Measurement of $^{59}Cu(p,\alpha)^{56}Ni$ reaction rate to constrain the flow of ***ν***p-process

Nikhil Bhati

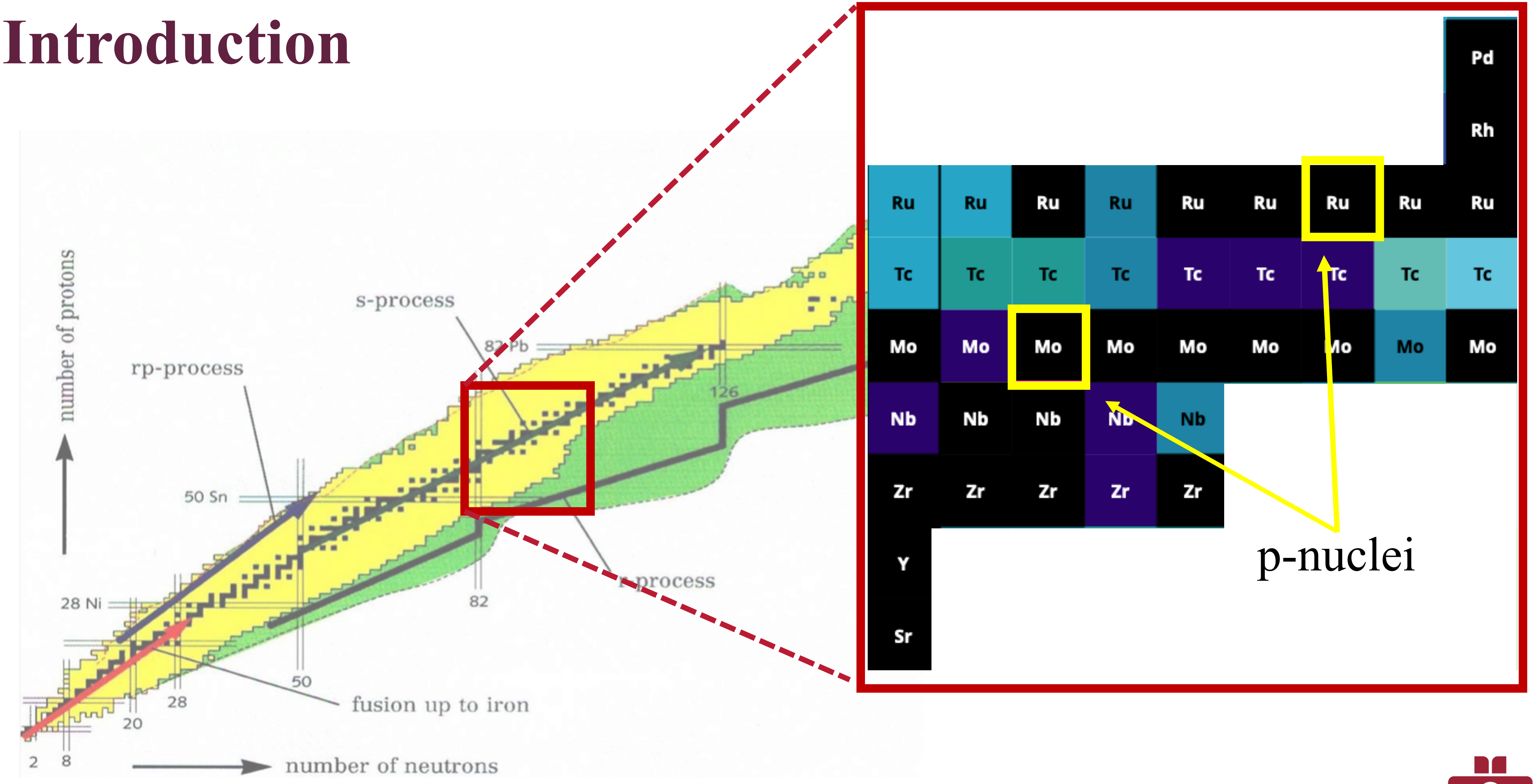
Supervisor: Dr. Rituparna Kanungo

WNPPC 2024

CINP ICPN Canadian Institute of Nuclear Physics Institut canadien de physique nucléaire

Saint Mary's University

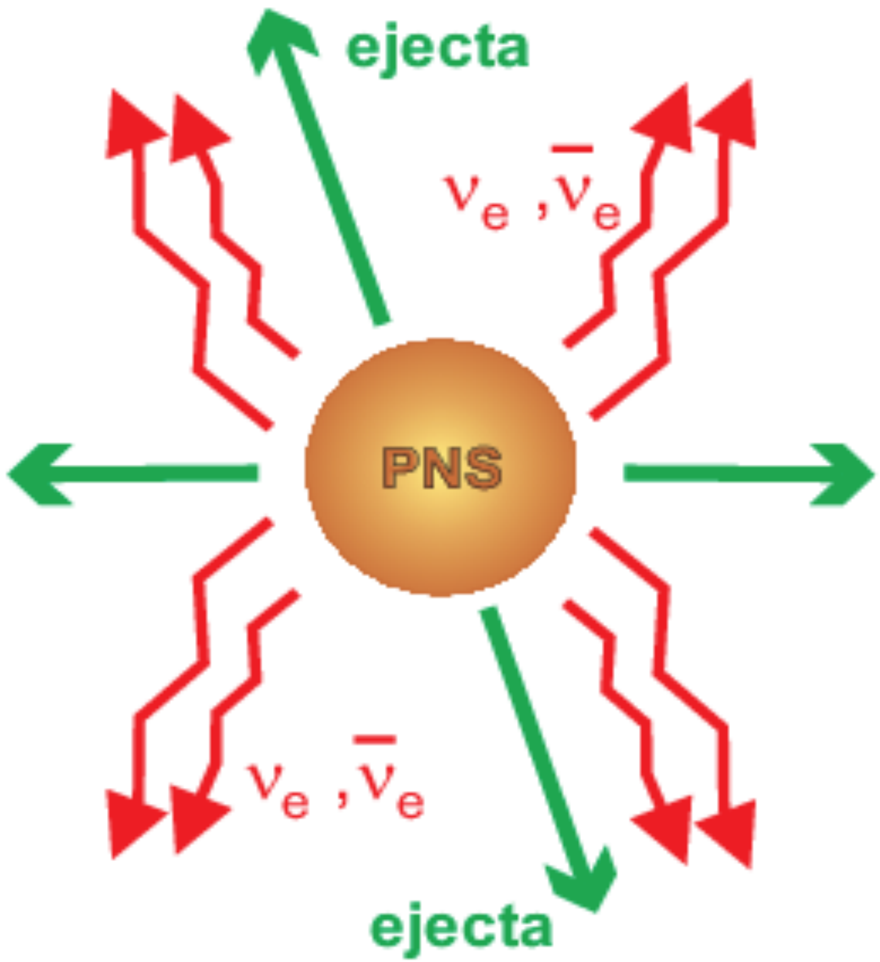
Introduction



νp-process

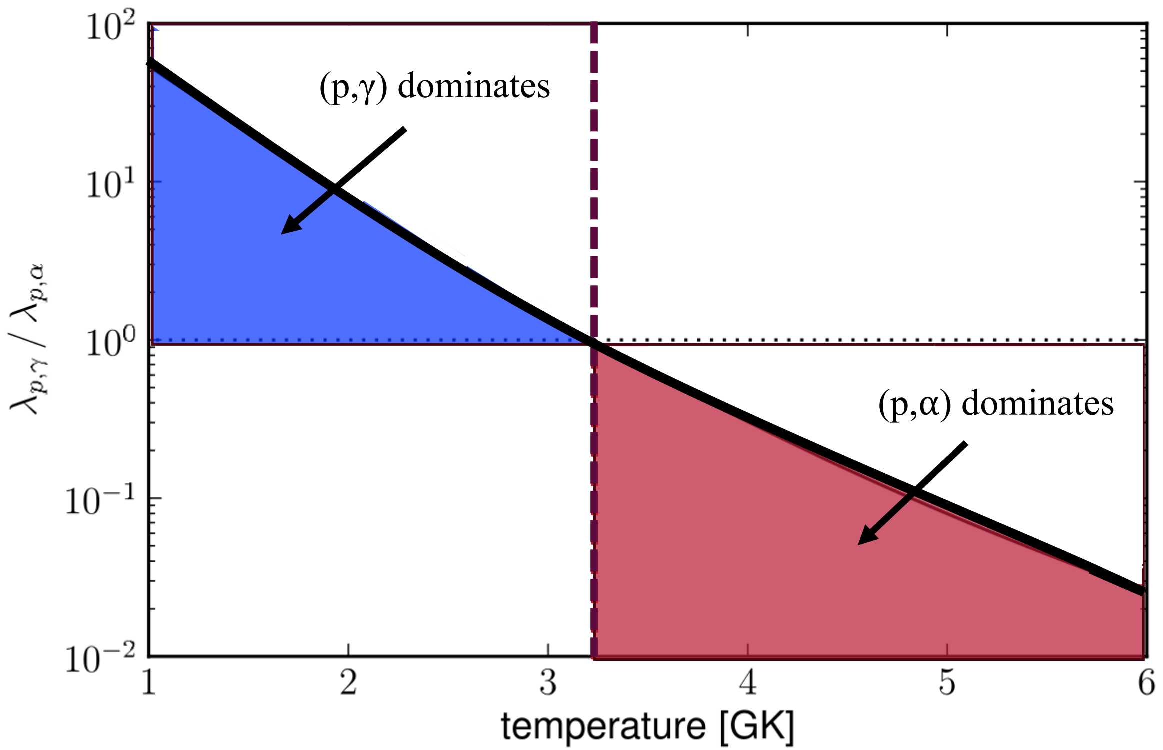
- After the supernova explosion, intense neutrino flux originates from the cooling of hot PNS.
- These neutrinos interact with the stellar matter present between the surface of the hot PNS and the expanding shock wave.

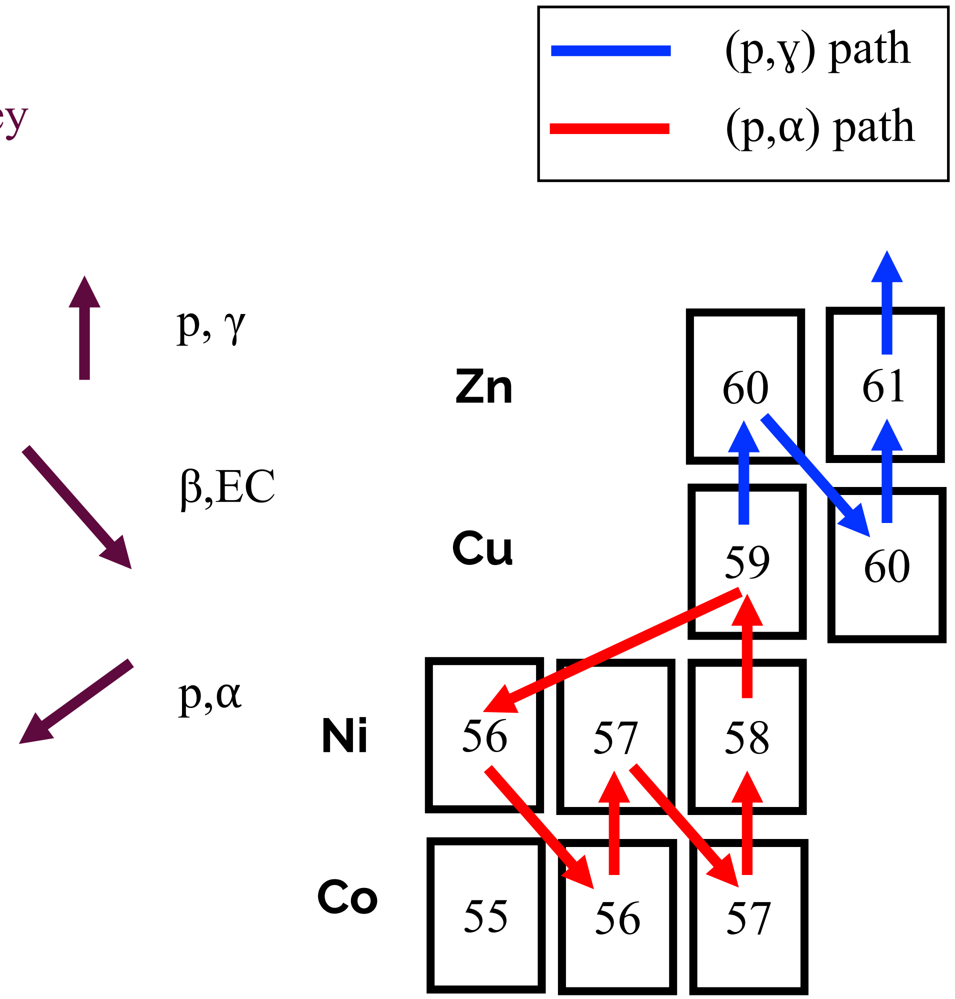
$$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$$



νp-process

- An end point nuclear cycle "Ni-Cu" was identified which is key to the ability of the νp-process to form heavy elements.

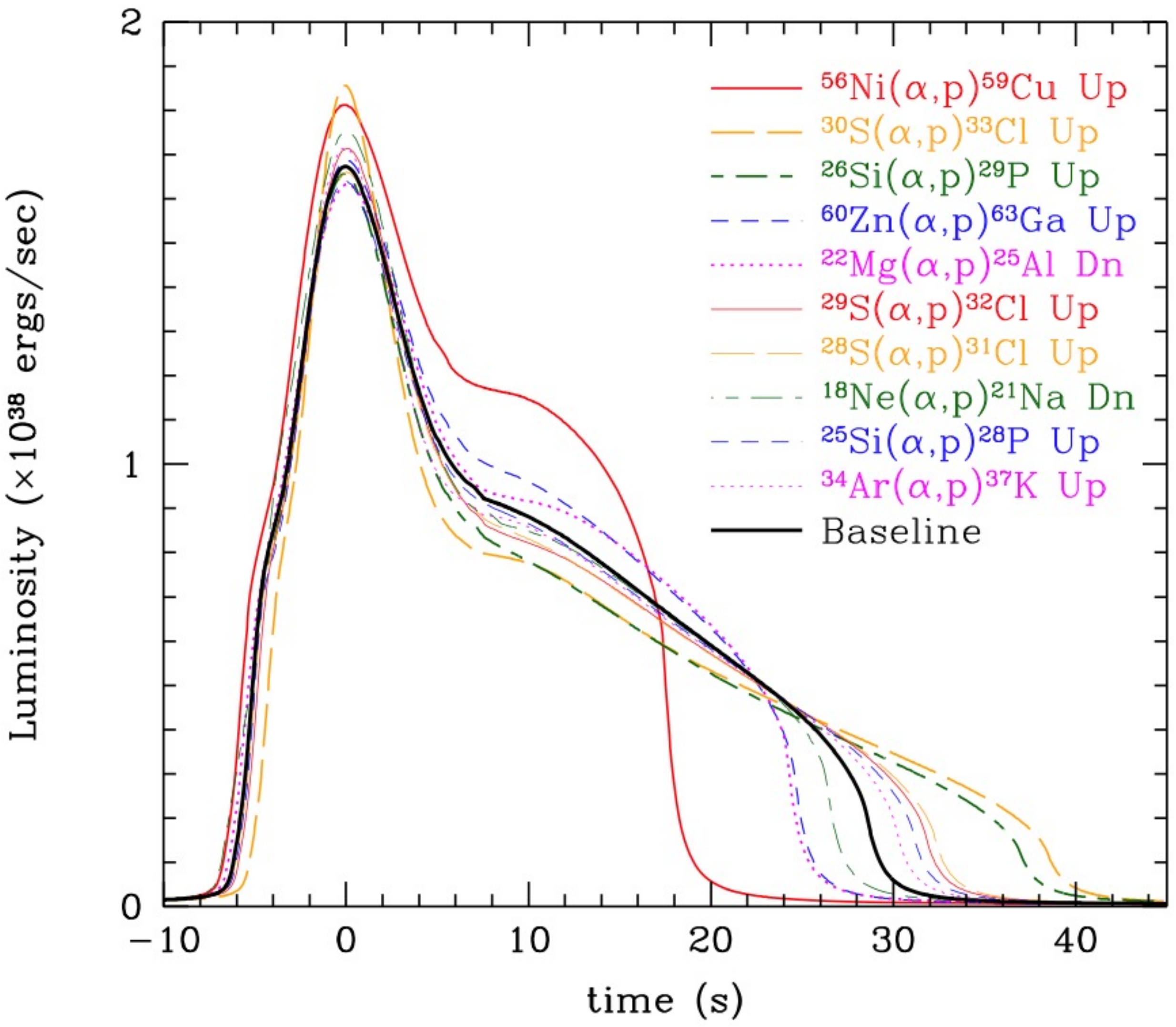




Arcones et al. 2012. The Astrophysical Journal, 750, p 18.

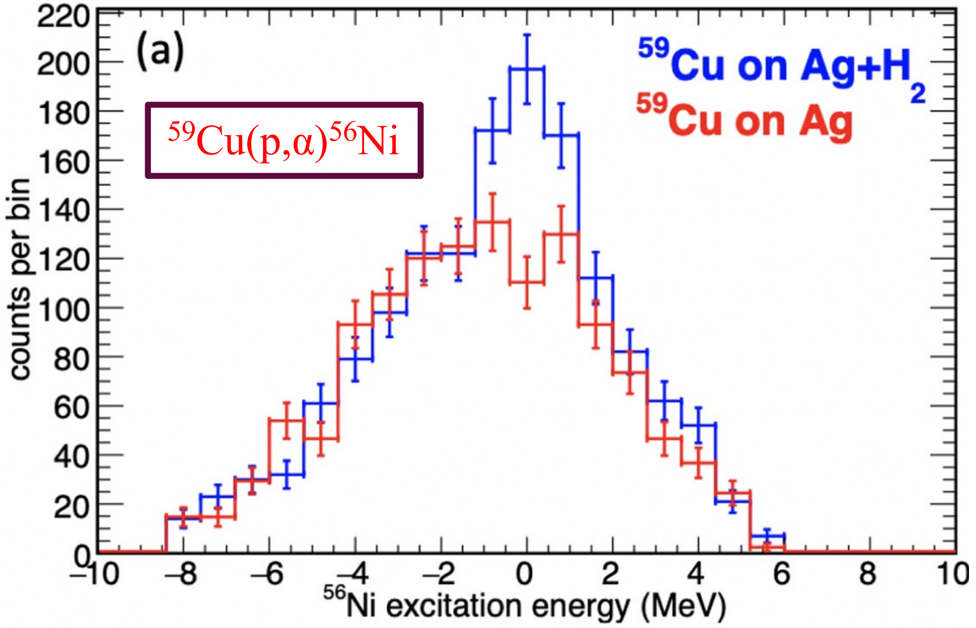
Impact on XRB light curve

- Sensitivity studies shows that the light curve is affected the most if the $^{59}Cu(p, \alpha)^{56}Ni$ reaction rate is varied.

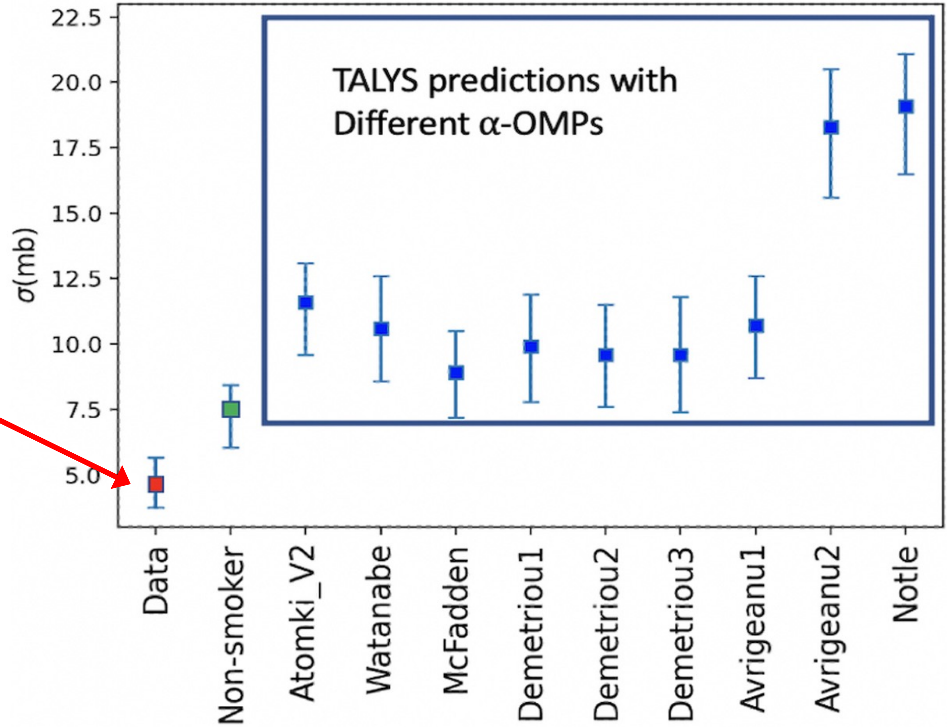


Cyburt,et al. (2016). *The Astrophysical Journal*. 830, p 55.

Previous Measurements



Measurement at $E_{c.m.}$ = 6.0 MeV

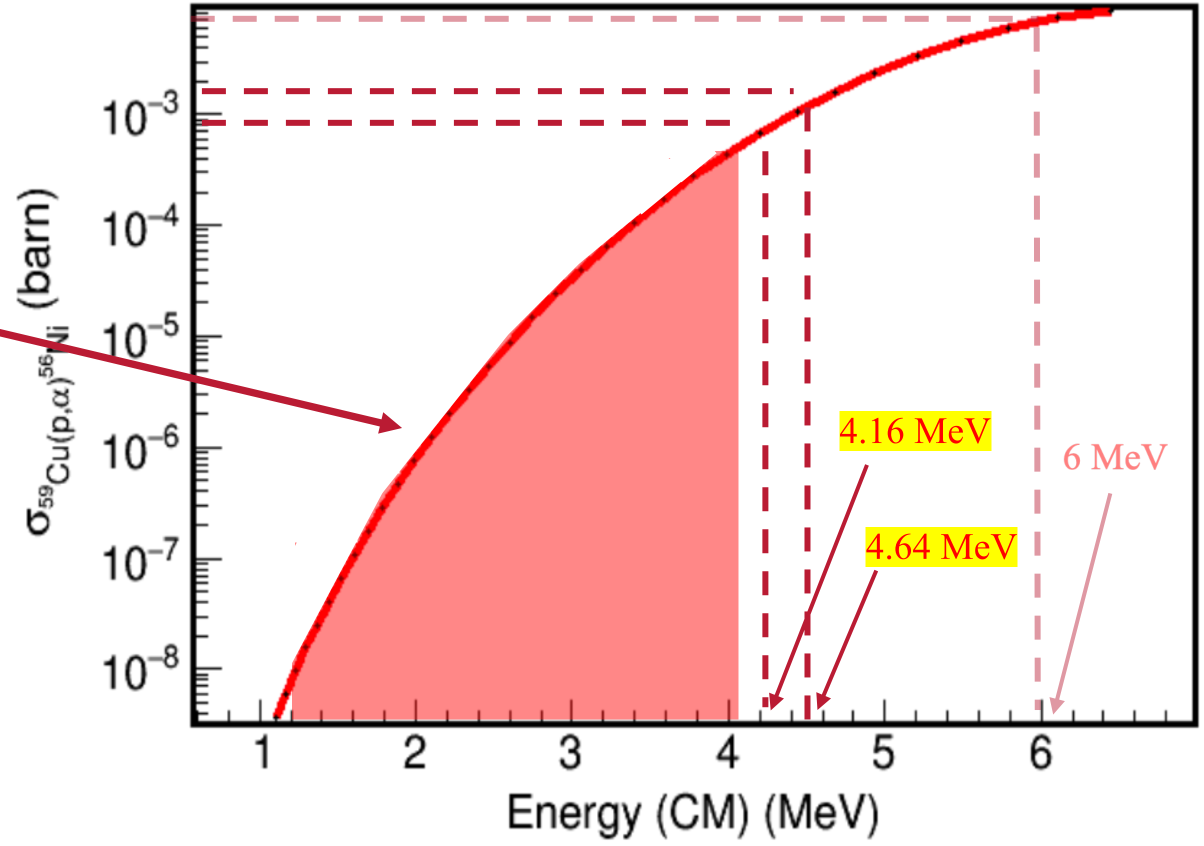


Randhawa, J. S. et al. (2021). *Physical Review C.*

Objective

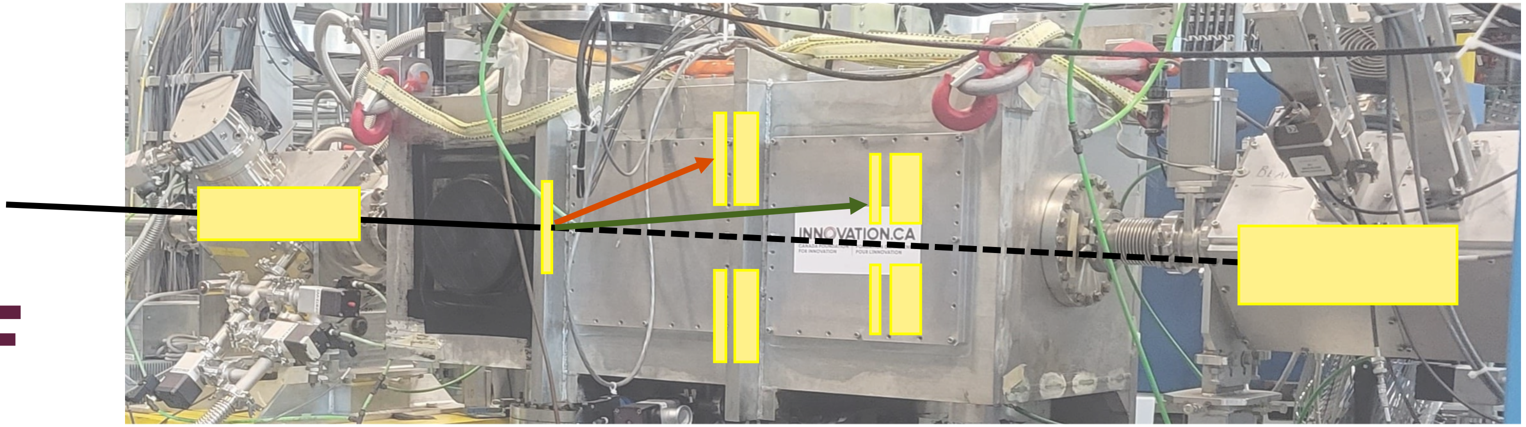
	Gamow peak	Gamow window
*ν*p-process	2.9 MeV	1.1 – 4.01 MeV
Type-I XRBs	1.25 MeV	1.1 – 1.4 MeV

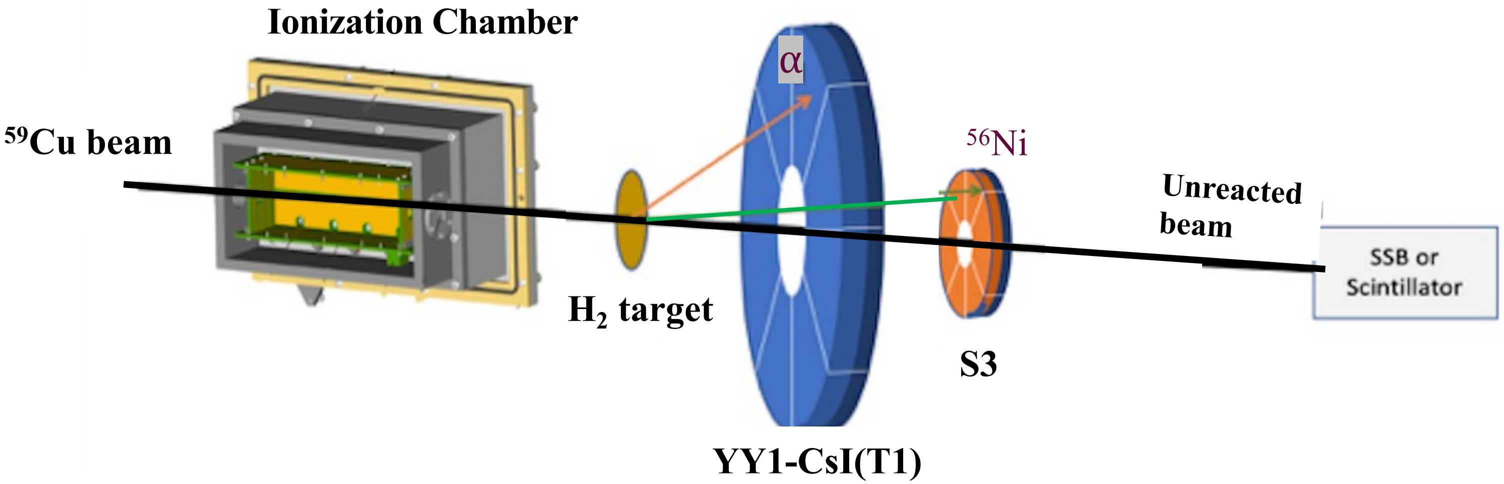
- $^{59}Cu(p,\alpha)^{56}Ni$ reaction rate was measured at three centre of mass energies ($E_{c.m.}$) = 6.0 MeV (already reported), 4.64 MeV and 4.16 MeV.



Cross sections from Hauser-Feshbach calculations

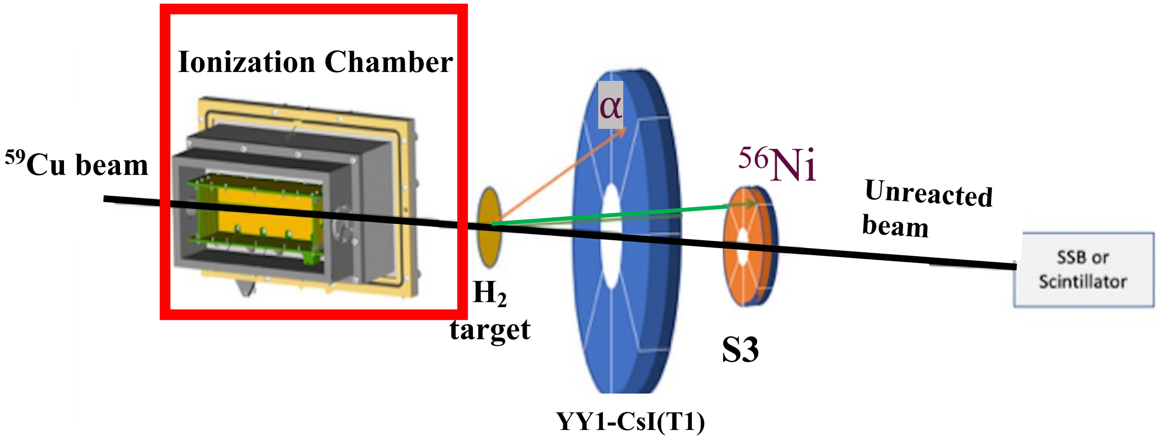
IRIS facility - TRIUMF

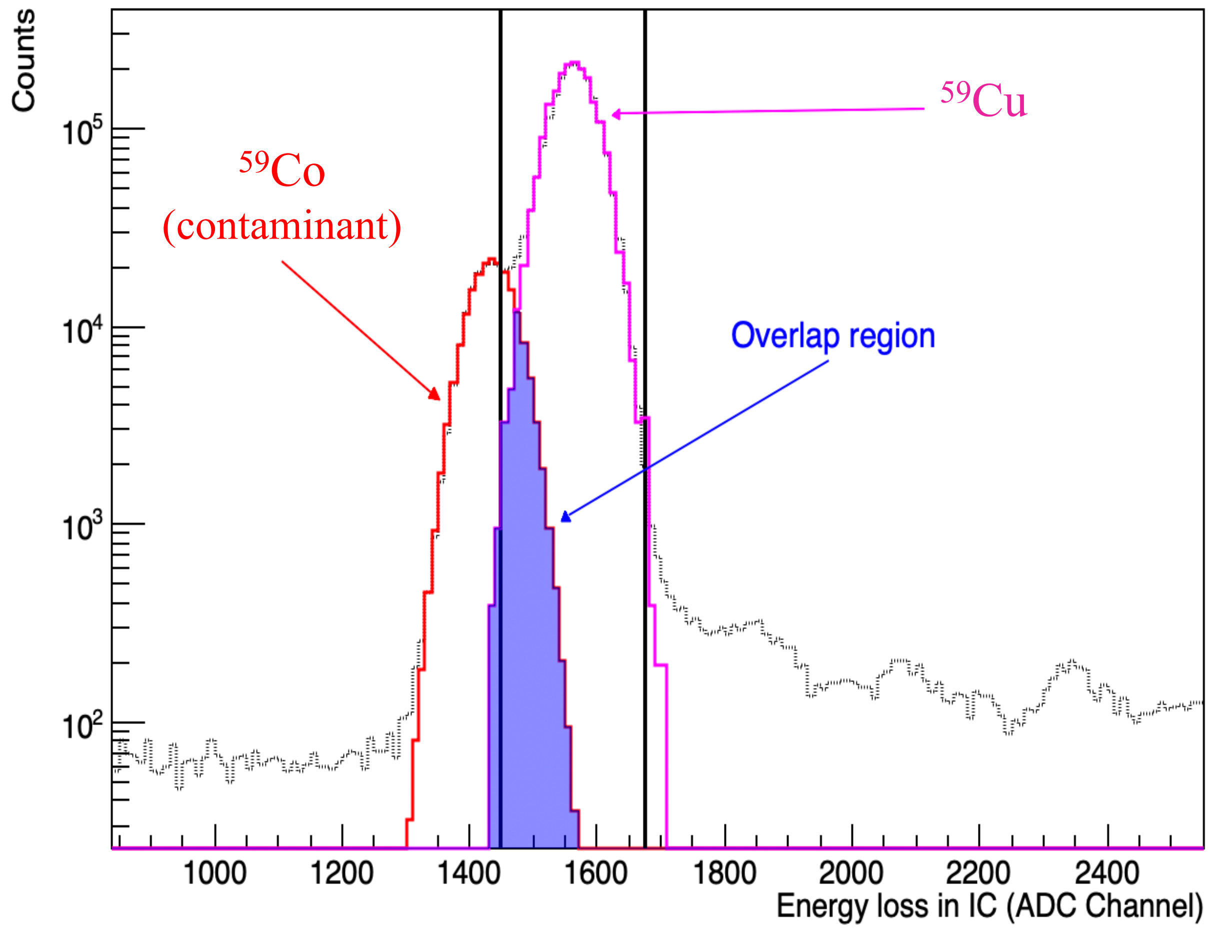




Ionization Chamber (IC)

- Identifies the beam particles
- Gas pressure for this experiment: 10 T and 19.5 T

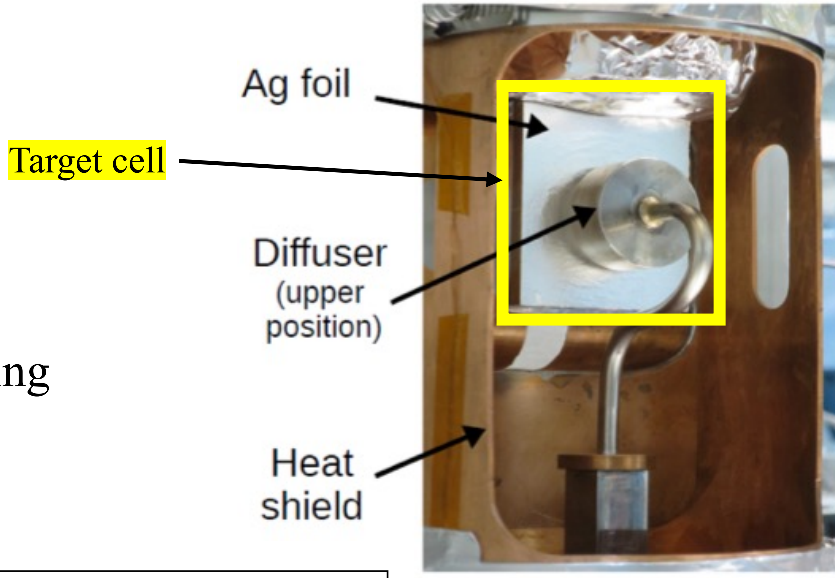


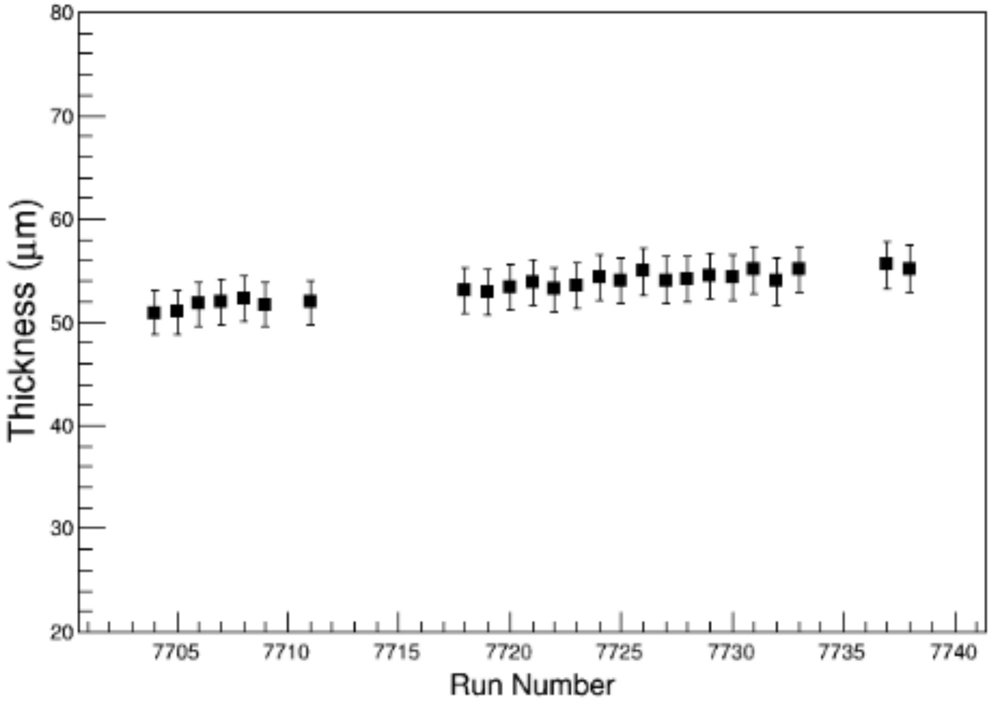


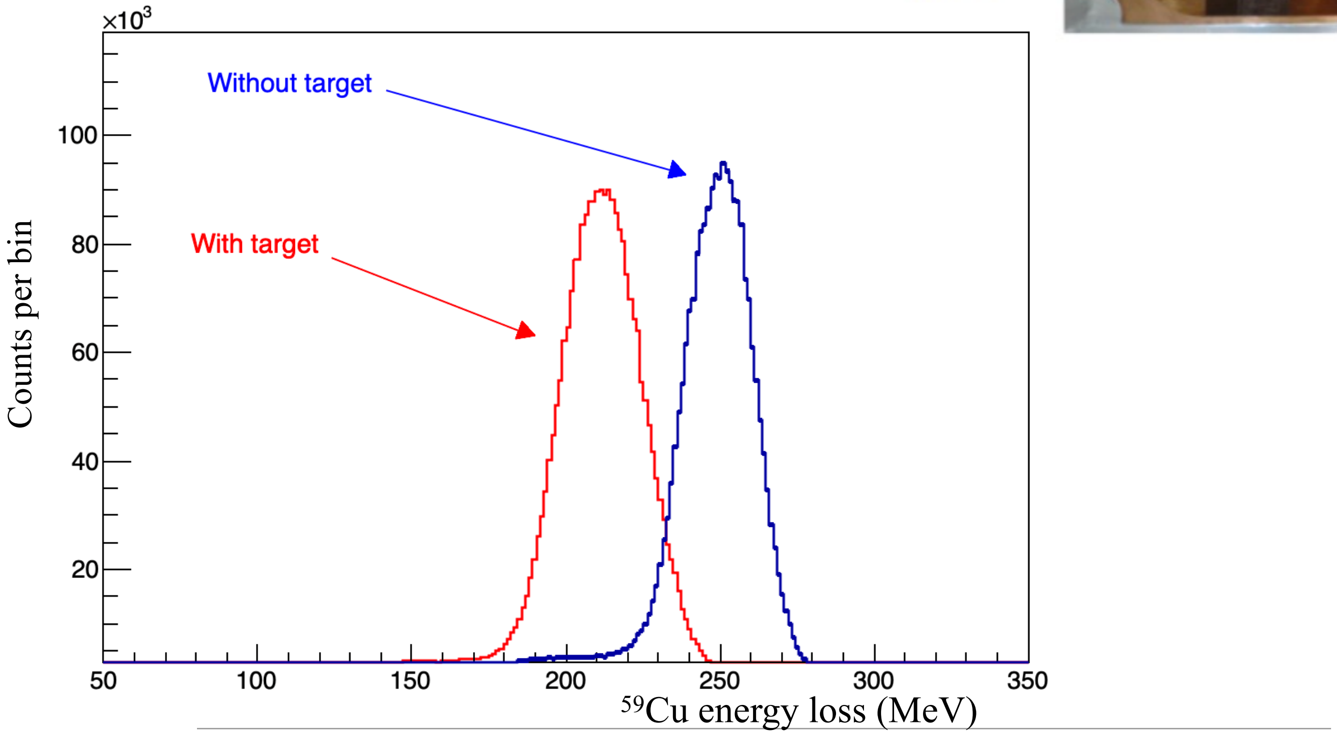
Solid Hydrogen Target

- Windowless target
- Energy loss with and without target was used to find the target thickness using

$$t = \int_{E_i}^{E_f} \frac{1}{S(E)}\, dE$$

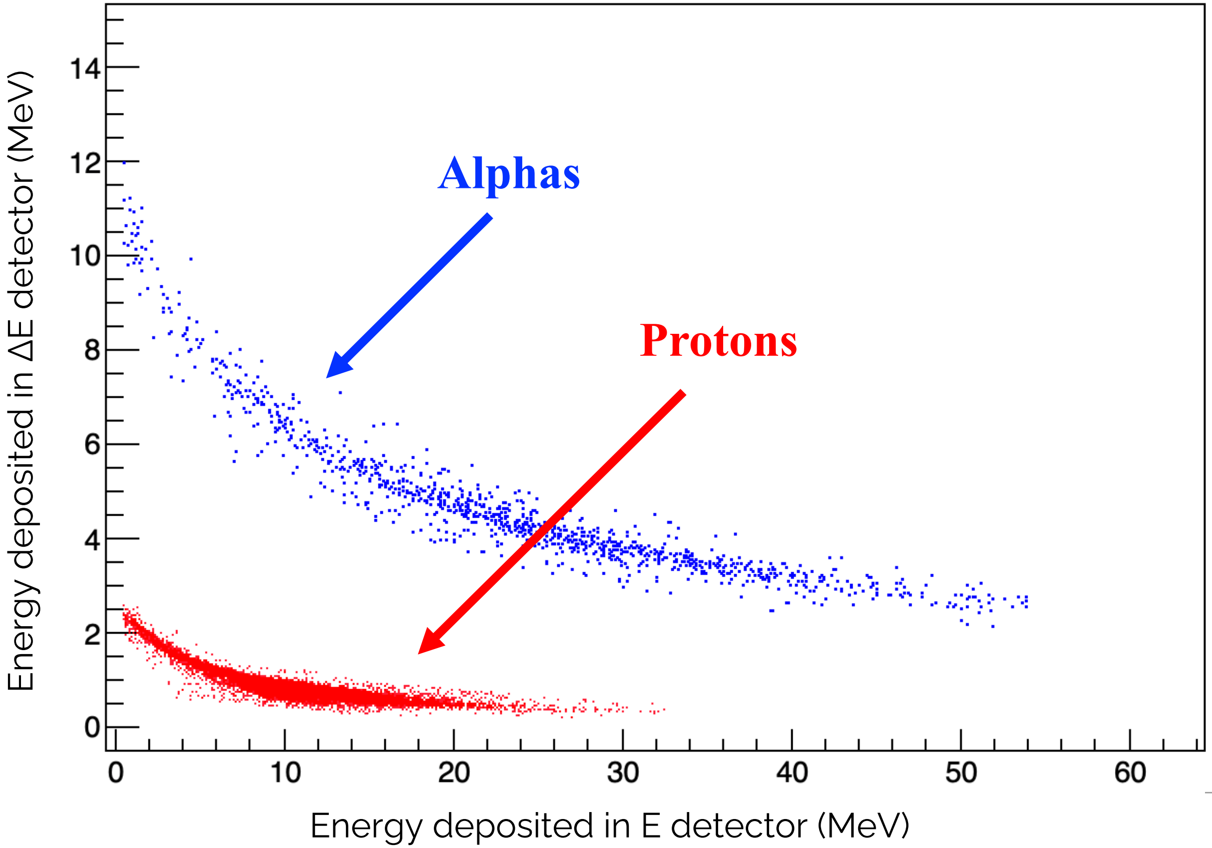


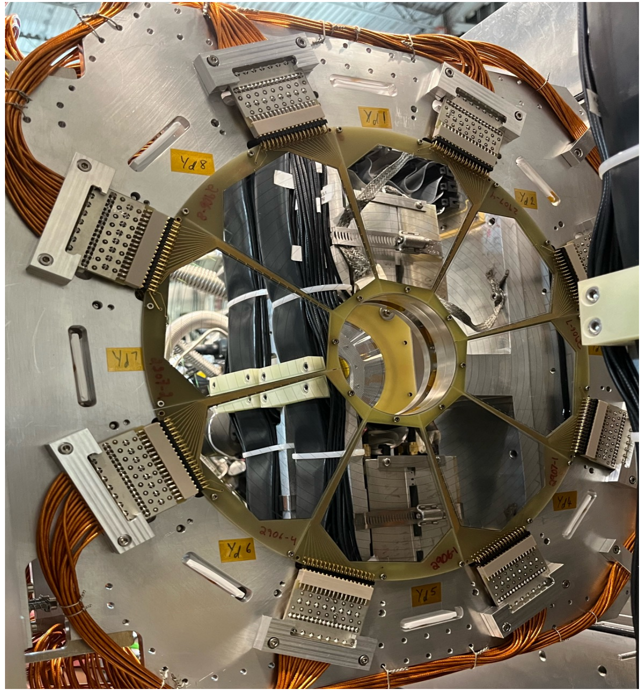


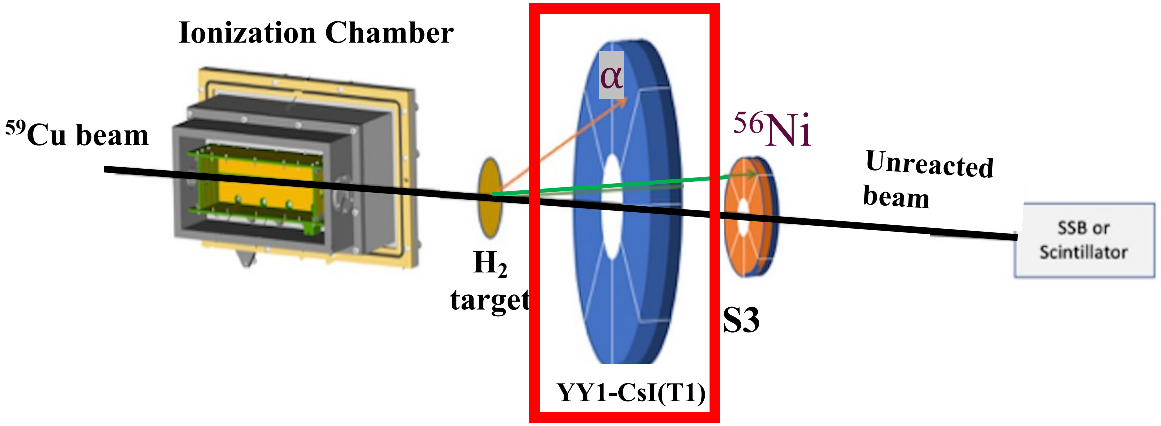


Charged Particle Detectors

- YY1 – Silicon strip detector
- CsI(TI) – Cesium Iodide Thallium doped detector

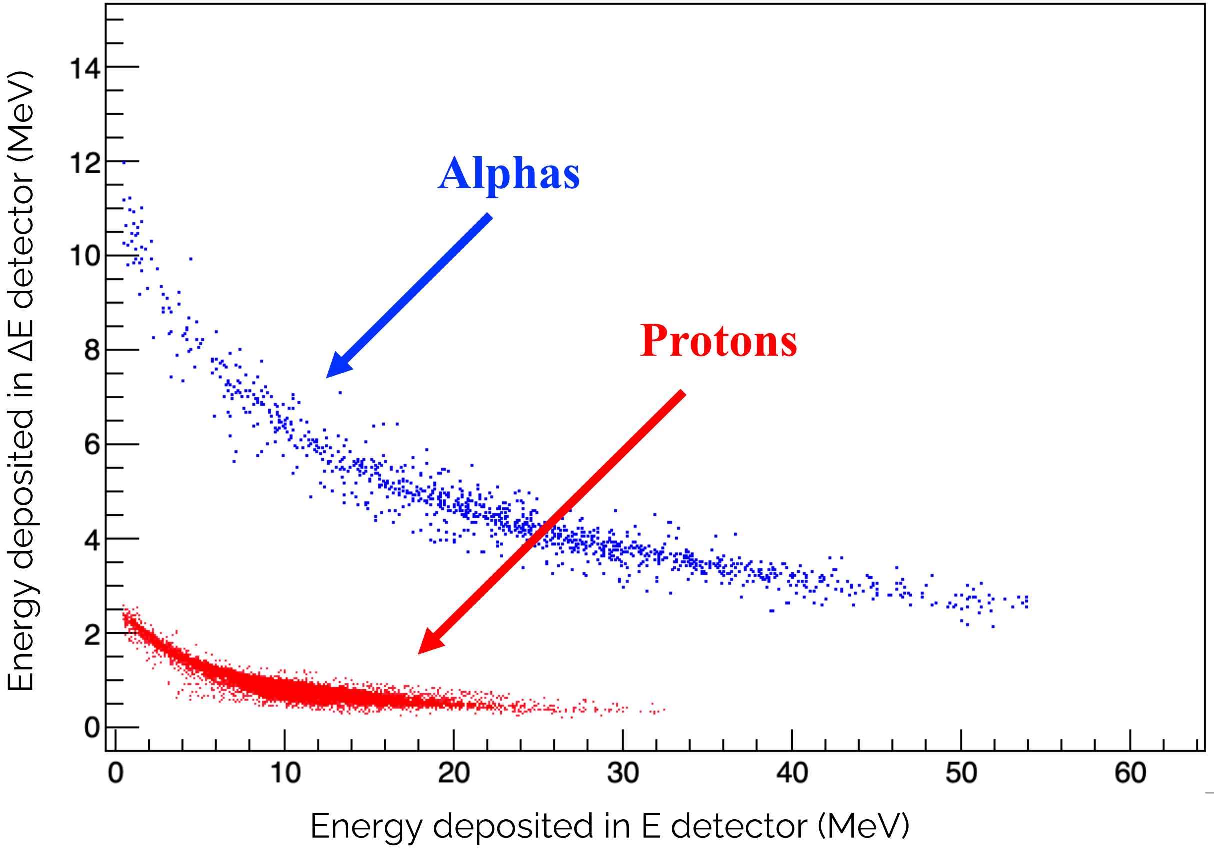


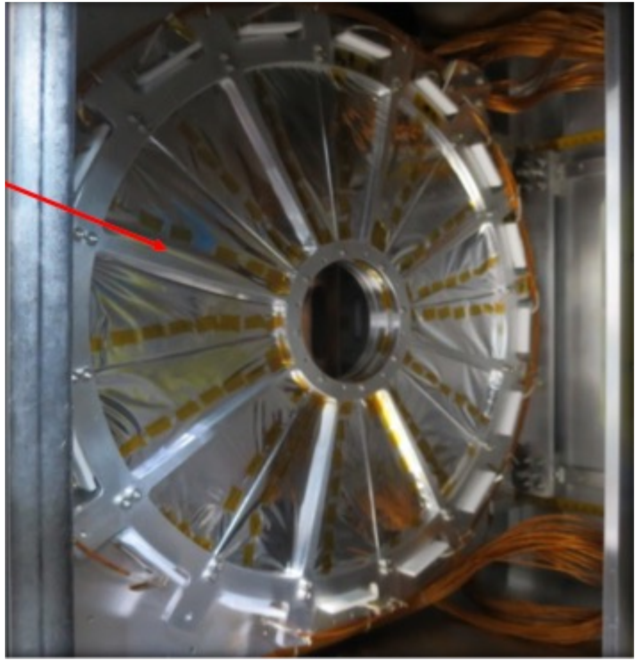


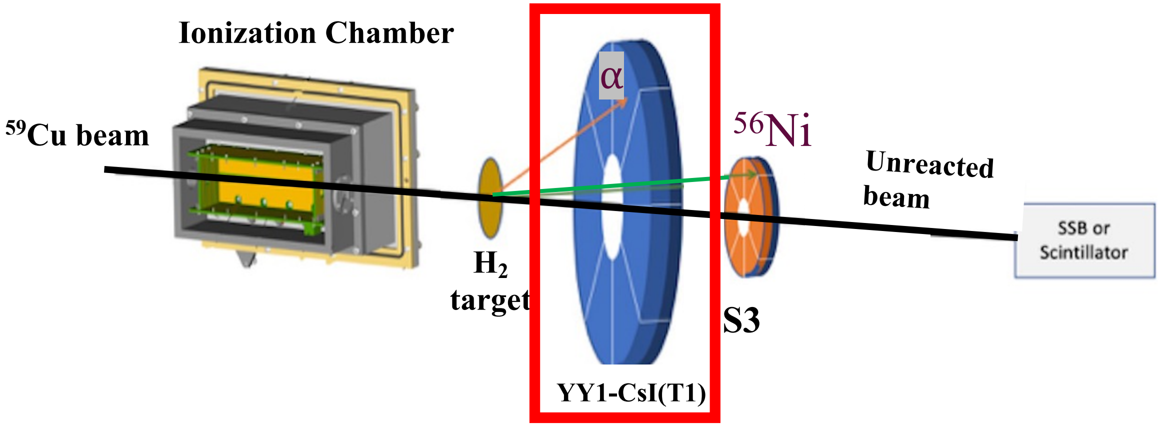


Charged Particle Detectors

- YY1 – Silicon strip detector
- CsI(TI) – Cesium Iodide Thallium doped detector







Excitation spectrum

- Missing mass technique.
- For a given reaction,

$$A + B \longrightarrow C + D$$

- The Q-value can be written as,

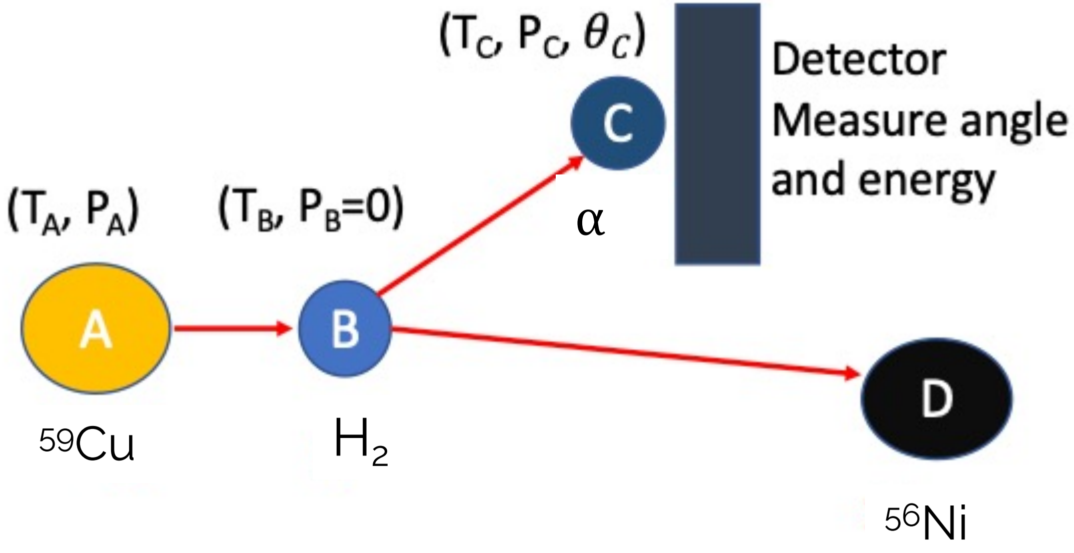
$$Q = m_A + m_B - m_C - m_D$$

- Missing mass (assume D) is,

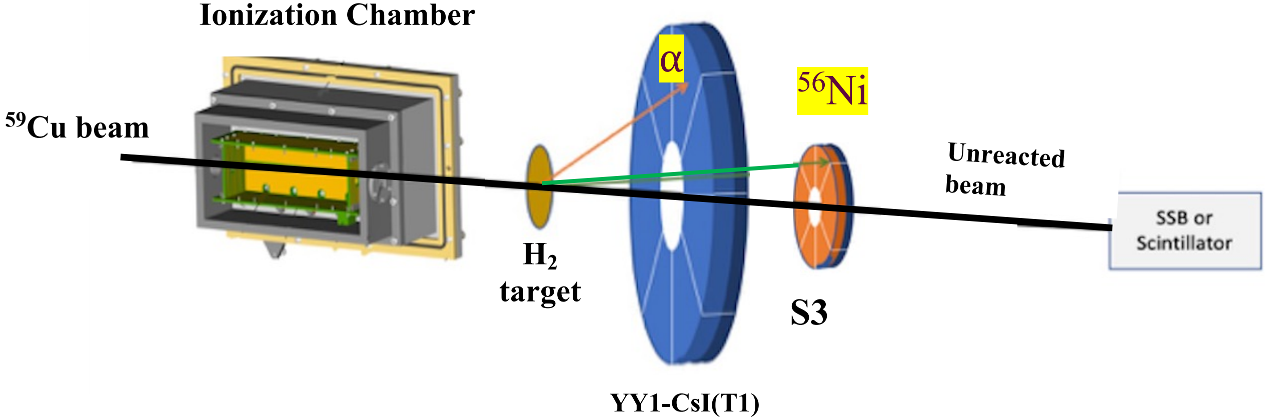
$$\mathrm{m_D} = \sqrt{\mathrm{m_A^2 - m_B^2 + m_C^2 + 2m_B(T_A + m_A) - 2(T_A + m_A + m_B)(T_C + m_C) + 2P_AP_C \times \cos(\theta_C)}}$$

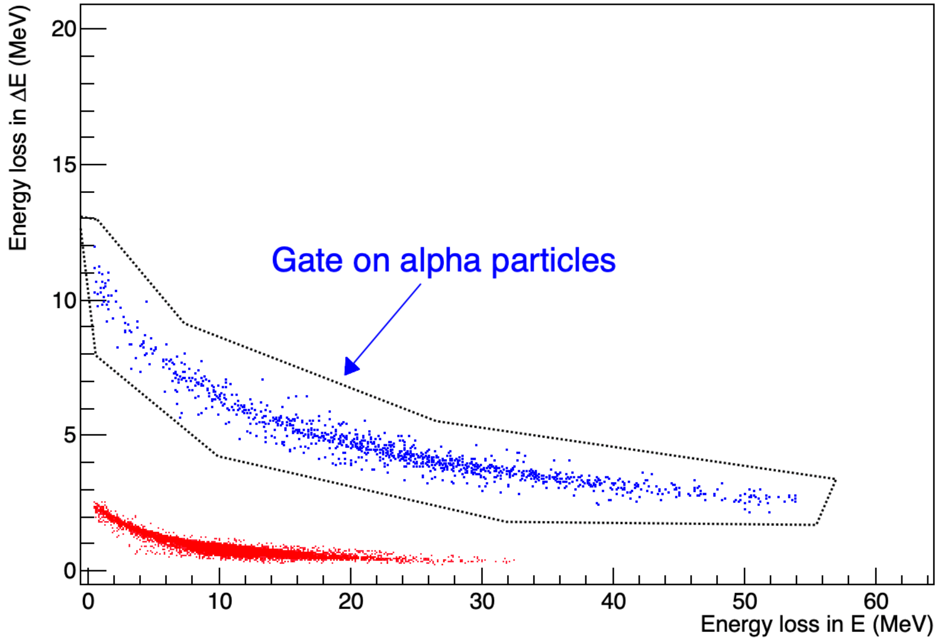
- Then,

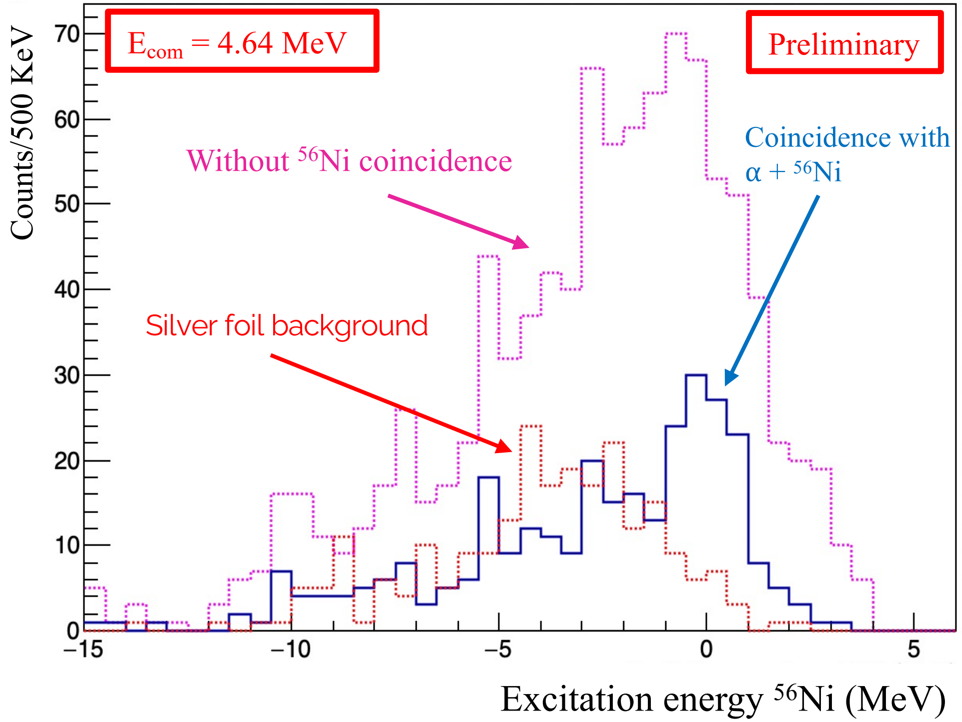
$$Q = m_A + m_B - m_C - (m_D + E_{exc})$$

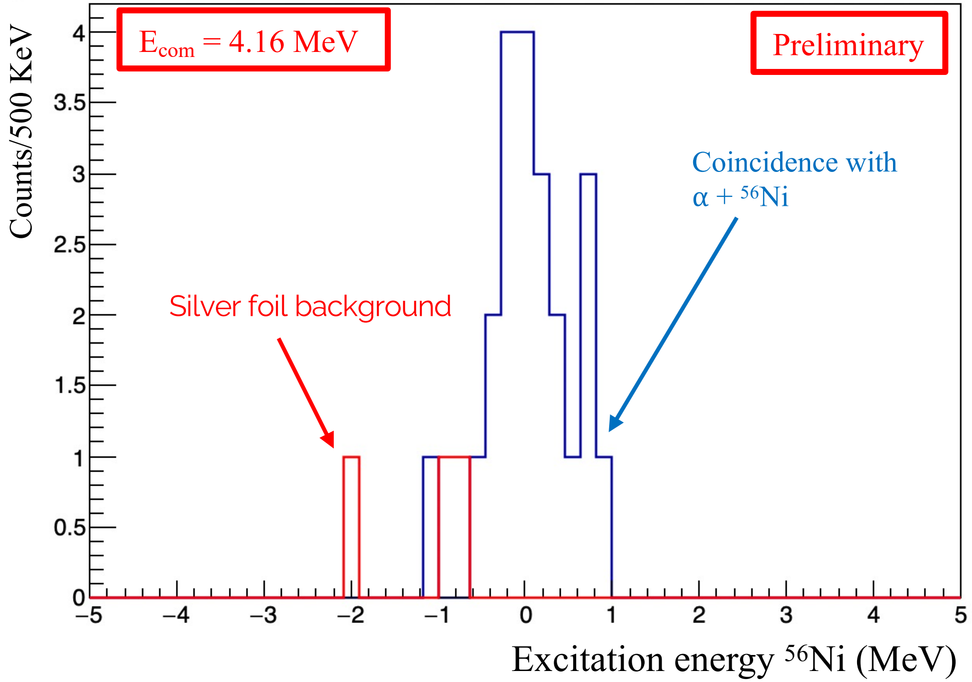


Preliminary results









Outlook

- $^{59}Cu(p,\alpha)^{56}Ni$ reaction cross-section at 4.64 and 4.16 MeV centre-of-mass energy will allow a direct comparison to the Hauser-Feschbach based statical model predictions.
- Future measurements to constrain the $^{59}Cu(p,\gamma)^{60}Zn$ reaction rate would be required to further elucidate the flow in the Ni-Cu cycle.

Acknowledgements

- Supervisor Dr. Rituparna Kanungo
- IRIS group and TRIUMF
- CINP, NSERC and SMU for funding

TRIUMF

NSERC CRSNG

CINP ICPN

Canadian Institute of Nuclear Physics

Institut canadien de physique nucléaire

Saint Mary's University

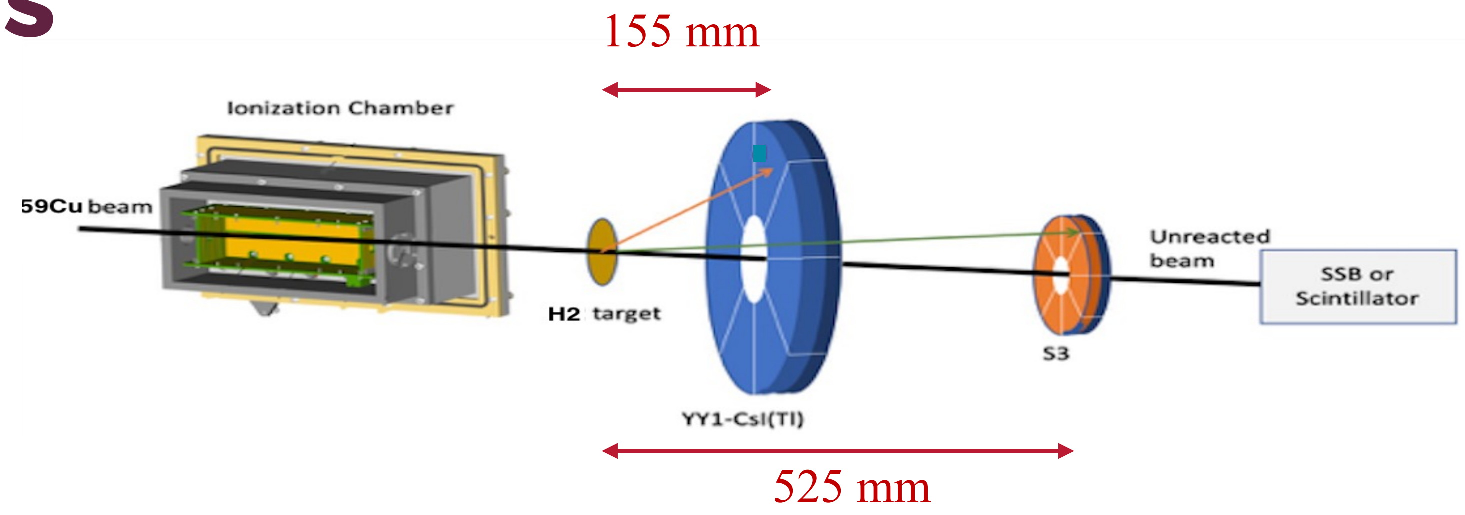
Measuring conditions

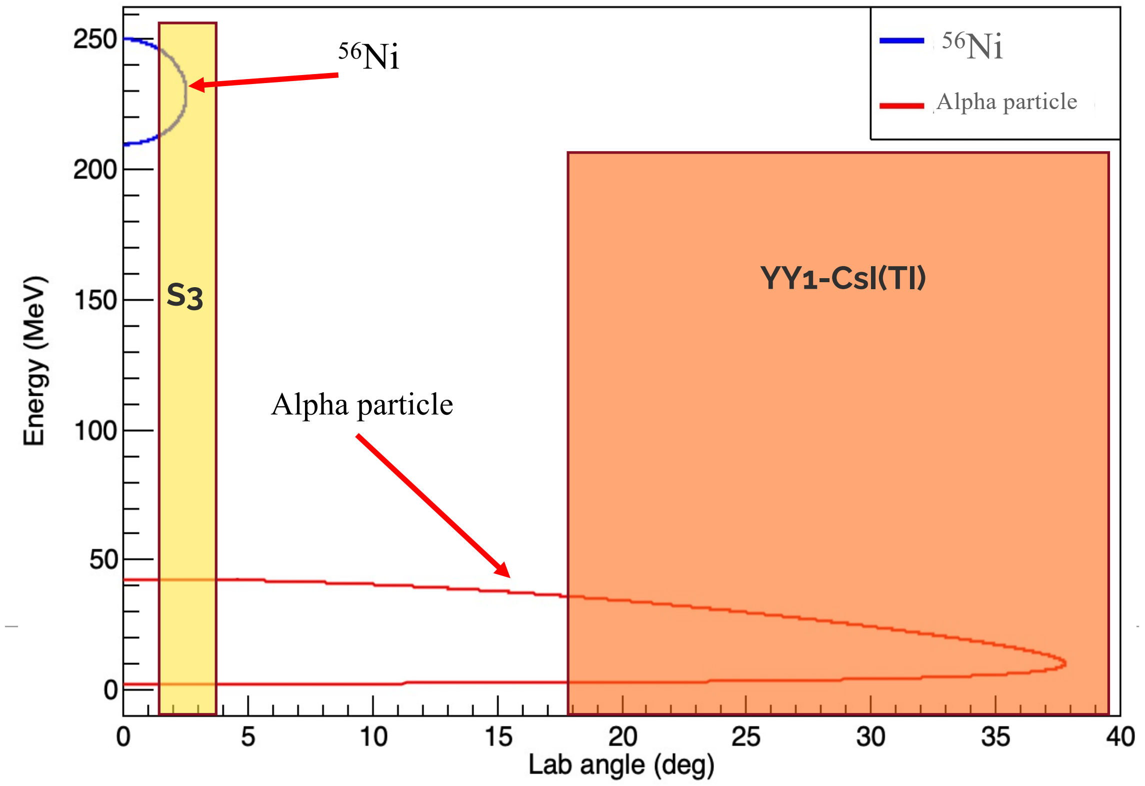
- IC pressure = 10 T and 19.5 T
- Light particle detector distance = 155 mm
- Heavy particle detector distance = 525 mm
- ^{59}Cu beam intensity at IRIS was 3600 pps.
- Measurement time:
  - Beam energy E/A= 9 MeV (12 shifts)
  - Beam energy E/A= 6.7 MeV
    - 10 T IC pressure = 6 shifts
    - 19.5 T IC pressure = 8 shifts

$E_{lab.}$ (A MeV)	No of shifts	Estimated α counts
9.0	12	~ 1700
6.7	14	~ 1300

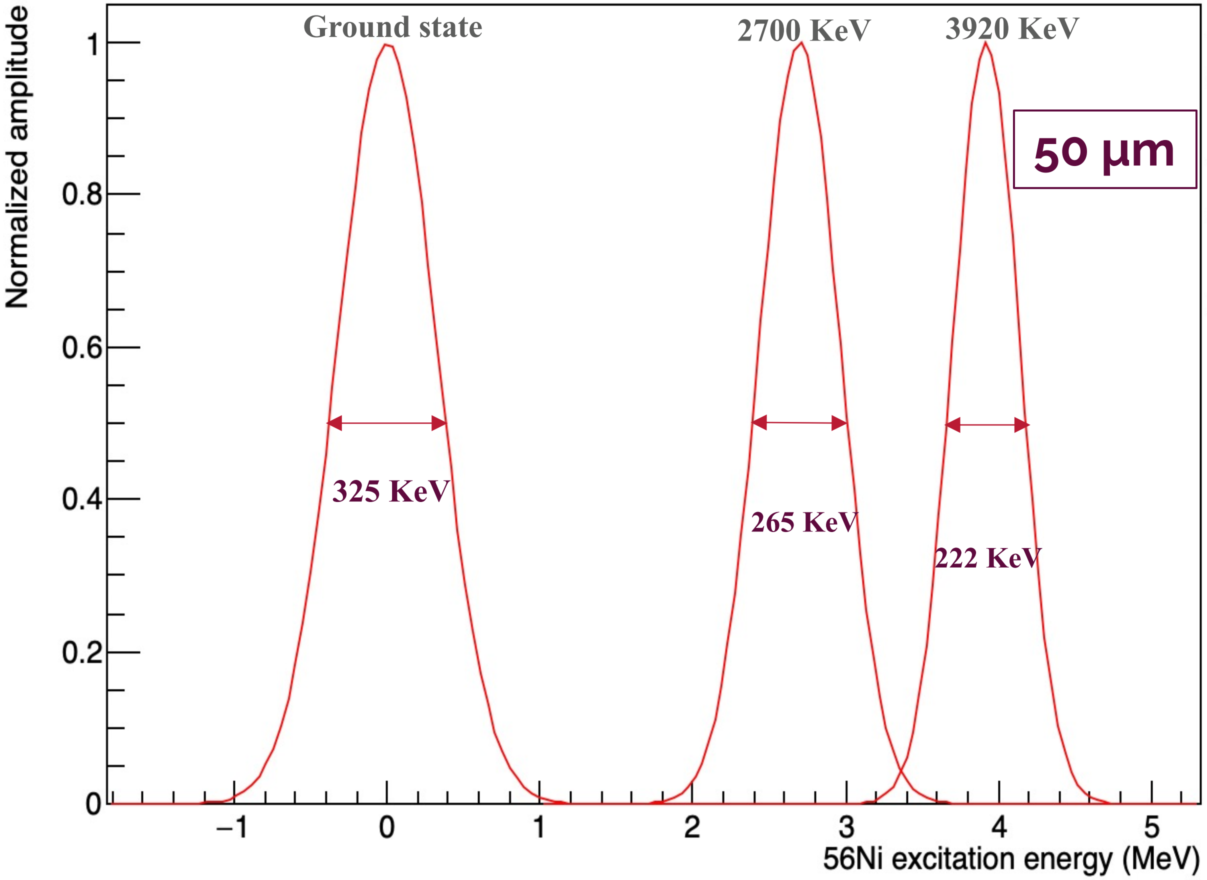
1 shift = 8 hours

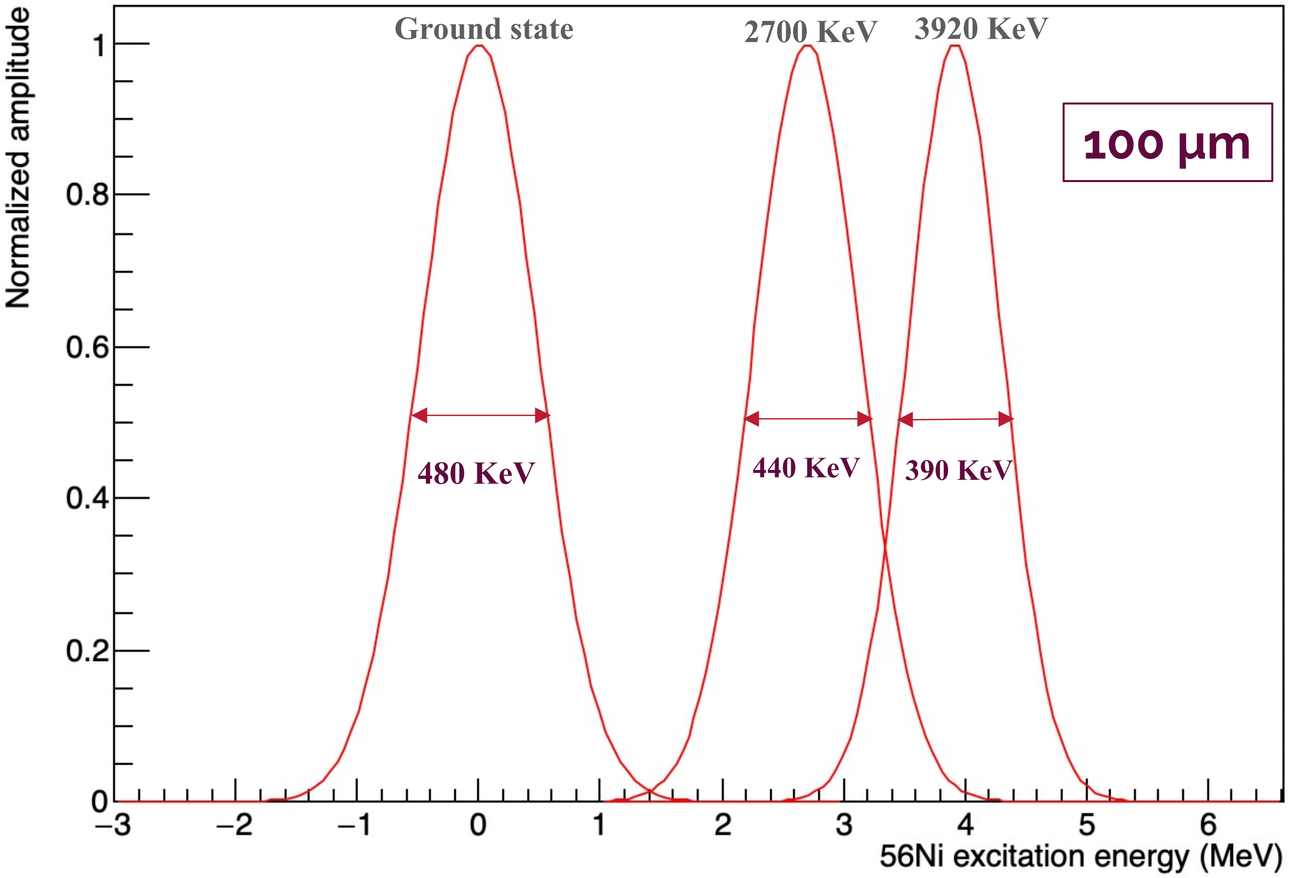
- Target Thickness = 50 μm
- ^{40}Ar stable beam data was also taken for 3 shifts to calibrate detectors.





Target Thickness

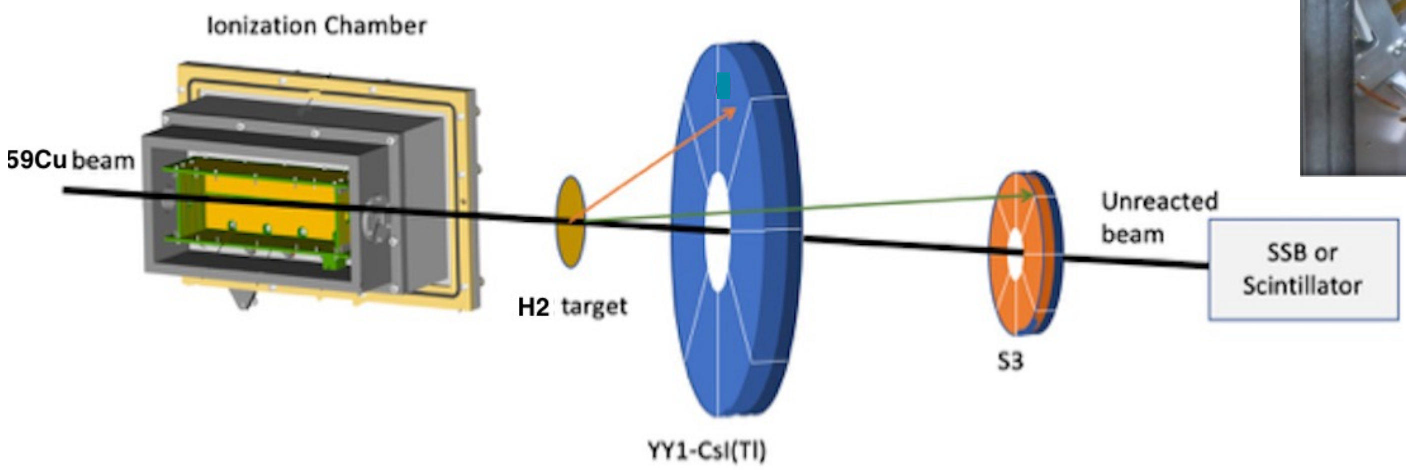


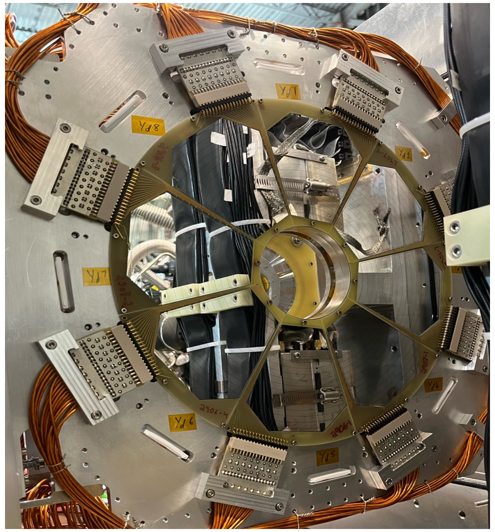


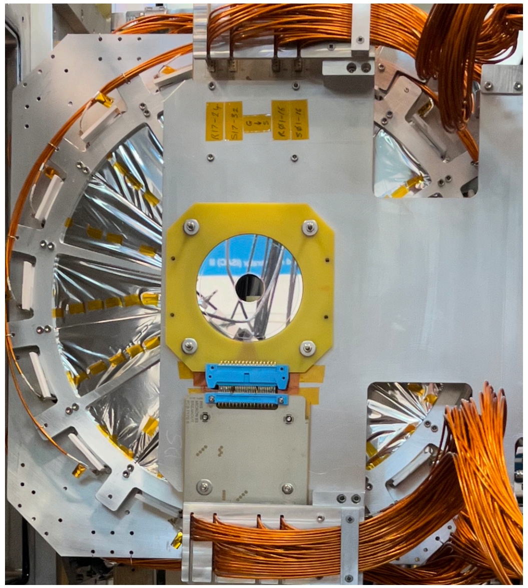
Less overlap between states and less energy straggling in 50 um target

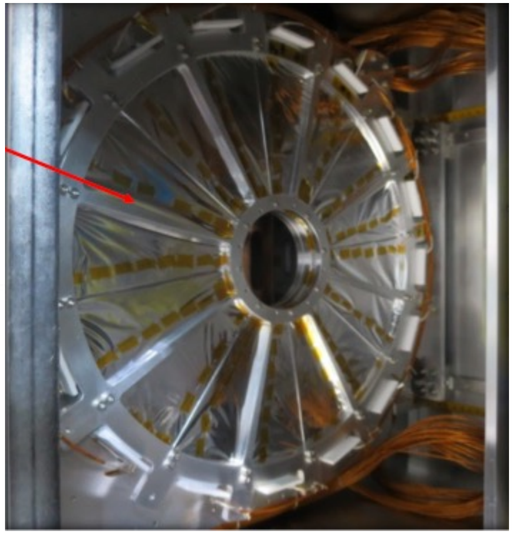
Charged Particle Detectors

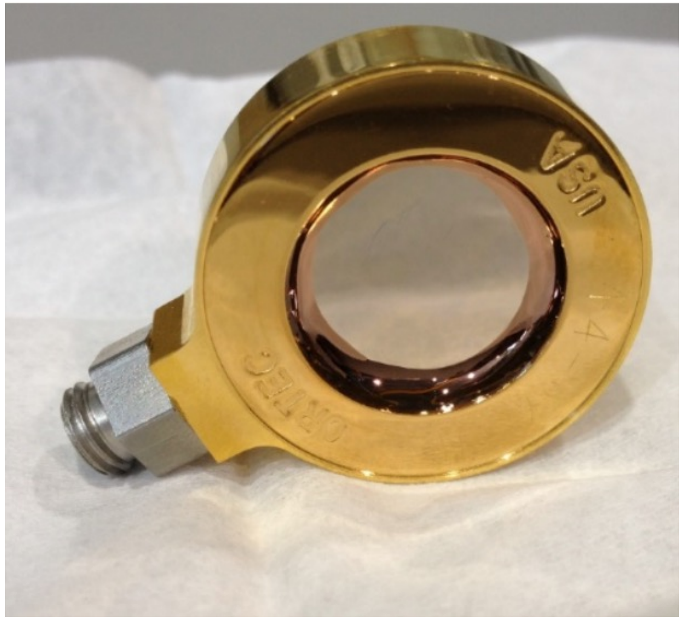
- YY1 – Silicon strip detector
    - 8 sectors and 16 rings
- CsI(TI) – Cesium Iodide Thallium doped detector
    - 16 sectors/crystals
- S3 – Double sided silicon strip detector (S3d1 and S3d2)
    - 32 sectors and 24 rings



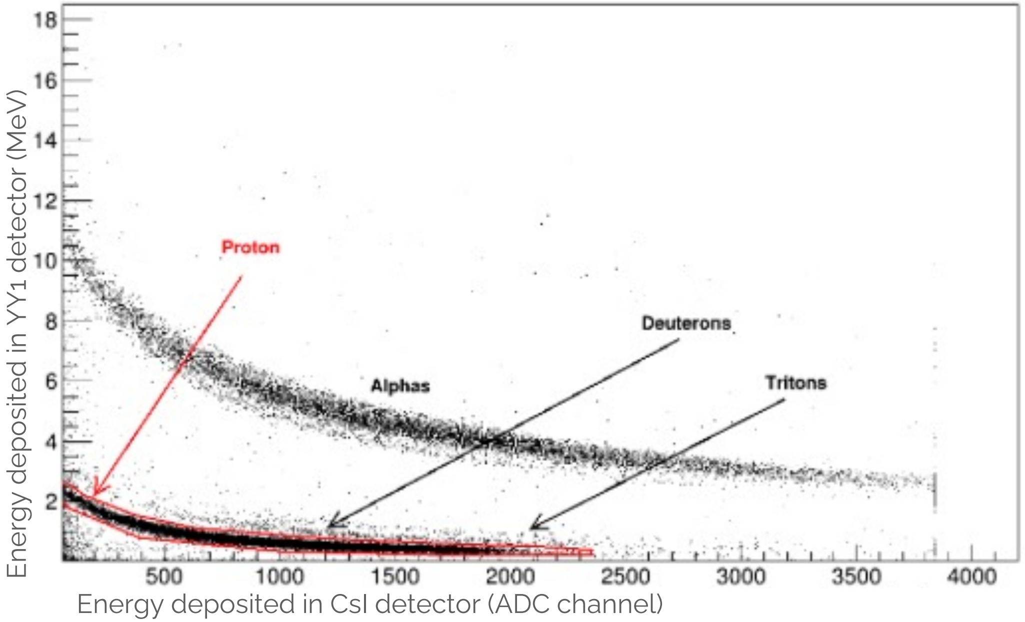


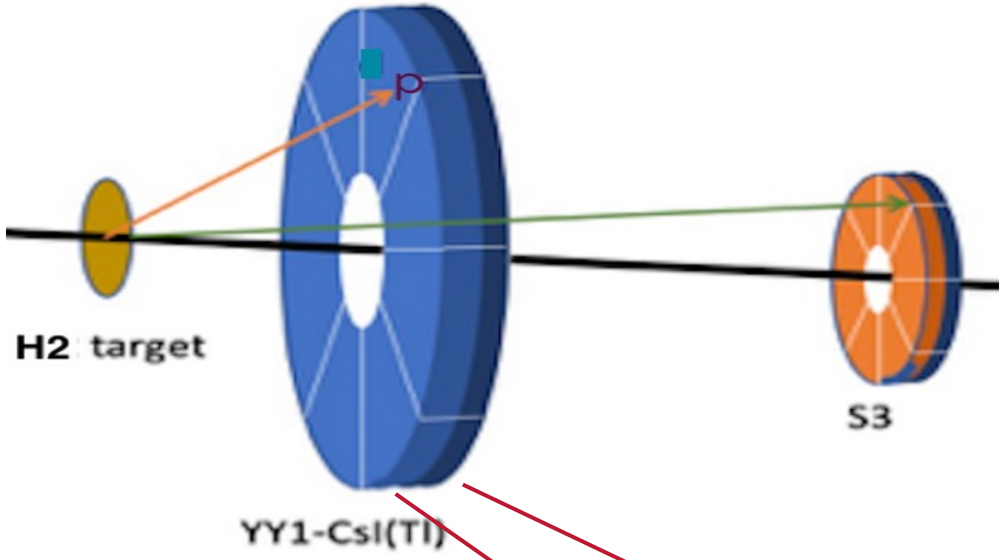


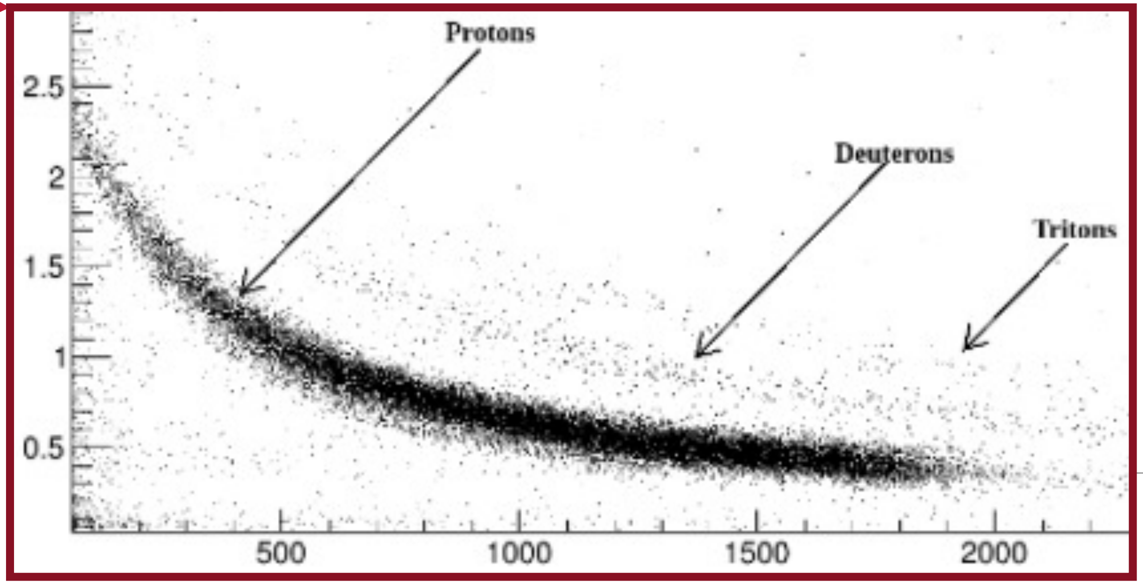


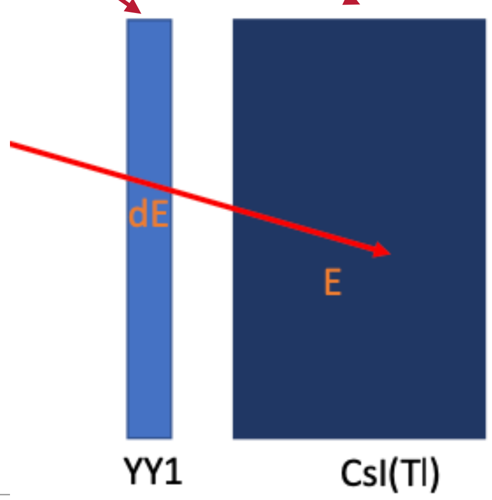


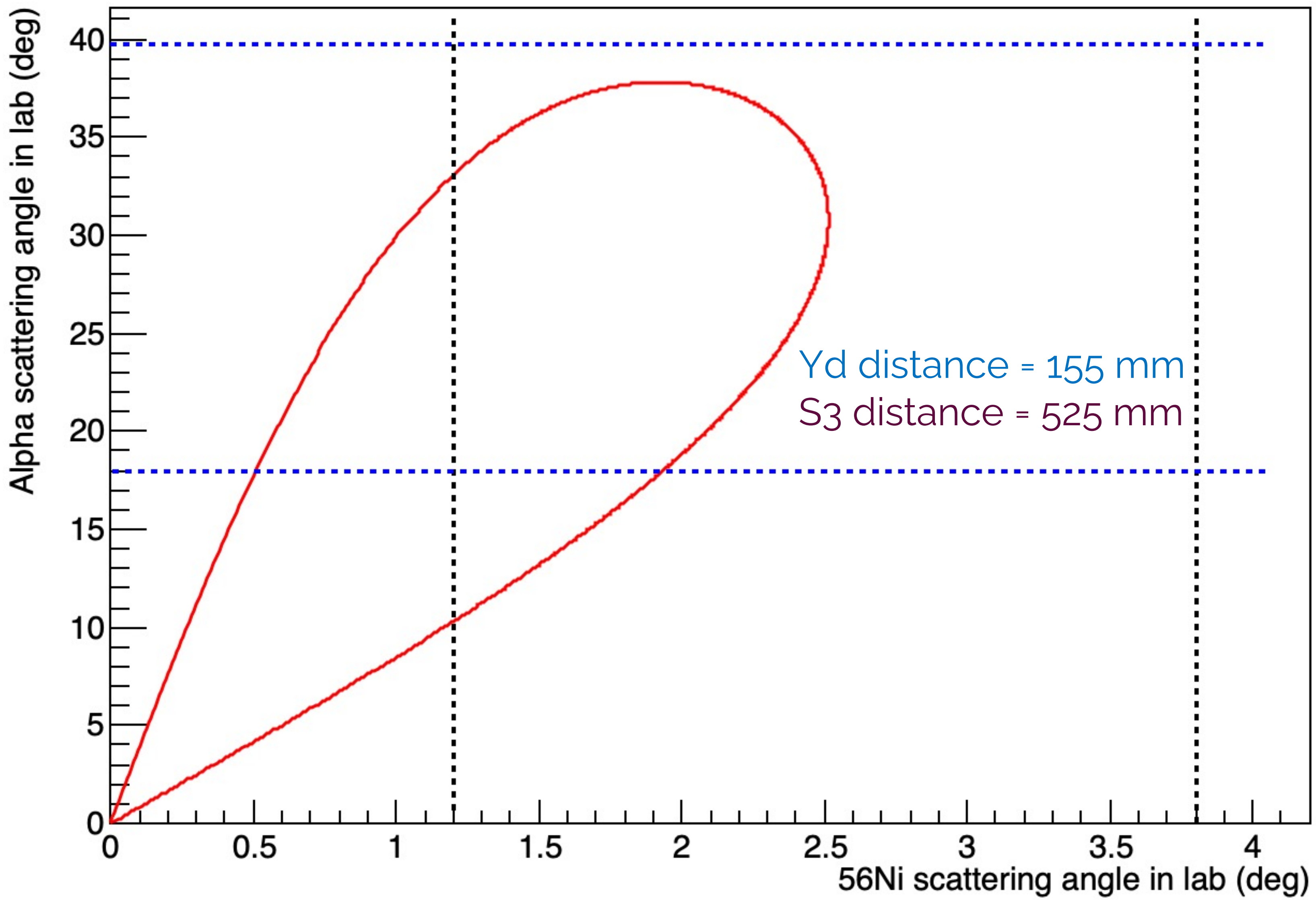
Light Particle Detection







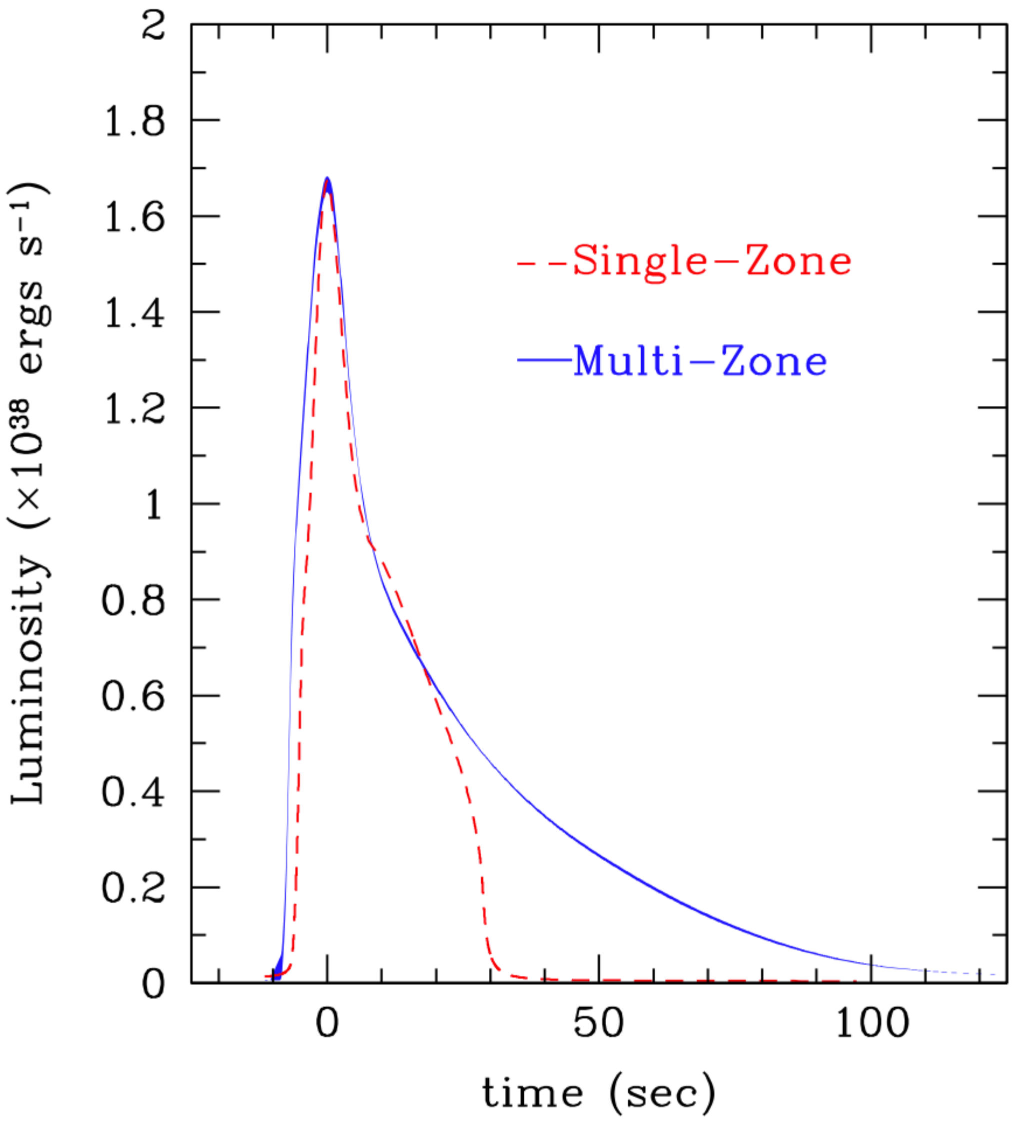




65% Coincidence

Coincident events producing ^{56}Ni in the ground state.

- Radiation transport modeling absent in One zone model.
- It neglects gradients in temperature, density, and composition, as well as radiative transport and convection.
- ONEZONE assumes nuclear burning at constant pressure P.
- It captures only some aspects of a more complicated situation.

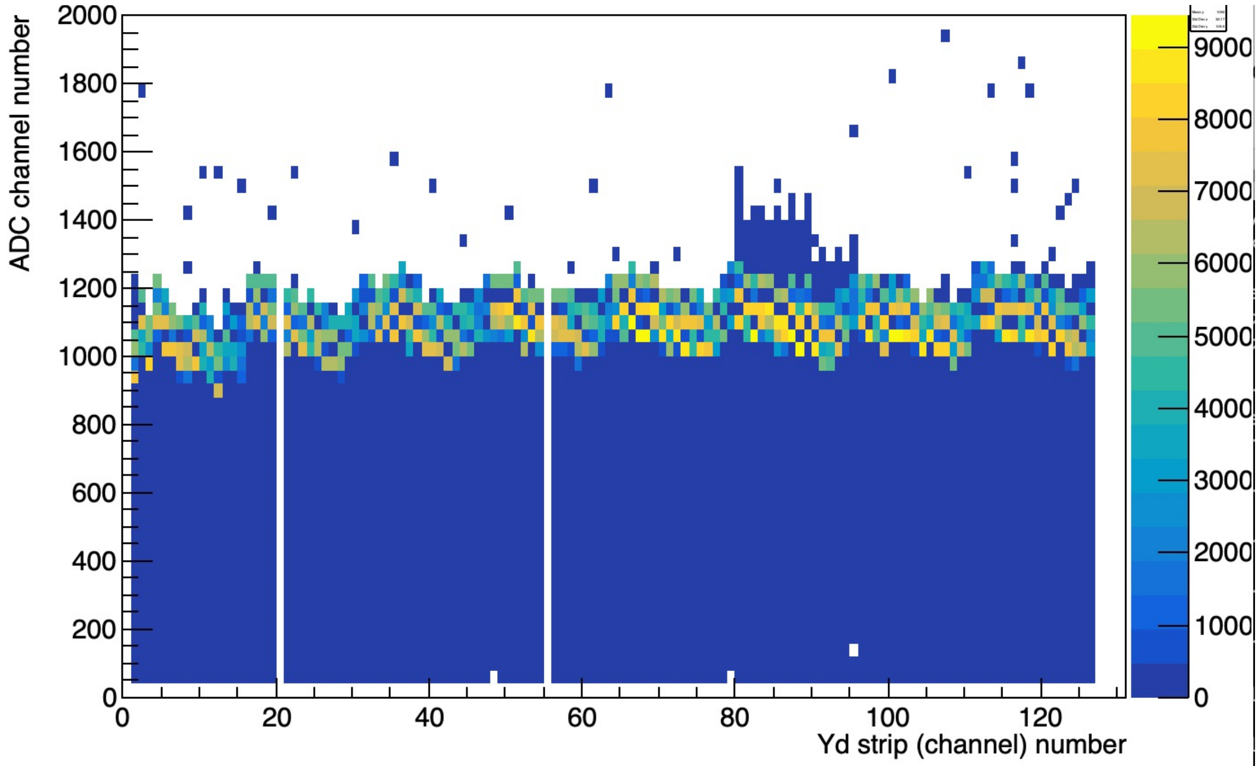


YY1 Calibration

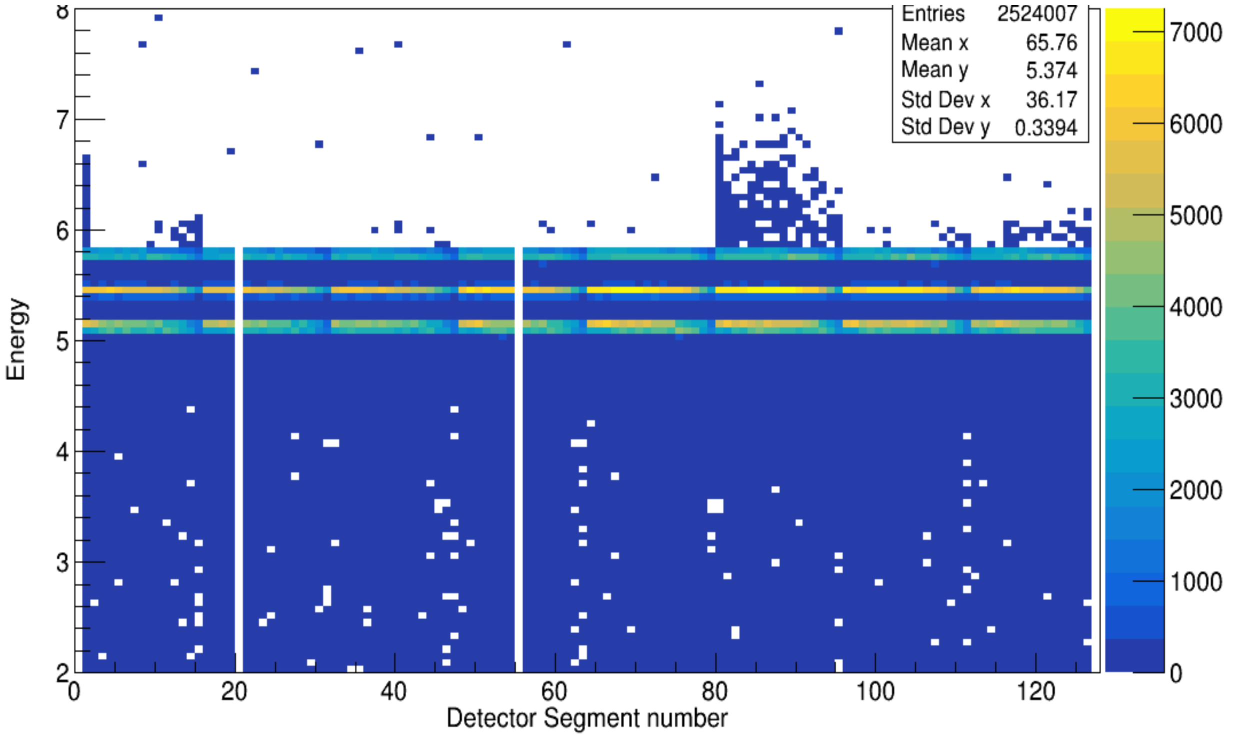
$$E = g^{*}\,(c-p)$$

Alpha source:

^{239}Pu = 5.155 MeV
^{241}Am = 5.486 MeV
^{244}Cm = 5.805 MeV

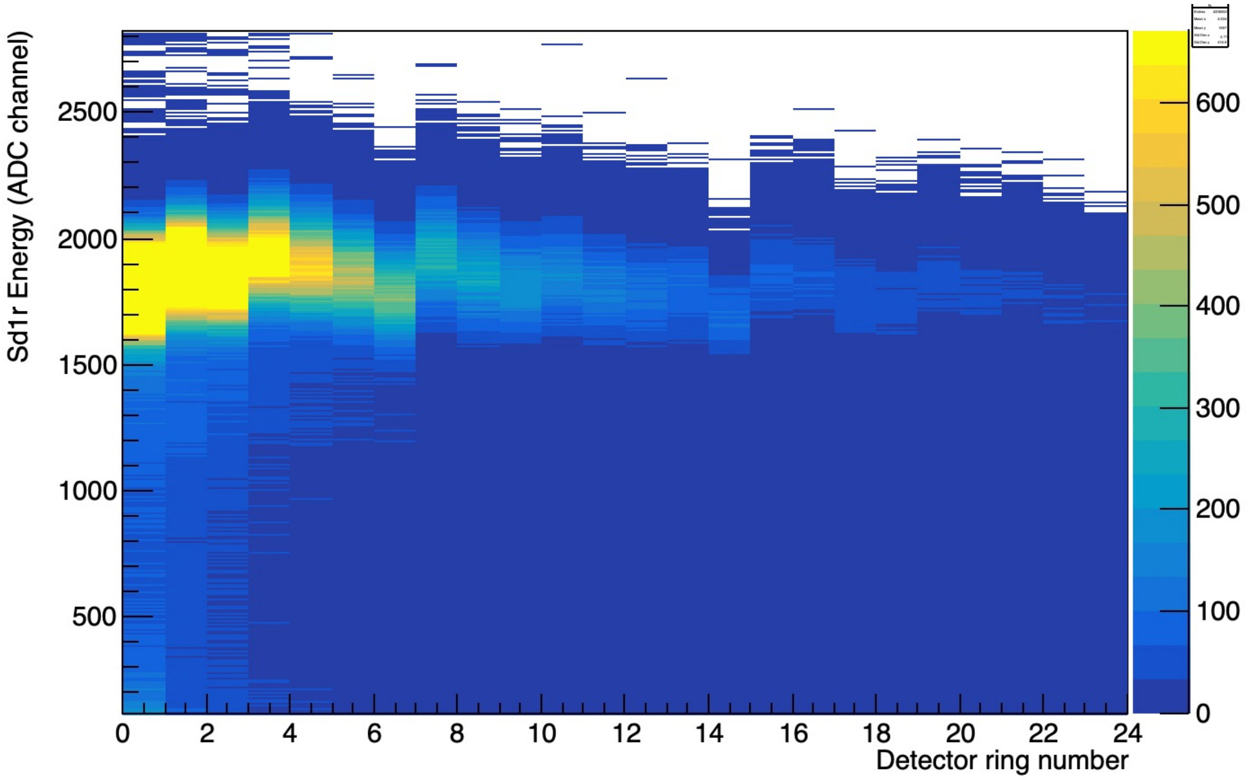


Uncalibrated spectrum

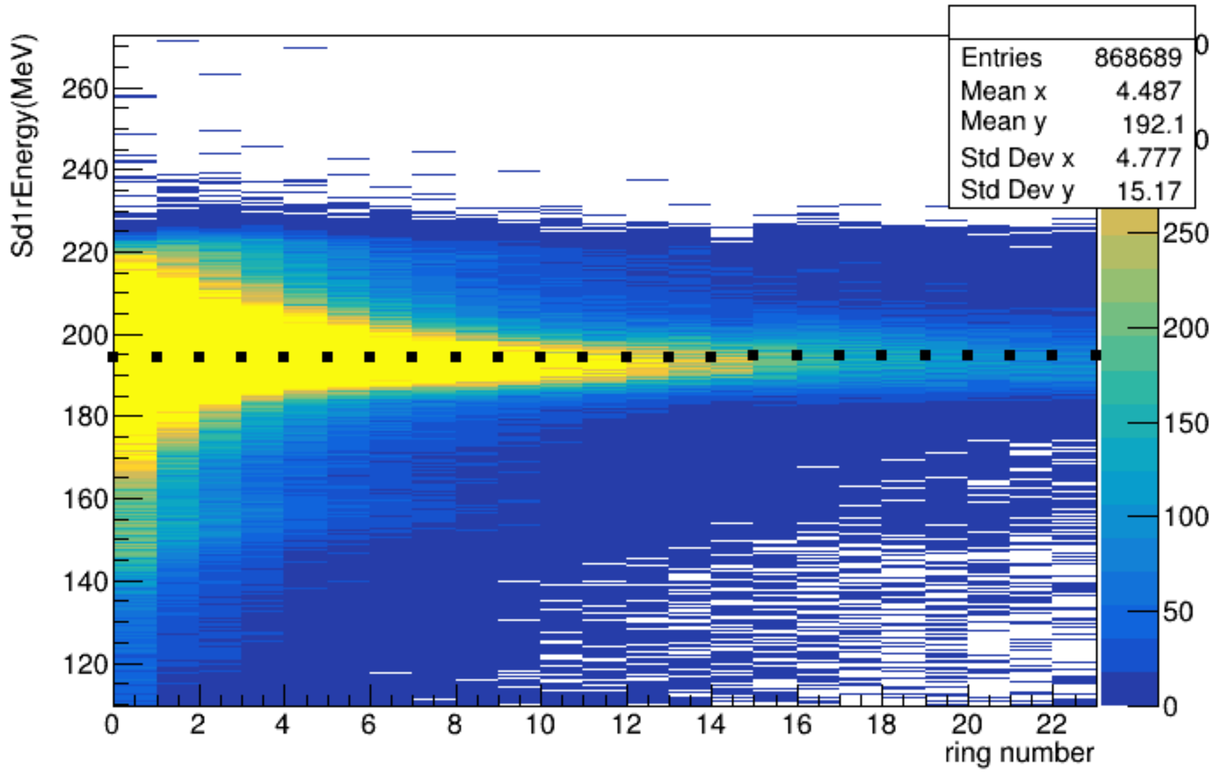


Calibrated spectrum

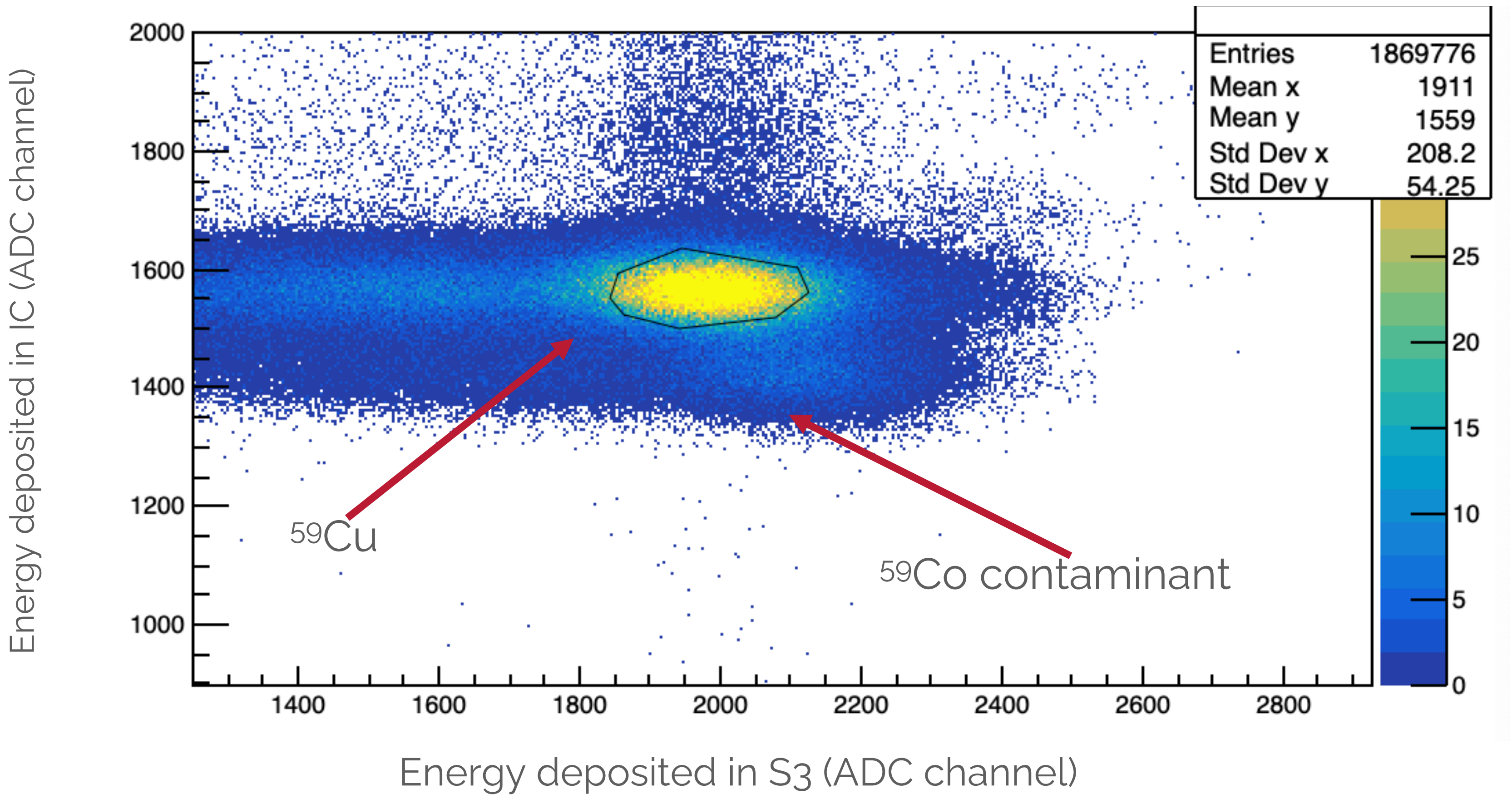
S3 Calibration



Uncalibrated spectrum



Calibrated spectrum



Entries 1869776
Mean x 1911
Mean y 1559
Std Dev x 208.2
Std Dev y 54.25
59Cu
59Co contaminant
Energy deposited in IC (ADC channel)
Energy deposited in S3 (ADC channel)

Target thickness- measured for a 59Cu beam with and without target

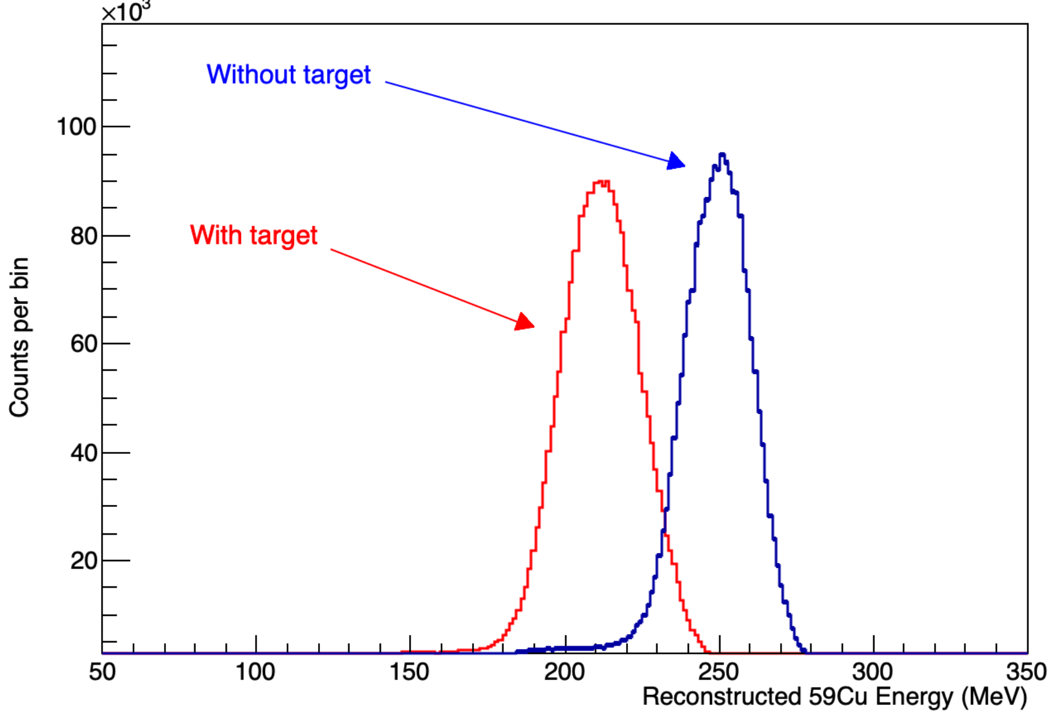
I am using this formula to find the thickness,

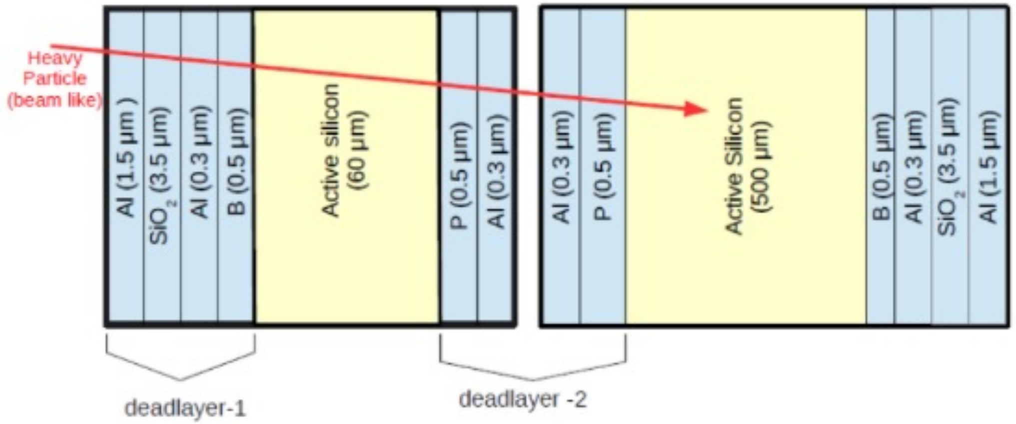
$$t = \int_{E_1}^{E_2} \frac{1}{S(E)} dE$$

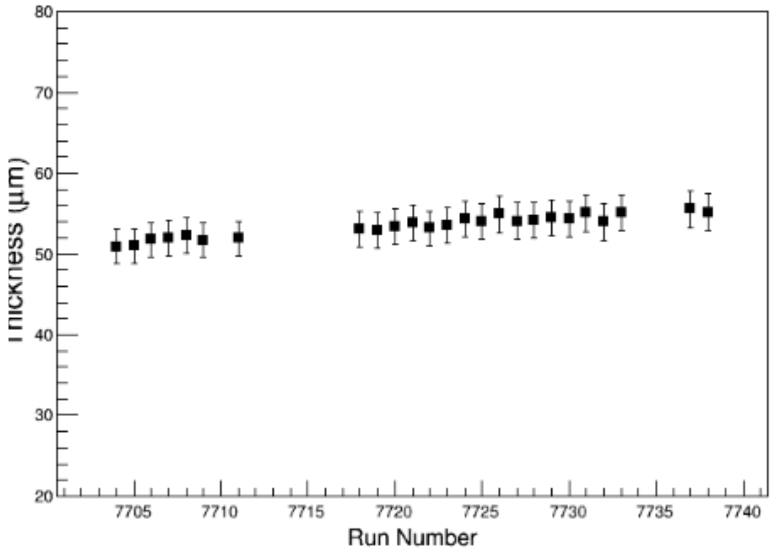
Where, E_2 = 59Cu beam energy after the target

E_1 = 59Cu beam energy before the target i.e. after Ag-foil.

S(E) = stopping power of 59Cu particles in the target.

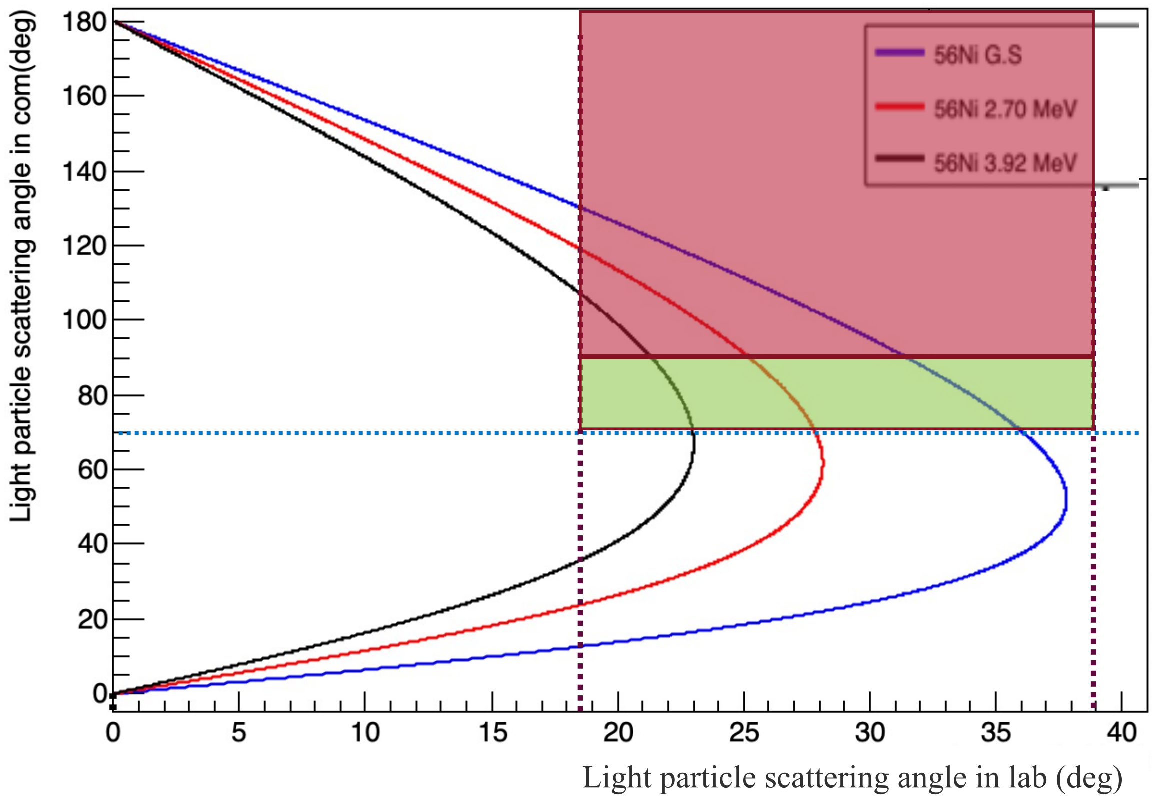




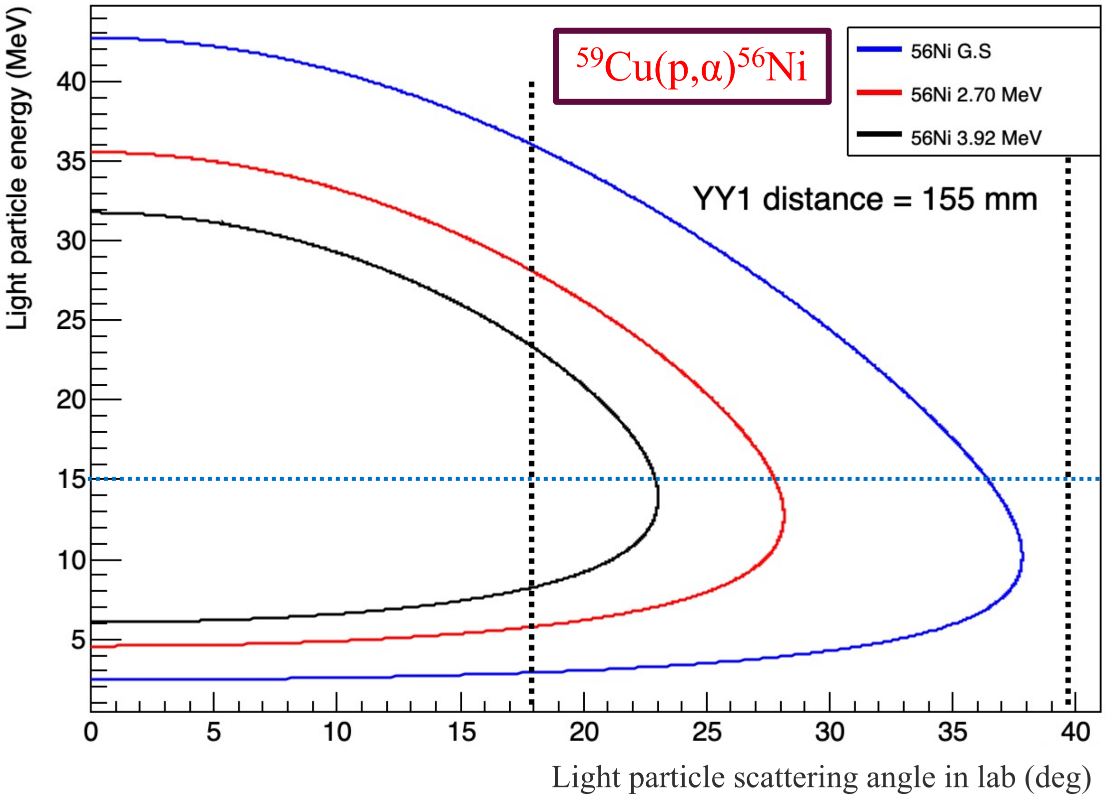


$$E_1 = E_{S3d2} + E_{dead\ layer\ 2} + E_{S3d1} + E_{dead\ layer\ 1}$$

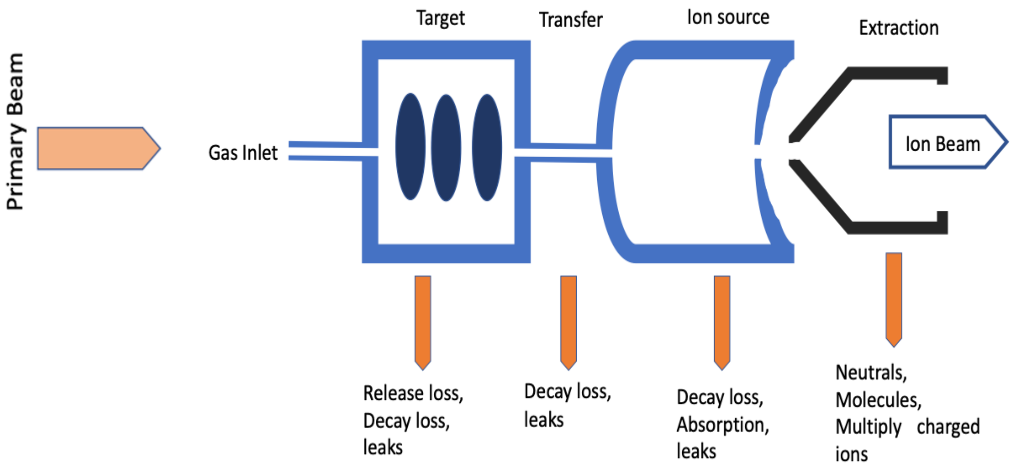
Light Particle Detection

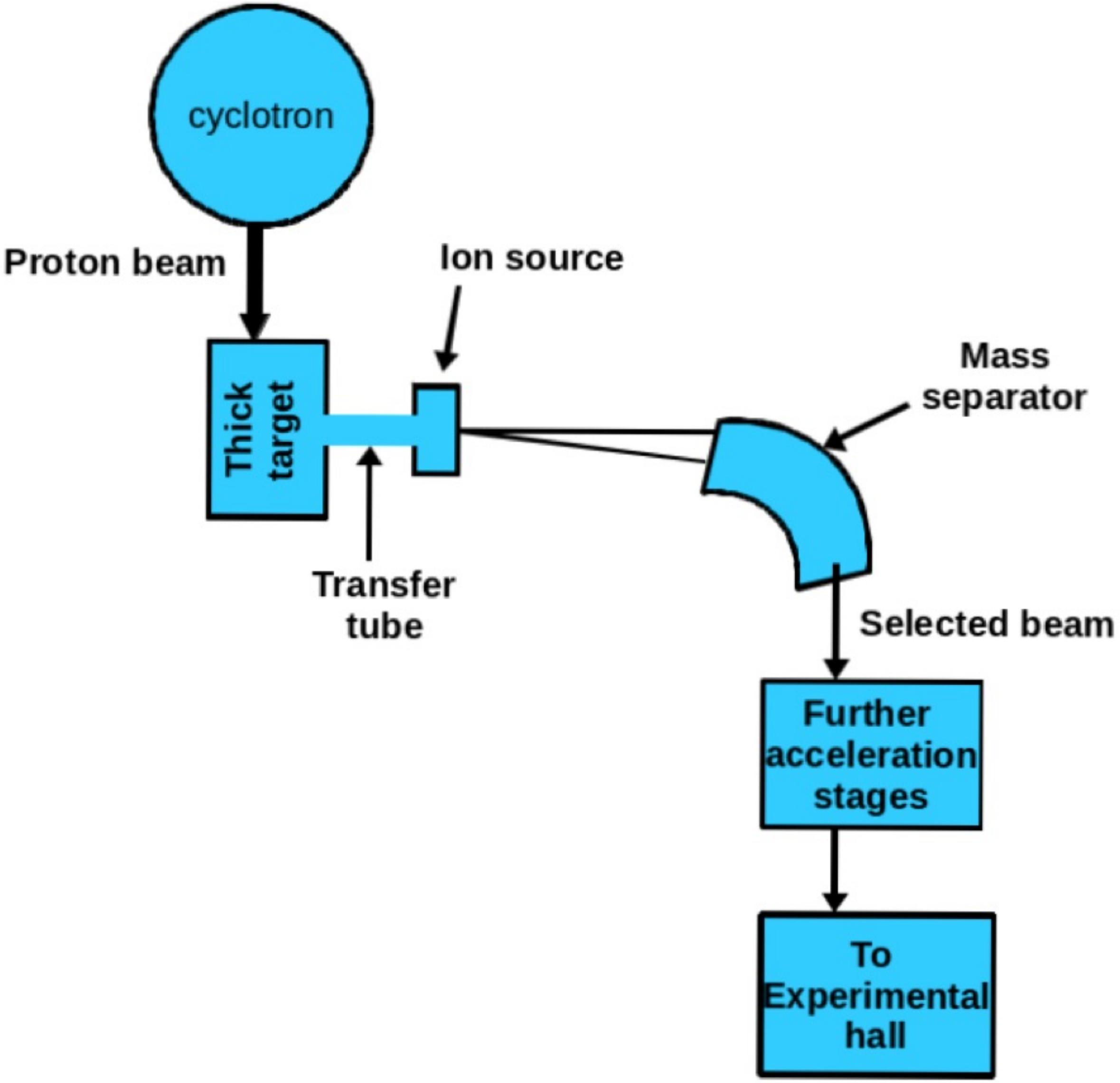


Forward scattering and backward scattering region is shown in green and red, respectively.



Horizontal line shows the threshold energy for alpha particle to be detected in ΔE-E telescope.


Primary Beam
Gas Inlet
Target
Transfer
Ion source
Extraction
Ion Beam
Release loss,
Decay loss,
leaks
Decay loss,
leaks
Decay loss,
Absorption,
leaks
Neutrals,
Molecules,
Multiply charged
ions


cyclotron
Proton beam
Ion source
Thick target
Mass separator
Transfer tube
Selected beam
Further acceleration stages
To Experimental hall

Other open channels

$^{60}Zn + \gamma$

$^{56}Ni + \alpha$

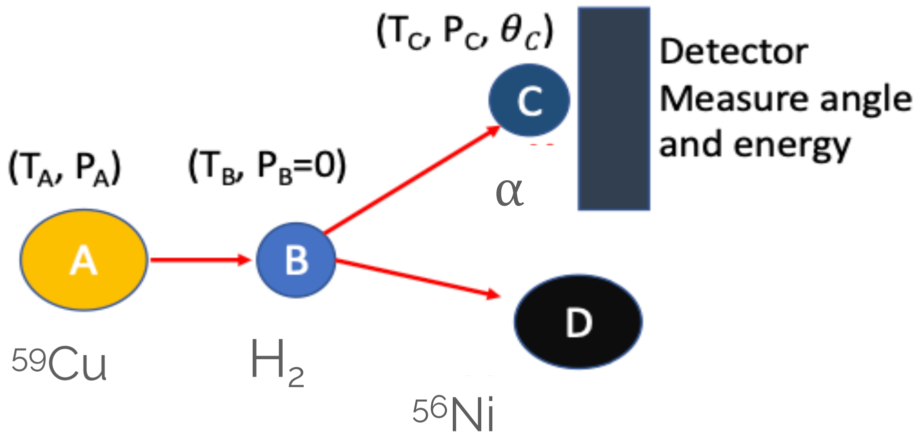
$^{59}Cu + p$

$^{58}Ni + 2p$

$^{55}Co + p + \alpha$

$^{52}Fe + 2\alpha$

Excitation spectrum



- Invariant mass technique
- Consider *A+B* → *C+D* , then Q-value is

$$Q = m_{oA} + m_{oB} - m_{oC} - m_D$$

Where m_{oA}, m_{oB}, m_{oC} and m_{oD} are rest masses of the particles.

If its possible to measure the E and p of ^{56}Ni it will be

$m_{oD}c^2 = \text{sqrt}\,(E_D^2 - c^2 p_D^2)$