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A new experimental setup to measure the astrophysical $^{15}O(\alpha,\gamma)^{19}Ne$ reaction rate in inverse kinematics

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- **Uhuru**, the first designated **x-ray satellite**, was launched 1970. This opened up a new window into X-ray astronomy
- Launches of subsequent x-ray telescopes, such as **Chandra** and **XMM Newton** (both 1999), has lead to the discovery of x-ray emitting events
- One such discovery was that of **x-ray bursts** by the **Astronomical Netherlands Satellite** in 1974-75 [3]

Reconstruction of the Uhuru satellite [1]

Render of the Chandra satellite [2]

[1] The Smithsonian Institution, "Satellite, Uhuru, Reconstructed Craft", https://www.si.edu/object/satellite-uhuru-reconstructed-craft%3Anasm_A19761823000
[2] A. Kasprak, "Ballistic Helix", https://svs.gsfc.nasa.gov/11185 (2013)
[3] J. Grindlay *et al.*, Astrophys. J. 203 L127 (1976)

X-Ray Bursts

- X-ray burst are **reoccurring explosions** that take place in binary systems consisting of a **neutron star** and **main sequence star**
- Represents the **most common explosive stellar phenomenon** in the universe
- Hence, being able to understand the nuclear processes that drive then is extremely important

Artist's impression of an X-ray burst

Nucleosynthesis in X-Ray Bursts

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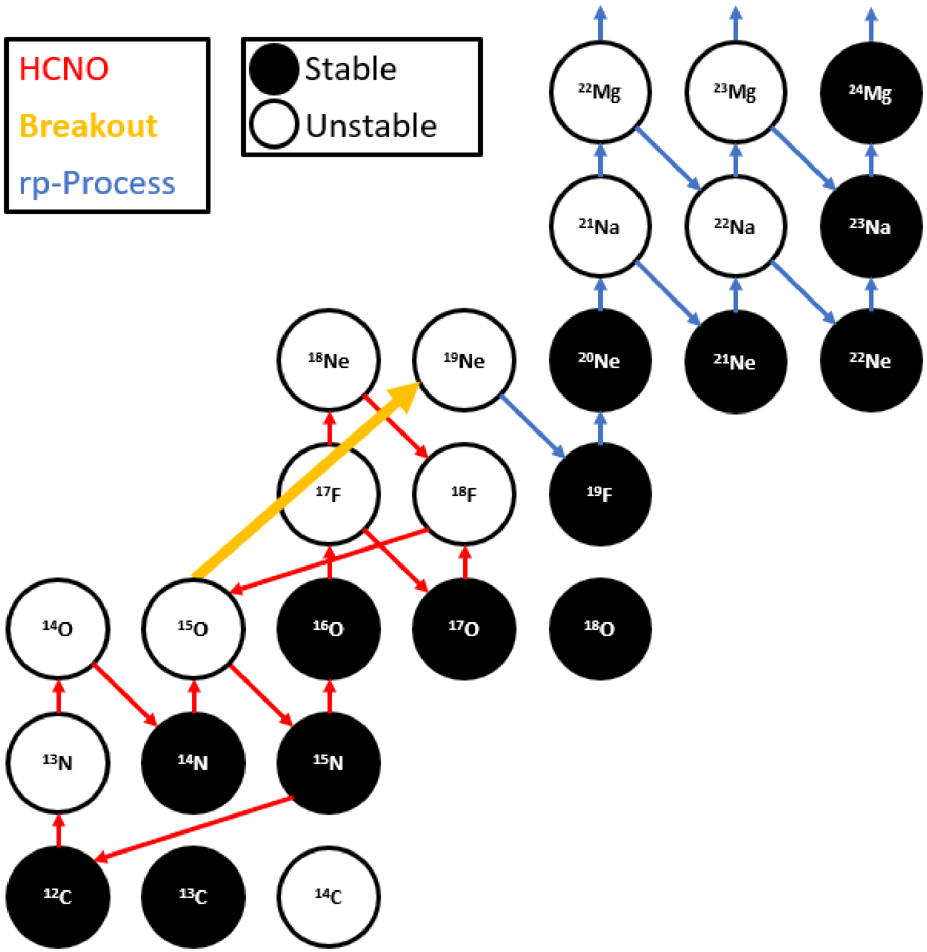
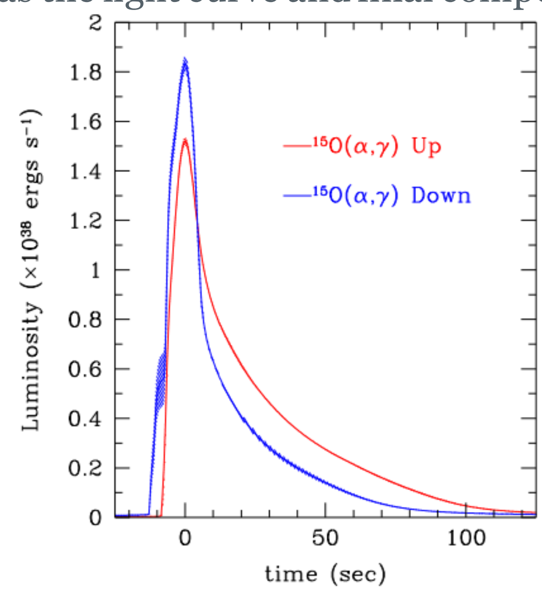


- Energy production is driven by the **HCNO cycle** during the early stages of the burst
- Once the temperature of the accreted material becomes sufficient, **breakout from the HCNO** cycle into the **rp-process** can occur
- The **^{15}O(α,γ)^{19}Ne** reaction is a proposed breakout reaction [4]
- This reaction has been shown to have a large impact on key observables of the X-ray burst such as the light curve and final composition



Impact of the ^{15}O(α,γ)^{19}Ne reaction rate on the X-ray burst light curve. Rate varied by ×100 & ×0.01 [5]

[4] R. K. Wallace & S. E. Woosley, Astrophys. J. **45** 389 (1981)
[5] R. Cyburt *et al.*, Astrophys. J. **830** p55 (2016)

Measuring the $^{15}O(\alpha,\gamma)^{19}Ne$ Reaction Rate

- It is currently not possible to study the reaction directly

- In order to determine the reaction rate indirectly, the **excitation energies, J^π and alpha partial widths** of all states in ^{19}Ne above the alpha separation energy need to need to be determined

$$\langle\sigma v\rangle = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2 \sum_i (\omega\gamma)_i \exp\left(-\frac{E_i}{kT}\right)$$

$$\omega\gamma = \omega\frac{\Gamma_\alpha\Gamma_\gamma}{\Gamma_\alpha+\Gamma_\gamma} \approx \omega\Gamma_\alpha$$

$$\omega = \frac{(2J+1)}{(2J_\alpha+1)\left(2J_{^{19}Ne}+1\right)}$$

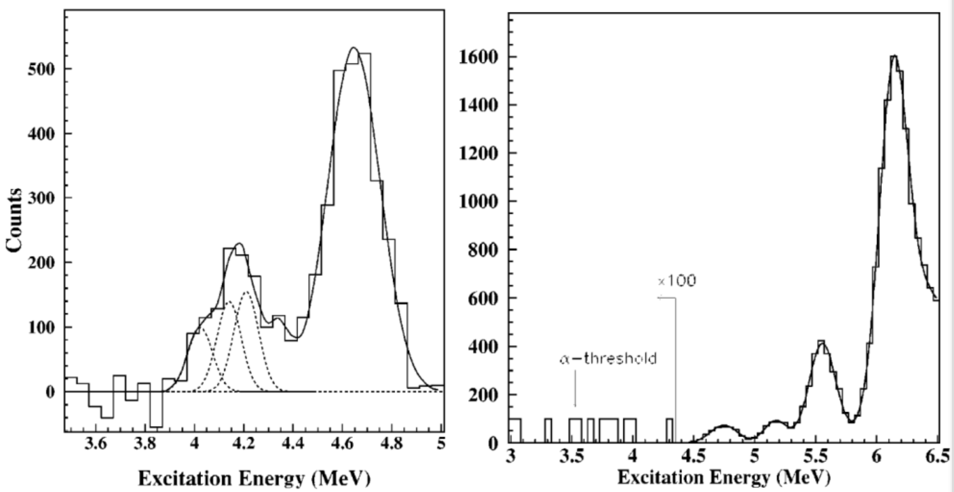
- Since the excitation energies, spins, parities and lifetimes [6,7], and hence radiative width, are known, the alpha-branching ratio now represents the key nuclear physics uncertainty

$$\Gamma_\alpha = \frac{B_\alpha}{1-B_\alpha}\Gamma_\gamma$$

- Previous calculations have suggested that the reaction rate at energies of interest is **dominated by a single $\frac{3}{2}^+$ resonances at $E_x = 4.033\ MeV$** [8]

[6] W. P. Tan *et al.*, Phys. Rev. C **72** 041302 (2005)
[7] S. Mythili et.al., Phys. Rev. C 77 035803 (2008)
[8] K. Langanke *et al.*, Astrophys. J. **301** 629 (1986)

The 3/2+, 4.033 MeV Resonance

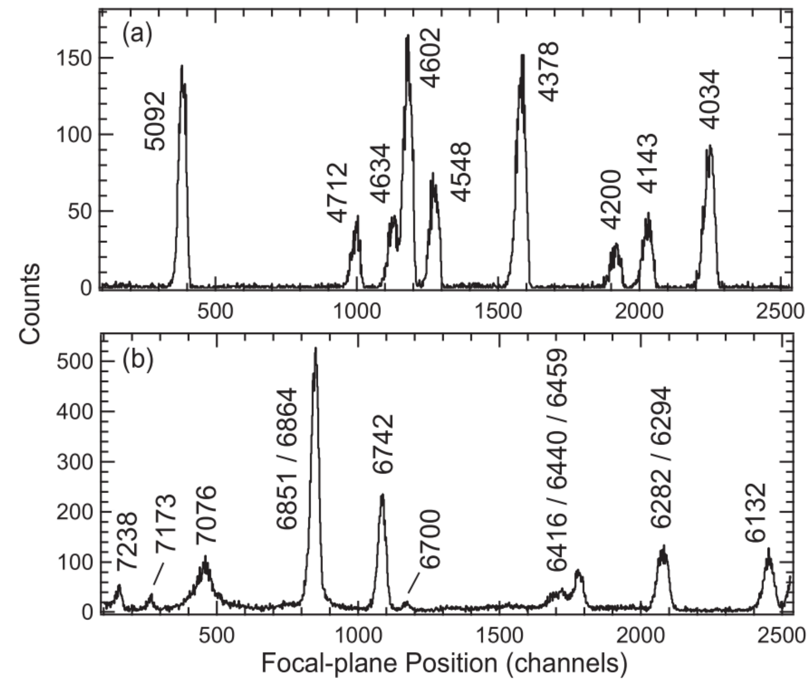


^{19}Ne excitation energy [9]. Left - total excitation spectrum. Right – gated on α-decays

[9] A. M. Laird *et al.*, Phys. Rev. C **66** 048801 (2002)

d*(^{18}Ne,^{19}Ne)*p reaction at Louvain-la-Neuve

Measured $B_\alpha < 0.01$



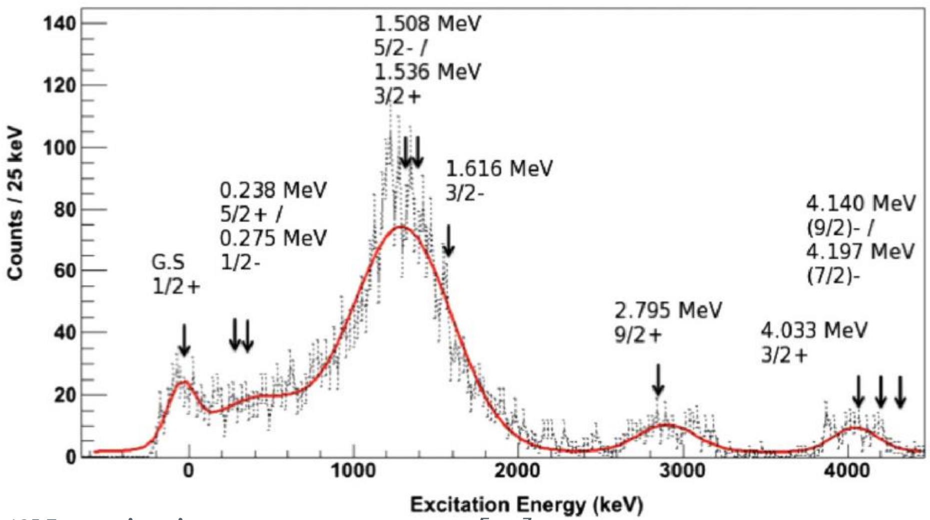
Triton position spectrum measured using the Q3D spectrograph [10]

[10] A. Parihk *et al.*, Phys. Rev. C **92** 055806 (2015)

^{19}F(^{3}He,*t*)^{19}Ne at the Maier-Leibnitz Laboratorium using the Q3D spectrograph

Able to confirm the 3/2+ assignment of the 4.033 MeV state

The 3/2+, 4.033 MeV Resonance

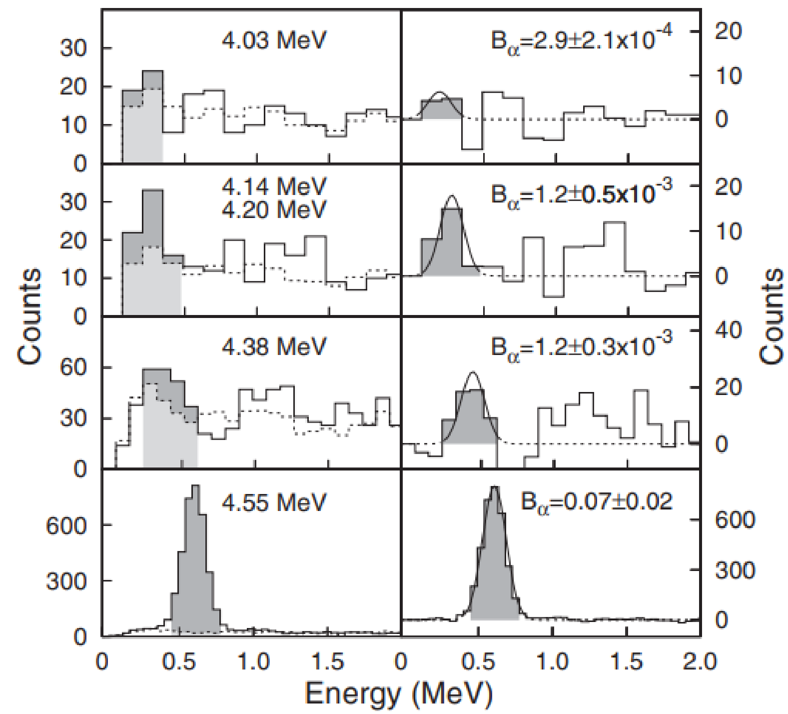


^{19}Ne excitation energy spectrum [11]

[11] D. T. Doherty *et al.*, Phys. Scr. **T166** 014007 (2015)

^{20}Ne(*p*,*d*)^{19}Ne in inverse kinematics using the **Experimental Storage Ring** (ESR) at GSI & and a gas target

Unable to measure B_α



Alpha energy spectrum of alpha-decays from ^{19}Ne [12]

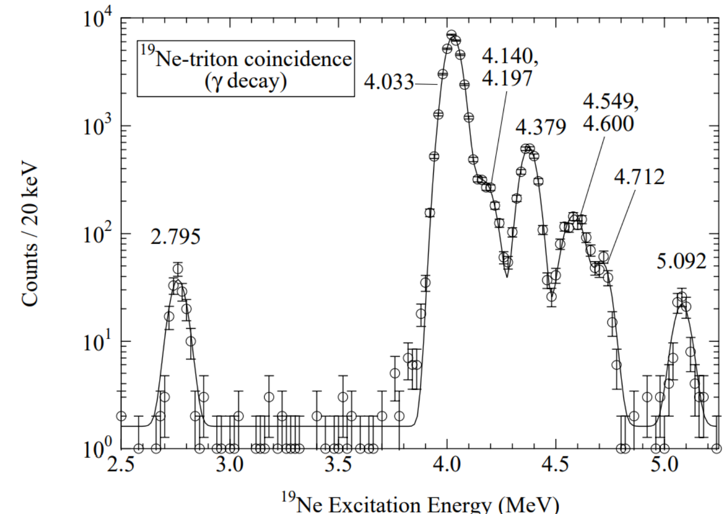
[12] W. P. Tan *et al.*, Phys. Rev. Lett. **98** 242503 (2007)

^{19}F(^{3}He,*t*)^{19}Ne*(α)^{15}O at the University of Notre Dame, measuring the energy of the alpha decays

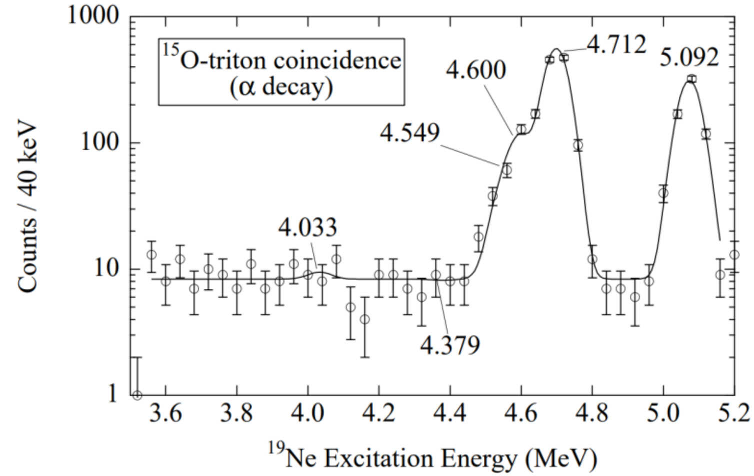
Measured $\boldsymbol{B_\alpha = 2.9(2.1) \times 10^{-4}}$

The $^{21}Ne(p,t)^{19}Ne$ Reaction

- Measuring the alpha branching ratio is extremely challenging
- David's [13] chose the **$^{21}Ne(p,t)^{19}Ne$** reaction, as this has been experimentally observed to **preferentially populate the 4.033 MeV excited state** [14]
- Experiment was carried out at the Kernfysisch Versneller Instituut (KVI)
- Both light (triton) and heavy (^{19}Ne & ^{15}O) reaction products pass through the Big Bite Spectrometer and were detected in separate phoswich detectors
- They were still only able to place an upper limit of $B_\alpha \leq 4.3 \times 10^{-4}$
- With greater statistics, the $^{21}Ne(p,t)^{19}Ne$ reaction represents the best way to measure the branching ratio



^{19}Ne excitation energy spectrum for ^{19}Ne-t coincidences from [13]



^{15}O-t coincidences from [13]

^{19}Ne excitation energy spectrum for ^{15}O-t coincidences from [13]

[13] B. Davids *et al.*, Phys. Rev. C, **67** 065808 (2003)
[14] H. T. Fortune *et al.*, Phys. Rev. C 18 1563 (1978)

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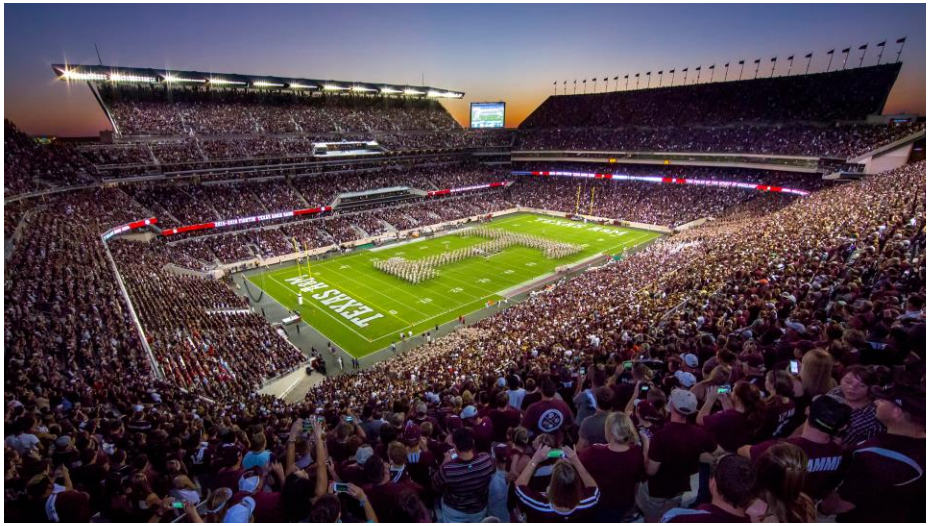
Texas A&M University



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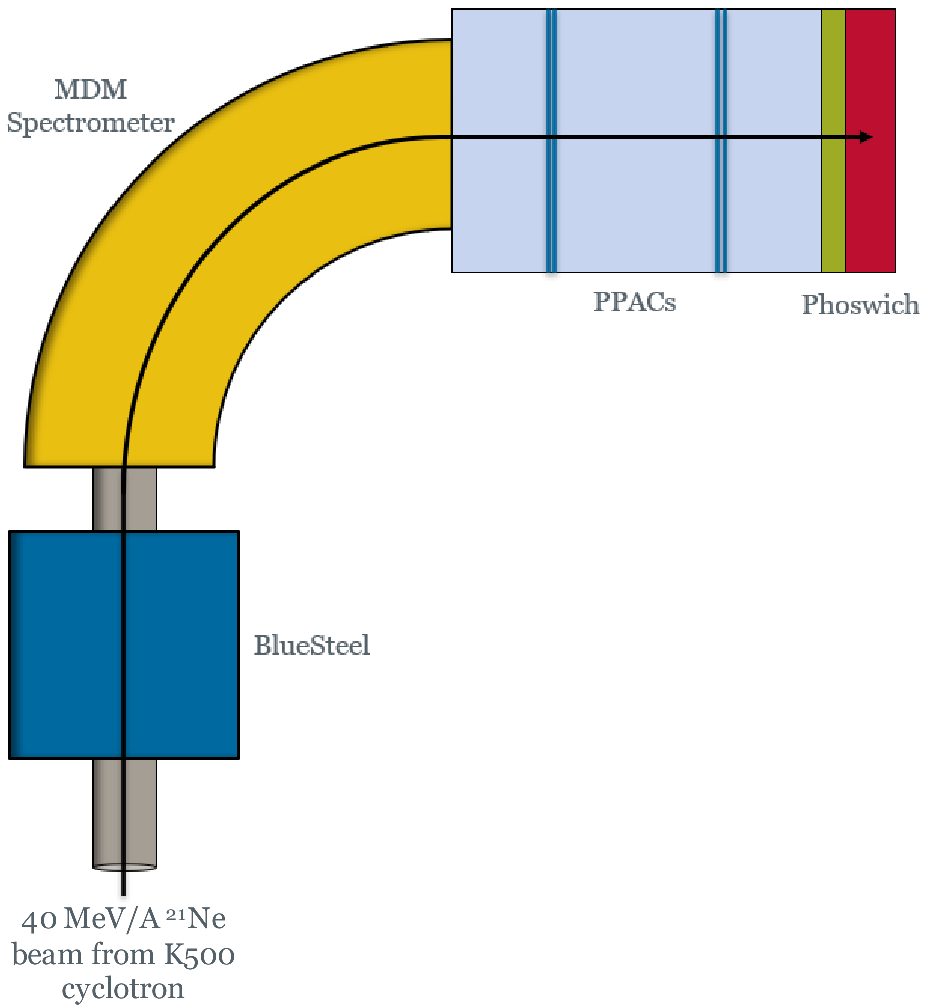
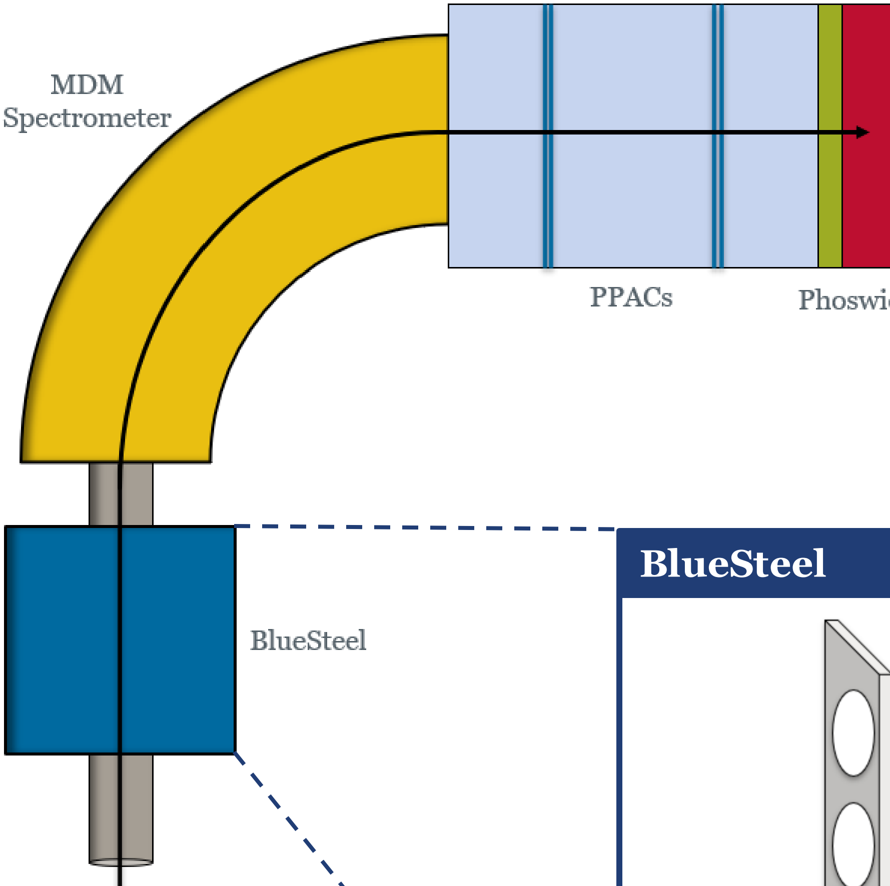
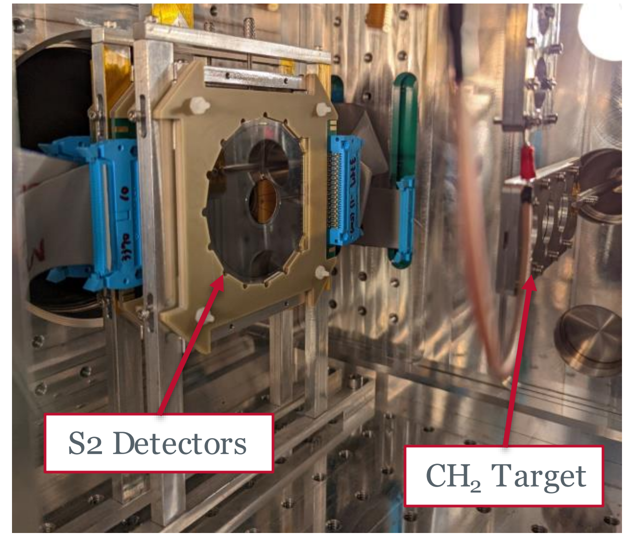
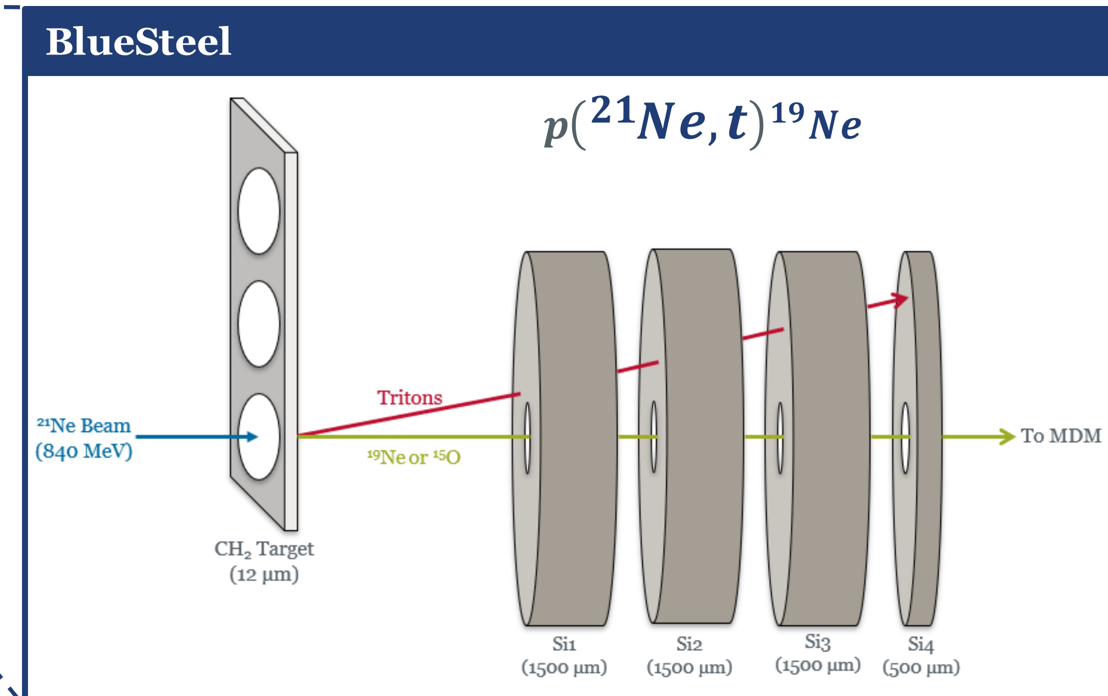
Experimental Setup



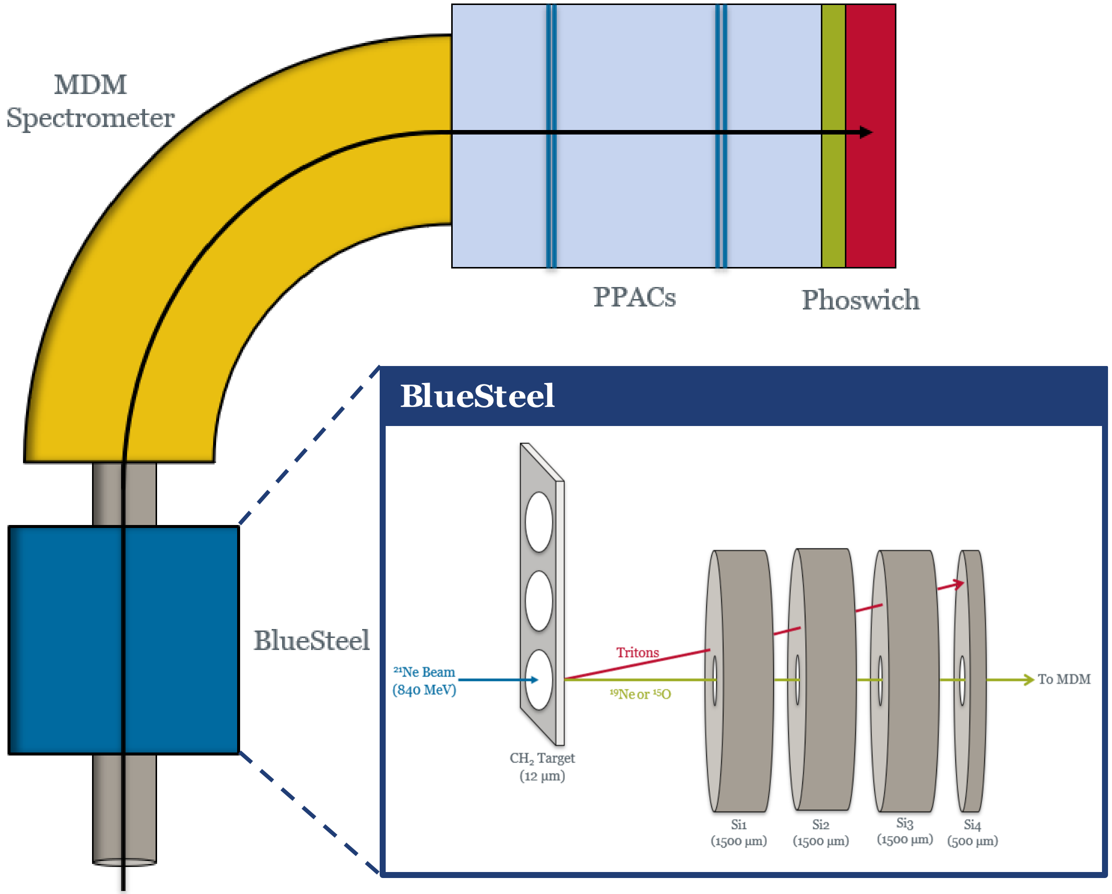
Experimental Setup



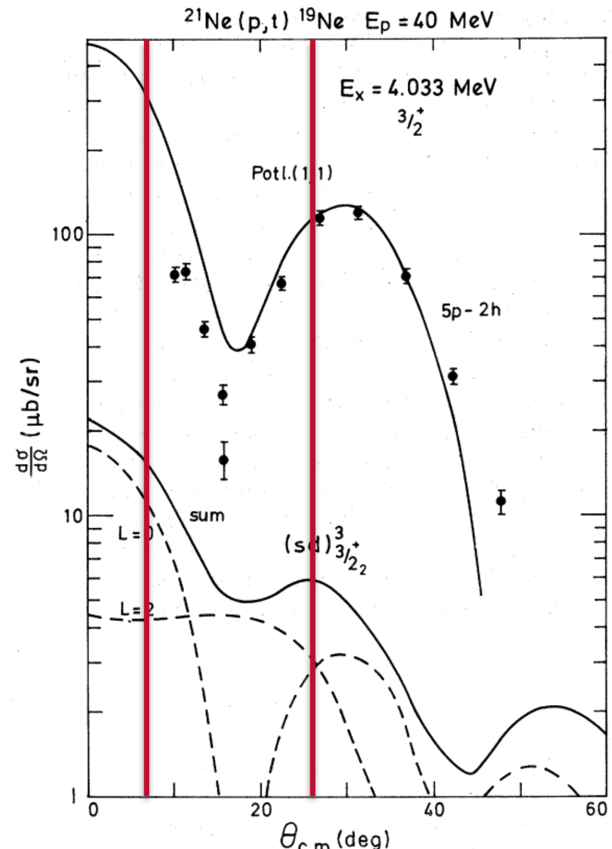




Experimental Setup



40 MeV/A ^{21}Ne beam from K500 cyclotron

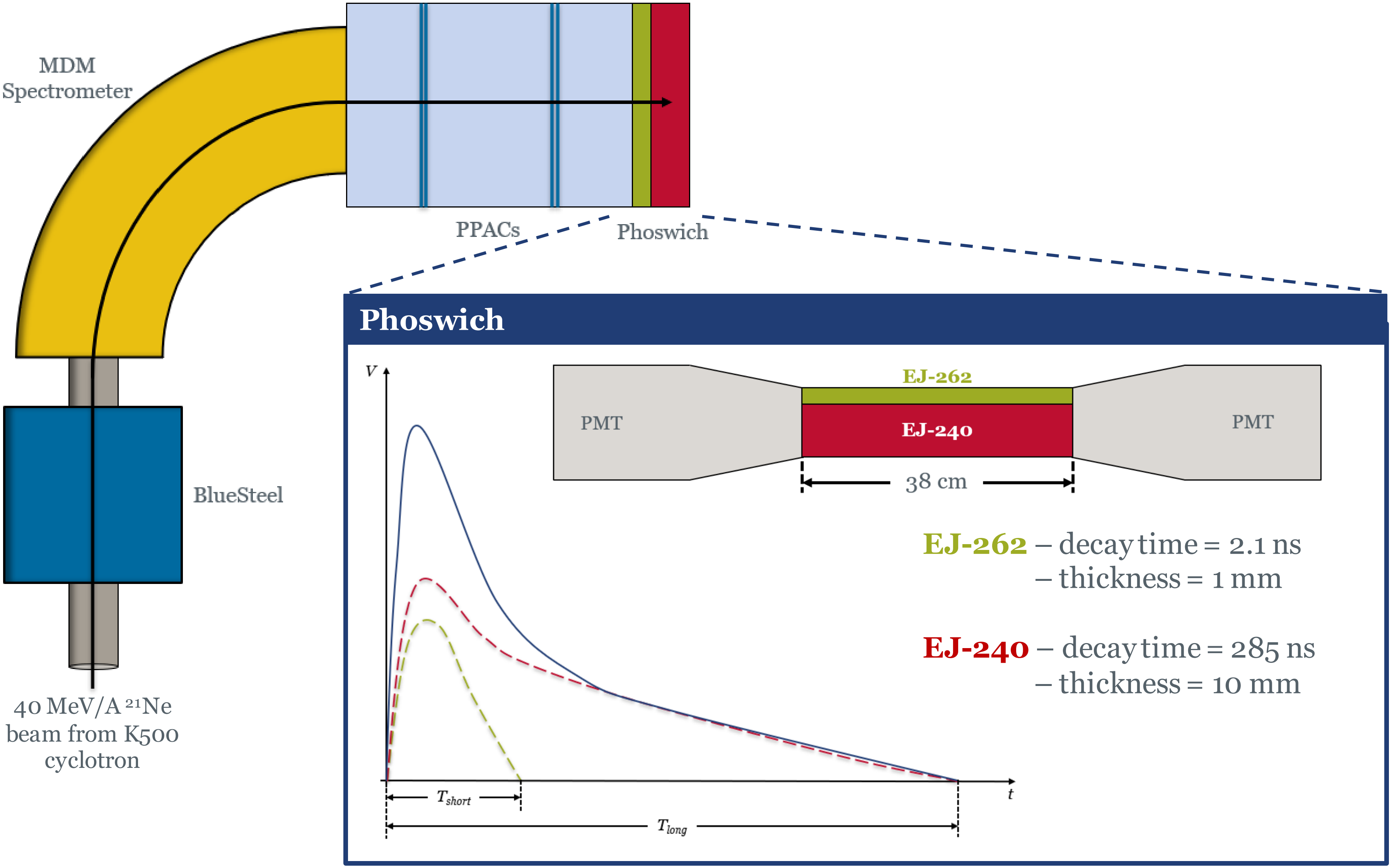


Angular distribution of tritons from ^{21}Ne(p,t)^{19}Ne populating the 4.033 MeV state [14]

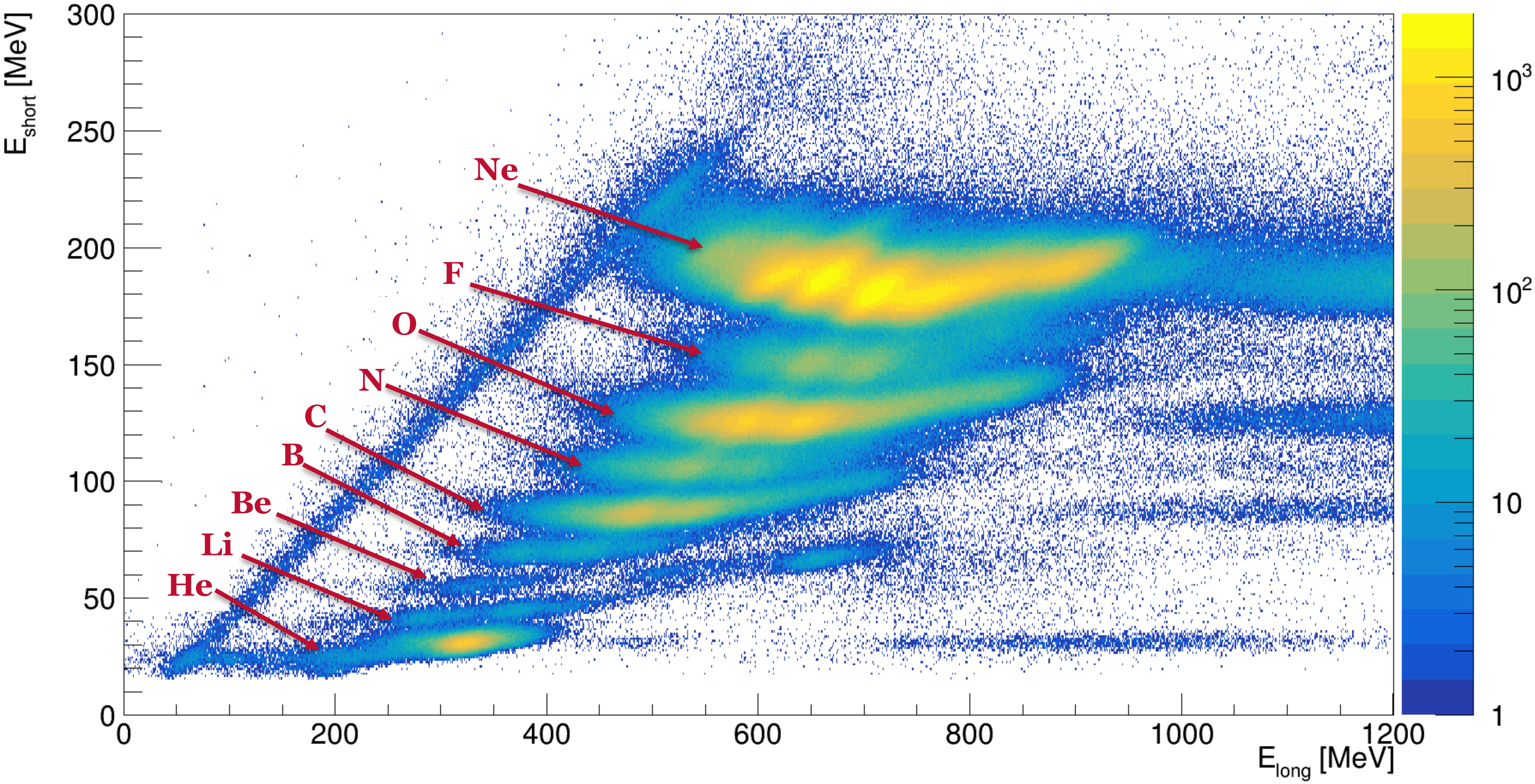
Si detector provide an angular coverage of $\mathbf{4.9^0 \le \theta_{lab} \le 13.5^o}$, which corresponds to $\mathbf{7.8^0 \le \theta_{CM} \le 23.7^o}$

[14] H. T. Fortune *et al.*, Phys. Rev. C 18 1563 (1978)

Experimental Setup

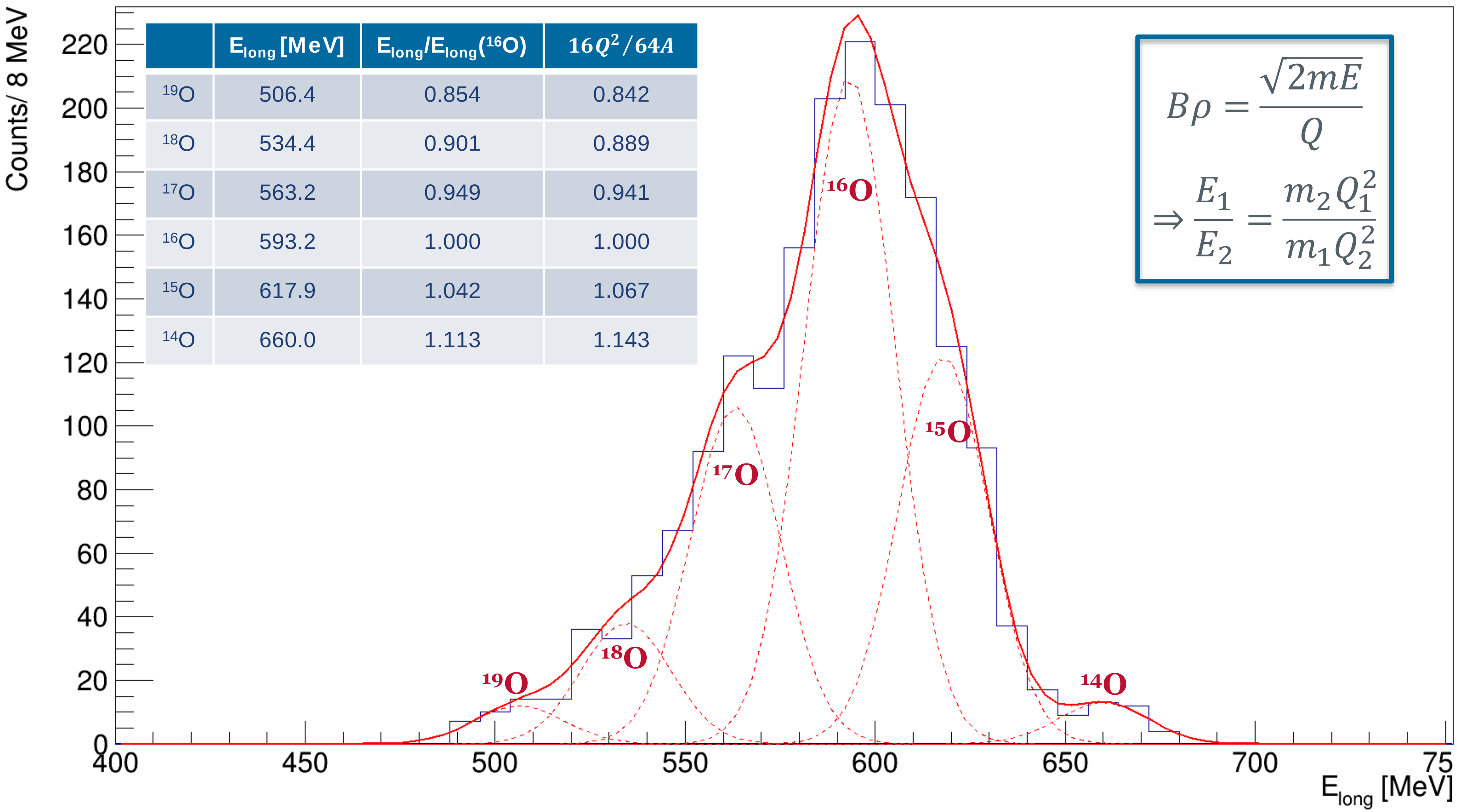


Phoswich Particle Identification



$\Delta E \propto \frac{mz^2}{E}$, where $\Delta E \sim E_{short}$ and $E \sim E_{long}$

Phoswich - Isotope Identification



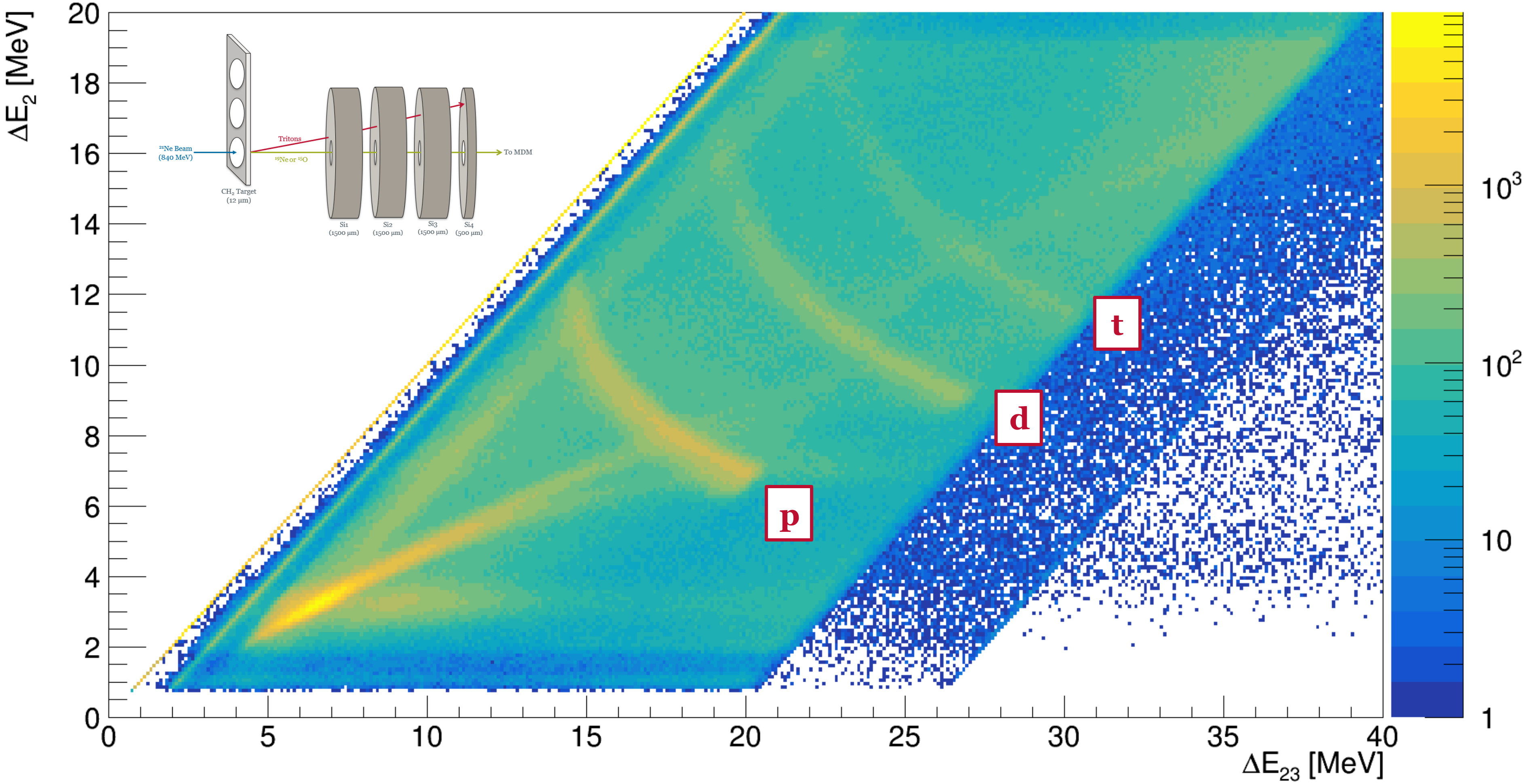
	E_{long} [MeV]	$E_{long}/E_{long}(^{16}O)$	$16Q^2/64A$
^{19}O	506.4	0.854	0.842
^{18}O	534.4	0.901	0.889
^{17}O	563.2	0.949	0.941
^{16}O	593.2	1.000	1.000
^{15}O	617.9	1.042	1.067
^{14}O	660.0	1.113	1.143

$$B\rho = \frac{\sqrt{2mE}}{Q}$$

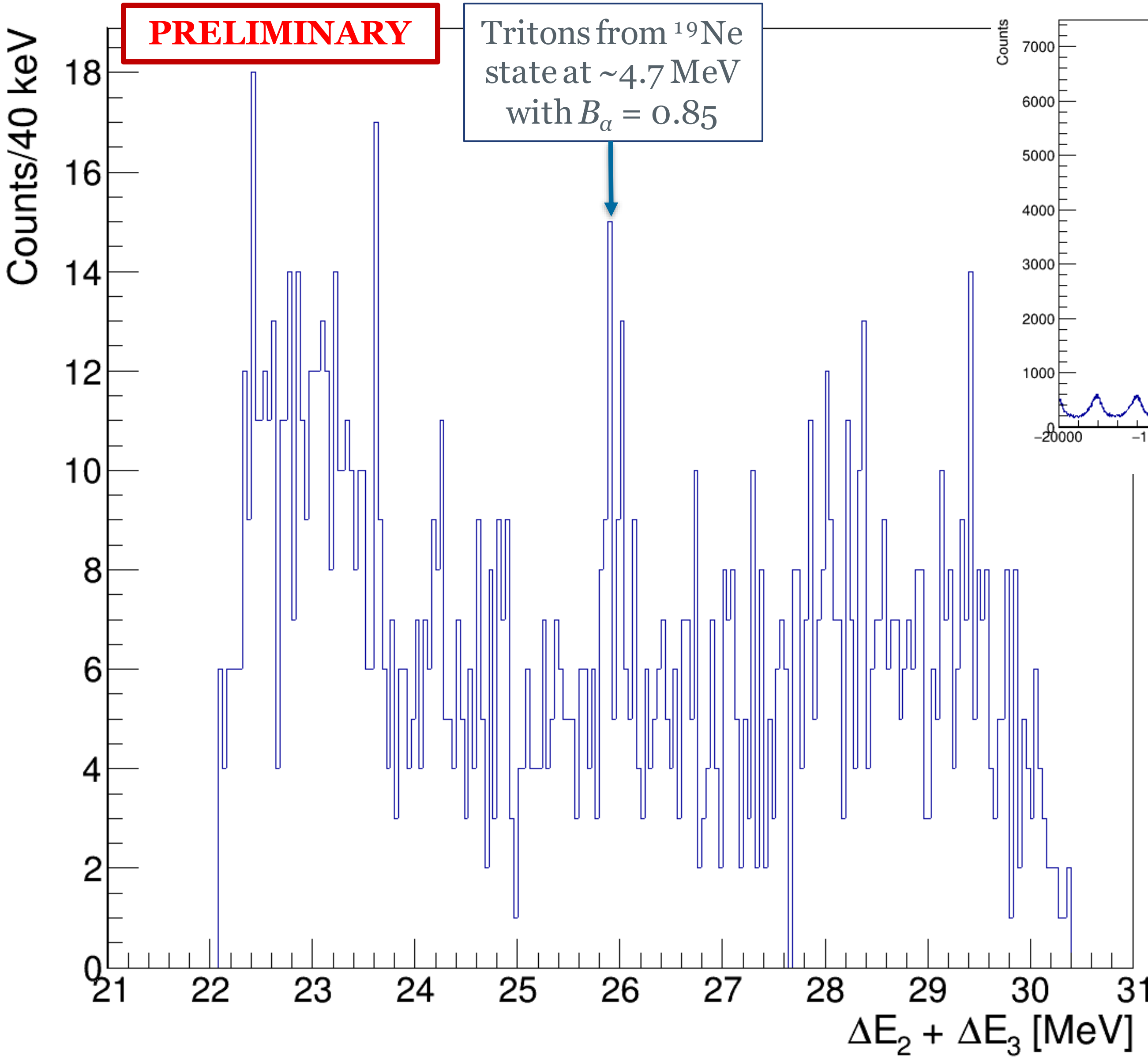
$$\Rightarrow \frac{E_1}{E_2} = \frac{m_2 Q_1^2}{m_1 Q_2^2}$$

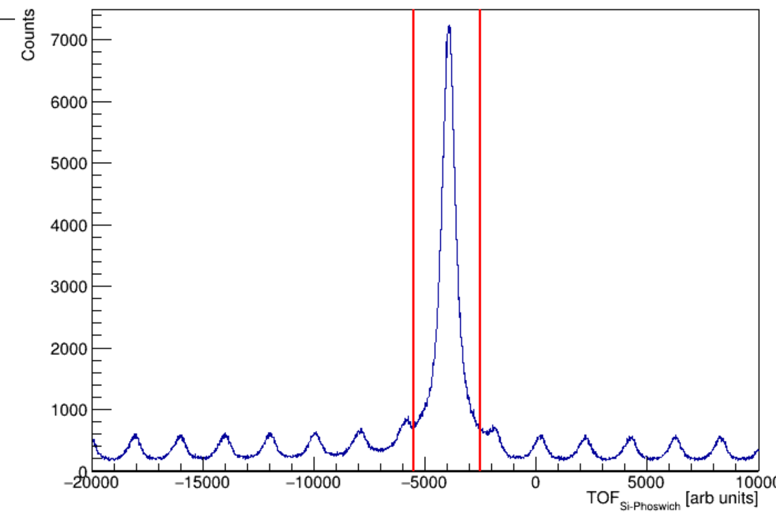
Different isotopes can be identified by gating on a single focal plane position and comparing their total energy

Si Particle Identification



Triton Energy Spectrum





Apply a TOF gate to gate on reaction products

Plot **energy in Si2 + Si3** gating on **rings 1-3** to remove angular effects

The angular range is:

$$4.9^o \leq \theta \leq 5.7^o$$

12 hours of data!

Conclusions & Future Work

- Both **phoswich and Si detectors show good PID**, which allows for the **identification of γ and α decays of ^{19}Ne**

- Gating on a narrow angle and plotting the energy deposited in the Si1 + Si2 s**hows some structure in the ^{15}O-t coincidences – work is ongoing to understand this**

<u>Future Work</u>

- Thickness calculations of Si dead layers
- Position corrections
- Calculate ^{19}Ne excitation energy
- Carbon reaction background removal

Acknowledgements

G. Christian[1], G. Lotay[2], D. T. Doherty[2], W. N. Catford[2], S. Ota[3,4], P. Adsley[3], G. Chubaryan[3], A. Crystal[1], S. Dede[3,5], E. Harris[3], Z. Lou[3], M. Roosa[3], A. Saastamoinen[3], J. Santucci[3], D.P. Scriven[3]

[1]Saint Mary's University, Canada
[2]University of Surrey, UK
[3]Texas A&M University, USA
[4]Brookhaven National Laboratory, USA
[5]University of Notre Dame, USA

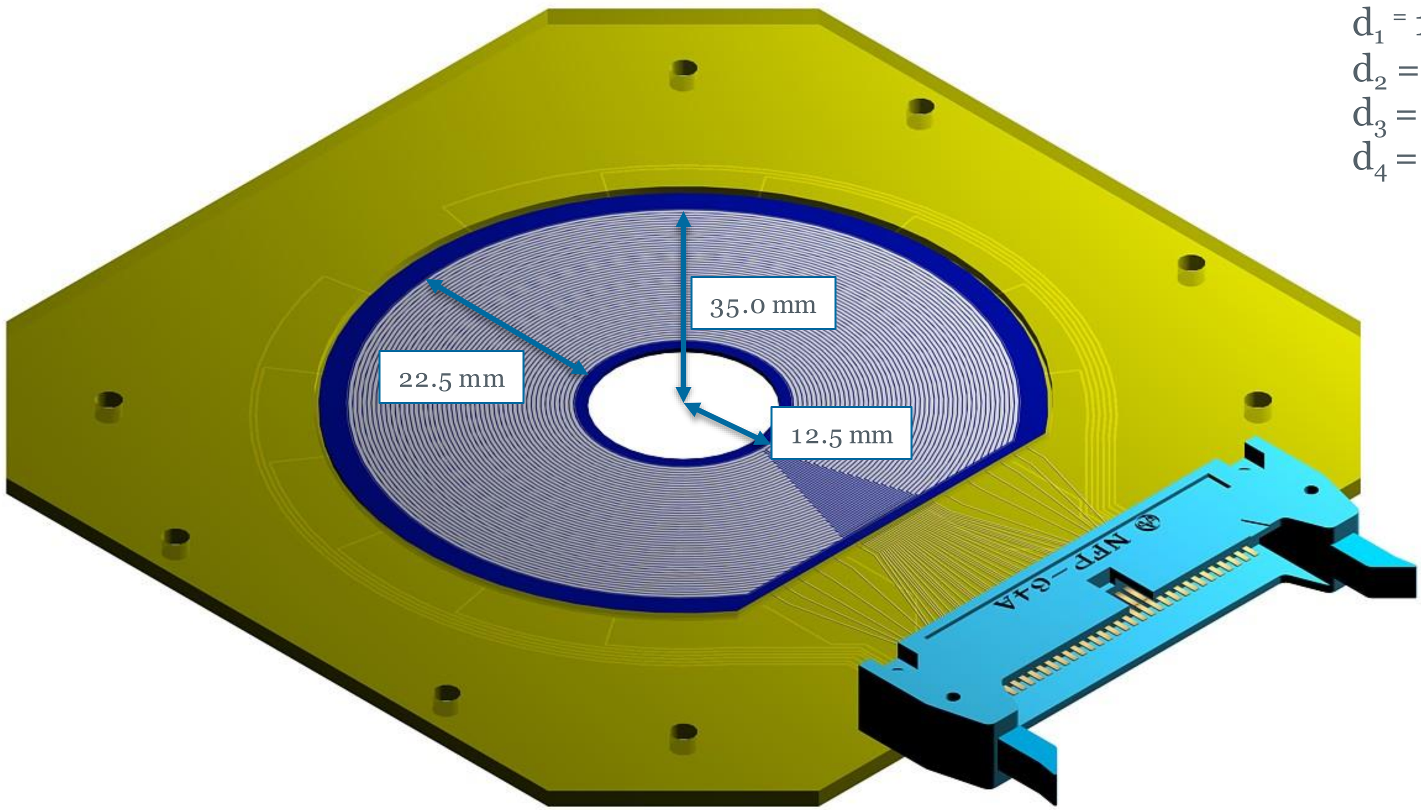
Any Questions?

S2 Detector Details

Single Ring Width = 1 mm
(Except Ring 1 = 0.5 mm)

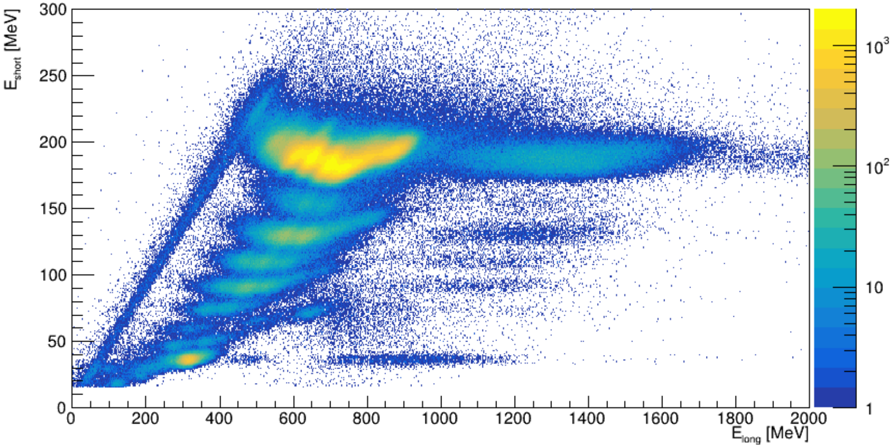
d_1 = 120.77 mm
d_2 = 133.28 mm
d_3 = 146.12 mm
d_4 = 158.68 mm

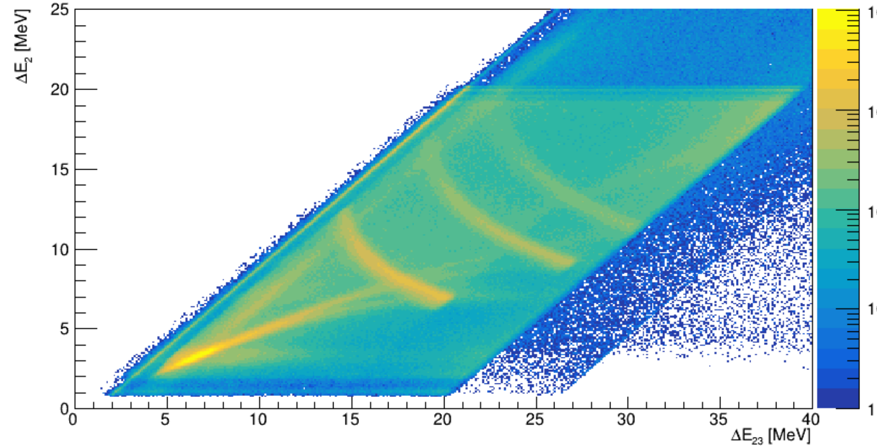
$\Delta\theta = 0.37^o - 0.39^o$

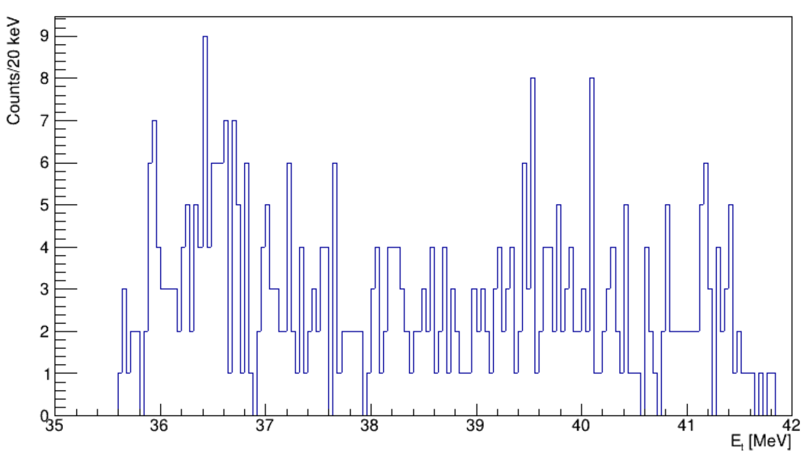


Render of Micron S2 Silicon detector from http://www.micronsemiconductor.co.uk/product/s2/

Carbon Target





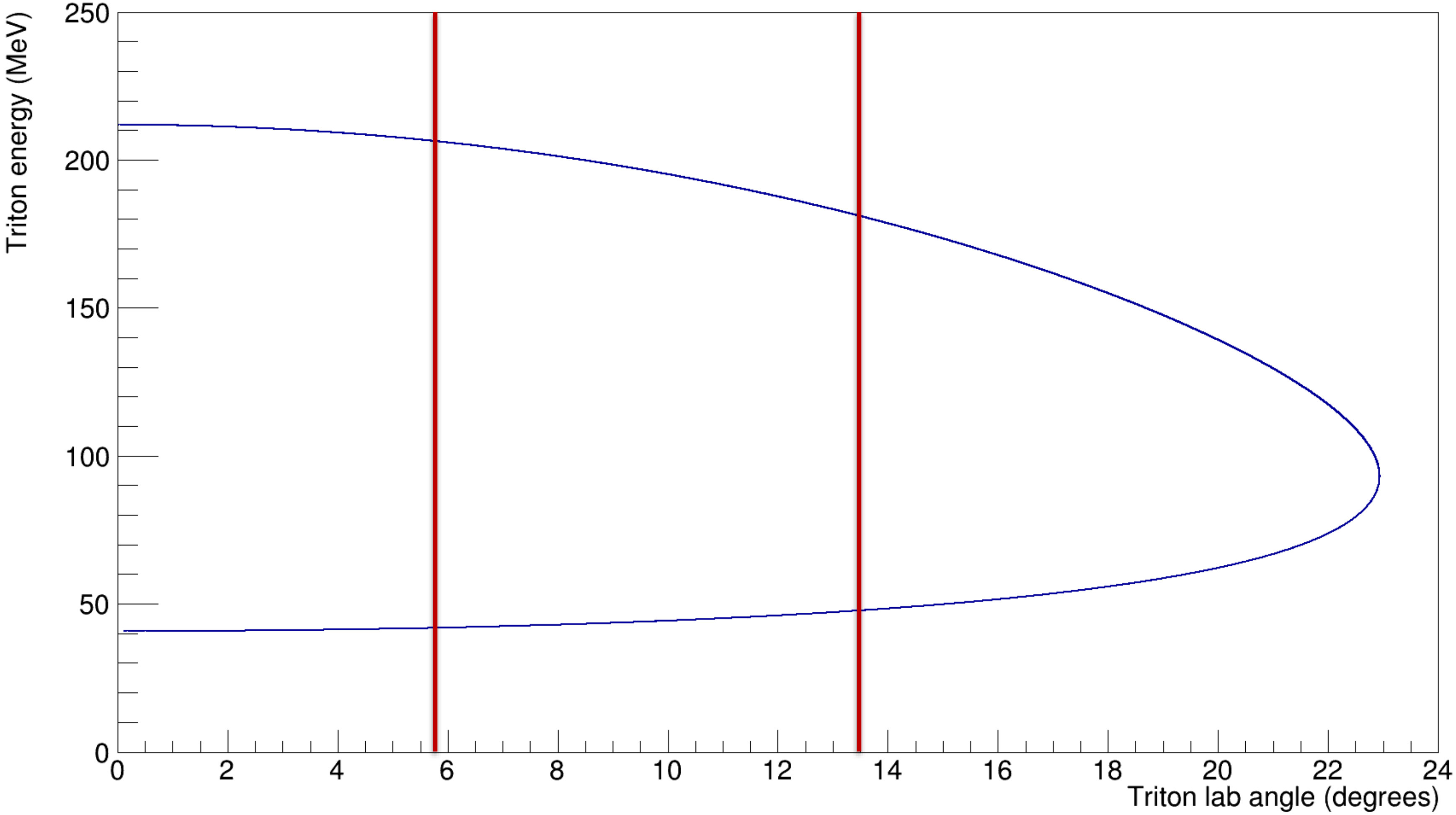


12C target of thickness 930 μg/cm^2

Thickness of CH_2 target was 958 μg/cm^2

Shown here is only 2 hours of data (12 hours was taken in total)

Kinematic Calculation



Phoswich