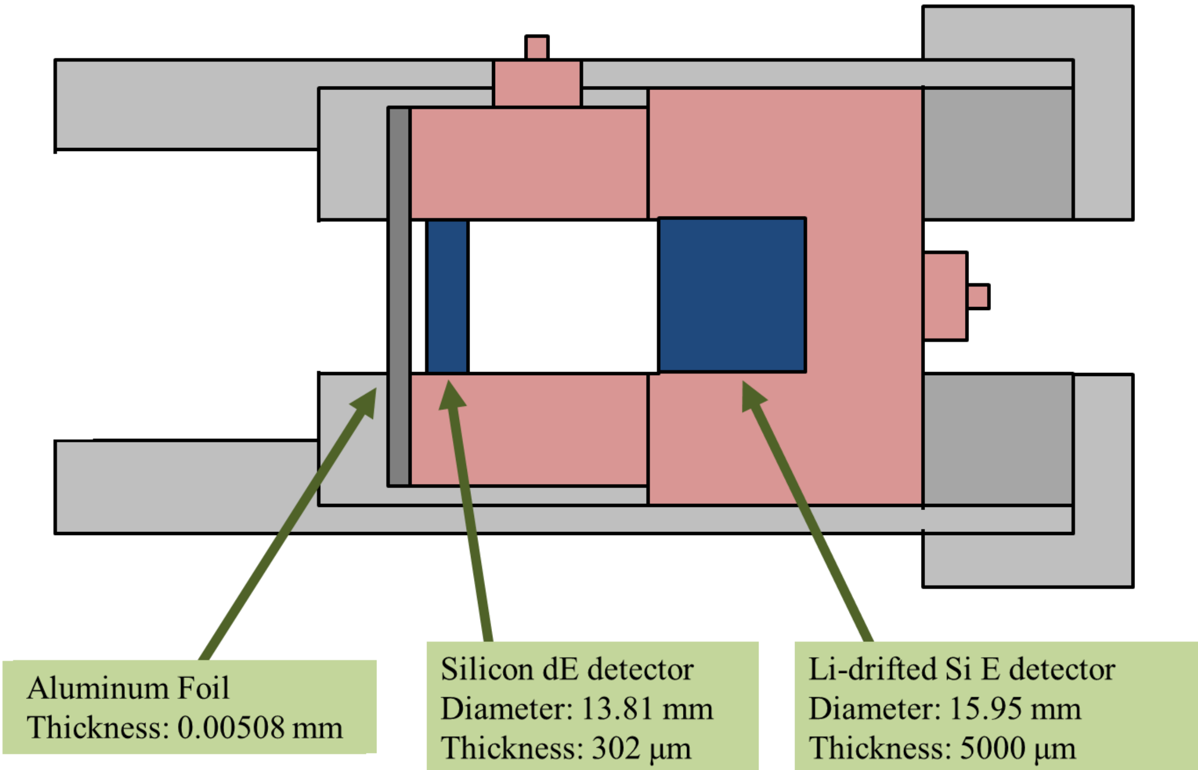
Ohio University 4.5-MV Tandem

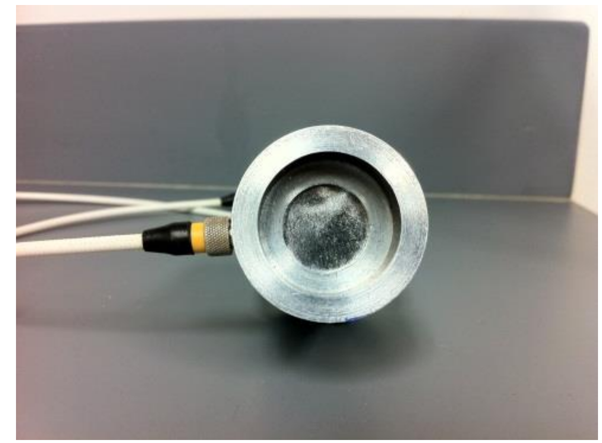




Houghton students setting up targets and detectors at Ohio University.

Proton Telescope





Proton telescope built at Houghton College, calibrated at SUNY Geneseo

Time and effort

23 days of beam time, summers 2012, 2013

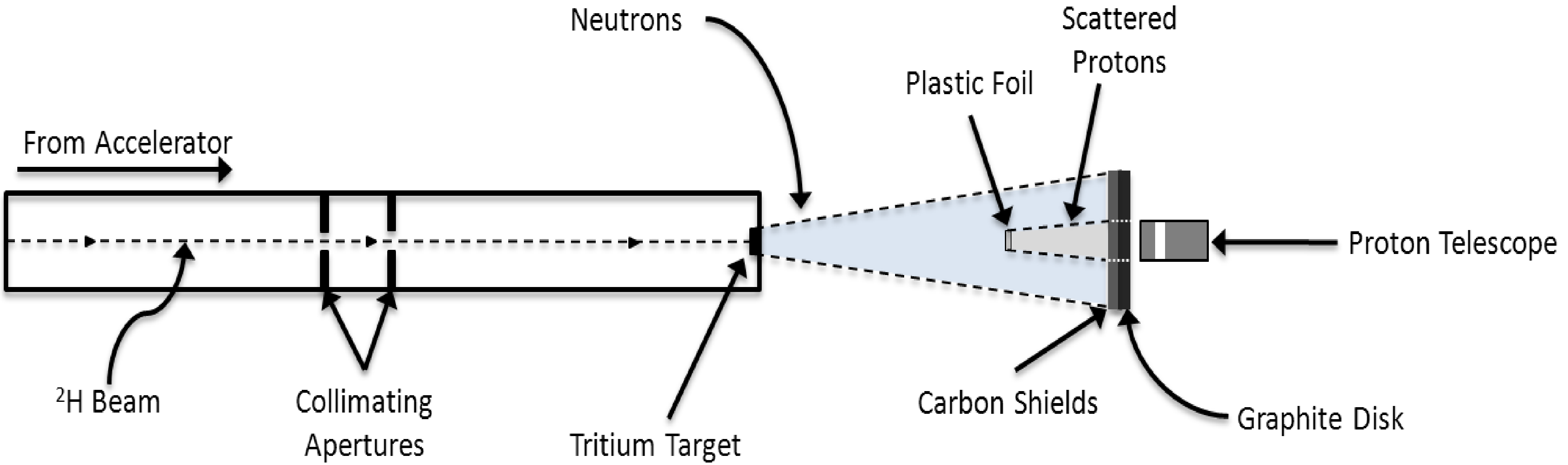
24 hour beam/ 8 hour shifts

Setup/testing

For each energy setting (5 hours)

1. Tune beam, tests
2. Activation: 90 minutes, count protons
3. Transport: 5 minutes
4. Counting: 180 minutes
5. Background: 30 minutes, count protons
6. Analysis: proton count, decay curve fitting

How do you extract the $^{12}C(n,2n)^{11}C$ cross section?

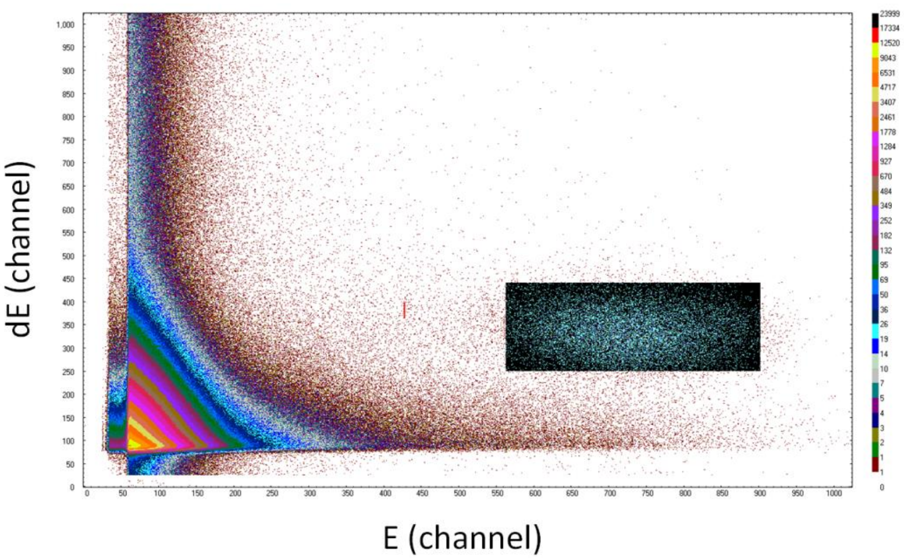


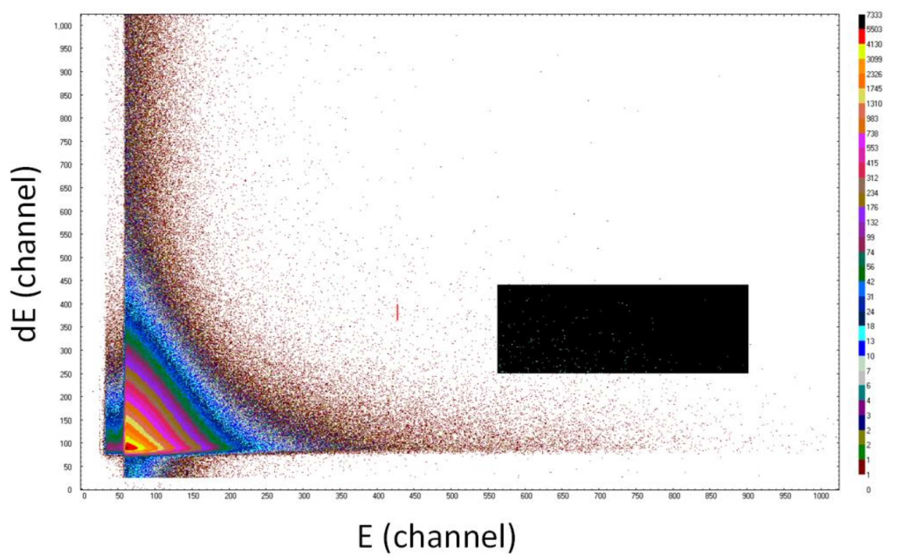
$$\frac{dN_{^{11}C}}{dt} = \sigma_{n2n} N_n T_C - \lambda N_{^{11}C}$$

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

Proton Identification (N_p)

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



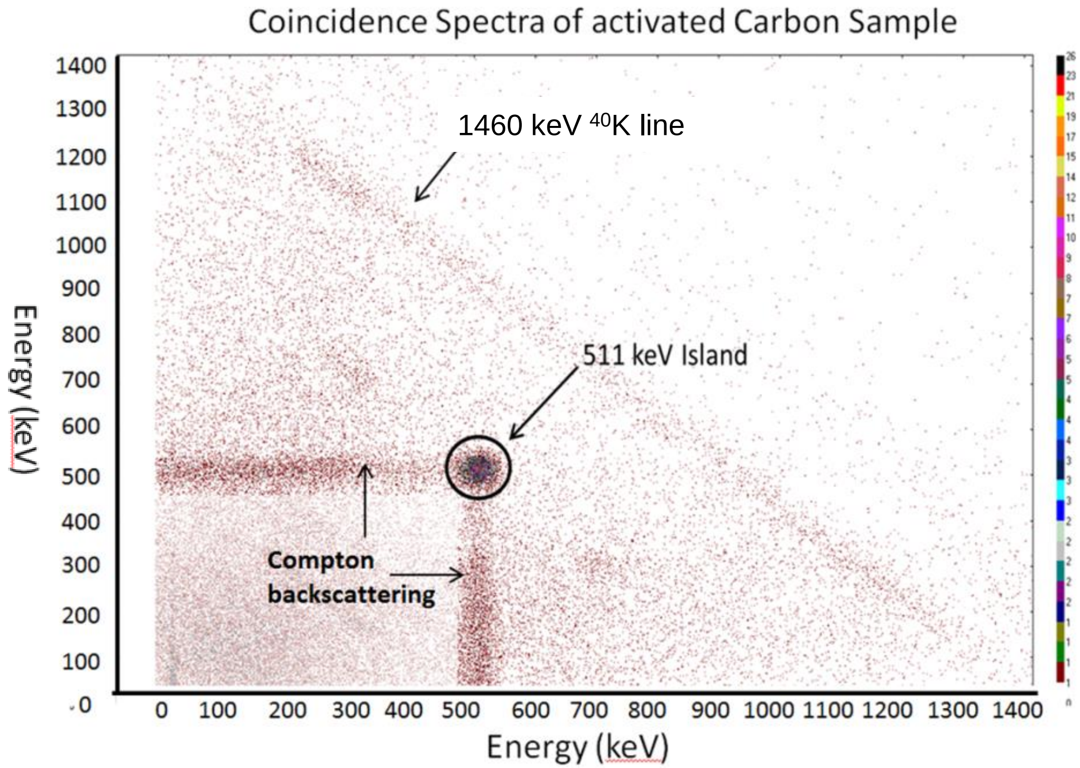


$$N_p = \frac{N_{\mathrm{p,fg}}}{f_{\mathrm{live,fg}}} - \frac{N_{\mathrm{p,bg}}}{f_{\mathrm{live,bg}}}$$

Measuring $N_{^{11}C}$

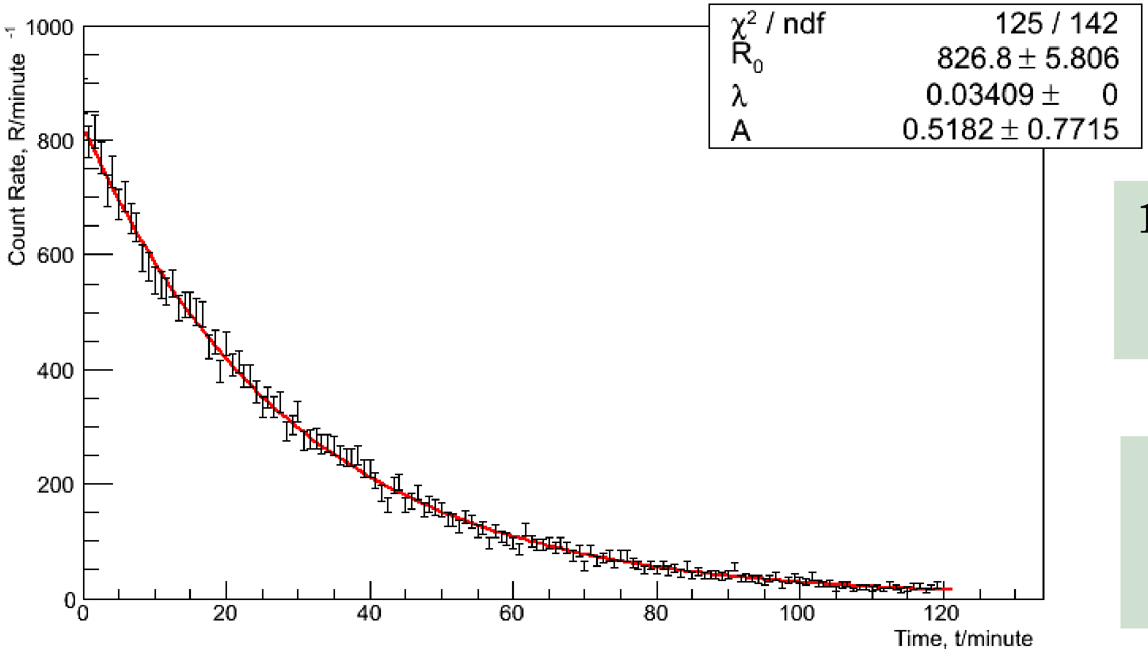
Geneseo students setting up counting station at Ohio University

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



Measuring $N_{^{11}C}$

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



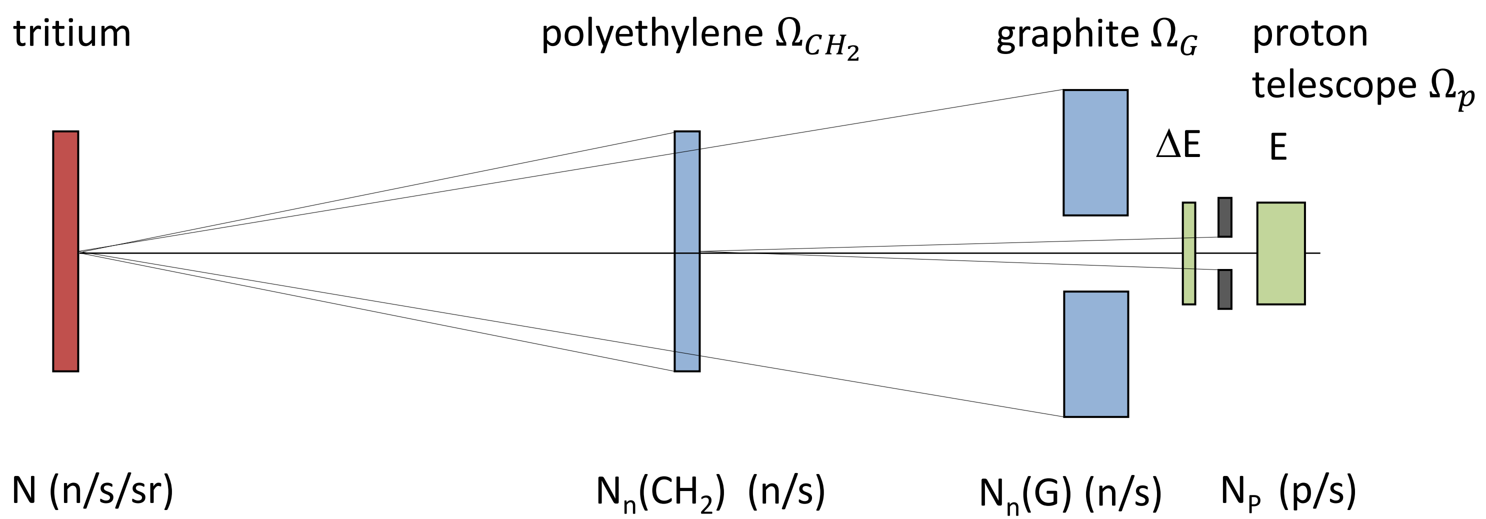
^{11}C decay curve

$$R(t) = R_0 e^{-\lambda t} + A$$

$$N_{^{11}C} = \frac{R_0 e^{\lambda\, t_{trans}}}{\lambda \cdot \text{ efficiency}}$$

What about geometry?

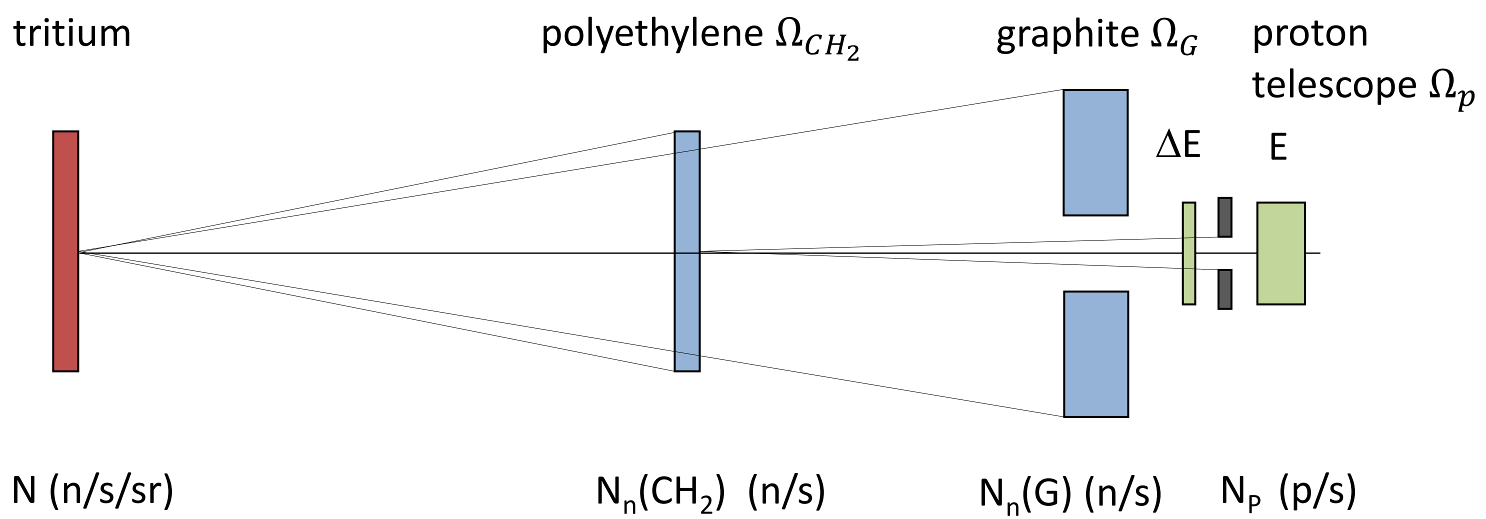
$$\sigma_{n2n} = \frac{N_{^{11}C}\,\lambda}{T_C(1 - e^{-\lambda\,t})}\left(\frac{N_p}{N_n}\right)\frac{1}{N_p}$$



1. Calculate from geometry and known cross sections.
2. First approximation: assume isotropic monoenergtic neutrons and point sources.

Ratio N_p/N_n

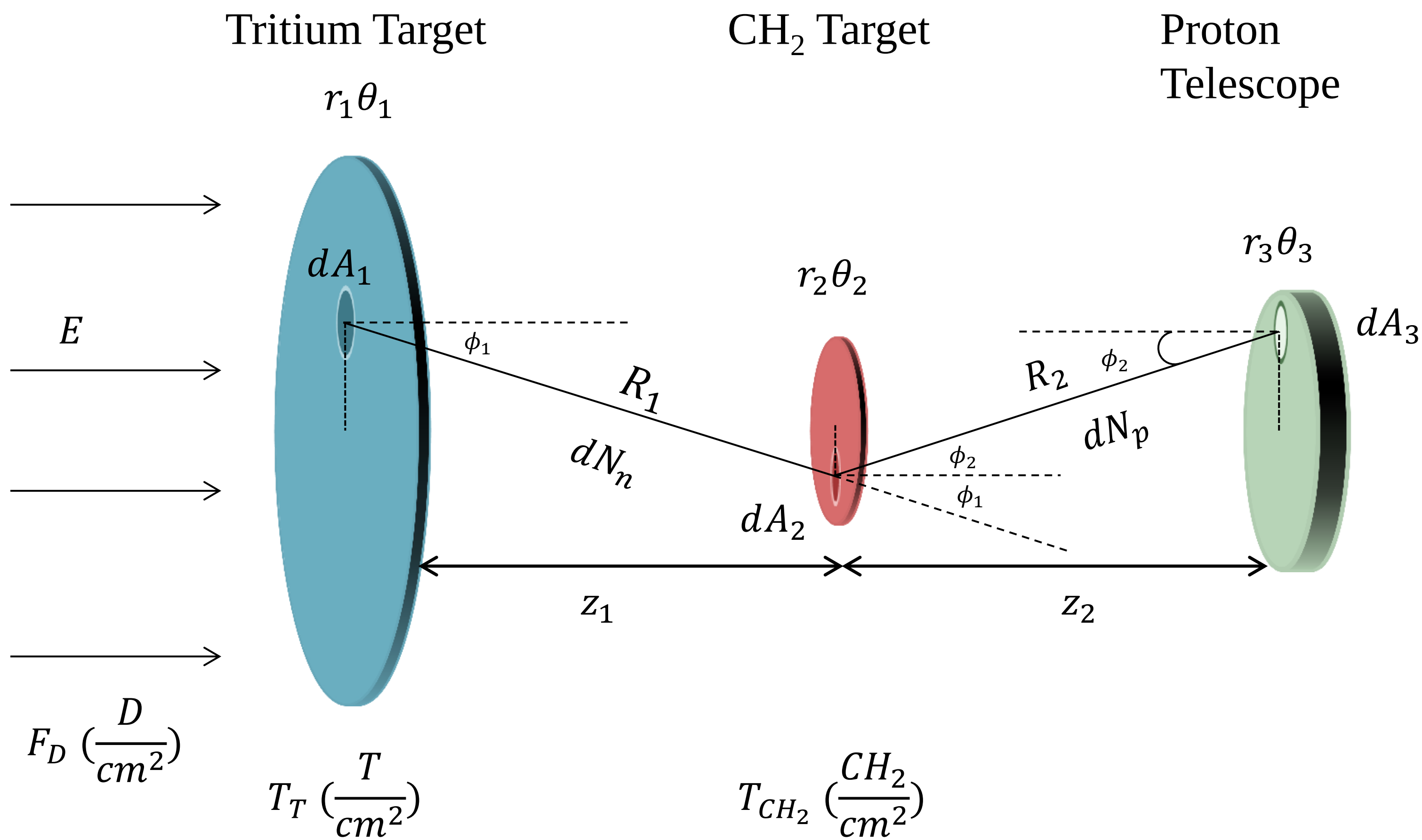
$$\sigma_{n2n} = \frac{N_{^{11}C}\,\lambda}{T_C(1-e^{-\lambda\,t})}\left(\frac{N_p}{N_n}\right)\frac{1}{N_p}$$



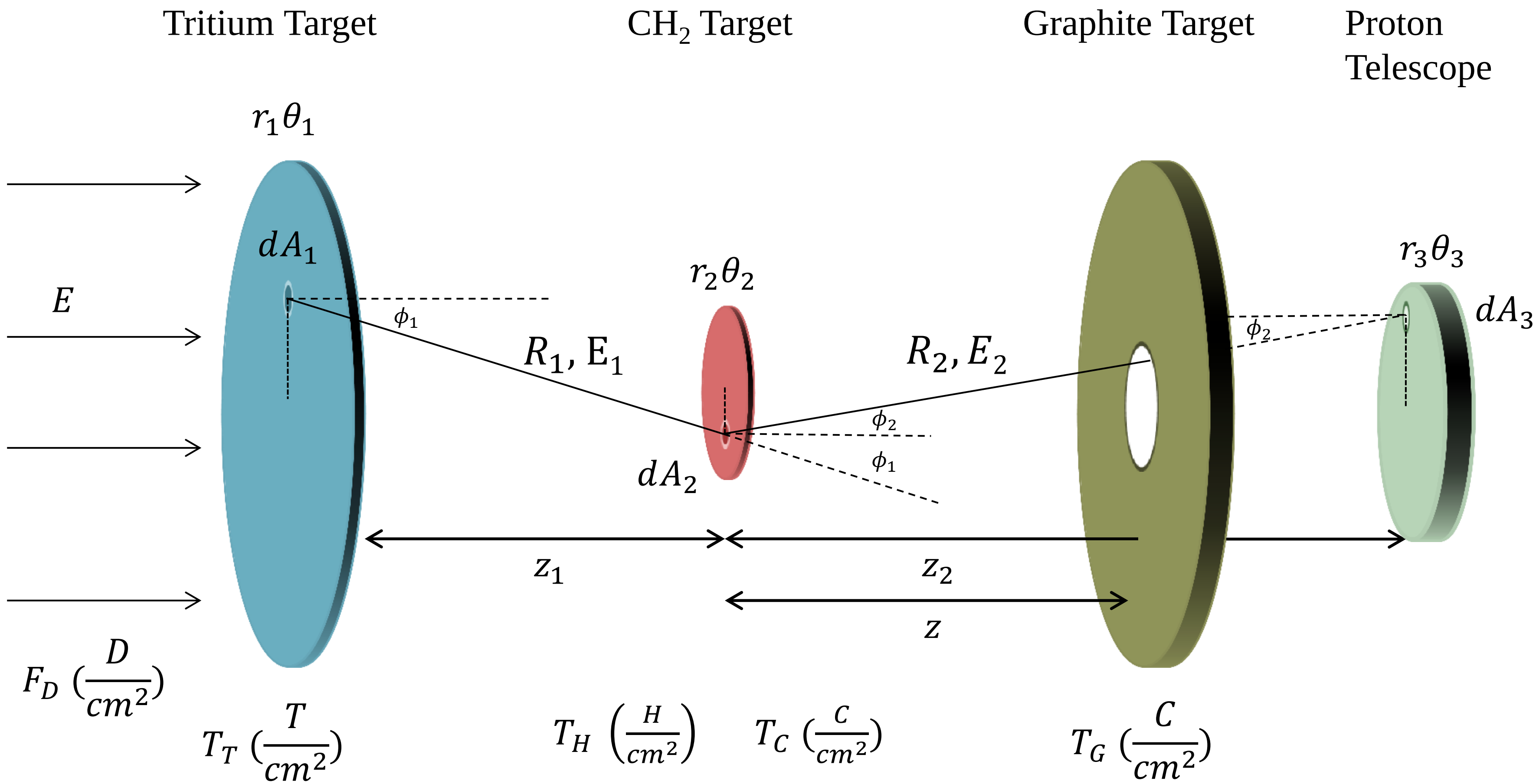
$$\frac{N_p}{N_n(\mathrm{CH_2})} = \sigma_{np}(0°)T_H\Omega_p$$

$$\frac{N_p}{N_n(\mathrm{G})} = \sigma_{np}(0°)T_H\Omega_p\left(\frac{\Omega_{CH_2}}{\Omega_G}\right)$$

Correction 1 – Extended target/cross section distribution



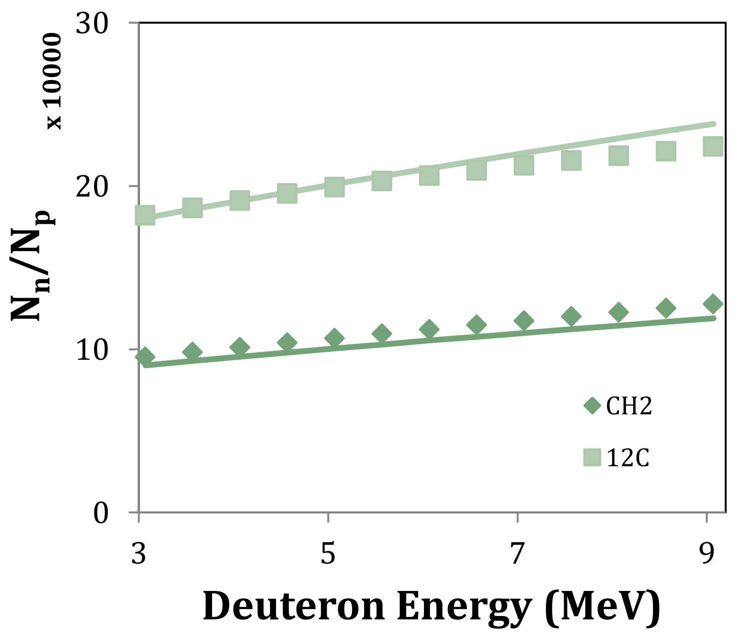
Correction 2 – Collimation

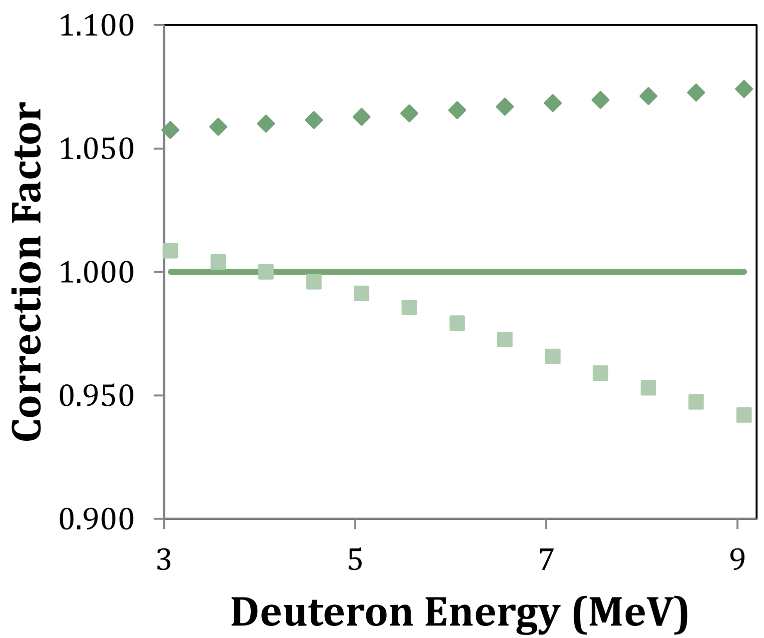


Corrections

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

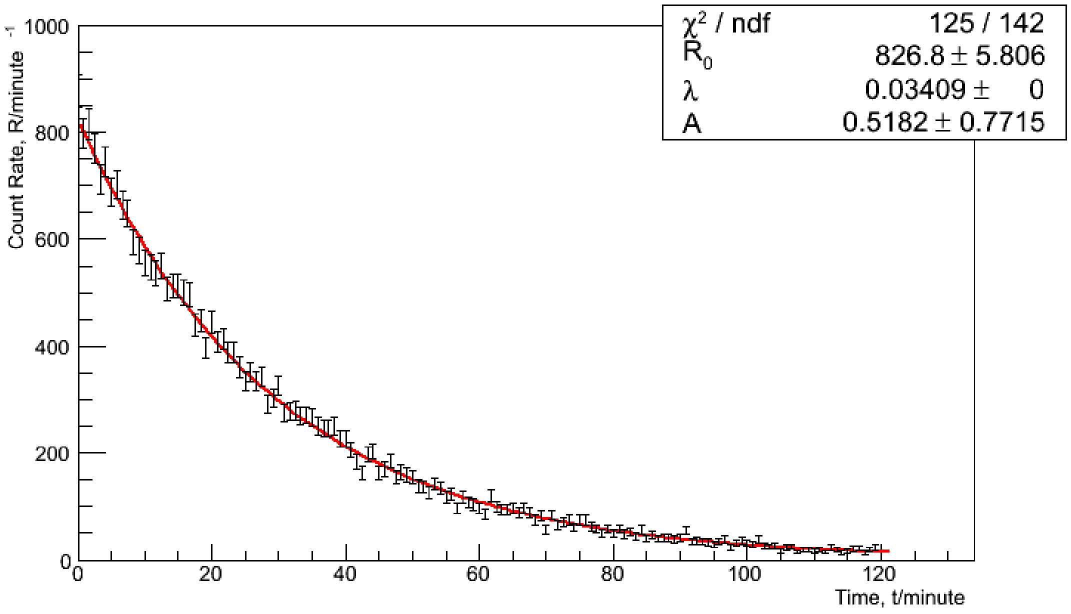
$$N_p = \int_0^{2\pi}\int_0^{R_d}\int_0^{2\pi}\int_0^{R_{CH_2}}\int_0^{2\pi}\int_0^{R_t} \begin{Bmatrix} 0, & r(z_f) \geq R_i\ or\ r(z_b) \geq R_i \\ \sigma_{dt}(\phi_1)\ \sigma_{np}(\psi, E_n(\phi_1)) F_d T_t \dfrac{T_H}{\cos\phi_1} & \end{Bmatrix} r_1 dr_1 d\theta_1 \frac{\cos\phi_1}{{R_1}^2} r_2 dr_2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





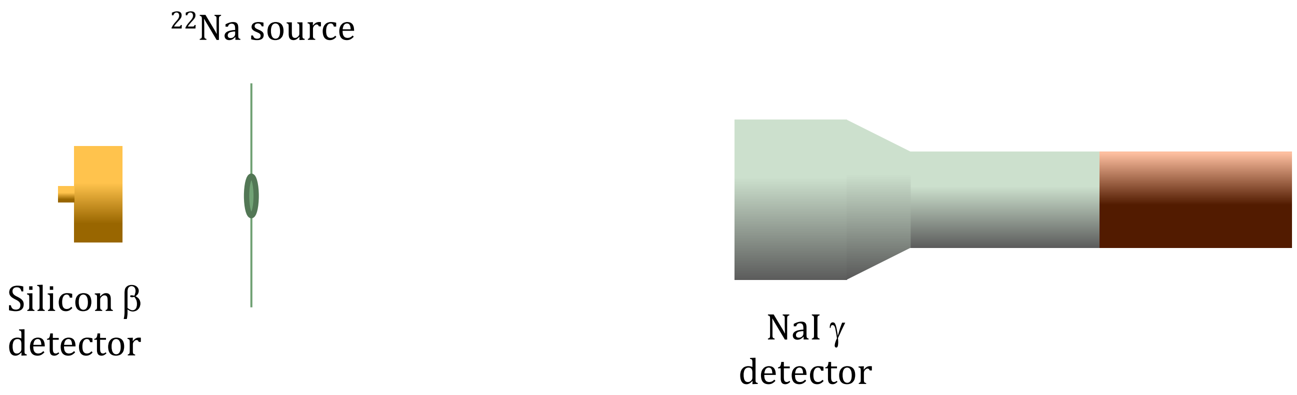
Why aren't you finished yet?

In order to measure the number of ^{11}C nuclei created by $^{12}C(n, 2n)^{11}C$, we need to know the <u>absolute full-peak coincidence efficiency</u> of our detectors.

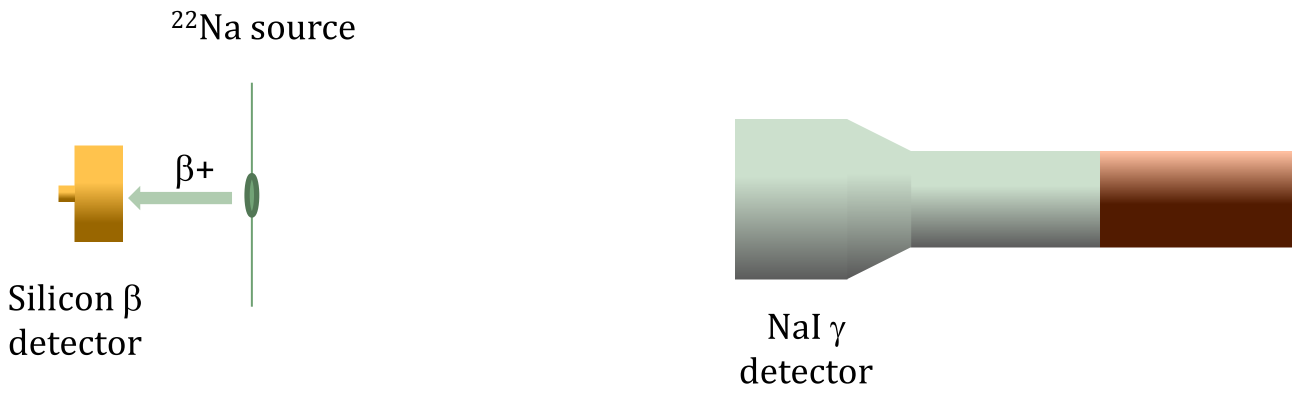


$$N_{^{11}C} = \frac{R_0 e^{\lambda\, t_{trans}}}{\lambda \cdot \text{efficiency}}$$

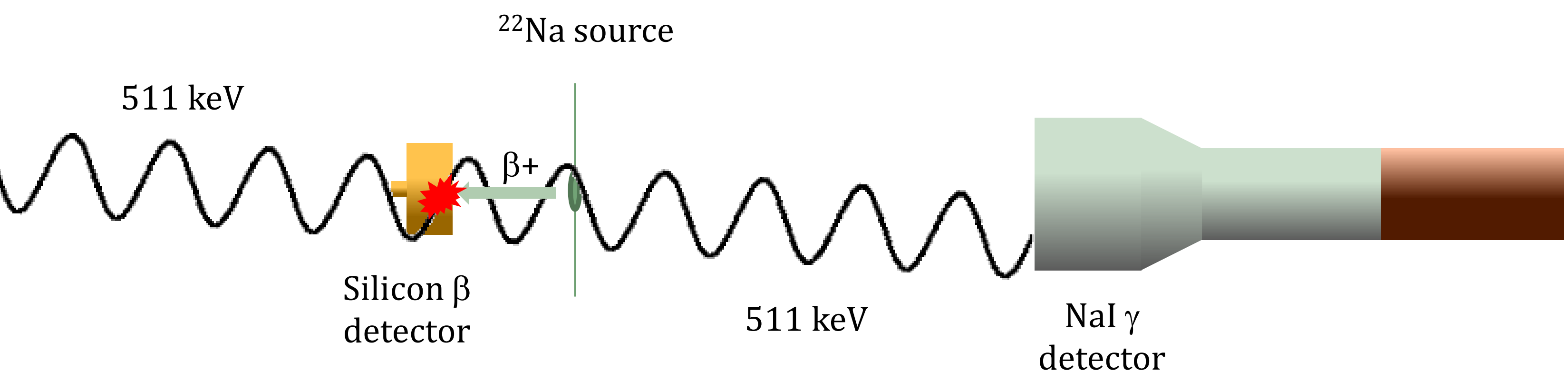
Absolute Efficiency



Absolute Efficiency

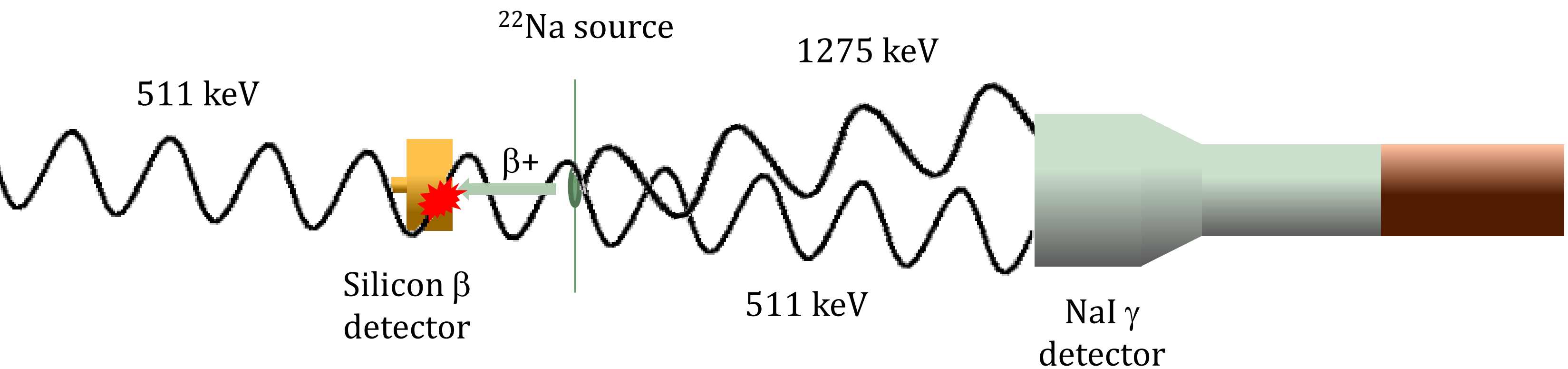


Absolute Full-Peak Efficiency



$$\varepsilon = \frac{N_{coincidence}}{N_{\beta}}$$

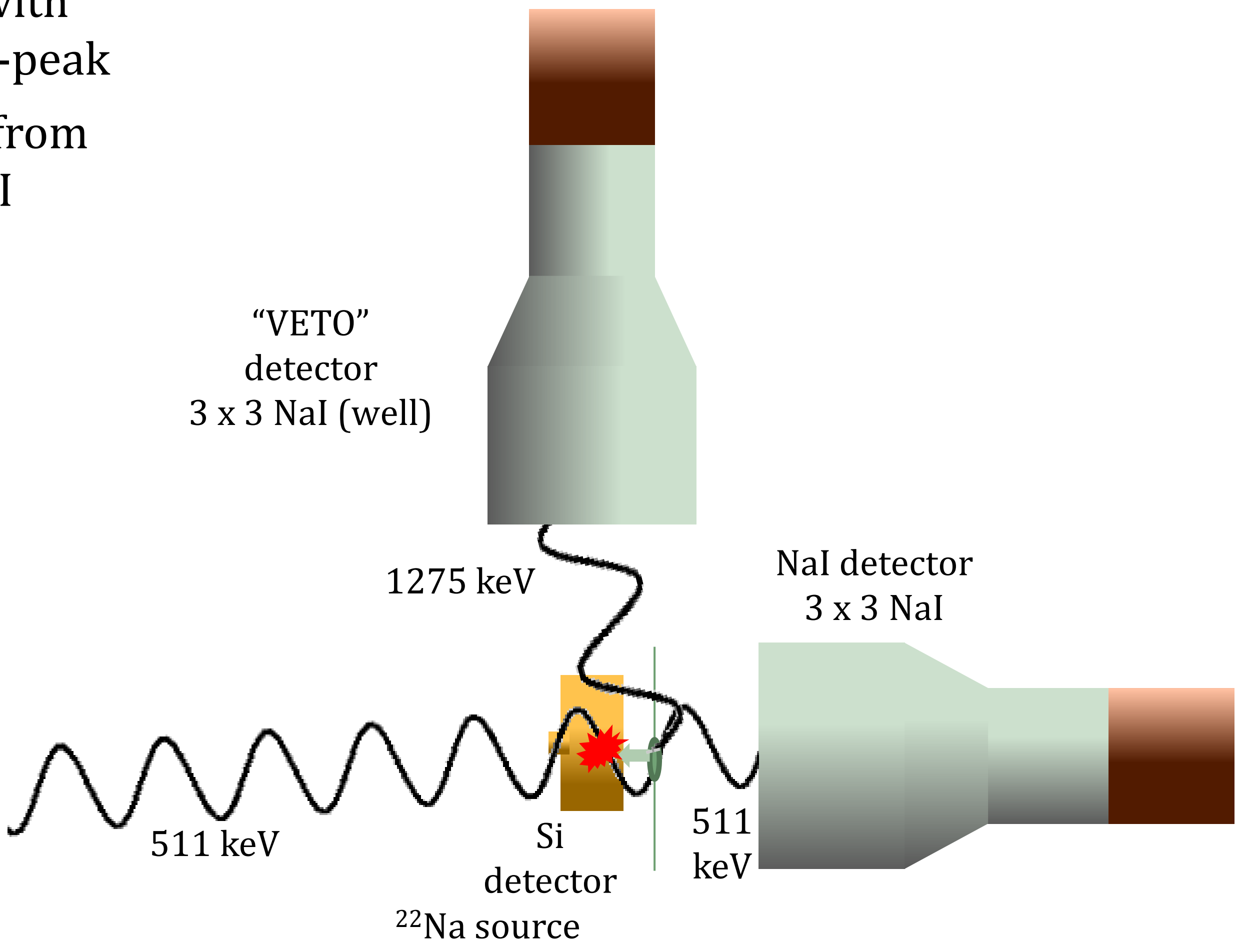
Problem: 1275 keV gamma rays



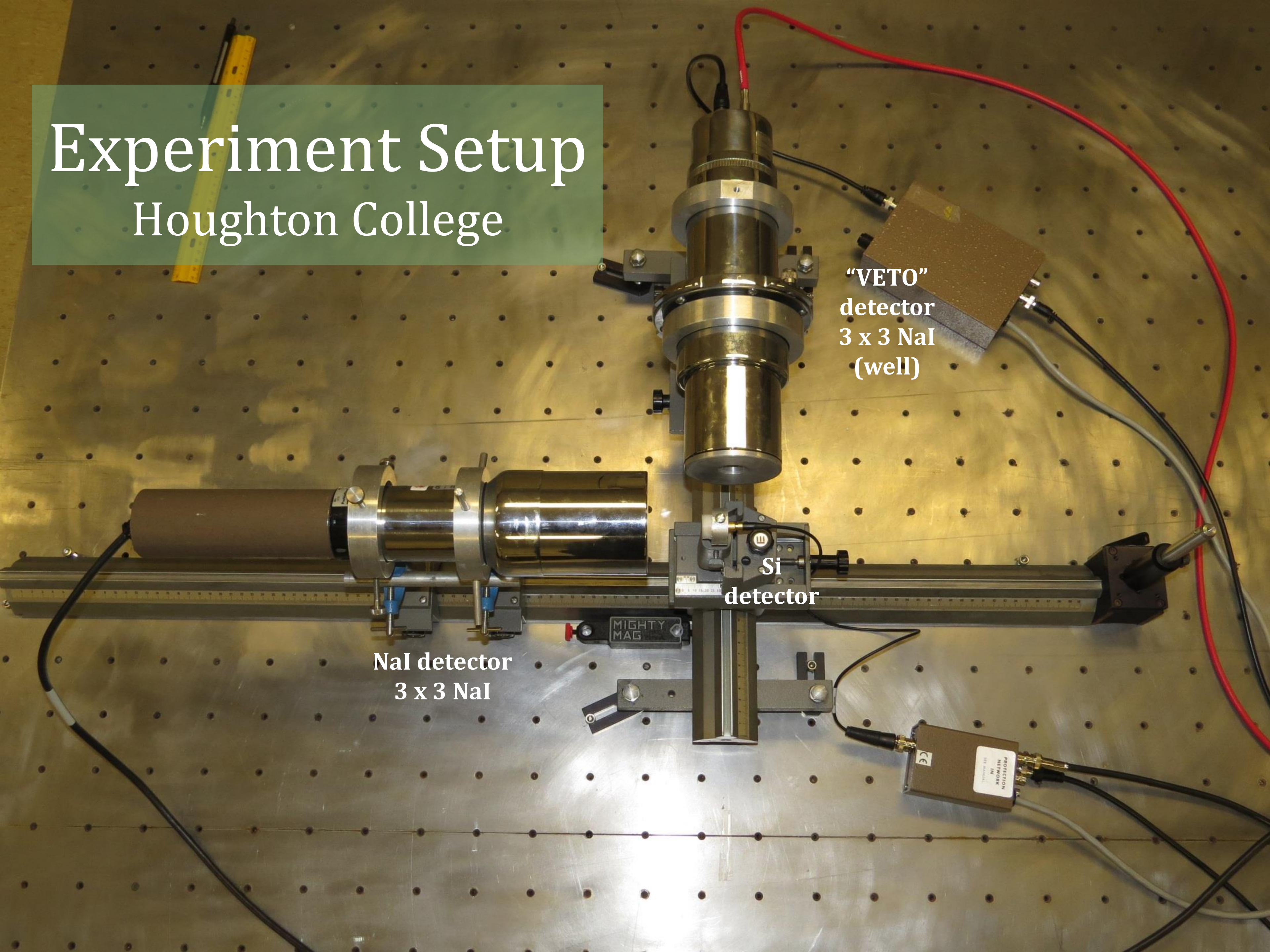
$$\varepsilon = \frac{N_{coincidence}}{N_{\beta}}$$

Solution: detect 1275 keV gamma rays

- Select events in coincidence with 1275 keV full-peak
- No Compton from VETO into NaI

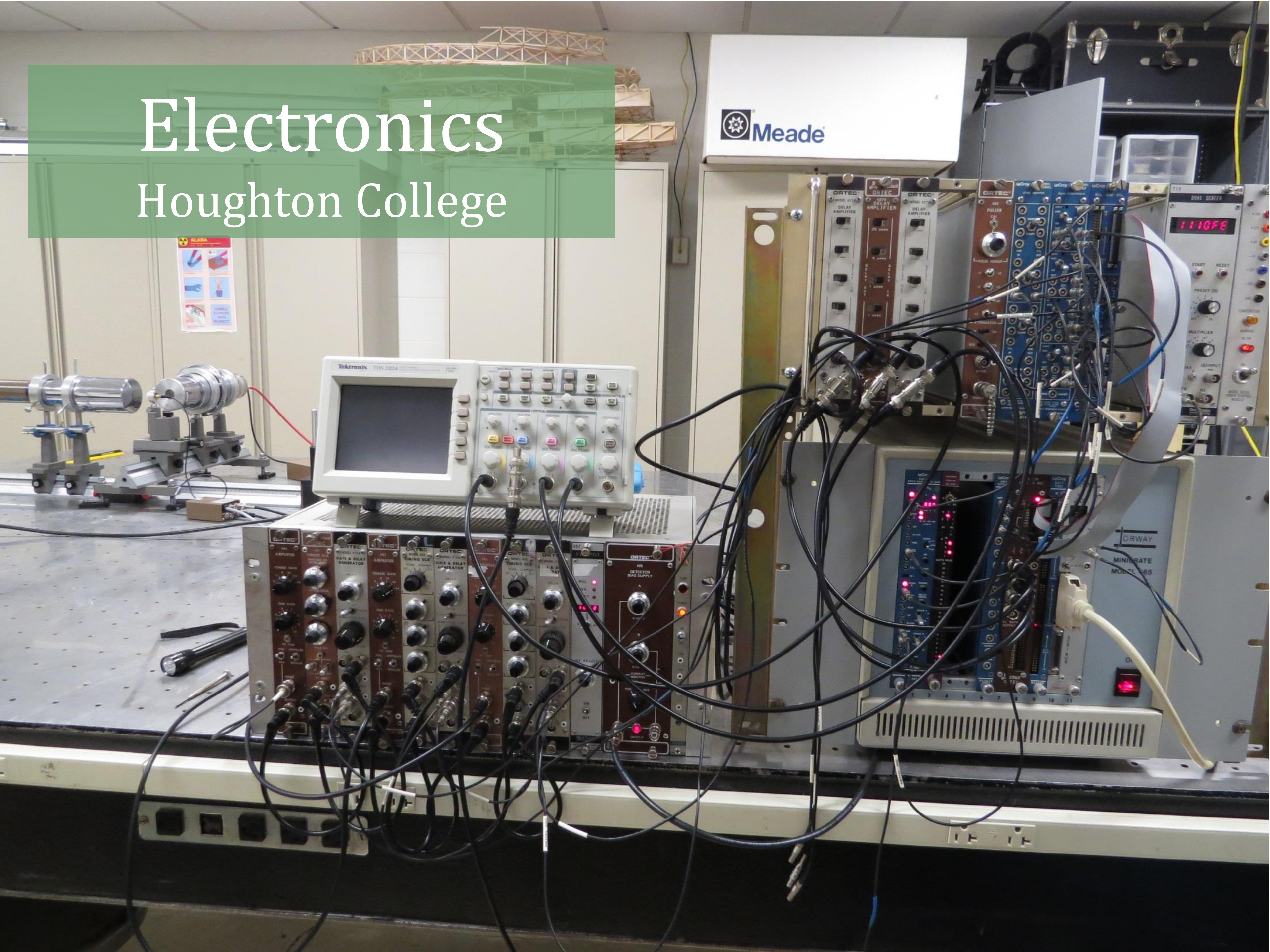


Experiment Setup
Houghton College

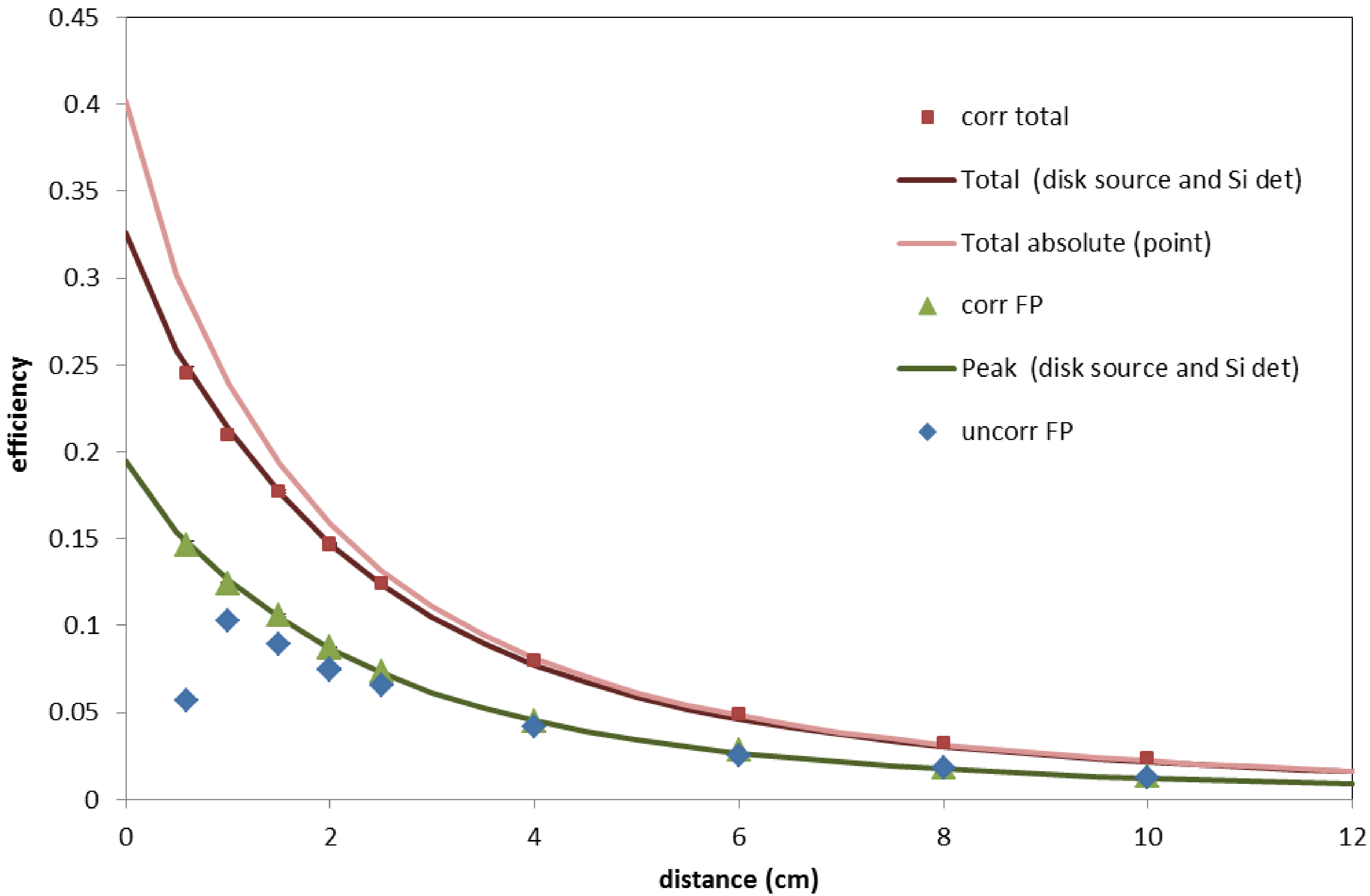


Electronics

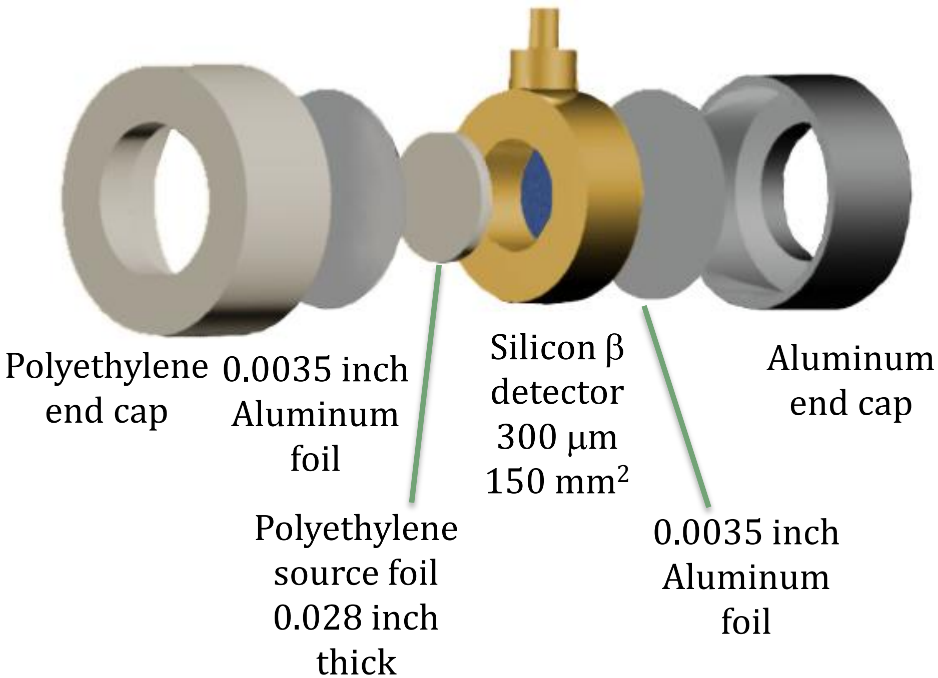
Houghton College

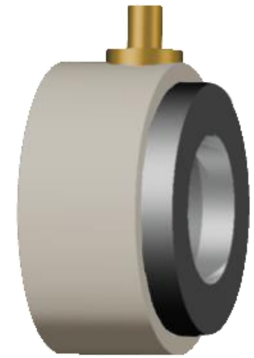


Extended Source + Si Detector Case



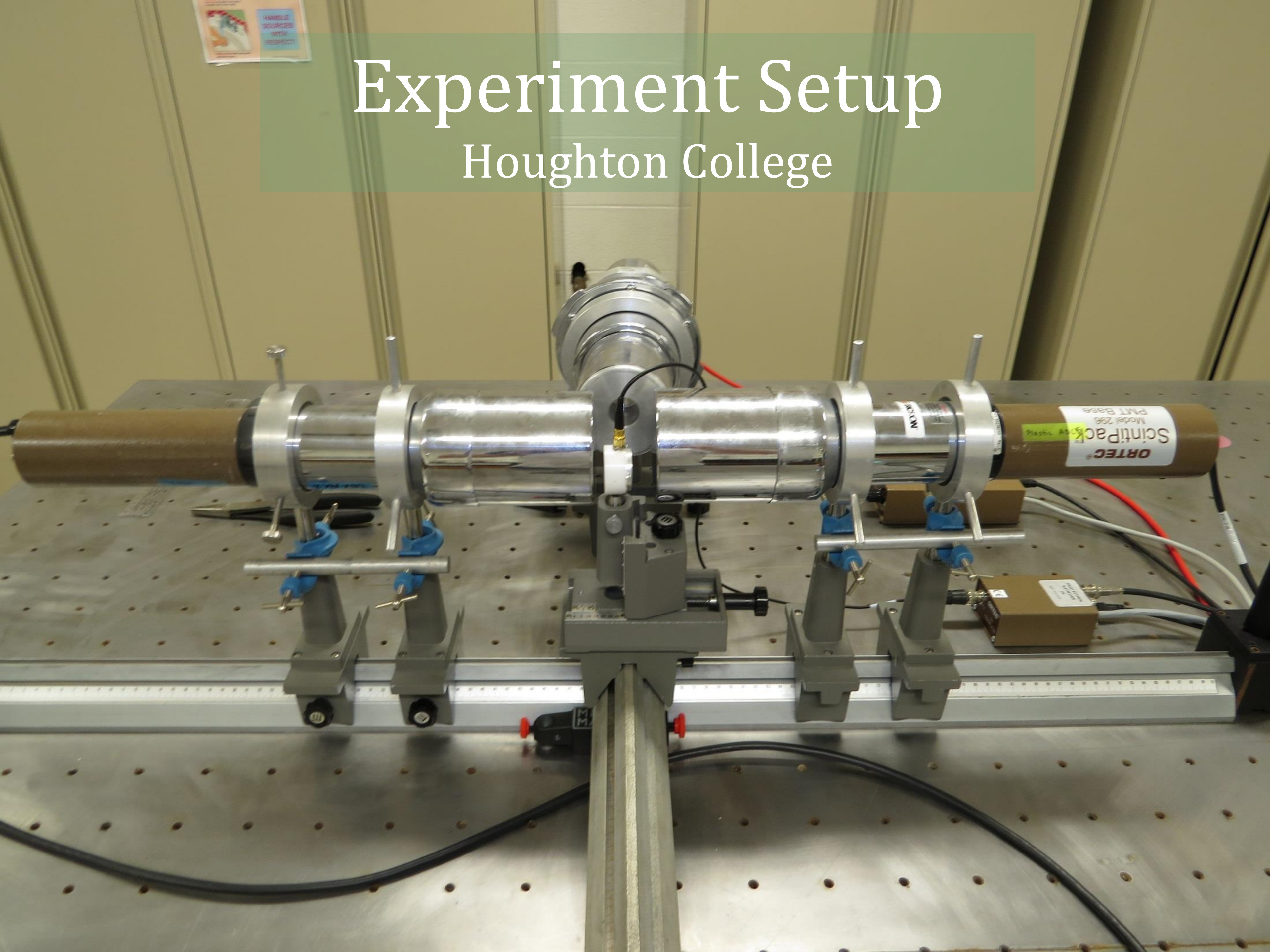
Coincidence Efficiency
^{22}Na Source and thin Si detector



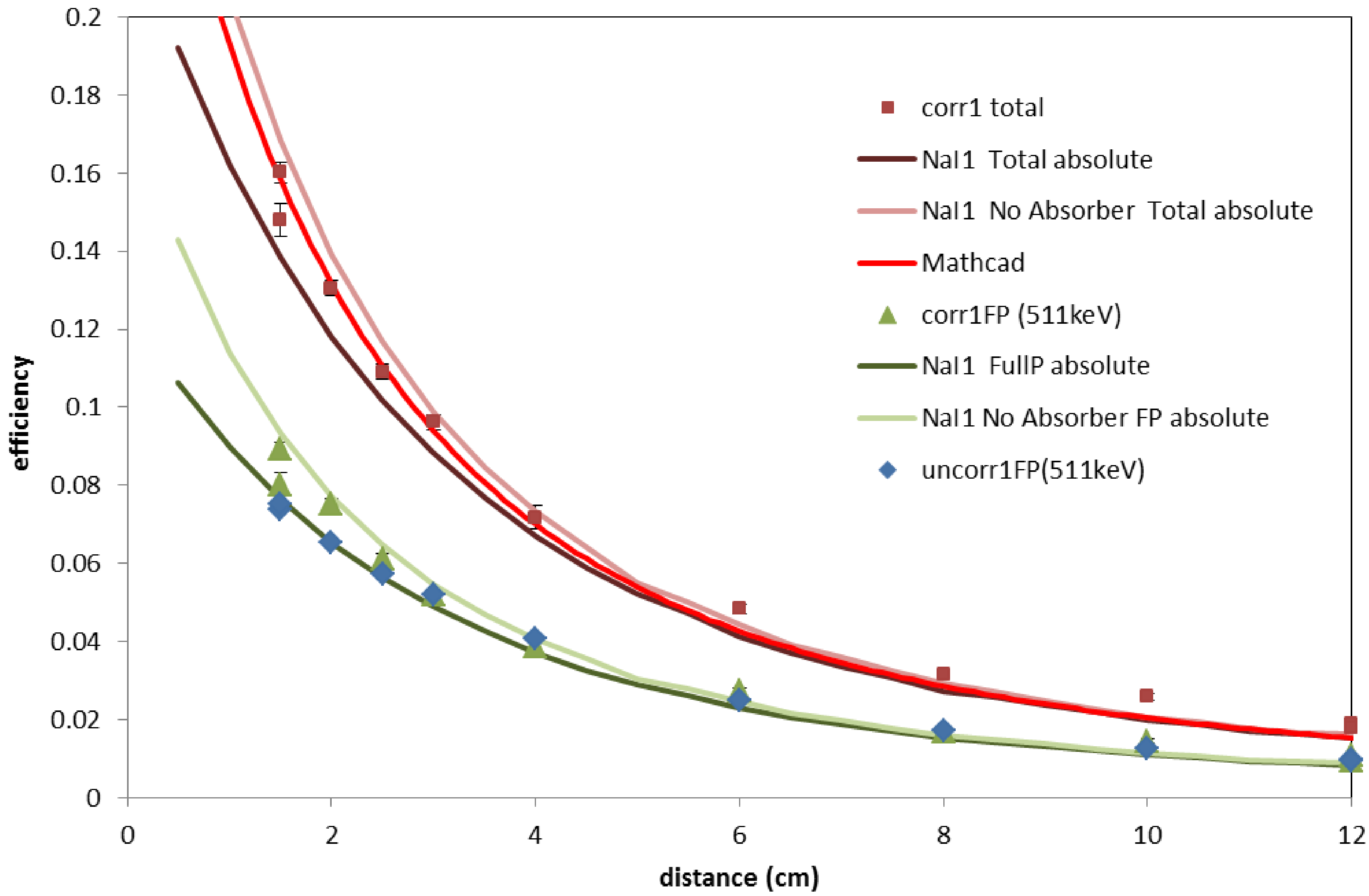


Experiment Setup

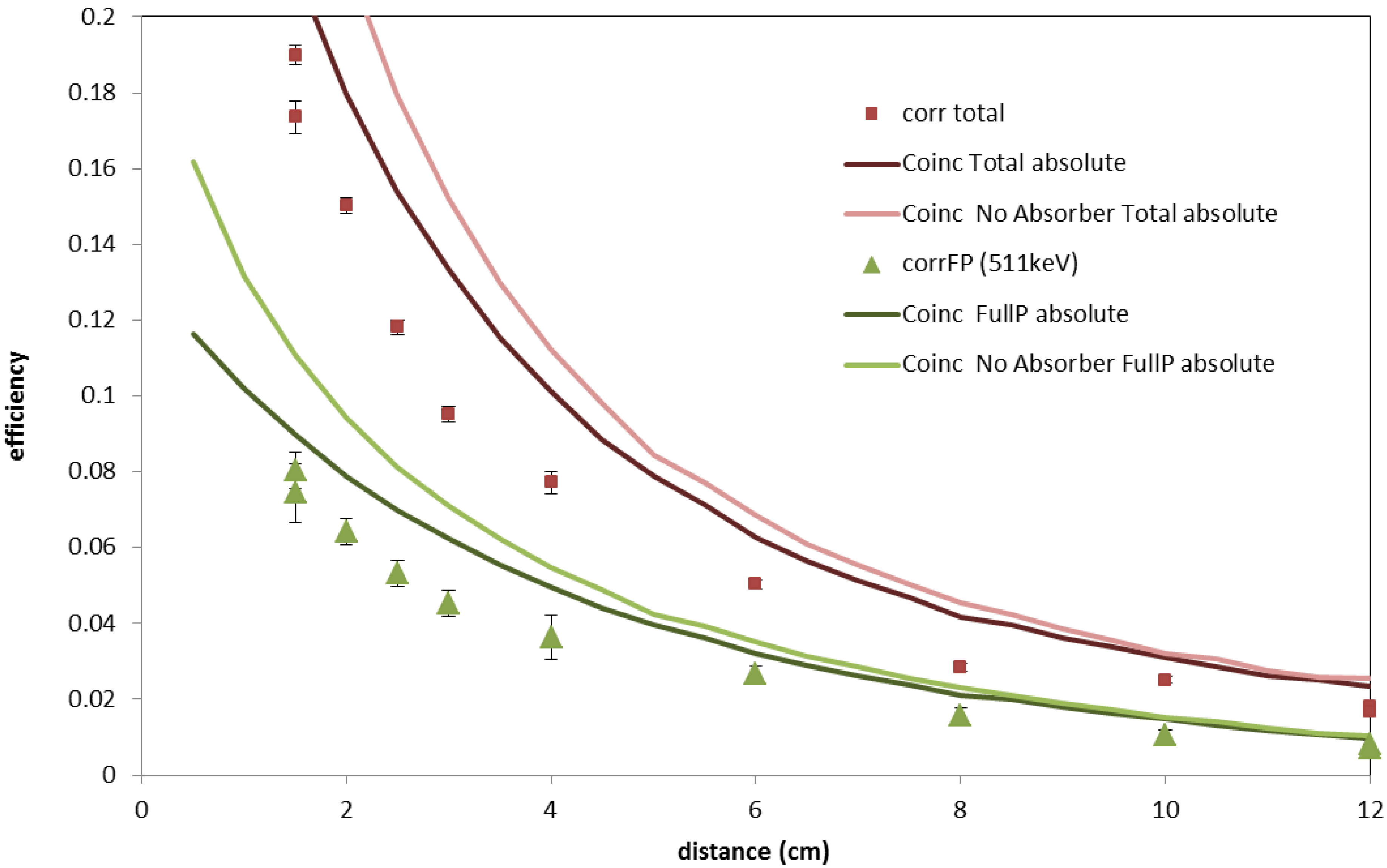
Houghton College



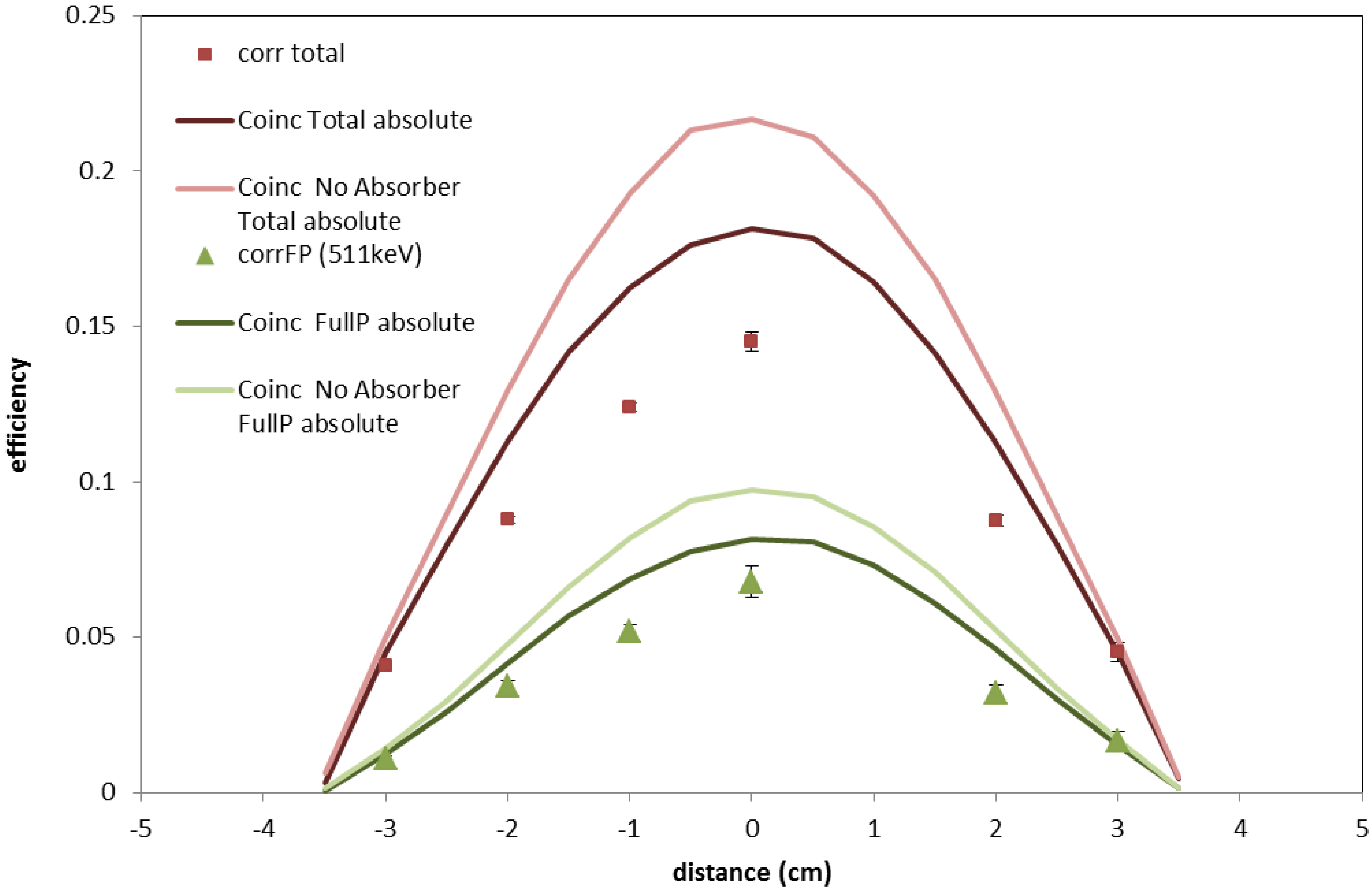
NaI 1 singles at center



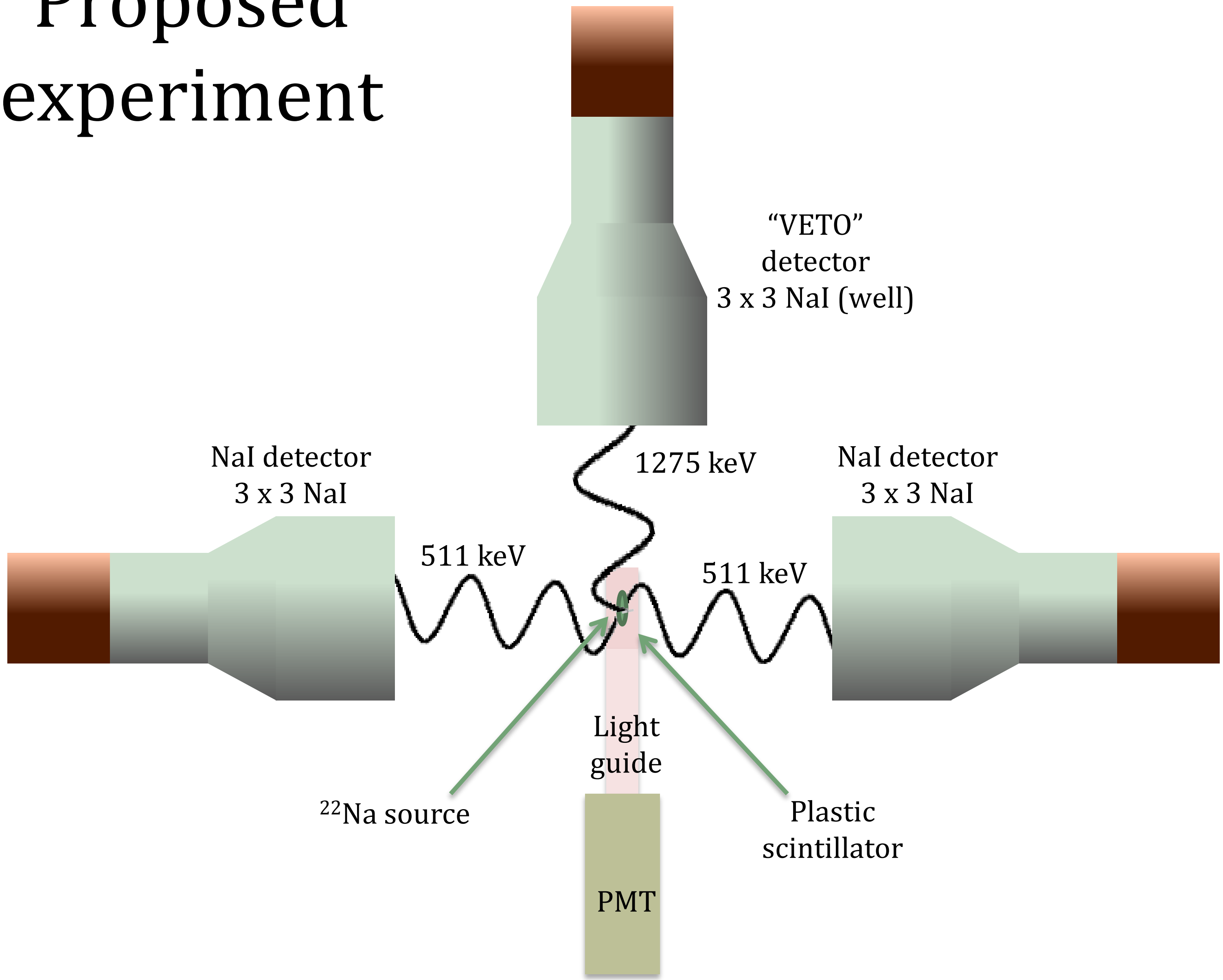
Coincidence at center



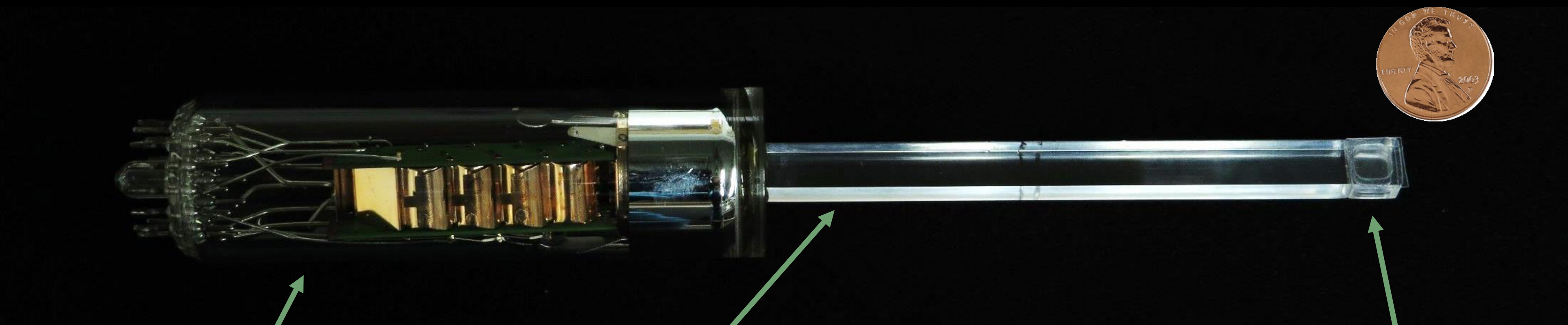
Coincidence at 2 cm



Proposed experiment



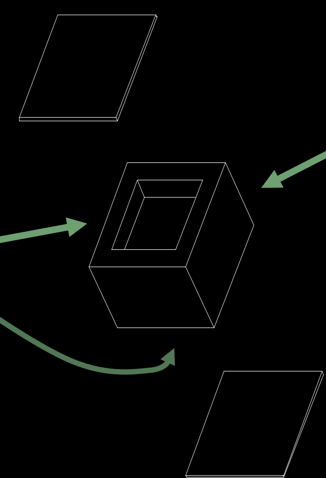
Plastic Scintillator Detector



Photonis XP2902
1-1/8 in PMT

Acrylic light guide

B C-400 plastic
scintillator
(2 mm thick)



< 1 μCi ^{22}Na
evaporated

cover slide

What's Next?

- NaI detector efficiency measurements
  - Coincidence technique, Houghton College
  - Calibrated sources, Ryan Fitzgerald (NIST)
  - Graphite

- GEANT efficiency simulation, Ryan Fitzgerald (NIST)

- $^{12}C(n,2n)^{11}C$ cross sections

Summary

1. This measurement is critical to use carbon activation as a diagnostic at NIF.
2. This is a difficult experiment – 5% uncertainty including systematic effects.
3. This is a well-designed experiment that addresses weaknesses of previous work .
4. This effort represents contributions from a number of collaborators with a breadth of expertise.

Collaborating Institutions

18 83
HOUGHTON
COLLEGE

STATE UNIVERSITY OF NEW YORK · COLLEGE AT GENESEO

1 8 0 4
OHIO
UNIVERSITY

NIST
National Institute
of Standards
and Technology

UR
LLE

NIF

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Previous Experiments

Year	Experiment	Accelerator	Neutron source	Target	Neutron Flux measurement	Activation measurement
1952	Brolley, Fowler, Schlacks	10.5 MeV deuterons from cyclotron	^{3}H(d,n) gas cell, neutron energy selected by angle	polyethylene (CH_2) foils, 11 mg/cm2	Calculated using ^{3}H(d,n) cross section	Calibrated end-window Geiger counters to detect ^{11}C decay positrons
1961	Brill et al.	20 MeV deuterons from cyclotron, slowed down by Pt foils (0.7 MeV resolution)	^{3}H(d,n) and ^{2}H(d,n), T+Zr solid and gas ^{2}H target	Teflon, CF_2	Energy/angle distribution measured using neutron TOF. Claims measured +/- 30%	Counted β+ annihilation gammas in Geiger counter, compared to 197Au.
1980	Dimbylow	Nuclear model calculation, statistical level density model based on optical model fits to experimental total, elastic and inelastic cross sections.				
1981	Anders, Herges, Scobel	7-16 MeV deuterons from cyclotron, degraded to 5.7-9.2 MeV by Be foil	^{3}H(d,n) Titanium foil, 10 um thick, adsorbed tritium	cylindrical (22 mm diam), reactor graphite	Recoil proton detector (stilbene crystal at 0 deg). Neutron monitor to correct for fluctuations in flux.	Annihilation gamma-gamma coincidence using 2 NaI detectors
1981	Welch et al.	Ohio University Tandem	^{3}H(d,n)	Natural sample, 1.77 cm-diameter by 1.0 cm thick	No information available.	Ge(Li) Detector calibrated with NaCl sample.
1992	Soewarsono et al.	20-40 MeV protons from cyclotron.	^{7}Li(p,n) quasimonoenergetic ; lithium on graphite backing, background subtracted.	Natural sample	Neutron TOF to NE-213 liquid scintillator detector, see Uno et al.	Single HPGe detector, Activate with Li target and no Li target and subtract
1996	Uno et al.	20-40 MeV protons from cyclotron.	^{7}Li(p,n) quasi-monoenergetic, width varies 2.3-1.4 MeV for 18-40 MeV neutrons, respectively.	Cylindrical (20 mm diam), graphite	Activation of Li target gave absolute normalization, neutron time of flight measured angular and energy distribution.	Two HPGe detectors detected decay gammas, no coincidence required.