^{59}Cu(p,α) cross section for the heavy element nucleosynthesis in core collapse supernovae

Collaboration

R. Garg, C. Lederer-Woods, T. Davinson, M. Dietz,
D. Kahl, S. J. Lonsdale, A. Murphy, P. J. Woods

- *University of Edinburgh, UK*

M. Barbagallo

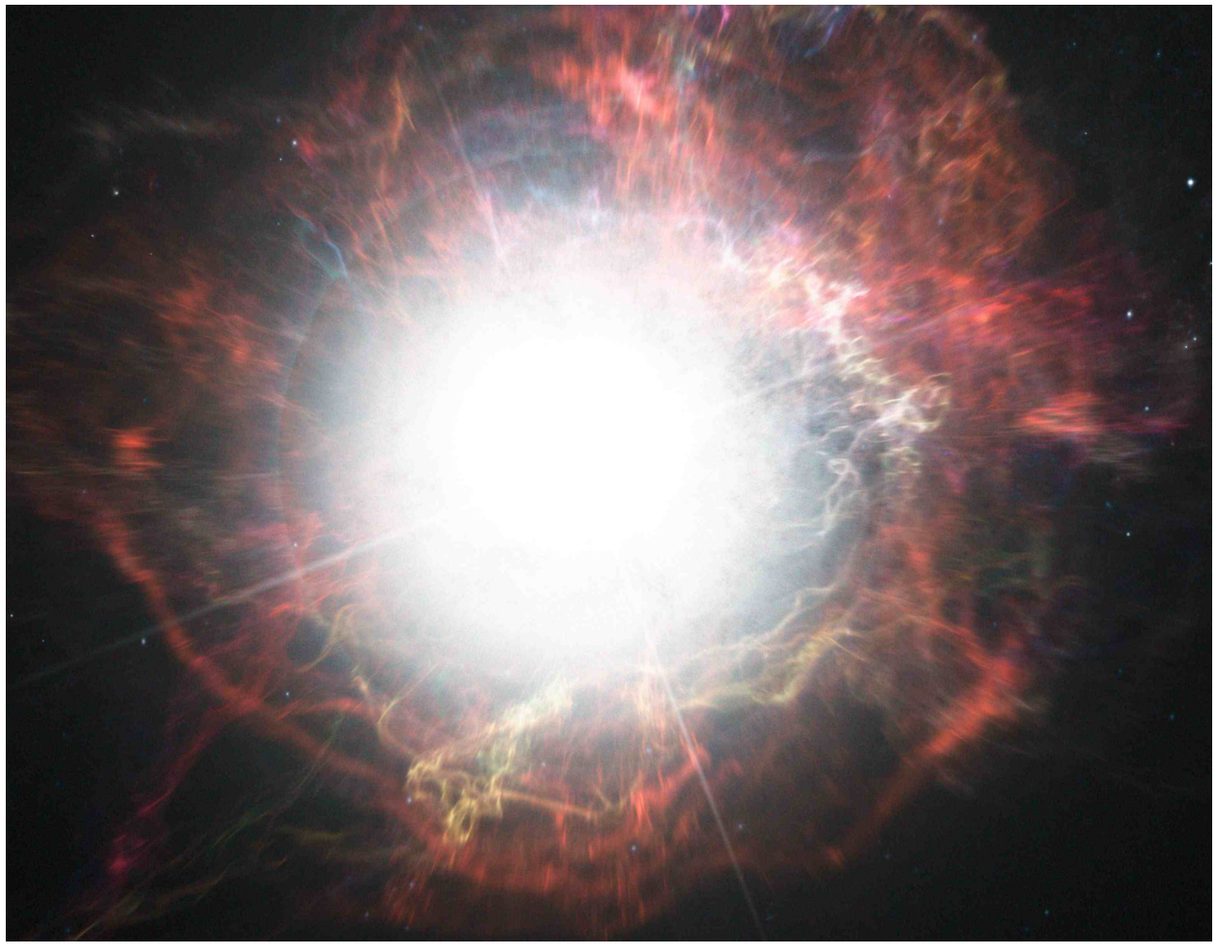
- *CERN, Switzerland*

Astrophysical Motivation

Origin of heavy proton-rich nuclei

- The p-nuclei are thought to be produced via p-processes; proton-capture and photo disintegration of heavy nuclei.

- However, the observed abundance of some lighter p-nuclei (^{92,94}Mo and ^{96,98}Ru) not reproduced in most stellar models with these processes.



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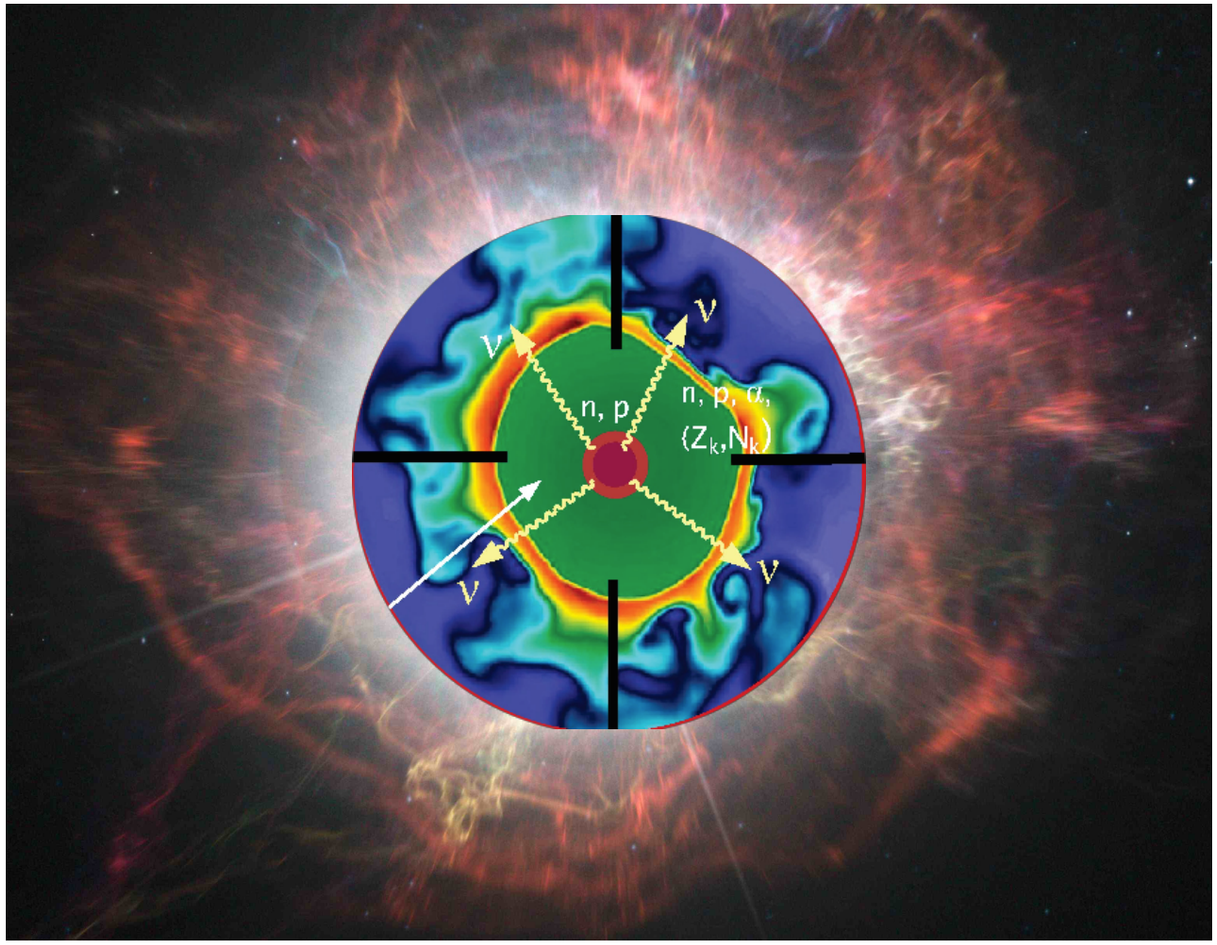
- However, the observed abundance of some lighter p-nuclei (^{92,94}Mo and ^{96,98}Ru) not reproduced in most stellar models with these processes.

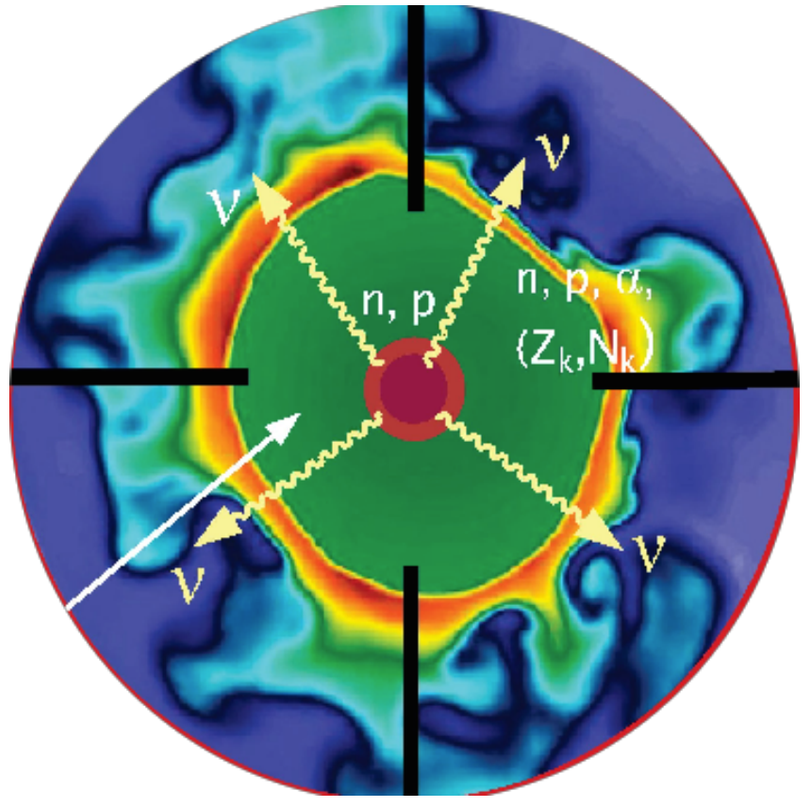
- Possible production of these p-nuclei in the vp-process in core collapse supernovae (*Fröhlich et al, PRL 96, 2006*)



Astrophysical Motivation

vp-process:

- The matter becomes proton-rich in core-collapse supernova by neutrino capture on free neutrons
- In this proton-rich ejecta, elements up to ^{64}Ge as proton captures probability drops at this point
- Antineutrino capture on protons can briefly cause a neutron density of 10^{14} -10^{15} cm^{-3}
- These neutron get captured on ^{64}Ge and unblock the matter flow to heavier element synthesis



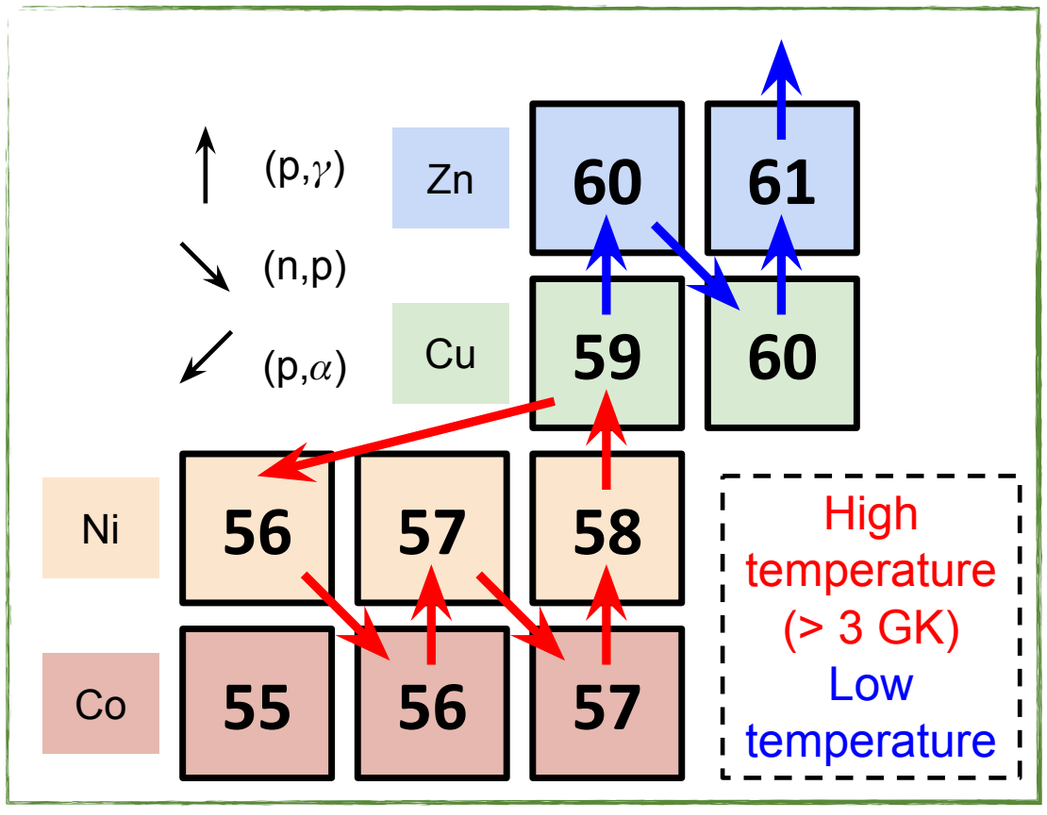
Astrophysical Motivation

Origin of heavy proton-rich nuclei

- NiCu cycle has been identified as the key end point at high temperatures (~3 GK)
  (A. Arcones et al, ApJ 750, 2012)

- Competition between (p,α) and (p,γ) on ^{59}Cu sets temperature where heavy element formation starts

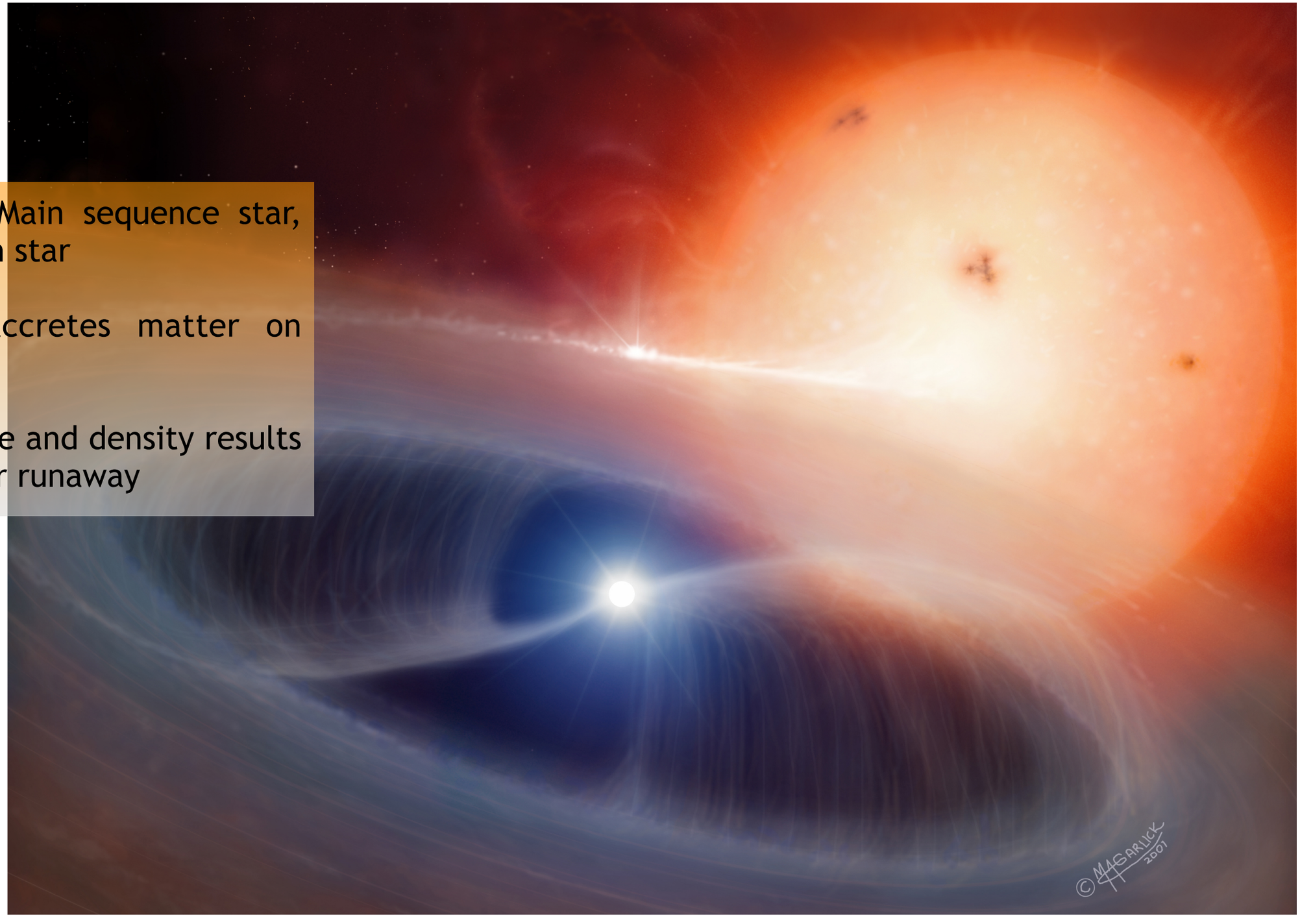
- Higher cross-over temperature = more efficient vp-process



Astrophysical Motivation

X-ray Bursts

- Binary system: Main sequence star, compact neutron star
- Neutron star accretes matter on surface
- High temperature and density results in thermonuclear runaway



Astrophysical Motivation

X-ray Bursts (light curve)

- ^{59}Cu(p,α) reaction is of key importance" for X-ray light curve *(R. Cyburt et al, ApJ 830, 2016)*

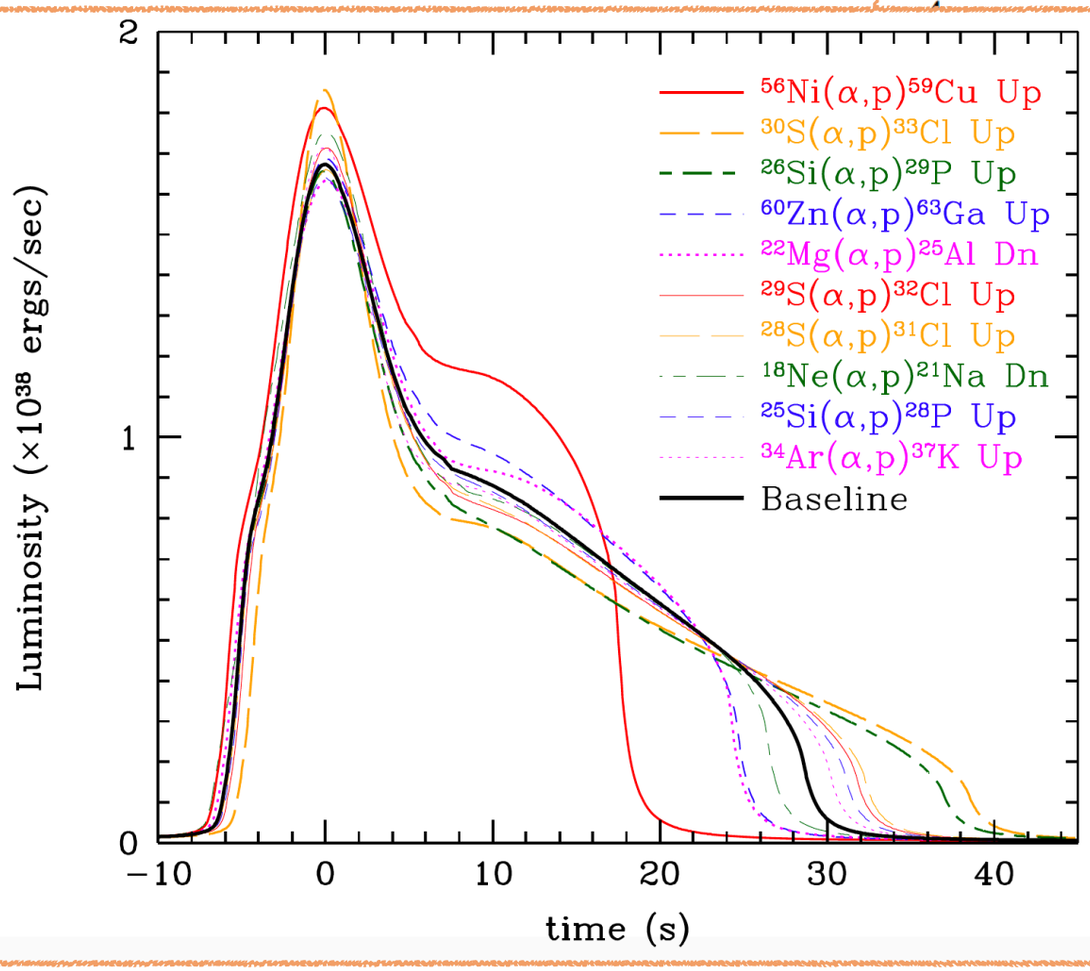


Table 1
Reactions that Impact the Burst Light Curve in the Single-zone X-Ray Burst Model

Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	^{56}Ni(α, p)^{59}Cu	U	12.5	1
2	^{59}Cu(p, γ)^{60}Zn	D	12.1	1
3	^{15}O(α, γ)^{19}Ne	D	7.9	1
	^{30}S(α, p)^{33}Cl	U	7.8	1
	^{26}Si(α, p)^{29}P	U	5.3	1
	^{61}Ga(p, γ)^{62}Ge	D	5.0	1
	^{23}Al(p, γ)^{24}Si	U	4.8	1
	^{27}P(p, γ)^{28}S	D	4.4	1
	^{63}Ga(p, γ)^{64}Ge	D	3.8	1
	^{60}Zn(α, p)^{63}Ga	U	3.6	1

Single-zone model results

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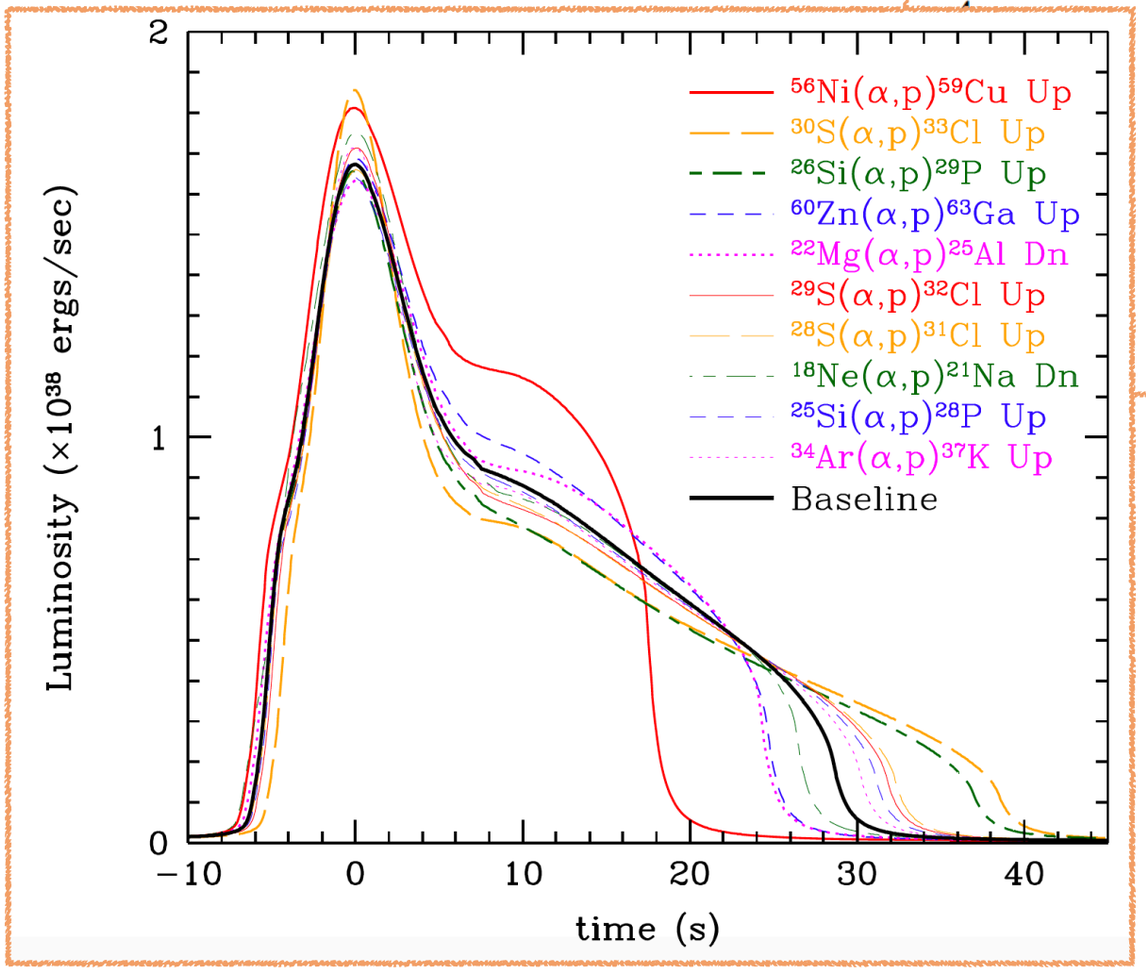

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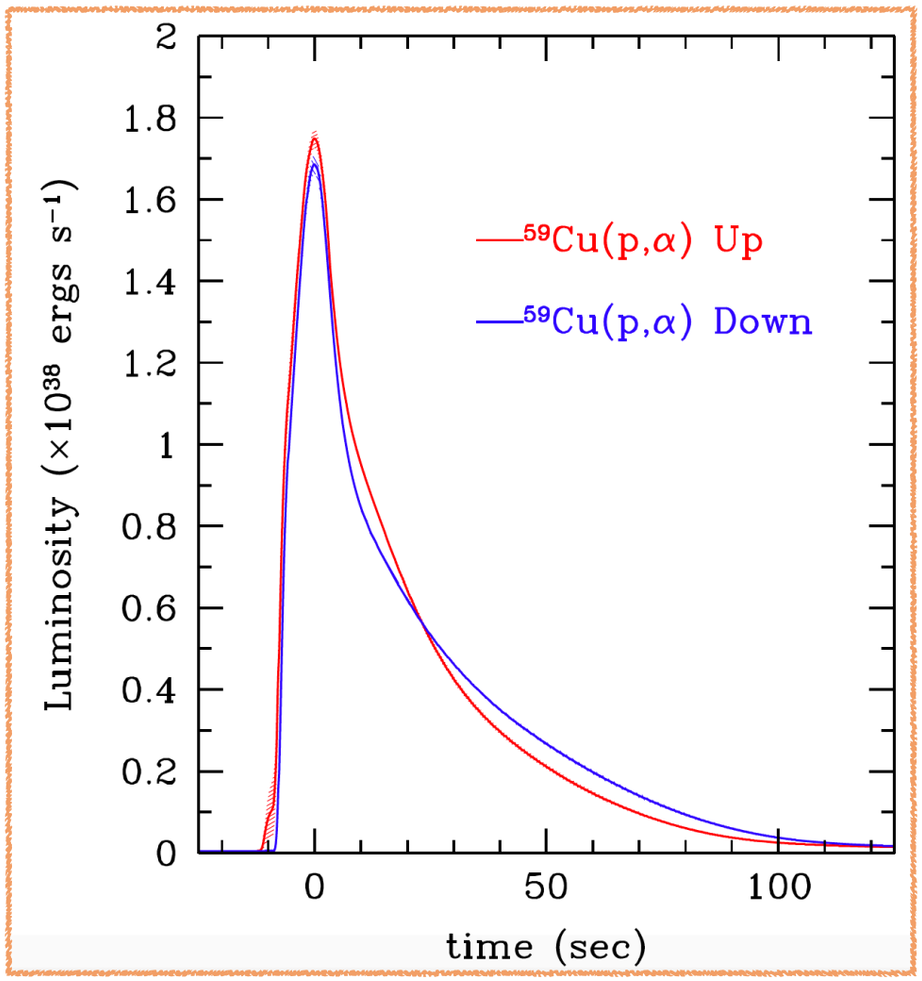

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Reactions that Impact the Burst Light Curve in the Multi-zone X-ray Burst Model

Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	$^{15}O(\alpha, \gamma)^{19}Ne$	D	16	1
2	$^{56}Ni(\alpha, p)^{59}Cu$	U	6.4	1
3	$^{59}Cu(p, \gamma)^{60}Zn$	D	5.1	1
4	$^{61}Ga(p, \gamma)^{62}Ge$	D	3.7	1
5	$^{22}Mg(\alpha, p)^{25}Al$	D	2.3	1
6	$^{14}O(\alpha, p)^{17}F$	D	5.8	1
7	$^{23}Al(p, \gamma)^{24}Si$	D	4.6	1
8	$^{18}Ne(\alpha, p)^{21}Na$	U	1.8	1
9	$^{63}Ga(p, \gamma)^{64}Ge$	D	1.4	2
10	$^{19}F(p, \alpha)^{16}O$	U	1.3	2

Multi-zone model results

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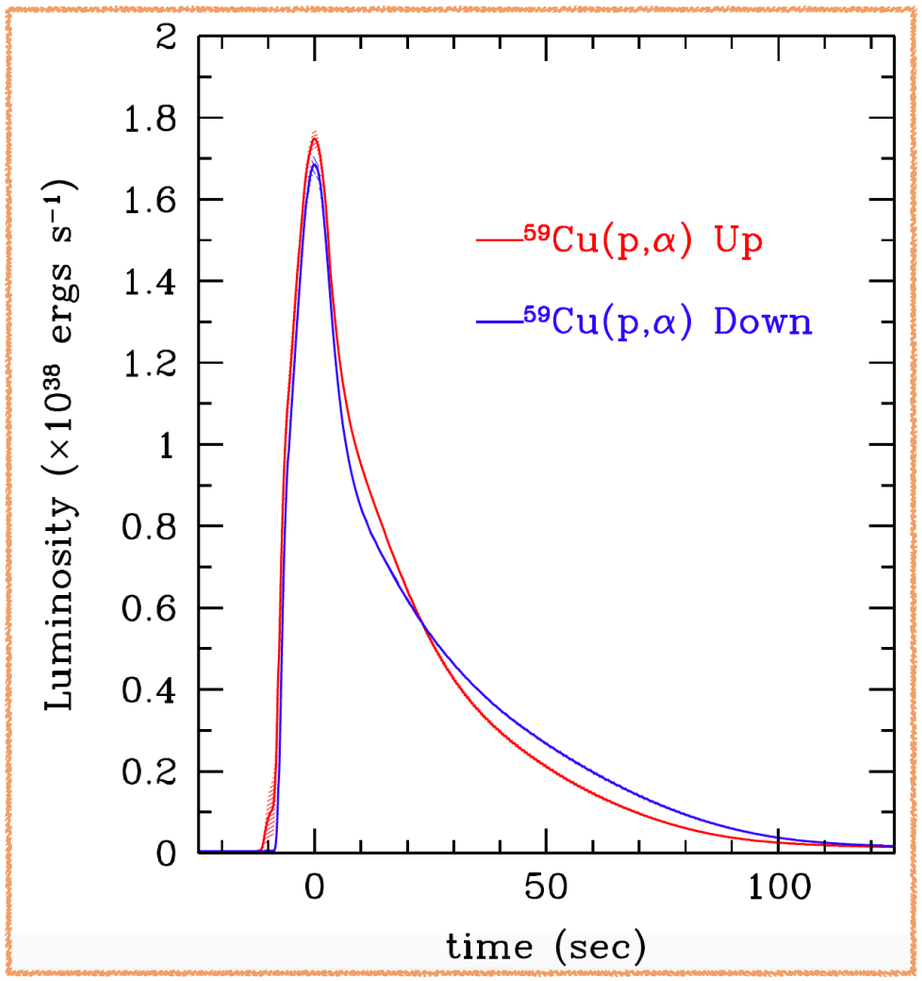

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Multi-zone model results

Astrophysical Motivation

X-ray Bursts (ash composition)

Multi-zone model results

- Inverse of ^{59}Cu(p,α) reaction affects the composition of the burst ashes *(R. Cyburt et al, ApJ 830, 2016)*

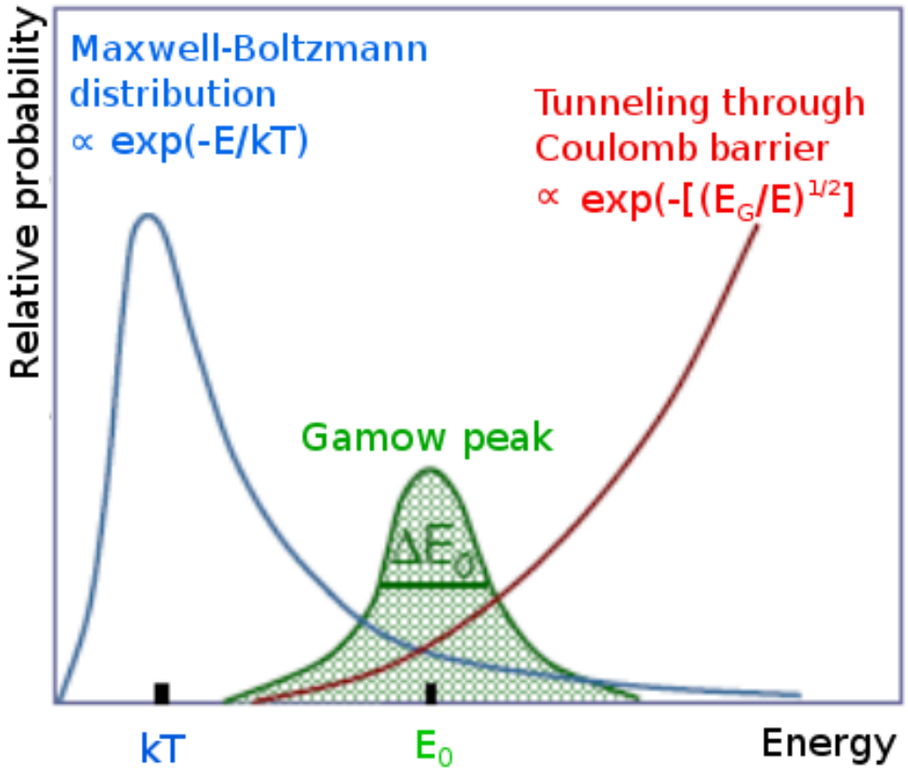
Table 5
Reactions that Impact the Composition in the Multi-zone X-Ray Burst Model

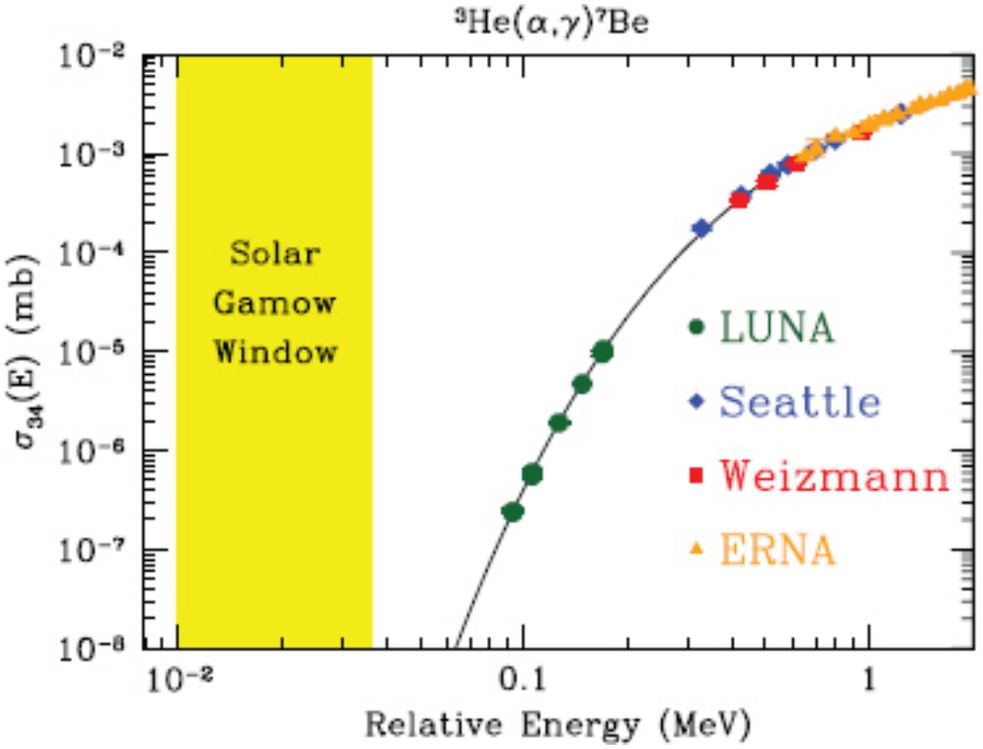
Count	Reaction	Max. Ratio[a]	Affected Mass Numbers with Mass Fraction $>10^{-4}$		
			max	$>\times 10$ change	$\times 2 <$ change $< \times 10$
1	^{8}Be(α, γ)^{12}C	3	98		30, 93–99
2	^{12}C(α, γ)^{16}O	2	28		28
3	^{14}O(α, p)^{17}F	4	29		29
⋮	⋮	⋮	⋮		⋮
23	^{54}Fe(p, γ)^{55}Co	6	54		54
24	^{56}Ni(α, p)^{59}Cu	5	29		12, 29–30, 56, 75, 78–79, 82
25	^{59}Cu(p, γ)^{60}Zn	200	59	59	12, 29–30, 75, 78–79

Experimental Measurement

Gamow Window: The relevant energy range for any stellar environment.

The reaction probability (cross-section, σ(E)) falls rapidly at lower energies!!

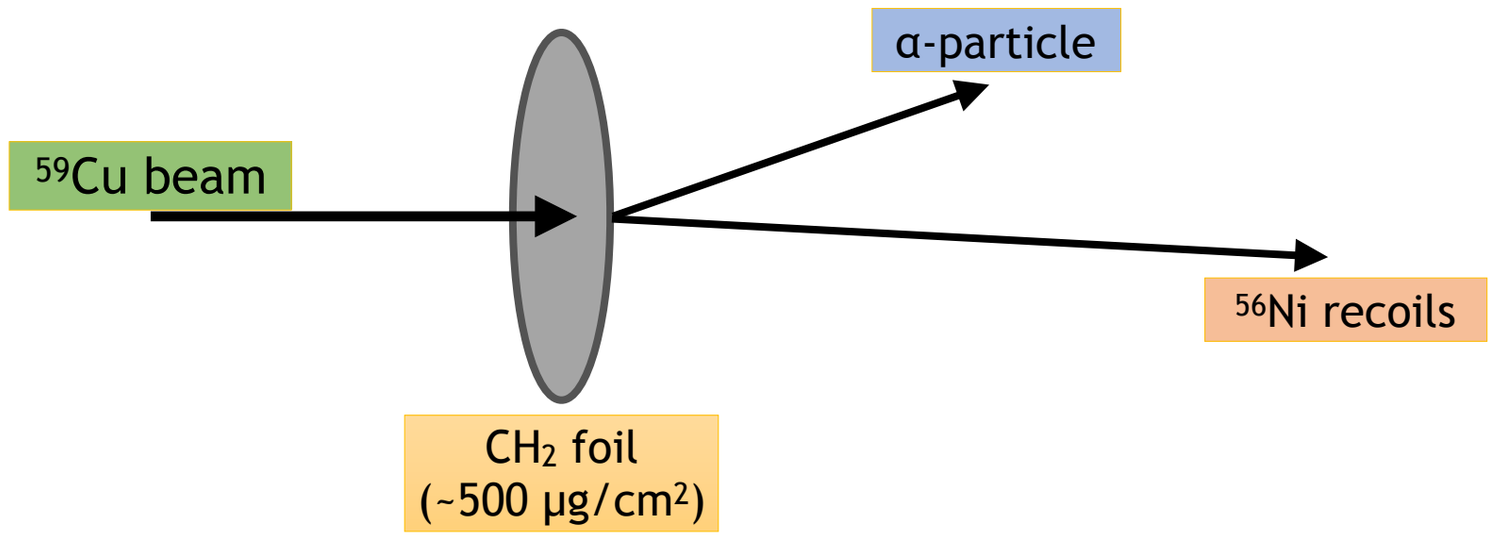




Challenge: The direct measurements in this energy range are not easy

Experimental Setup

^{59}Cu(p,α)^{56}Ni reaction studied in inverse kinematics



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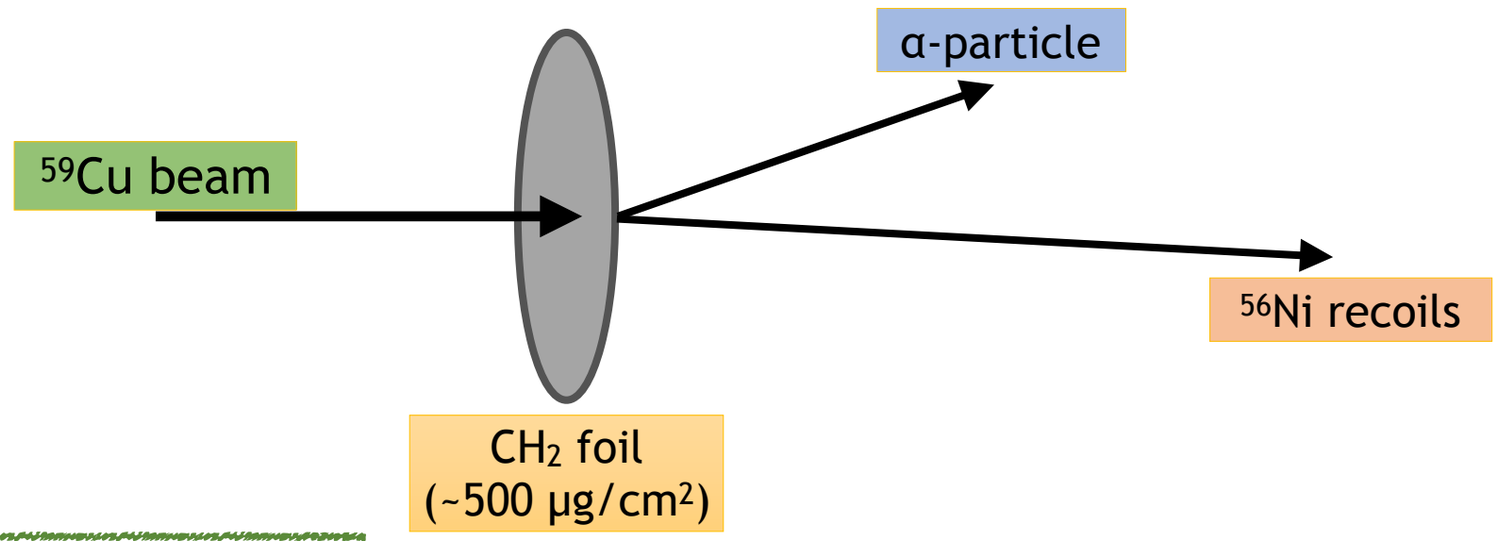
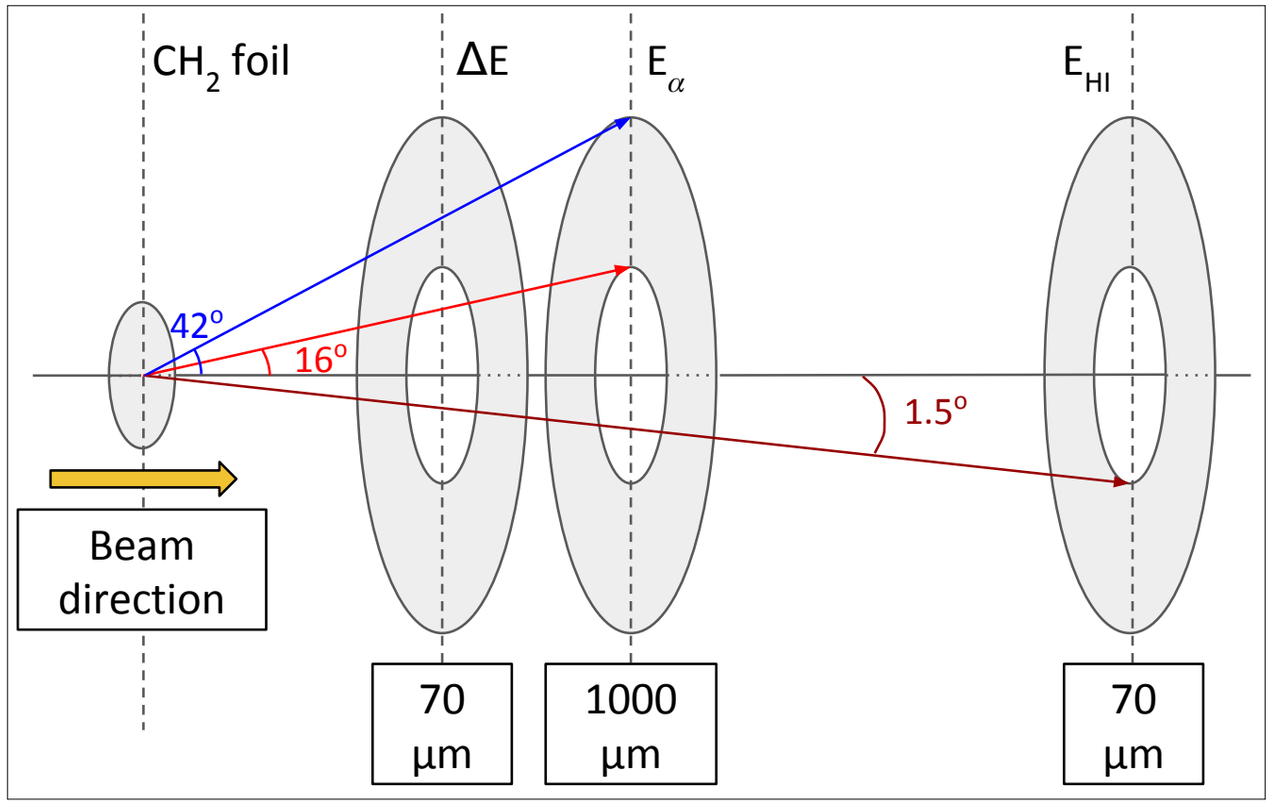


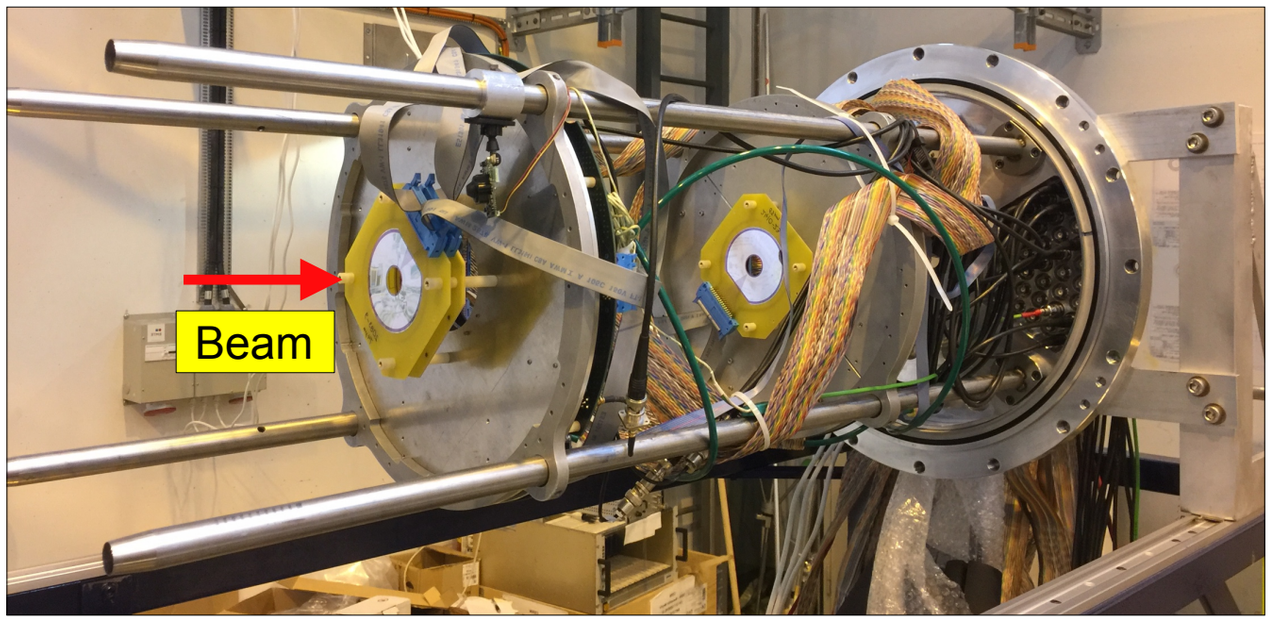
Radioactive ^{59}Cu beam delivered by **HIE-ISOLDE** at CERN

- Intensity ~**2 epA (5.5x10^5 pps)**
- High purity
- 5 different energies between **3.6 - 5.0 MeV/u**

Experimental Setup

- The reaction products were detected using S2-type silicon detector array (purpose-built by **University of Edinburgh**)





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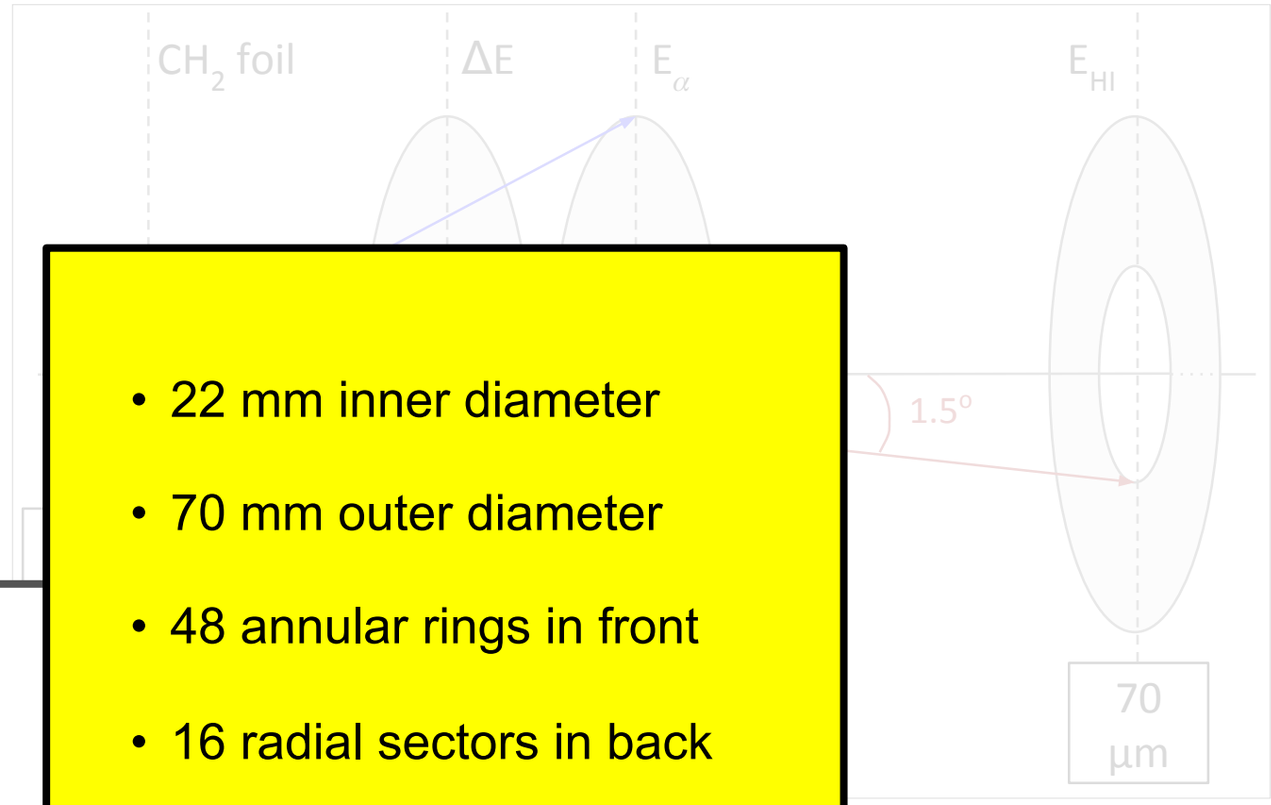
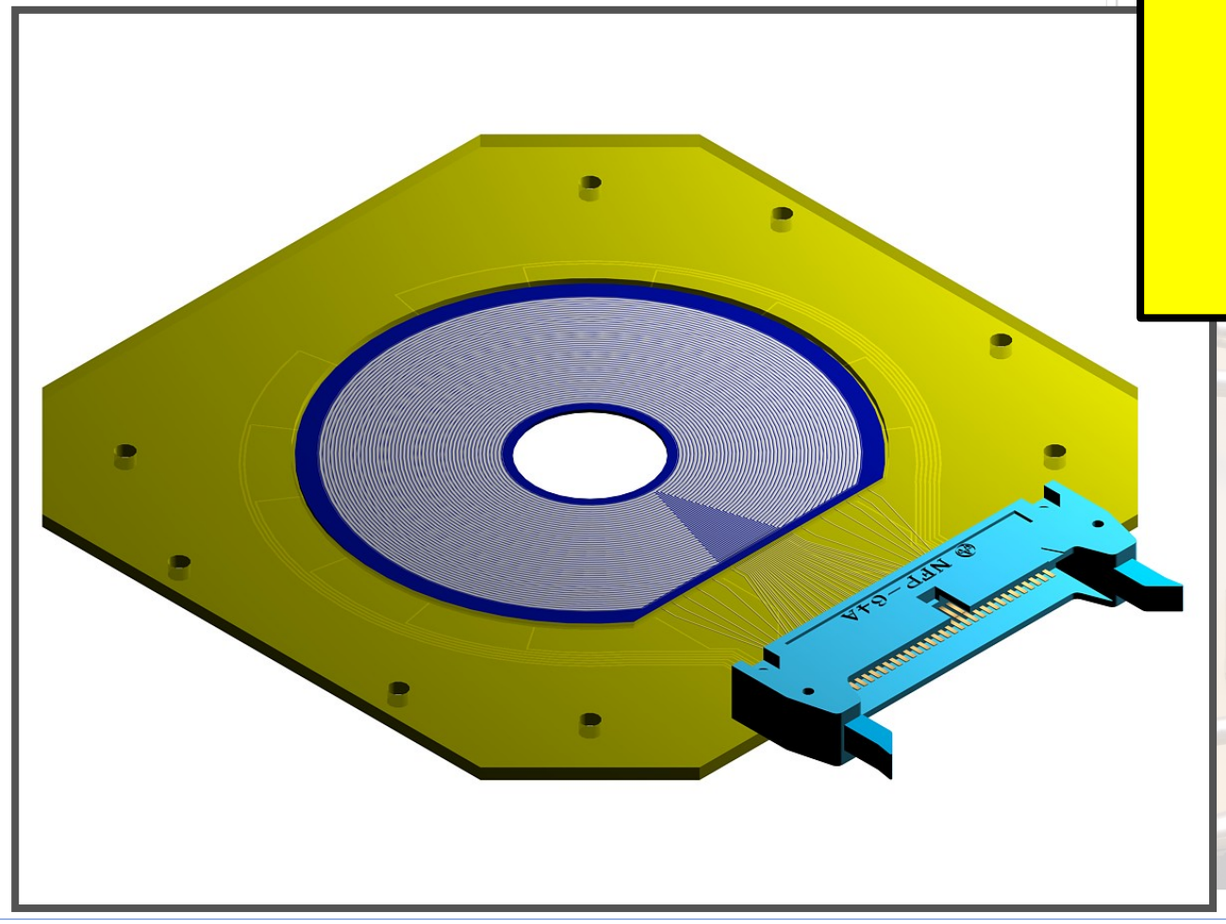
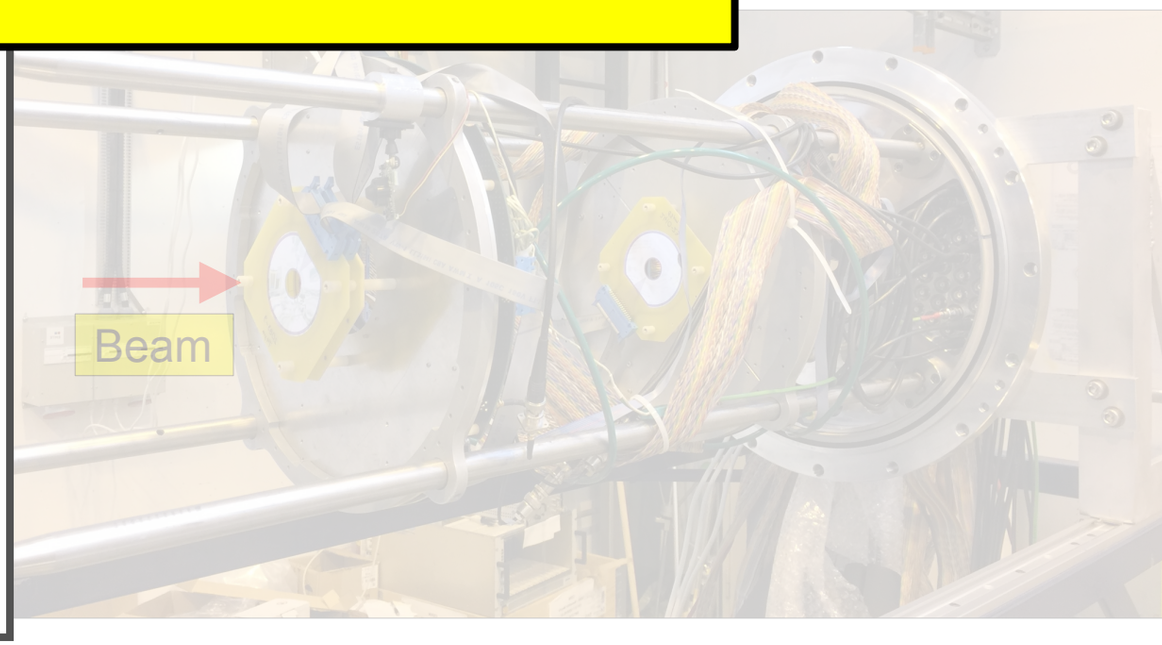


- 22 mm inner diameter
- 70 mm outer diameter
- 48 annular rings in front
- 16 radial sectors in back





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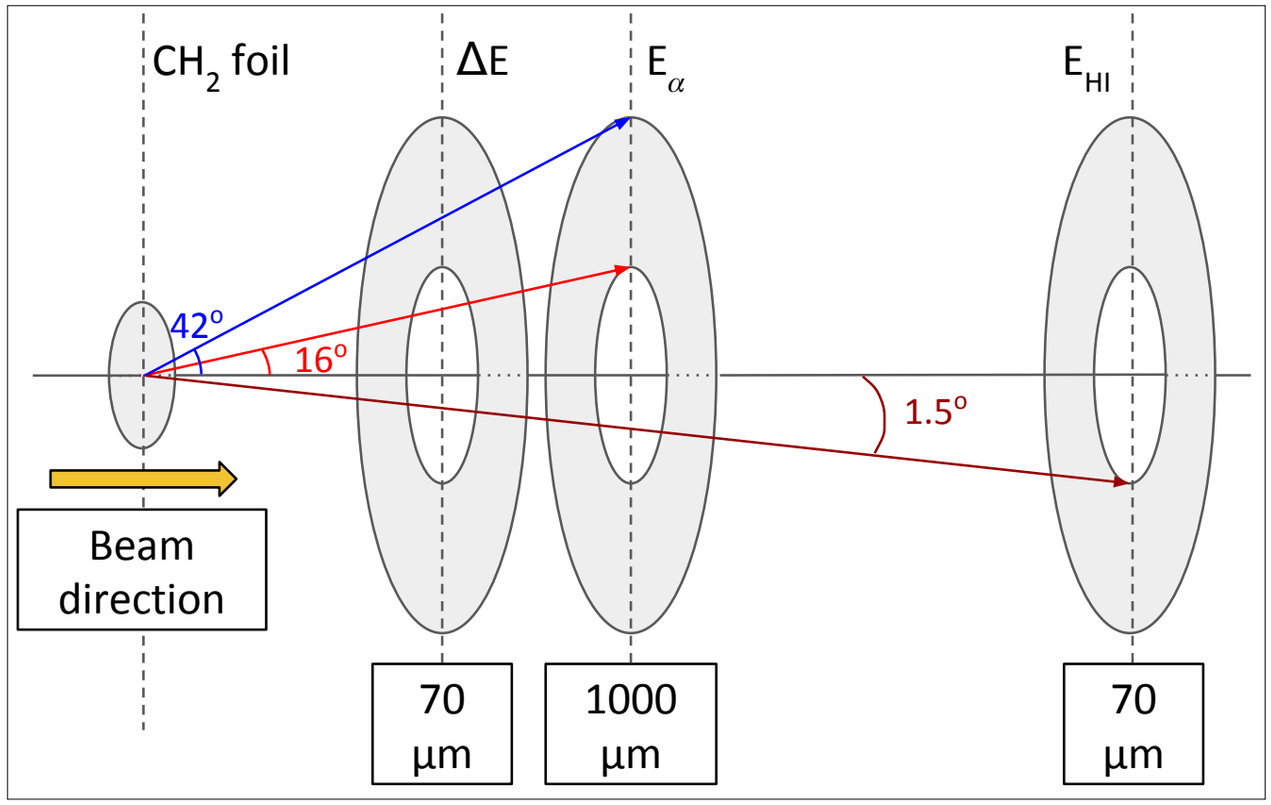

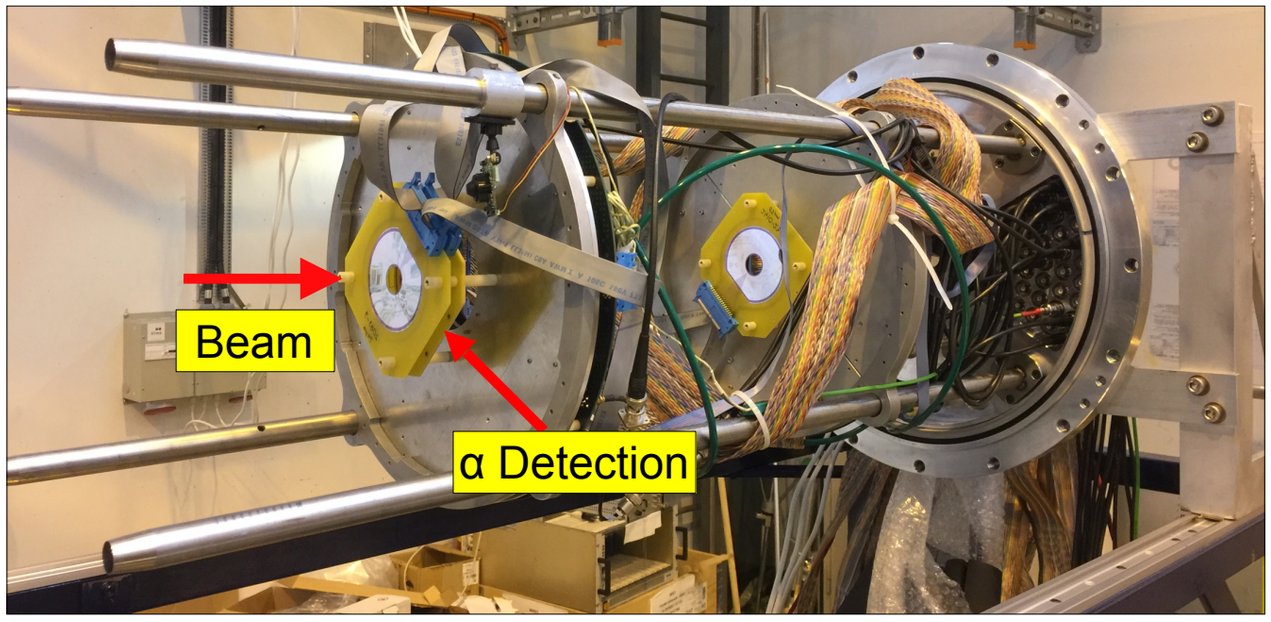

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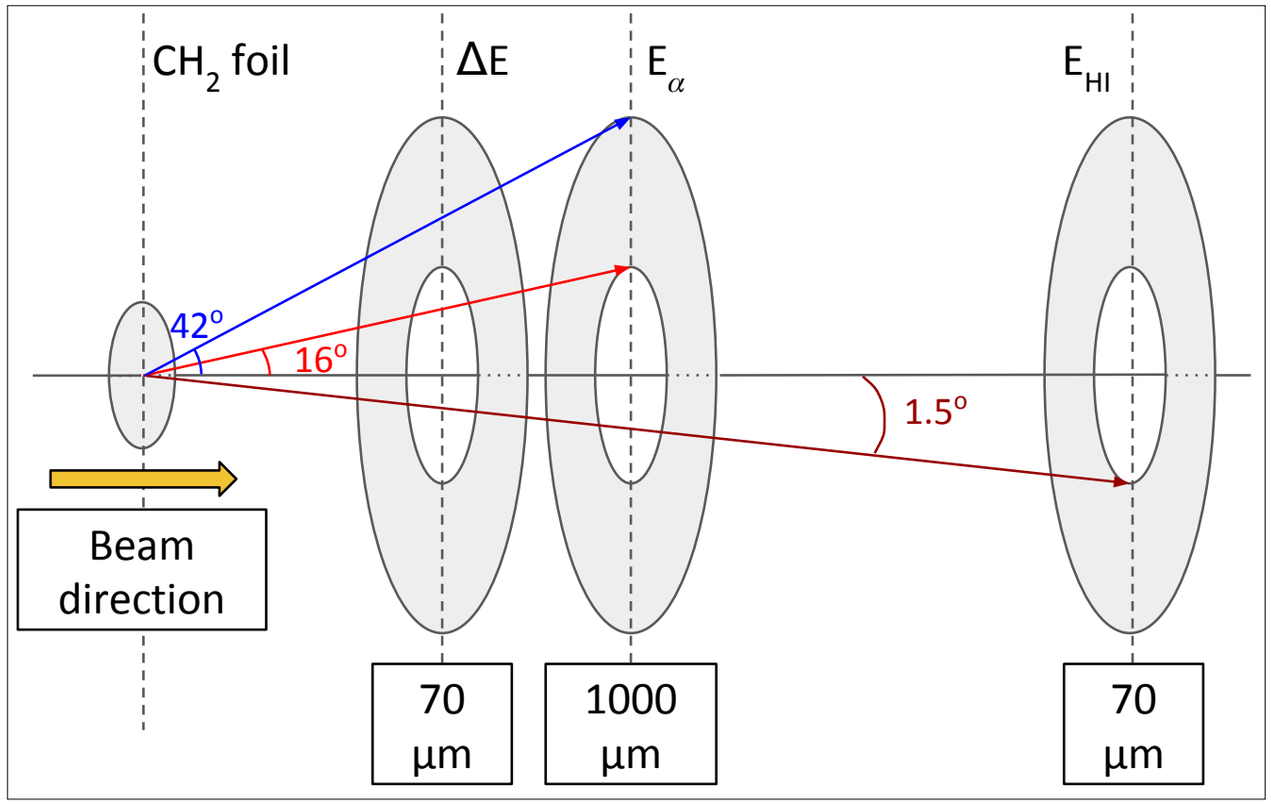
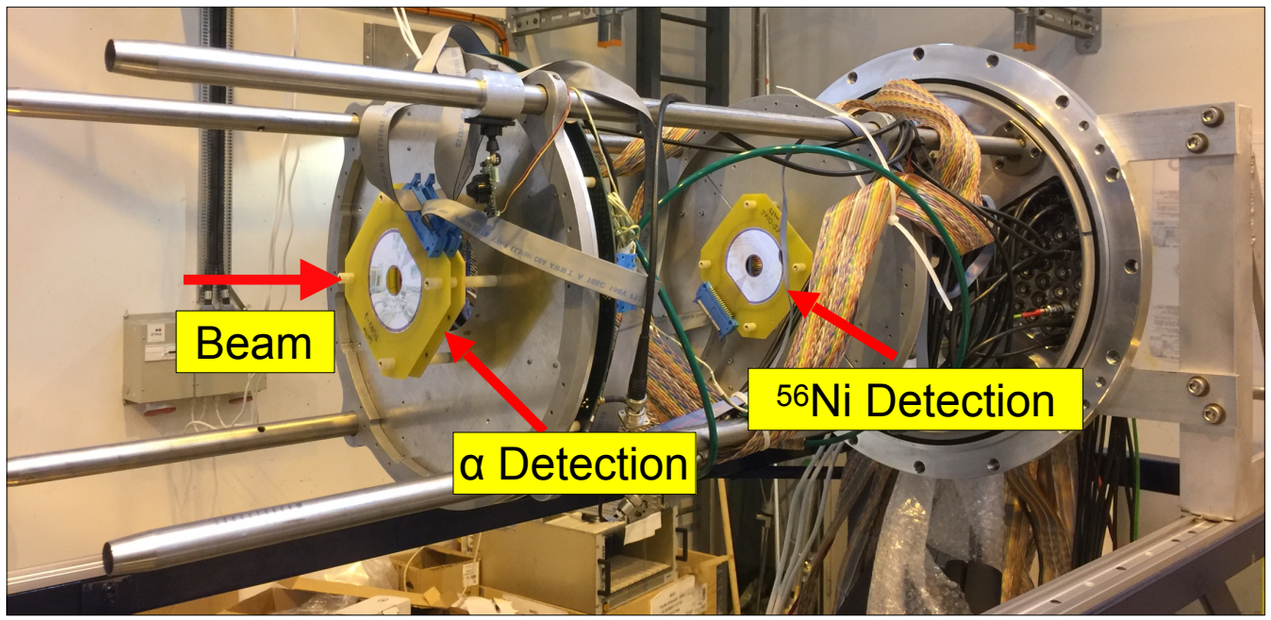




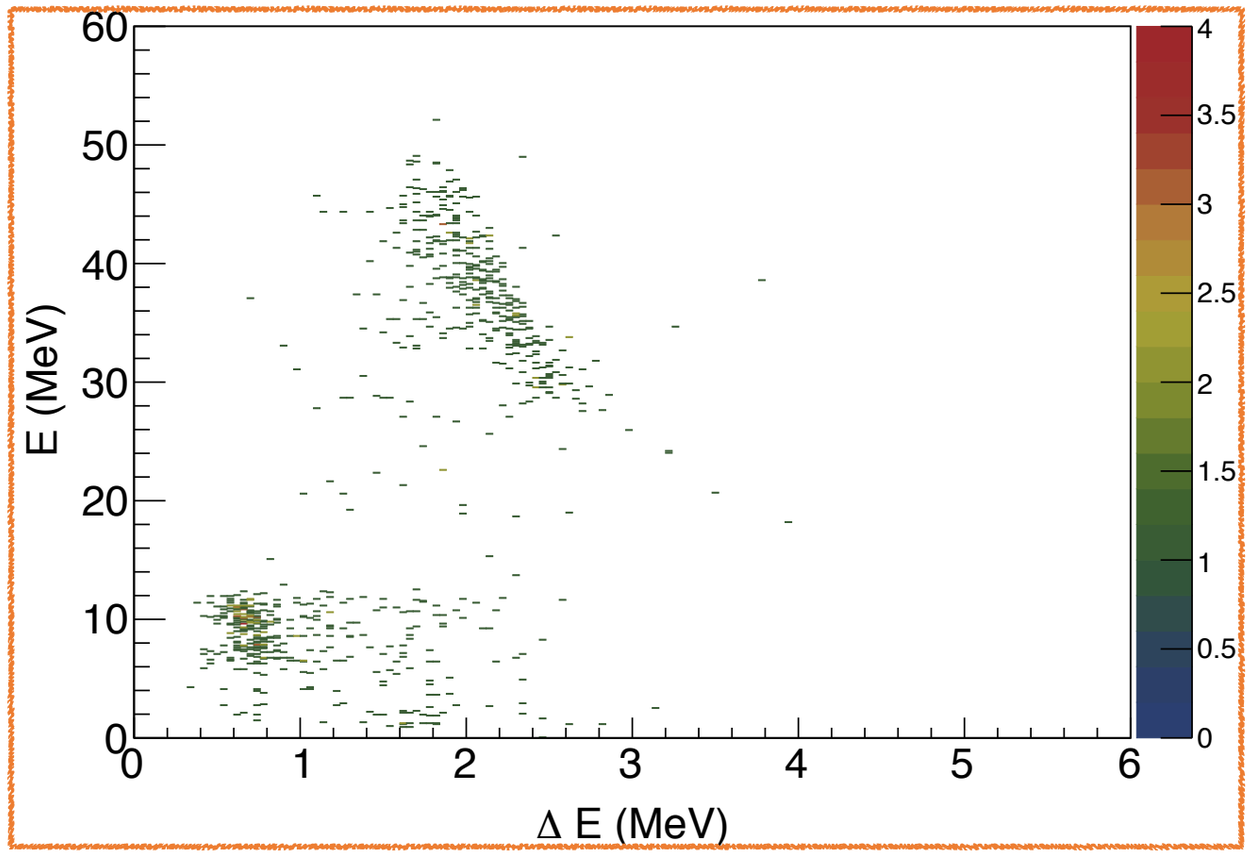
Data Analysis

Extra stuff: ISOLDE's 50 year anniversary video

Data Analysis

Coincidence detection of reaction products (α-particle and ^{56}Ni)

- α-particle detected using the ΔE-E telescope
- The α-particle identification done using the E vs ΔE plot



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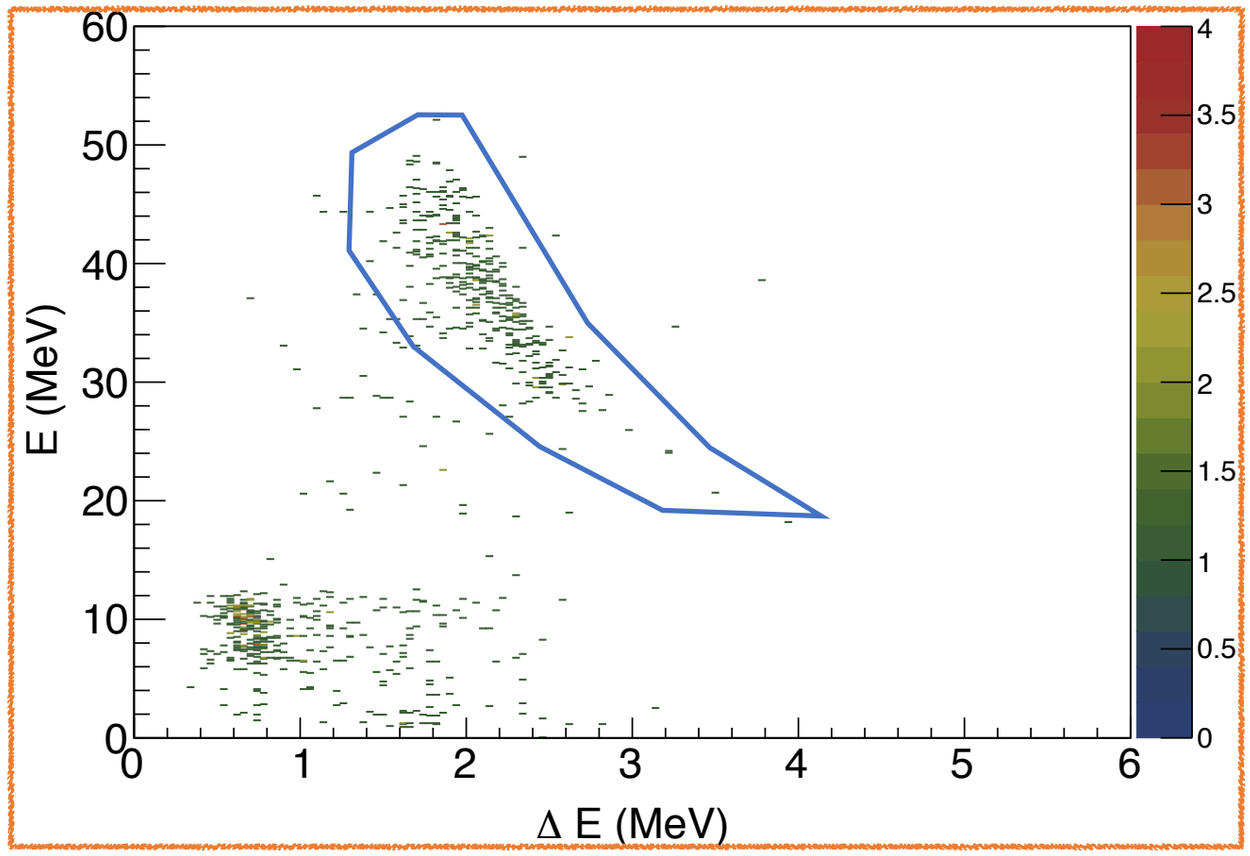

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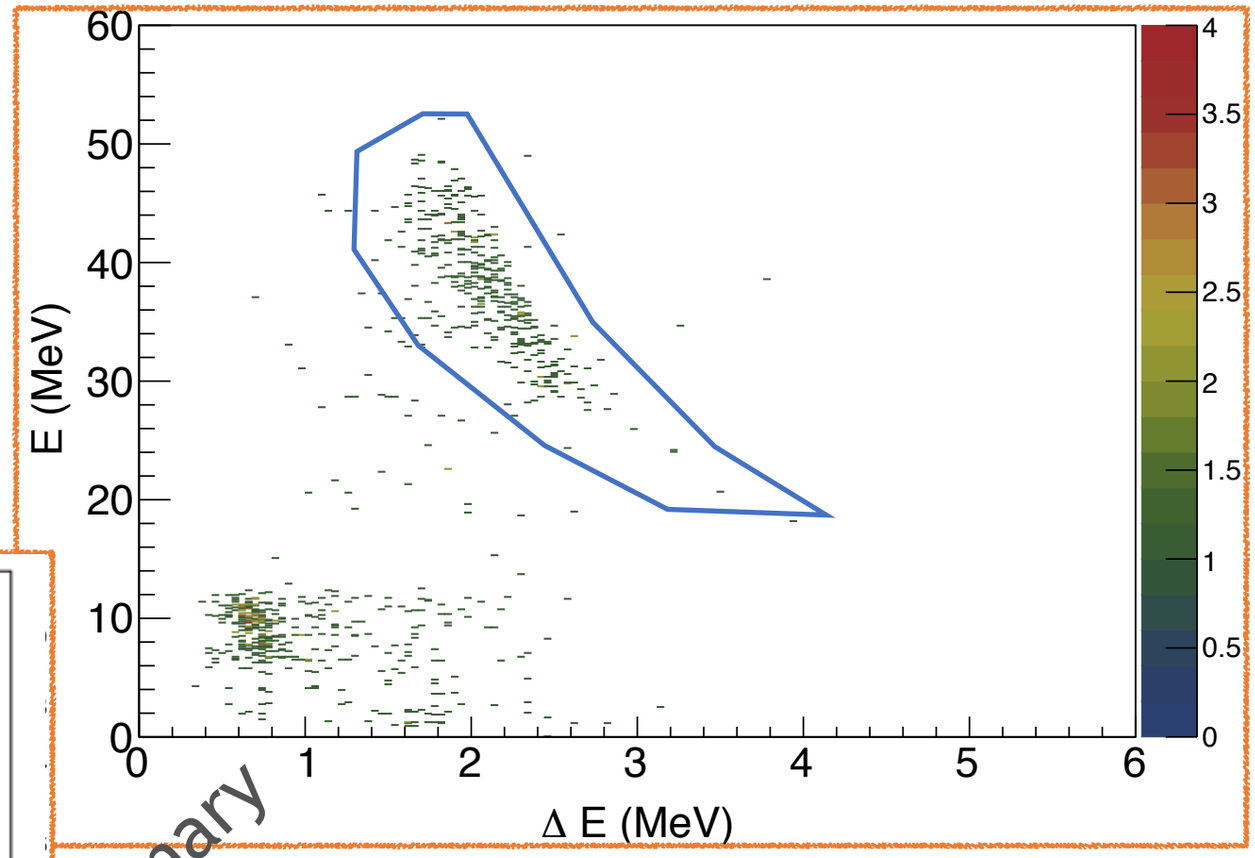

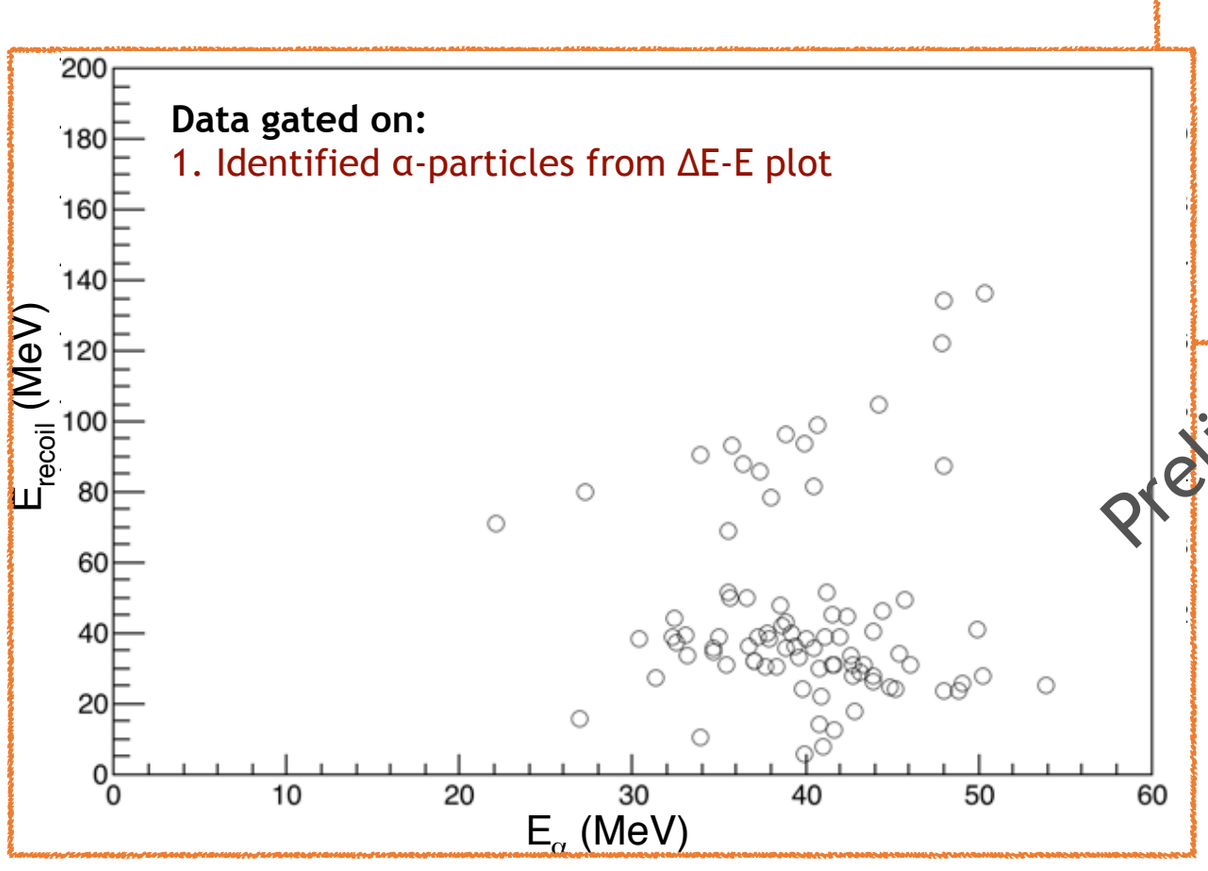

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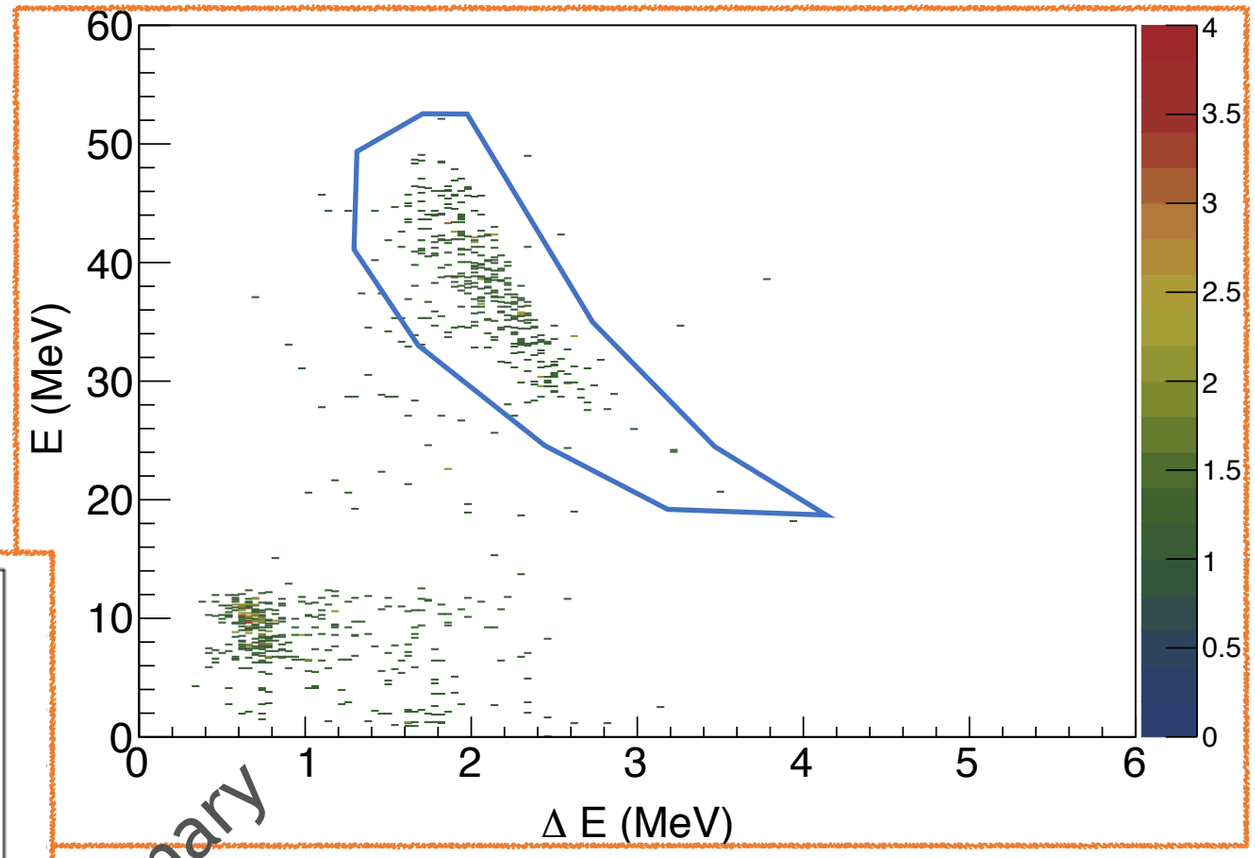

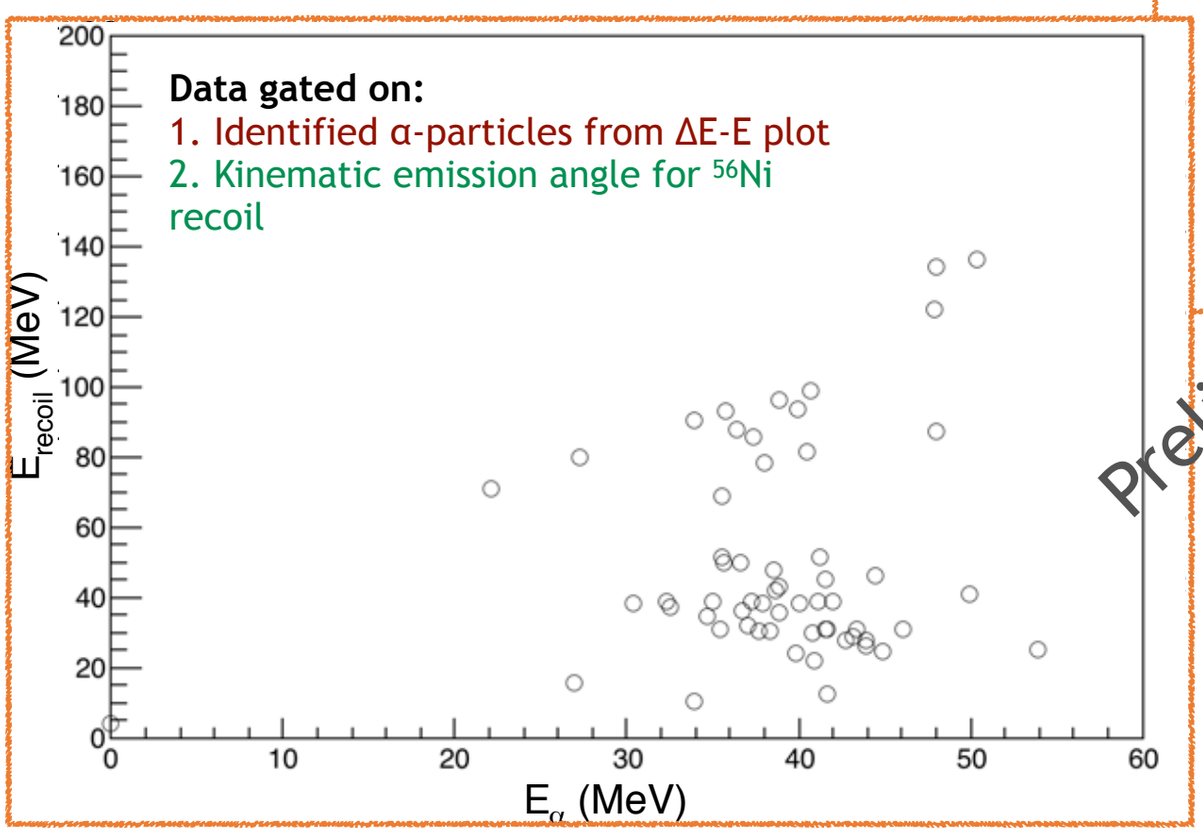

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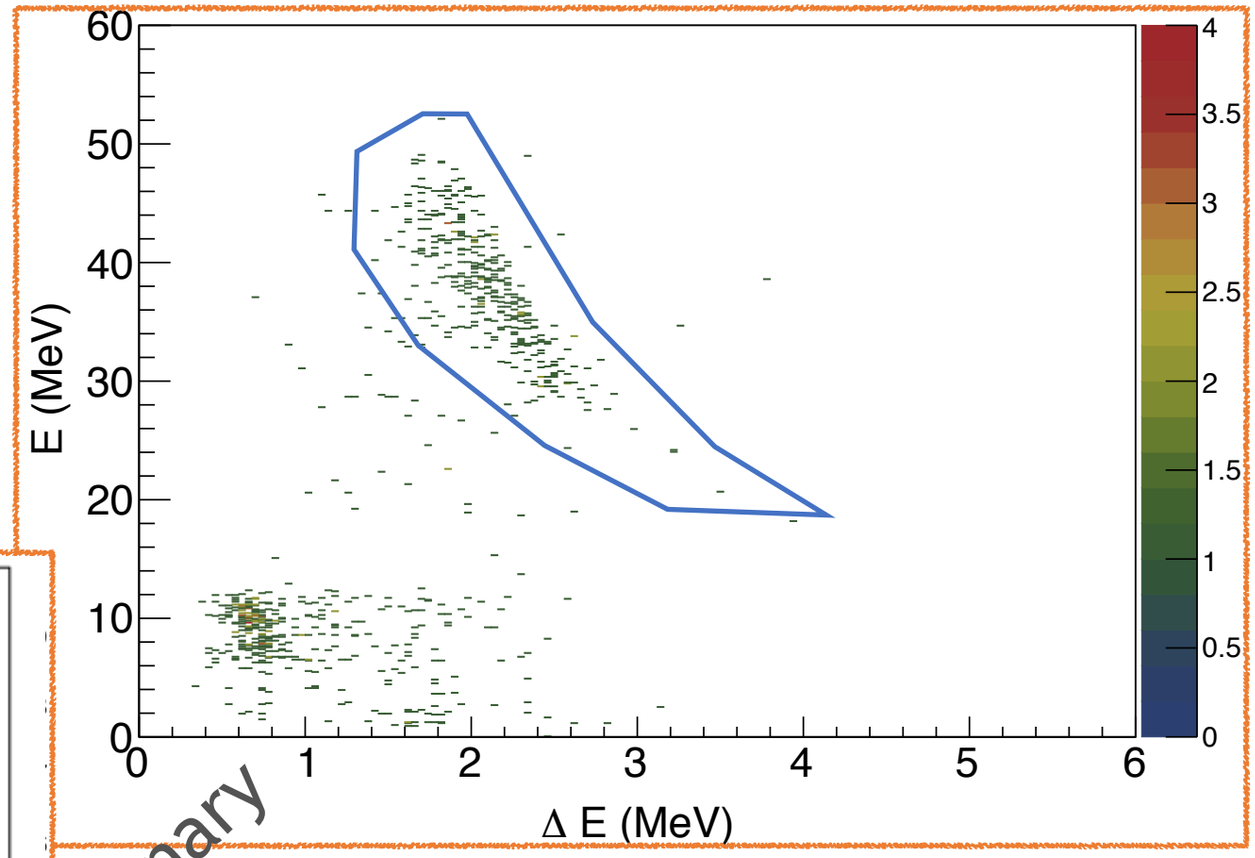

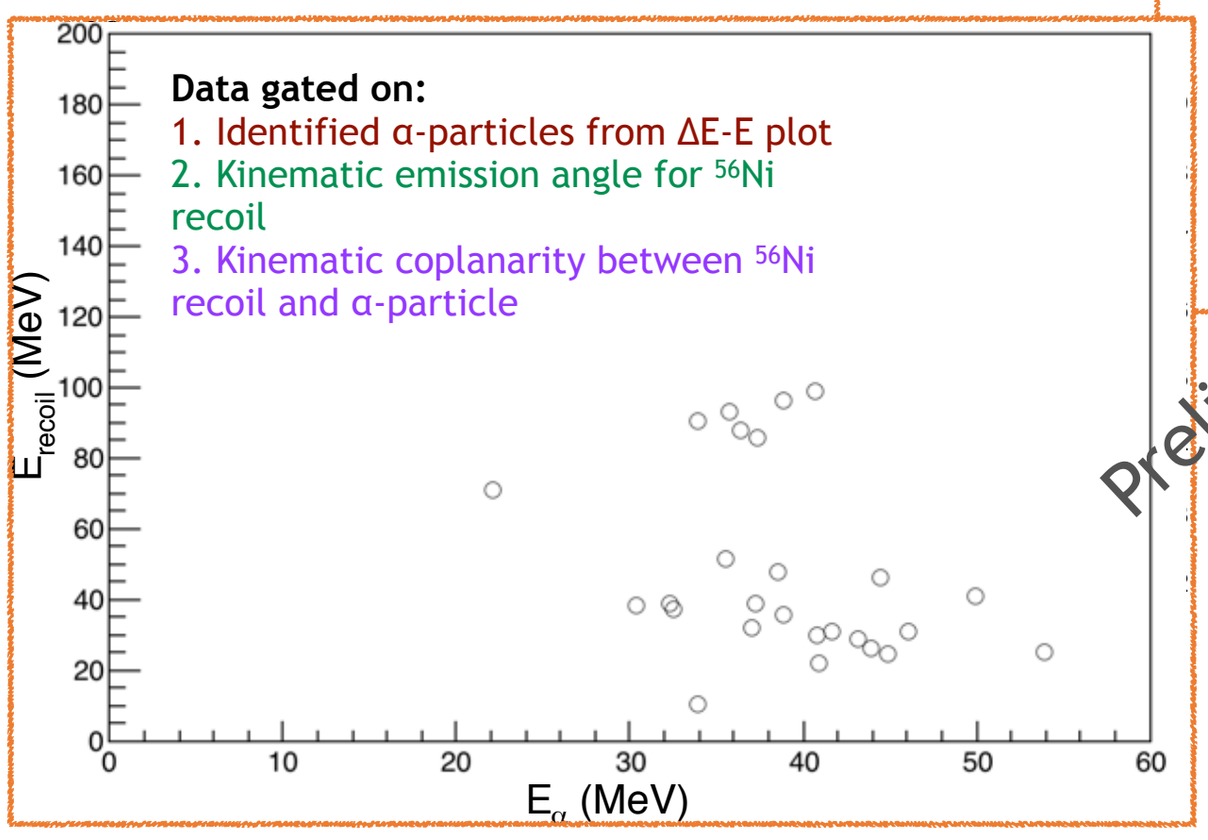

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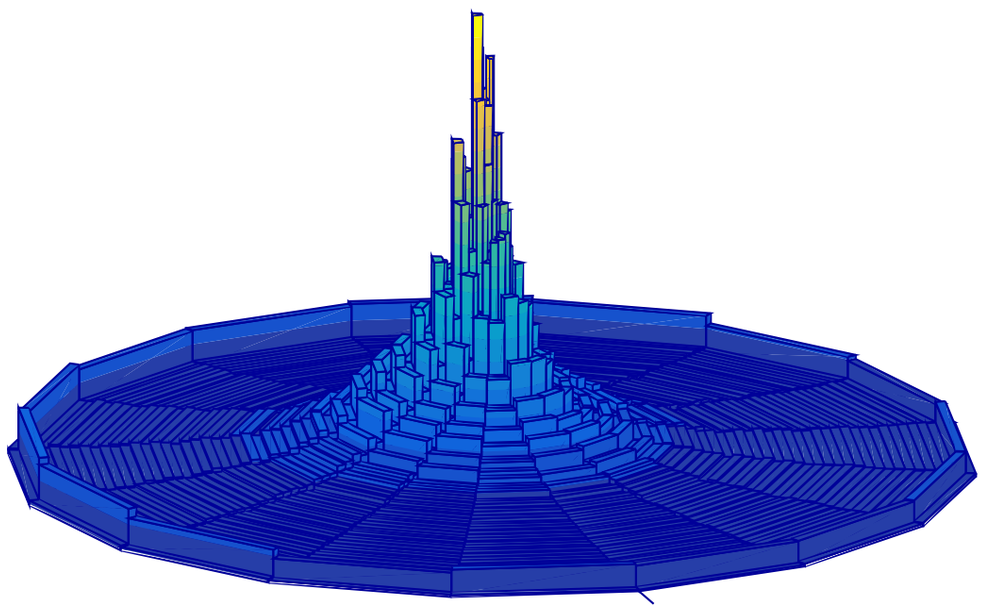

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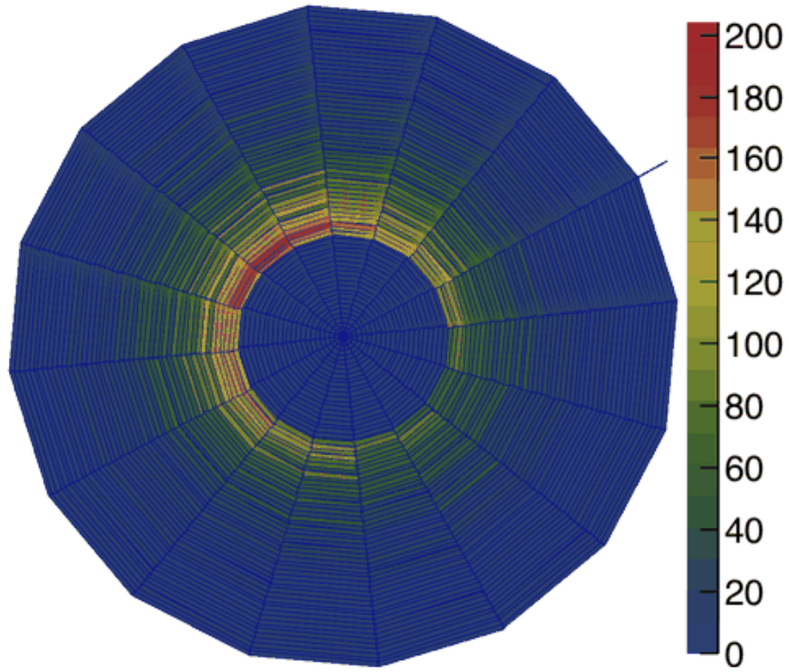

R147, E_beam = 5.0 MeV/u

Calculated beam current: 7.7 pA
FC reading: 2.1 pA

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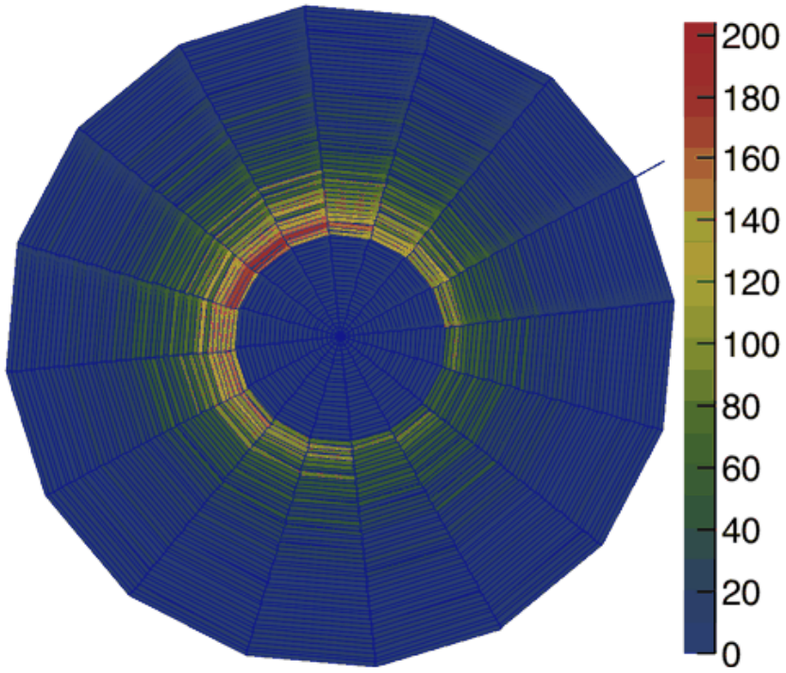
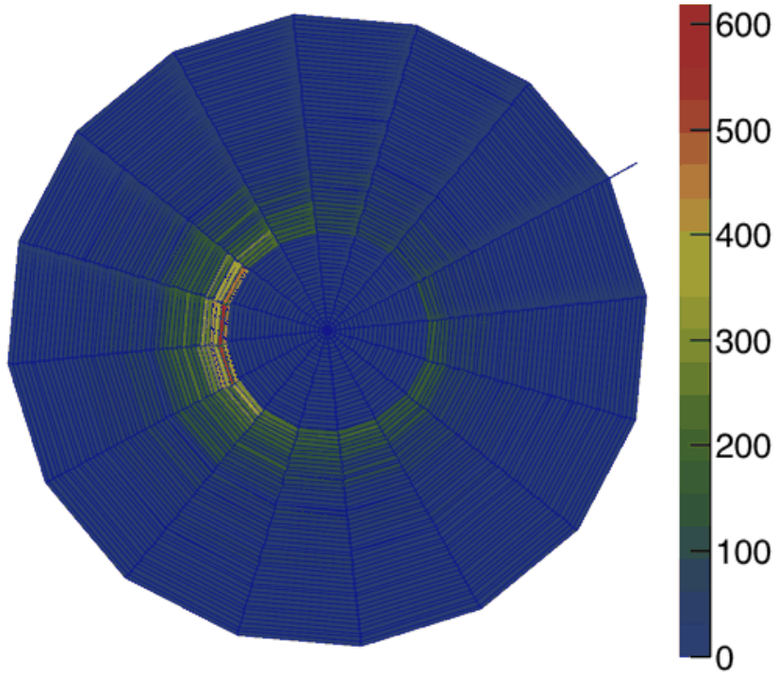
R77, E_beam = 4.7 MeV/u

Calculated beam current: 9.0 pA
FC reading: 1.85 pA





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Summary I: The $^{59}Cu(p,\alpha)^{56}Ni$ measurement

- $^{59}Cu(p,\alpha)^{56}Ni$ reaction cross section has implications on:
  - P-nuclei production in core collapse supernovae
  - X-ray burst light curve
  - X-ray burst ash compositions
- No experimental data available on direct measurement
- First direct measurement performed by University of Edinburgh group at HIE-ISOLDE, CERN
- Data analysis - ‘work in progress’

THE UNIVERSITY of EDINBURGH

ISOLDE CERN erc European Research Council

Thank you for your attention!