The E1 and E2 capture amplitudes in $^{12}C(\alpha, \gamma)^{16}O$ around the 2.42 MeV resonance

Kajol Chakraborty
(on behalf of ERNA collaboration)
Post-Doctoral Researcher
Università degli Studi della Campania "Luigi Vanvitelli"
and INFN Naples

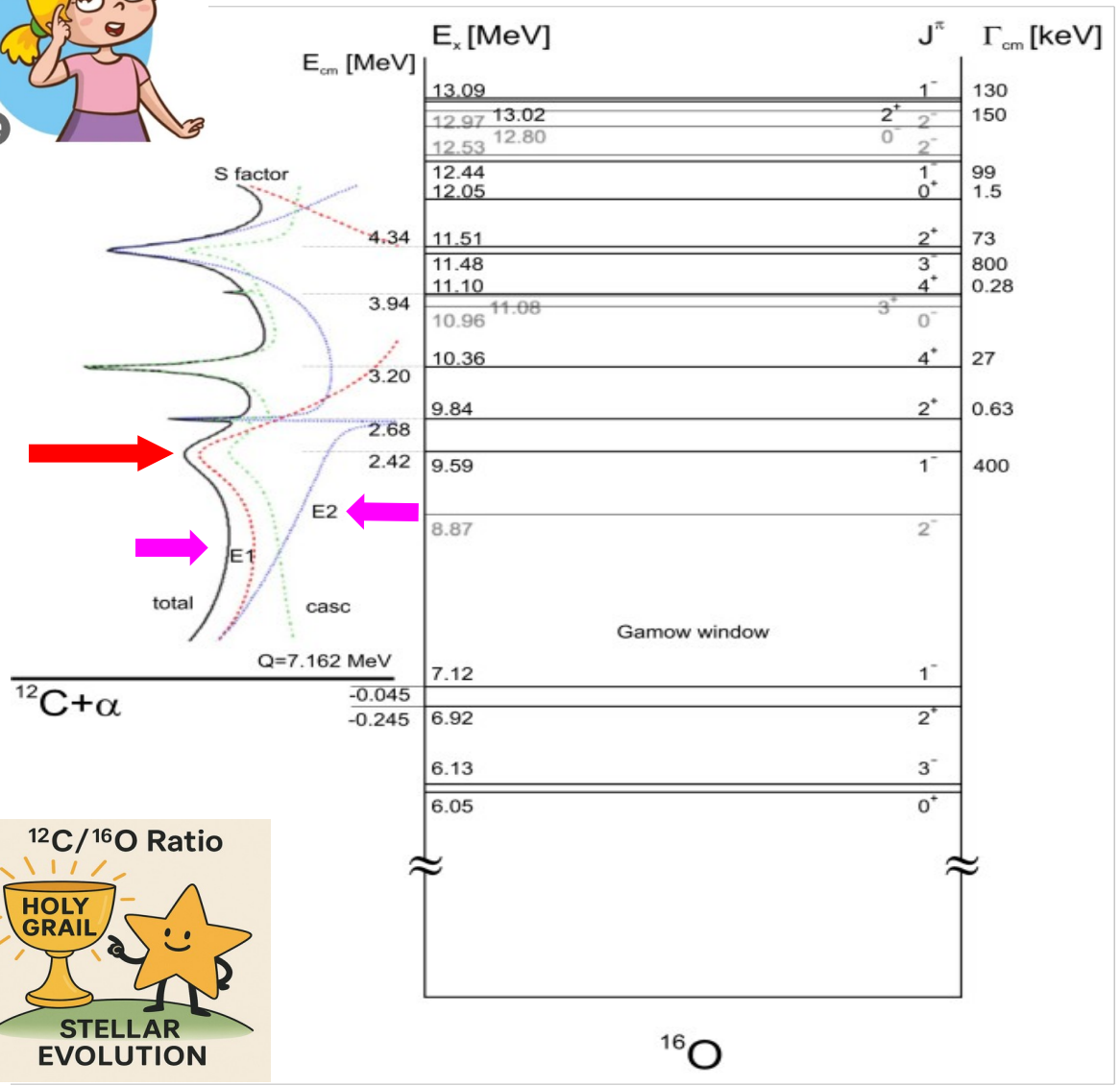
ERNA
European Recoil separator for Nuclear Astrophysics

INFN
Istituto Nazionale di Fisica Nucleare

Università
degli Studi
della Campania
Luigi Vanvitelli
Dipartimento di Matematica e Fisica

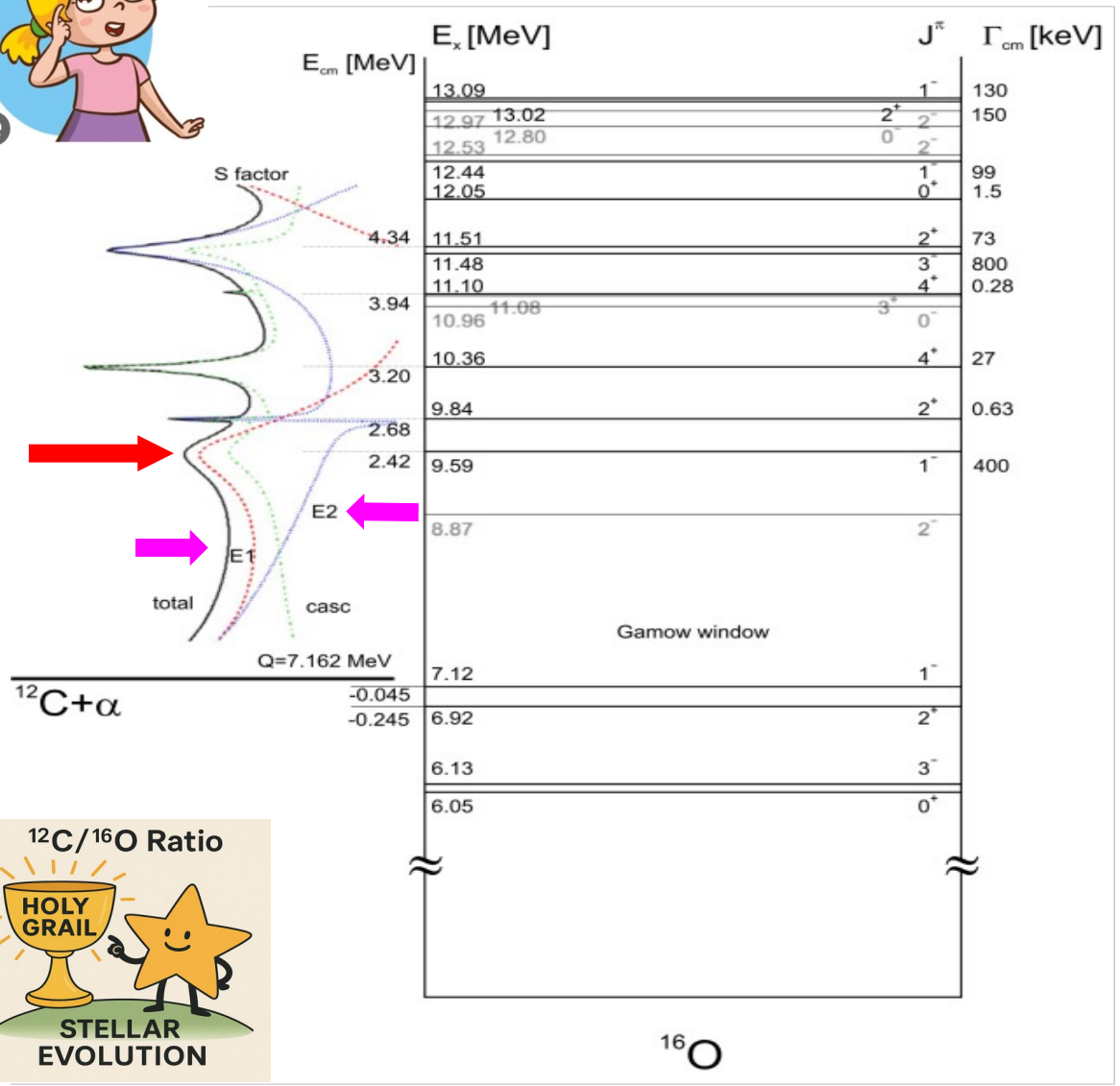
E1 and E2 capture amplitude around 2.42 MeV Resonance

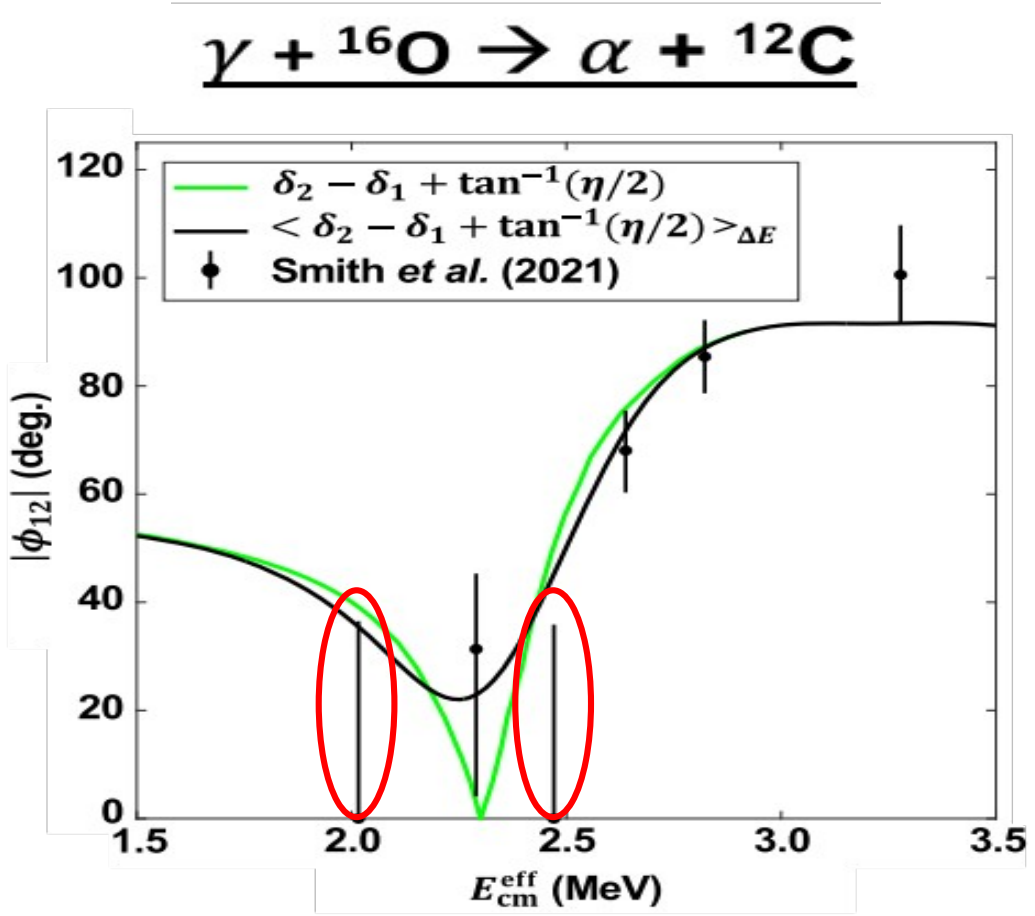
Reaction Rate of $^{12}C(\alpha,\gamma)^{16}O$



E1 and E2 capture amplitude around 2.42 MeV Resonance

Reaction Rate of $^{12}C(\alpha,\gamma)^{16}O$ Photo-dissociation at the HIγS facility, TUNL





The measured E1-E2 mixing phase angles by Smith *et al.*

R. Smith *et al.*, Nature Communications 12(2021) 5920

Our Approach: Direct Measurements of $^{12}C(\alpha,\gamma)^{16}O$ using ERNA

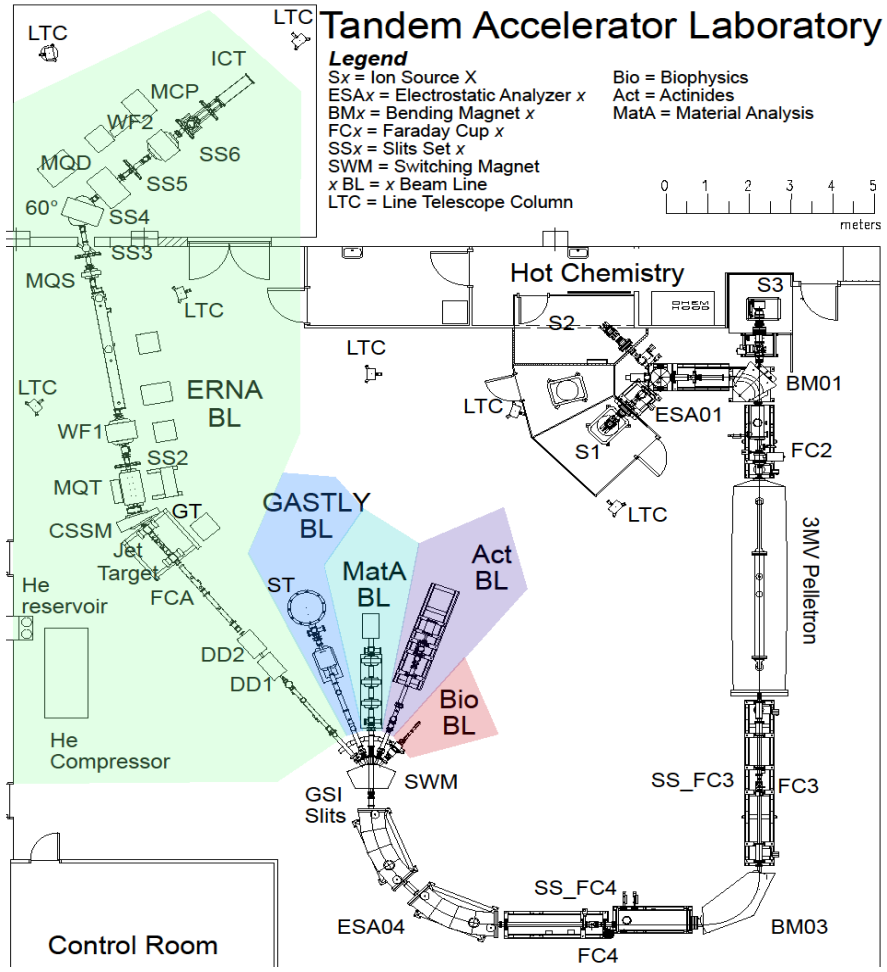
European Recoil Separator for Nuclear Astrophysics (ERNA) @ Center for Isotopic Research on the Cultural and Environmental heritage (CIRCE) Facility, University of Campania "Luigi Vanvitelli", Caserta, Italy

Inverse kinematics reaction with ^{12}C beam

Supersonic He Jet Target

Our Approach: Direct Measurements of $^{12}C(\alpha,\gamma)^{16}O$ using ERNA

European Recoil Separator for Nuclear Astrophysics (ERNA) @ Center for Isotopic Research on the Cultural and Environmental heritage (CIRCE) Facility, University of Campania "Luigi Vanvitelli", Caserta, Italy

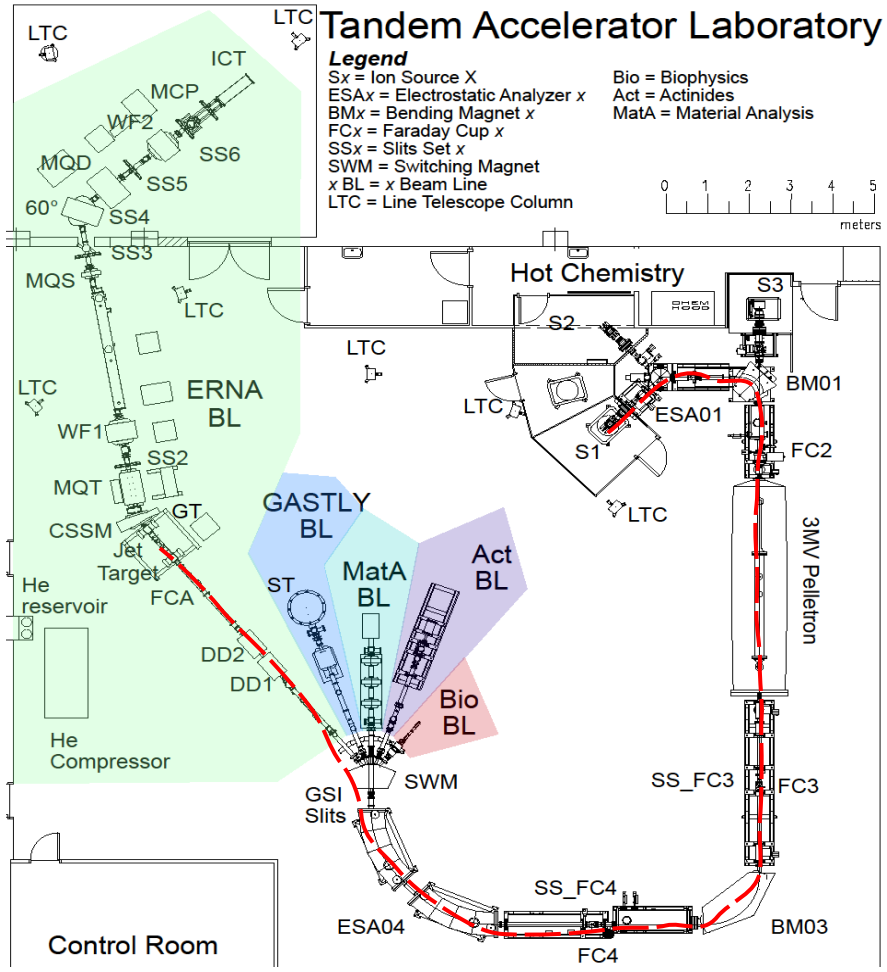


Inverse kinematics reaction with ^{12}C beam

Supersonic He Jet Target

Our Approach: Direct Measurements of $^{12}C(\alpha,\gamma)^{16}O$ using ERNA

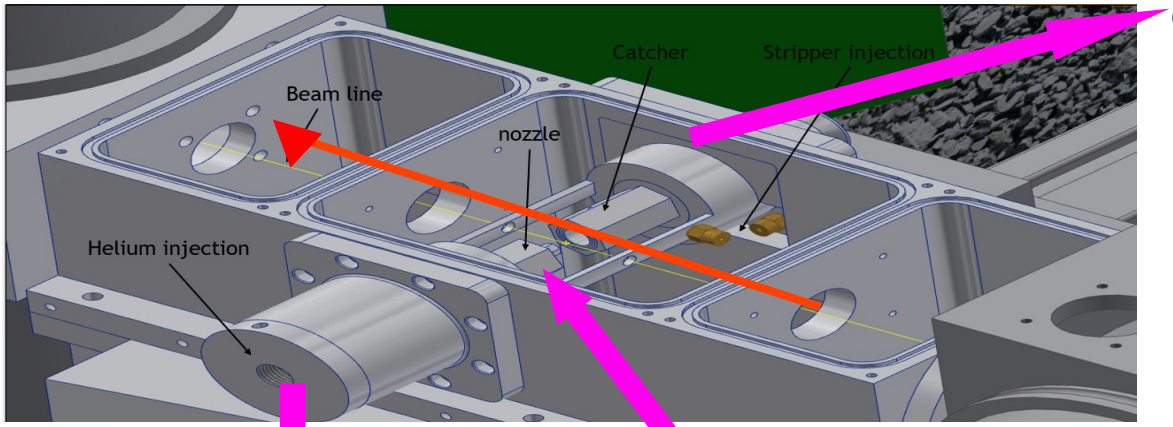
European Recoil Separator for Nuclear Astrophysics (ERNA) @ Center for Isotopic Research on the Cultural and Environmental heritage (CIRCE) Facility, University of Campania "Luigi Vanvitelli", Caserta, Italy



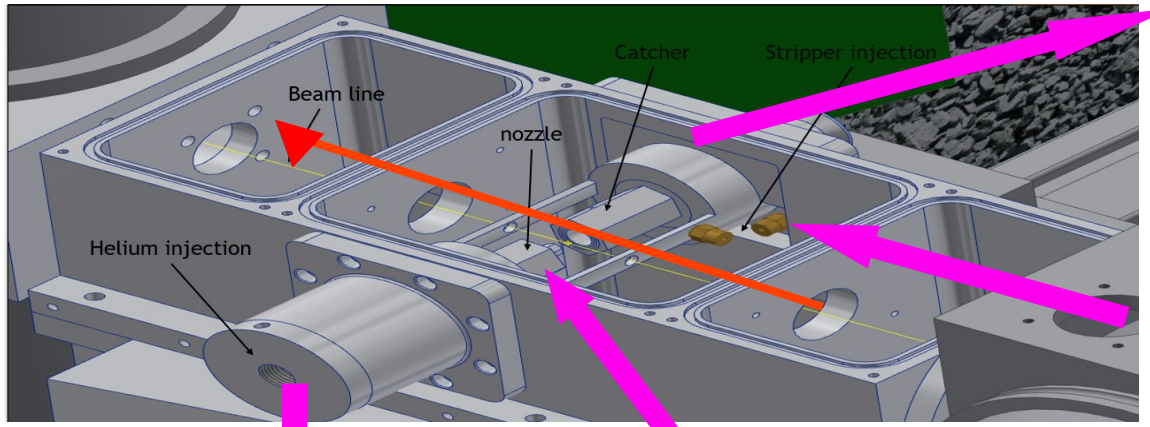
Inverse kinematics reaction with ^{12}C beam

Supersonic He Jet Target

SUPERSONIC JET TARGET



SUPERSONIC JET TARGET



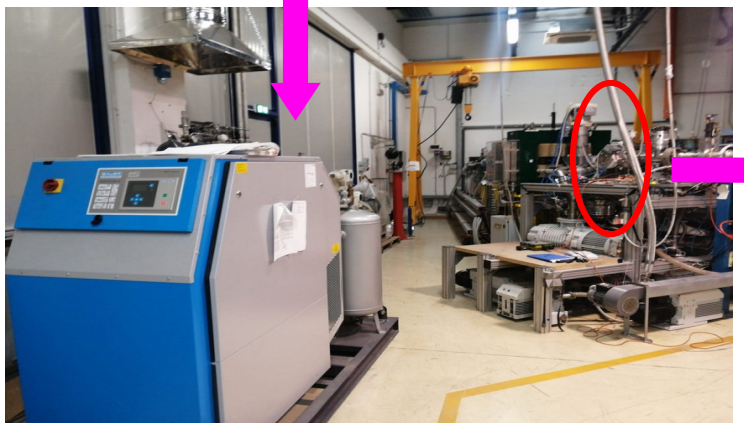
Catcher

Stripper For charge state equilibration

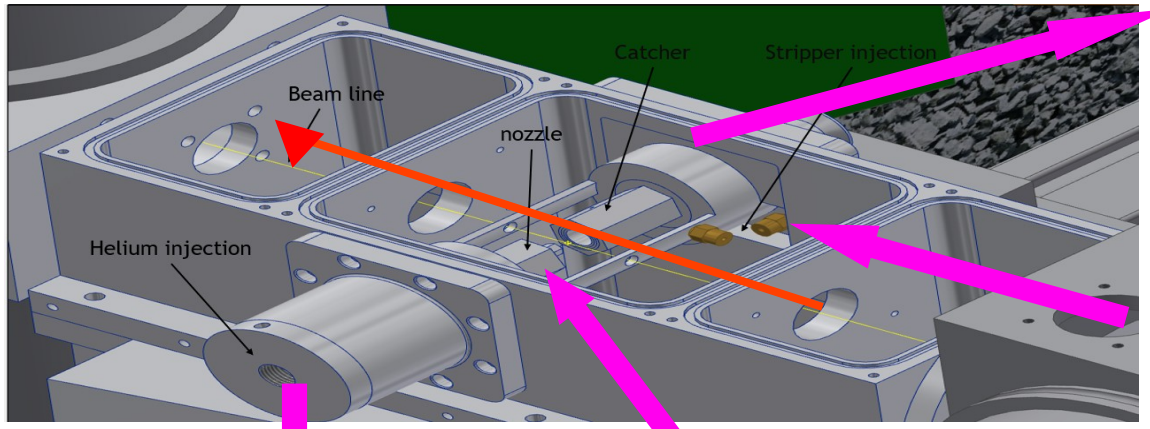
He Injection

Jet Nozzle

Jet Compressor



SUPERSONIC JET TARGET



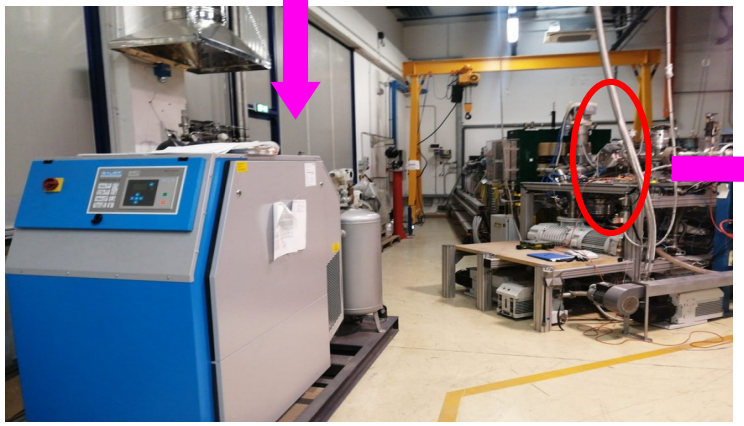
Catcher

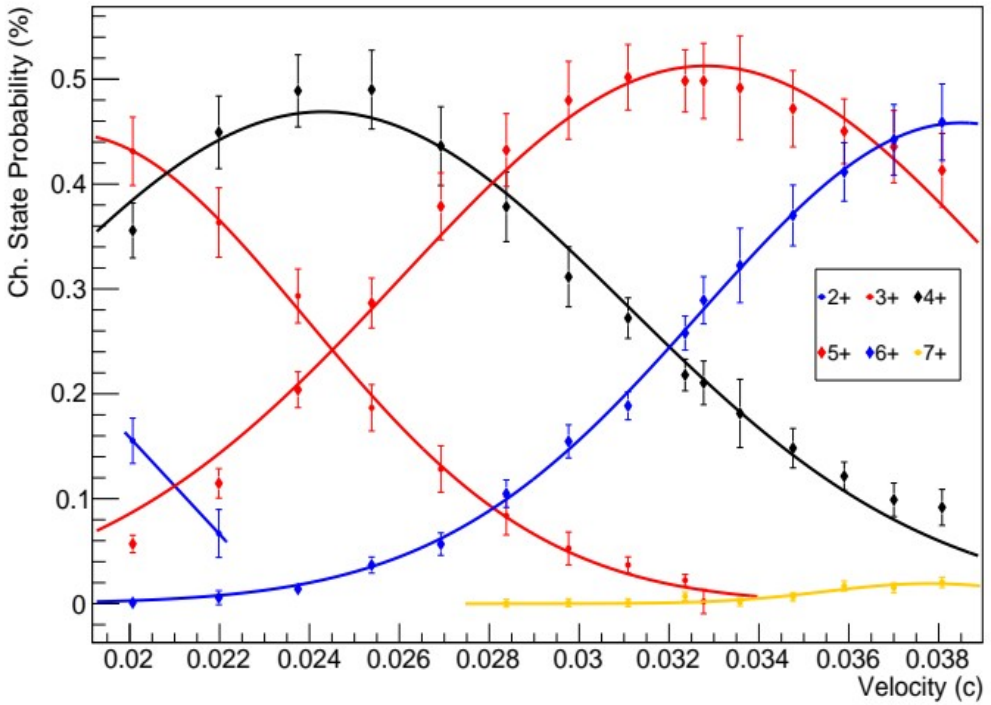
Stripper For charge state equilibration

He Injection

Jet Nozzle

Jet Compressor





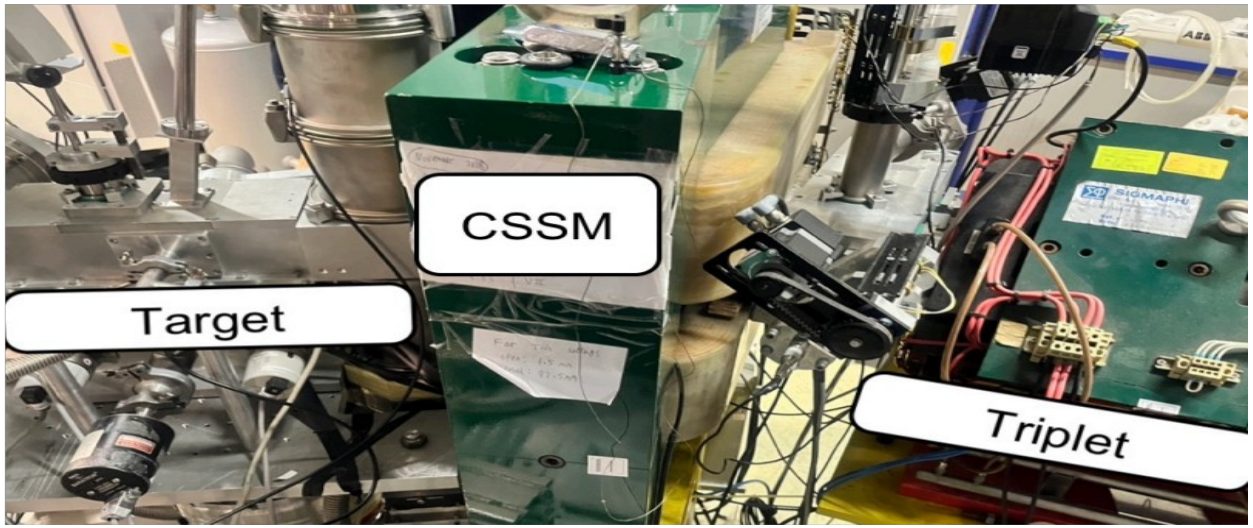
Equilibrium charge state distributions as a function of the ^{16}O ions velocity in unit of the speed of light (c).

Jet $(1.3 \pm 0.1) \cdot 10^{18}$ atoms/cm^2

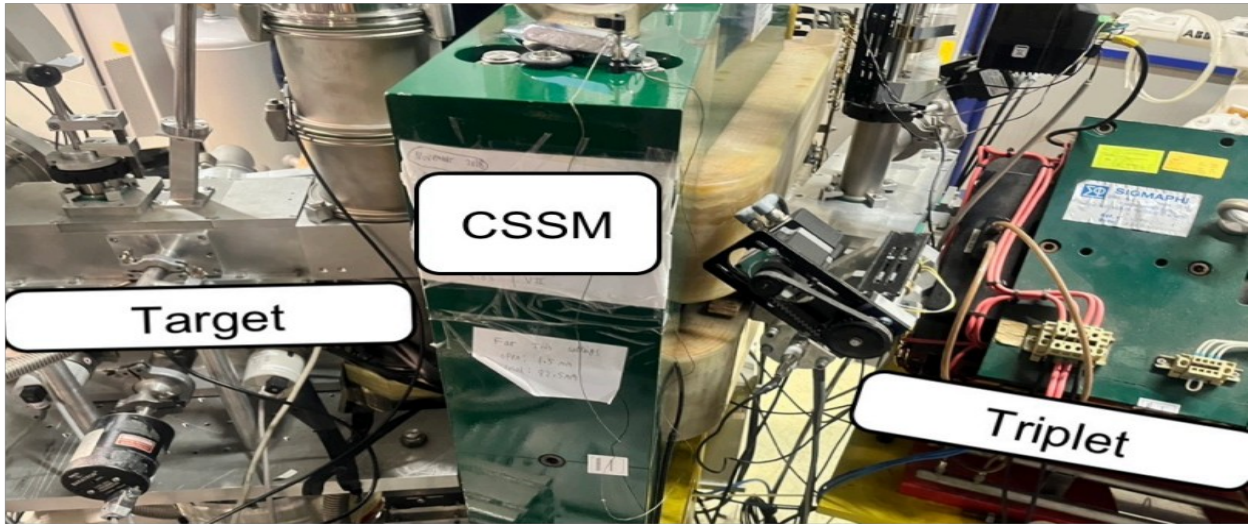
Stripper $(2.7 \pm 0.9) \cdot 10^{16}$ atoms/cm^2

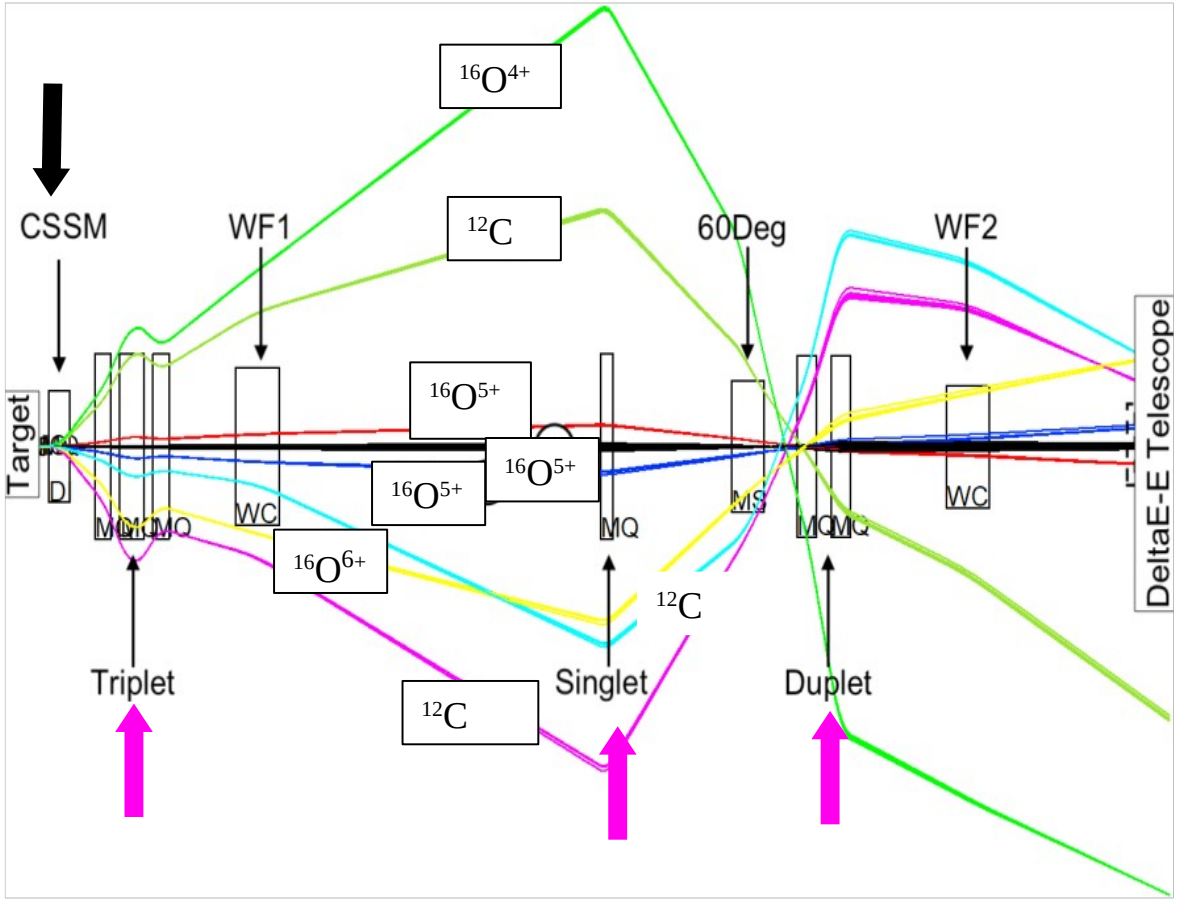
ERNA RMS FACILITY

ERNA RMS FACILITY

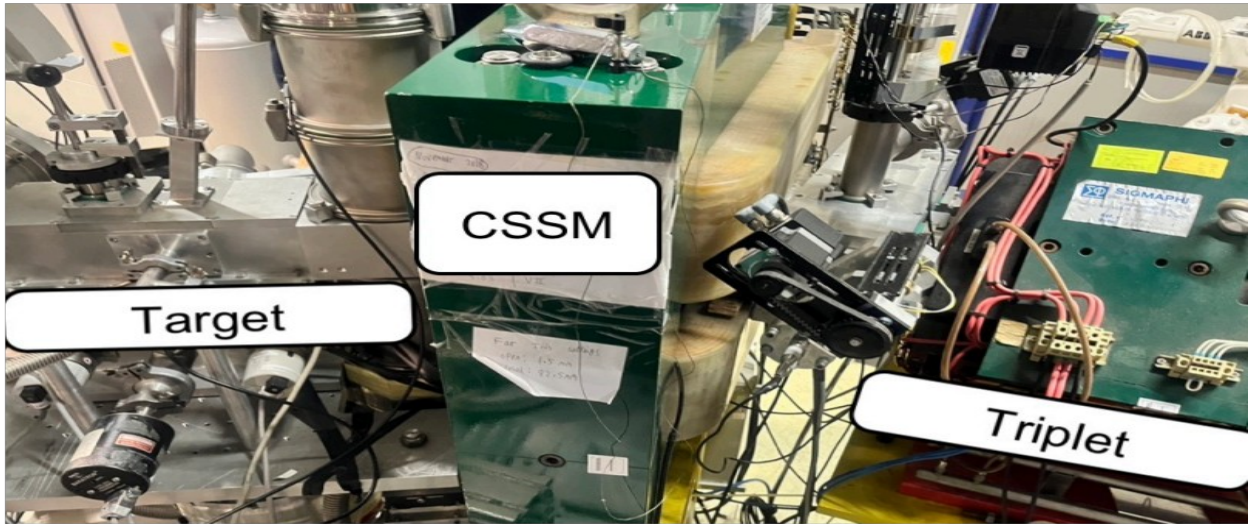


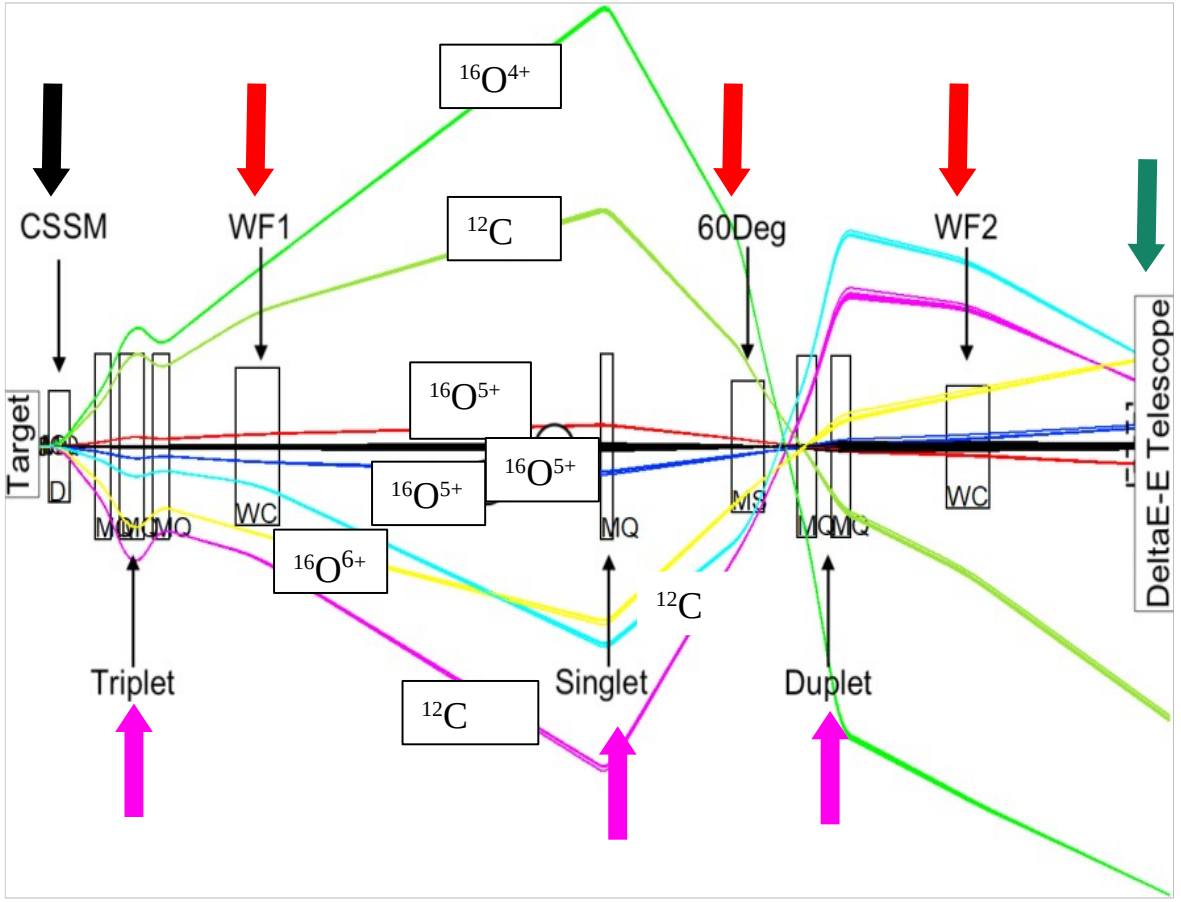
ERNA RMS FACILITY





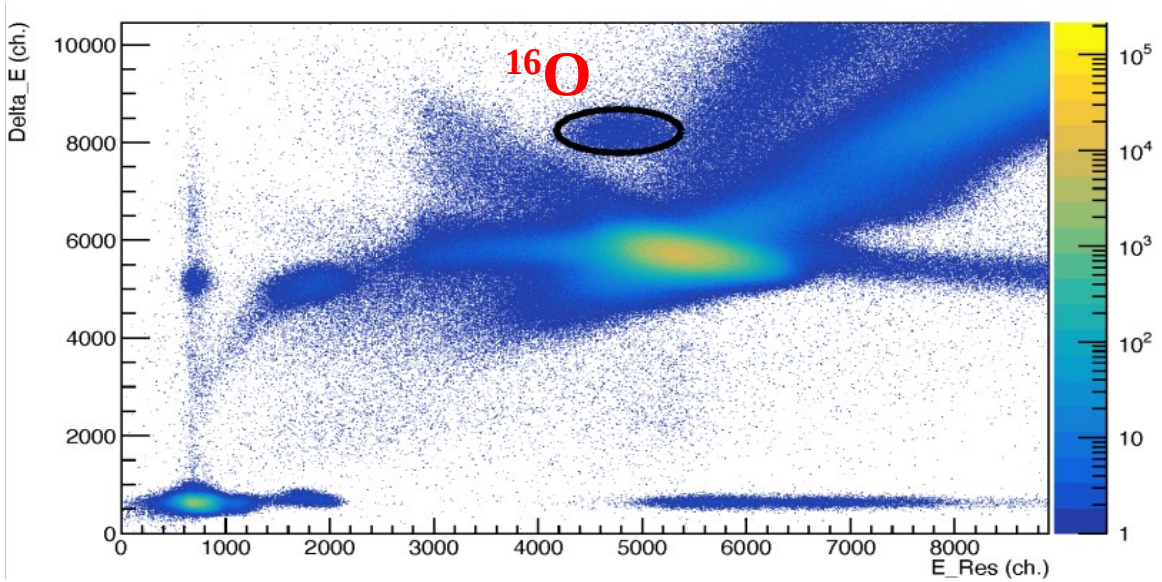
ERNA RMS FACILITY



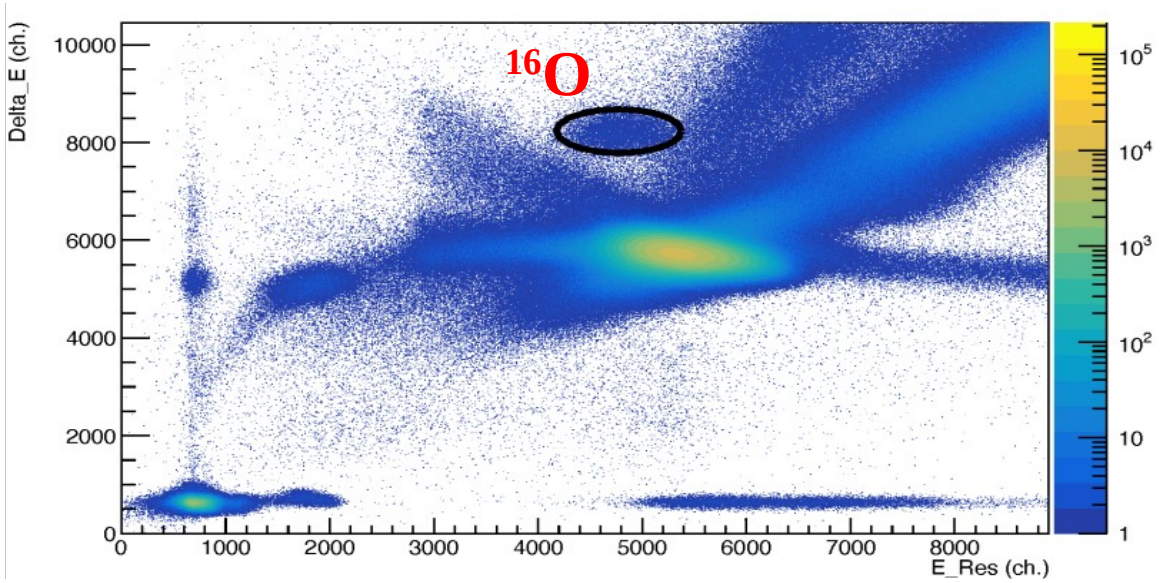


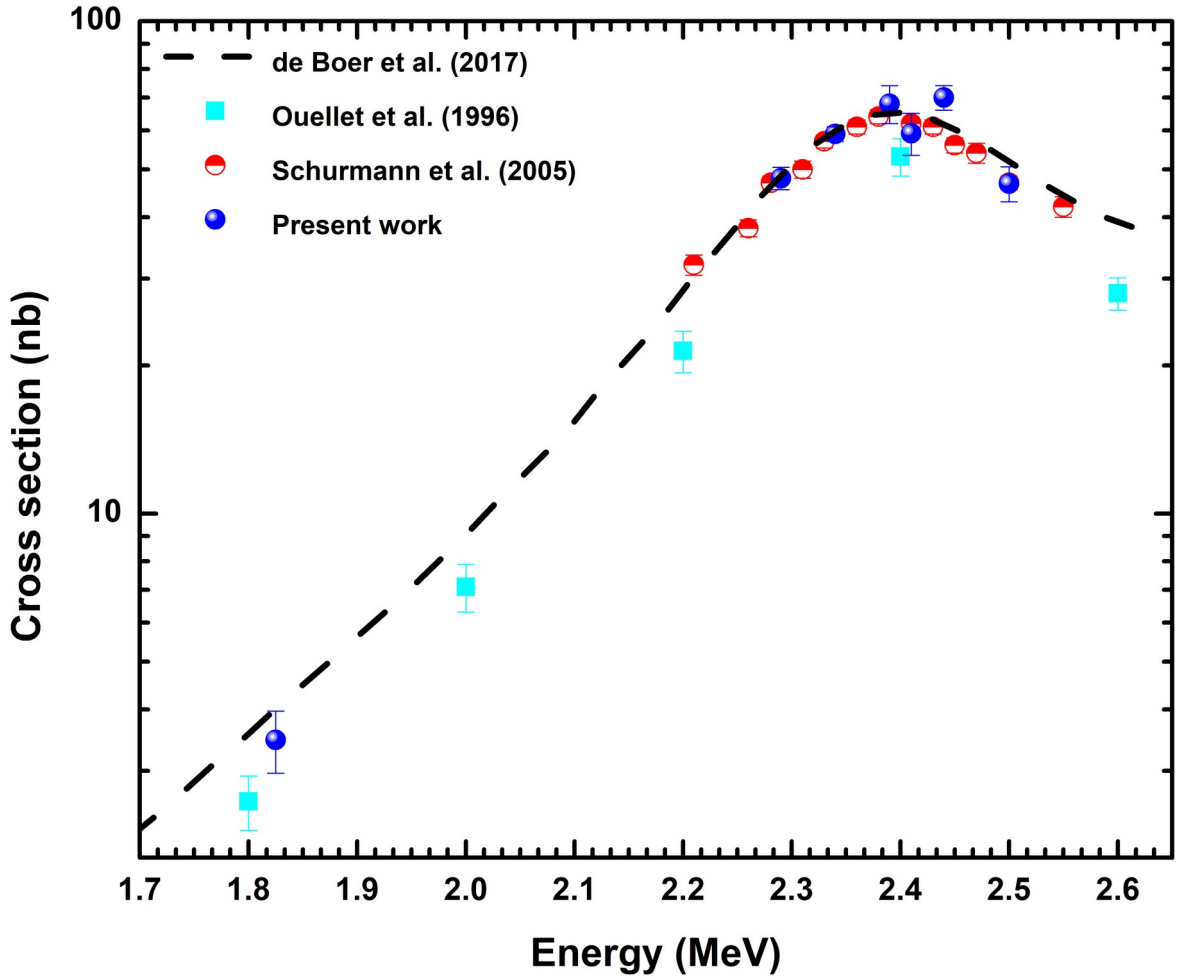
Successful tuning of the spectrometer for background free measurements down to E_{cm} = 1 MeV

Total cross-section measurements



Total cross-section measurements



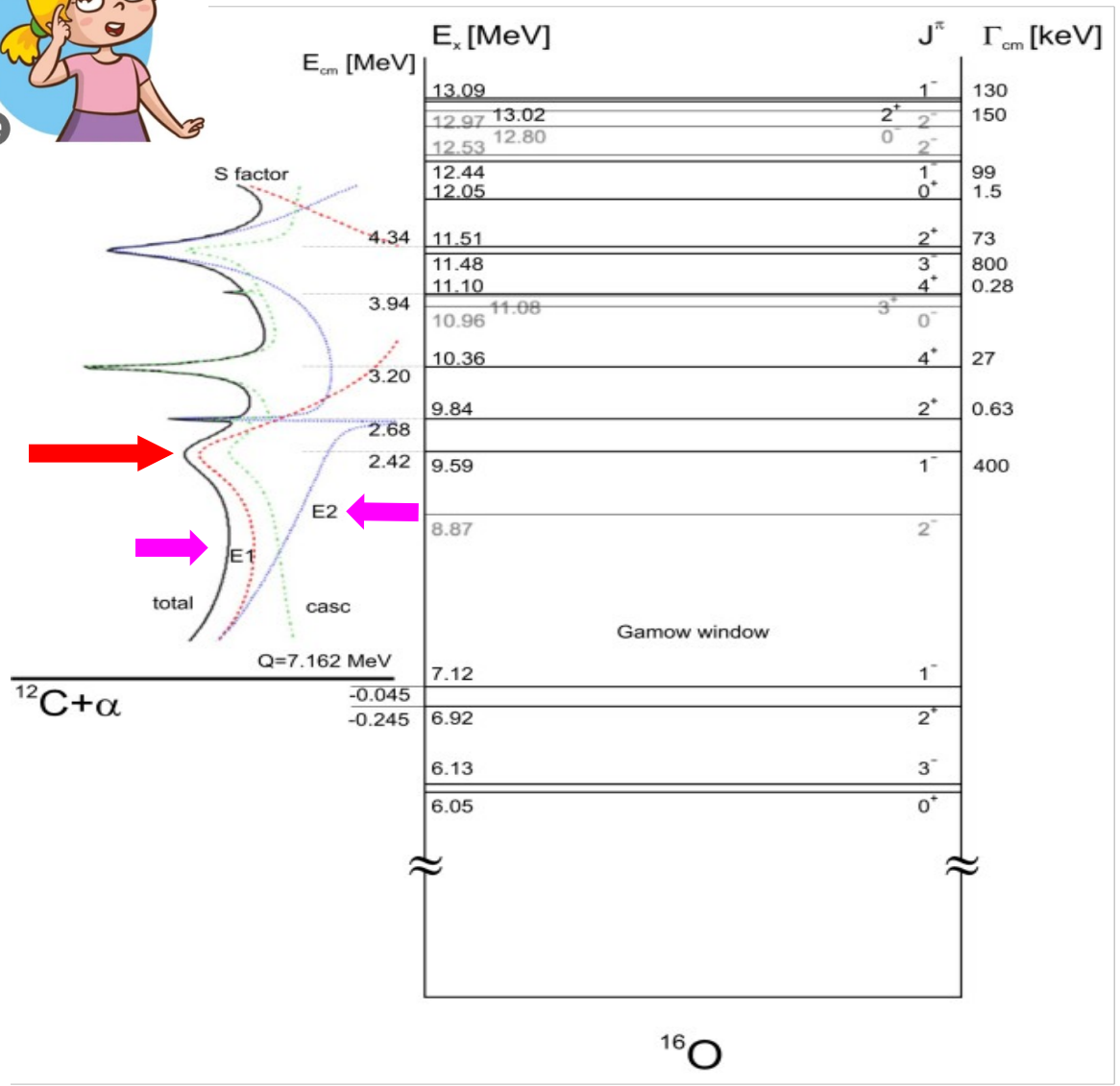


Total Cross-section measurements down to E_{cm} = 1.8 MeV

Ph.D. Thesis (C. Santonastaso), University of Campania “Luigi Vanvitelli” (2022)

E1 and E2 capture amplitude around 2.42 MeV Resonance

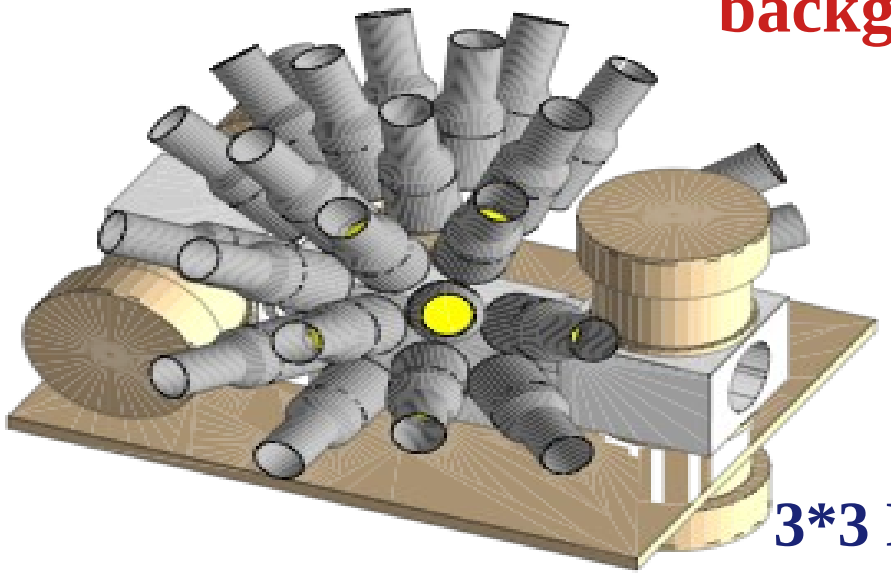
Reaction Rate of $^{12}C(\alpha,\gamma)^{16}O$



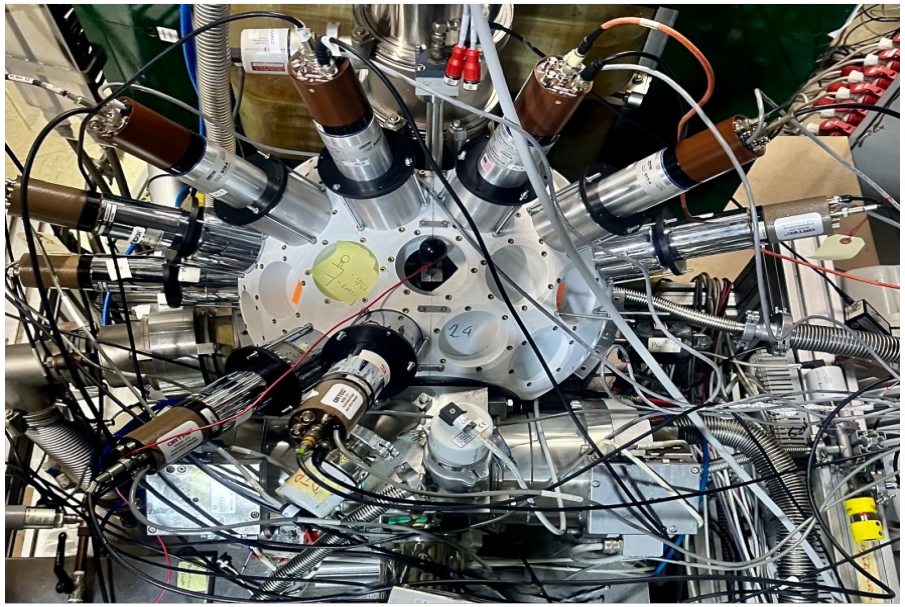
$$
\begin{aligned}
&4\pi\left(\frac{d\sigma}{d\Omega}\right)(E,\theta_\gamma)\\
&=\sigma_{E1}(E)[1-Q_2P_2(\cos\theta_\gamma)]\\
&\quad+\sigma_{E2}(E)\left[1+\frac{5}{7}Q_2P_2(\cos\theta_\gamma)-\frac{12}{7}Q_4P_4(\cos\theta_\gamma)\right]\\
&\quad+6\cos\phi(E)\sqrt{\frac{\sigma_{E1}(E)\sigma_{E2}(E)}{5}}[Q_1P_1(\cos\theta_\gamma)\\
&\quad-Q_3P_3(\cos\theta_\gamma)],
\end{aligned}
$$

INITIAL CAMPAIGNS WITH GAMMA ARRAY

Aim: Setup coincidence between the recoils and the gamma-array to achieve a background free gamma spectrum

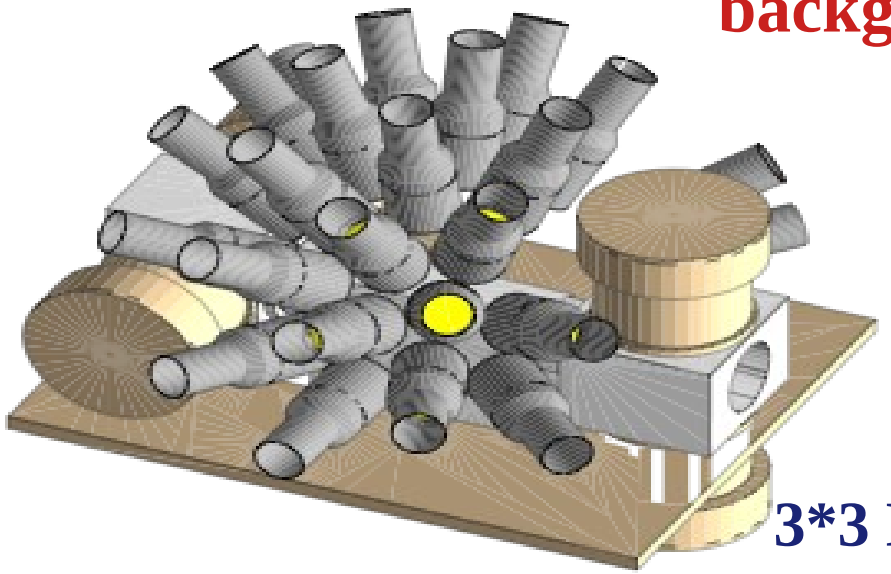


3*3 NaI Scintillators

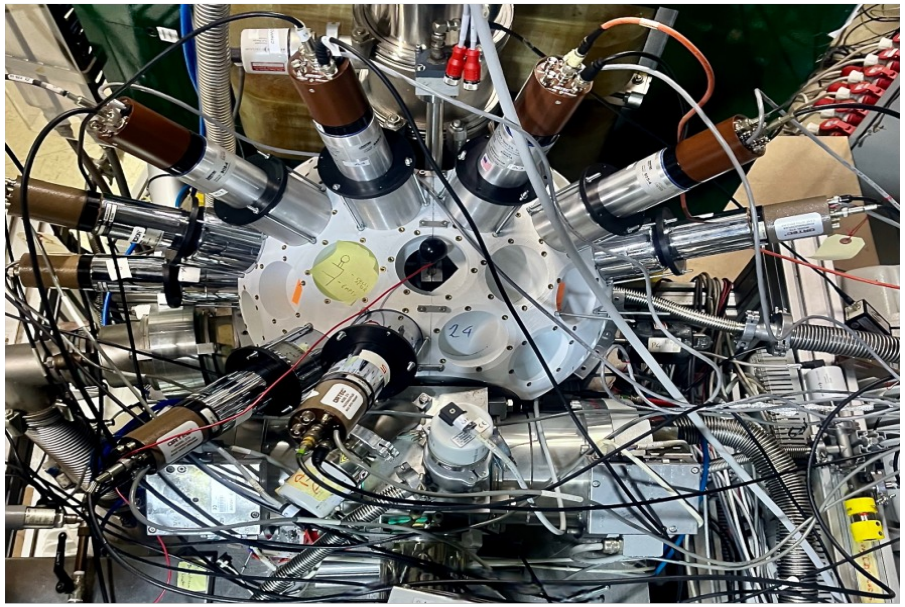


INITIAL CAMPAIGNS WITH GAMMA ARRAY

Aim: Setup coincidence between the recoils and the gamma-array to achieve a background free gamma spectrum



3*3 NaI Scintillators

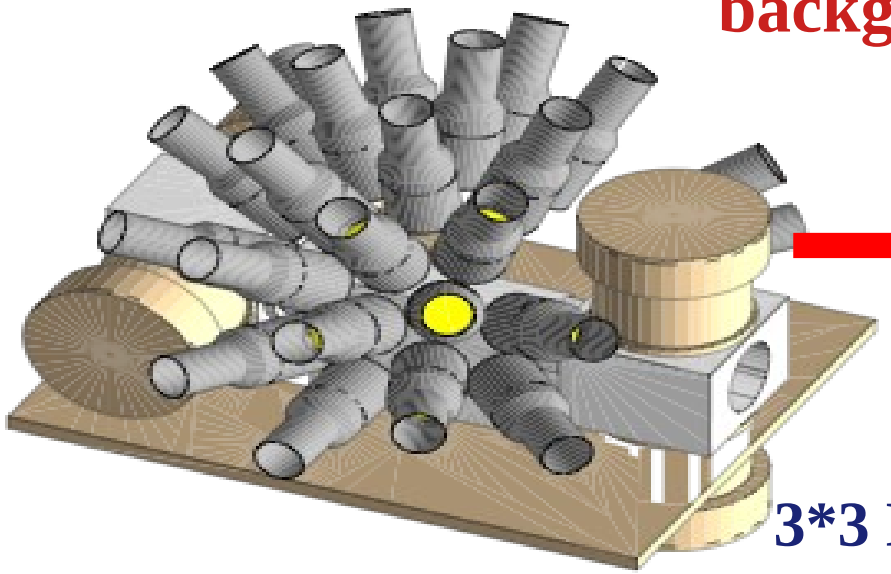


First campaign with the array included 7 detectors at θ = 90°

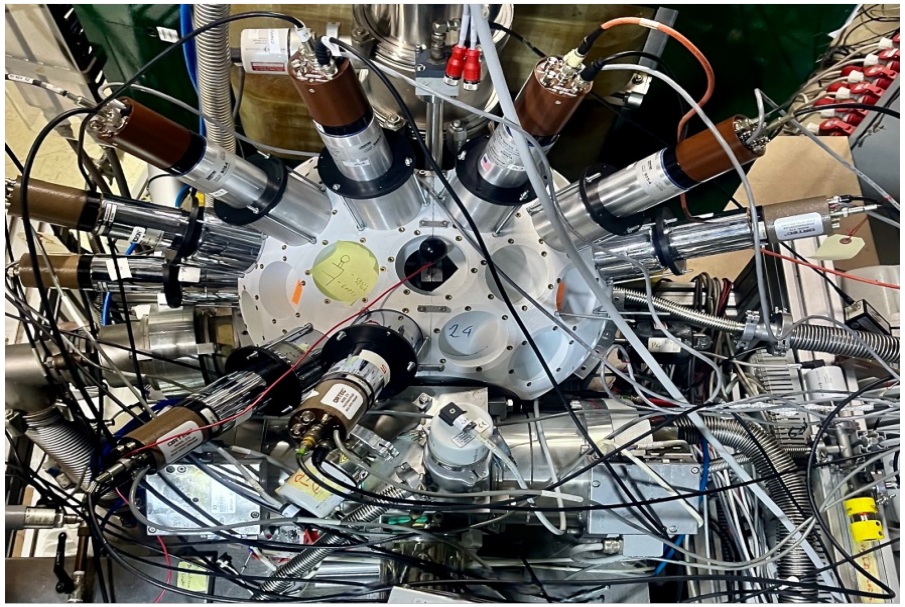
Second campaign with the array included 20 detectors

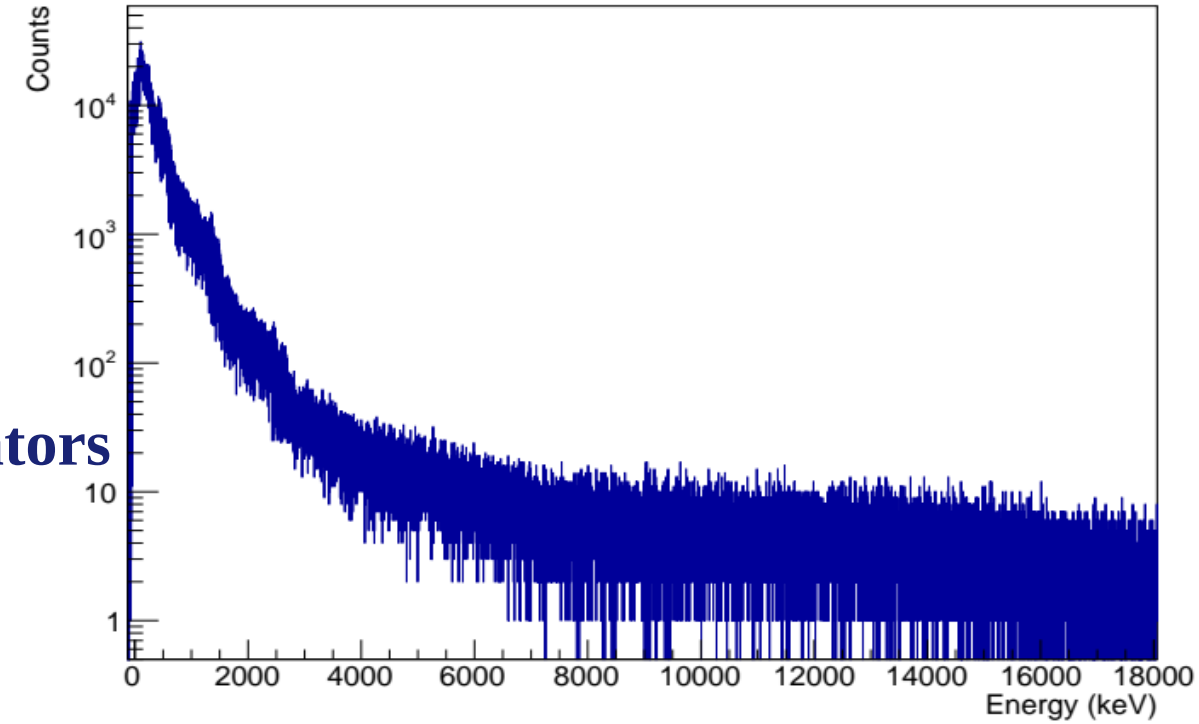
INITIAL CAMPAIGNS WITH GAMMA ARRAY

Aim: Setup coincidence between the recoils and the gamma-array to achieve a background free gamma spectrum



3*3 NaI Scintillators

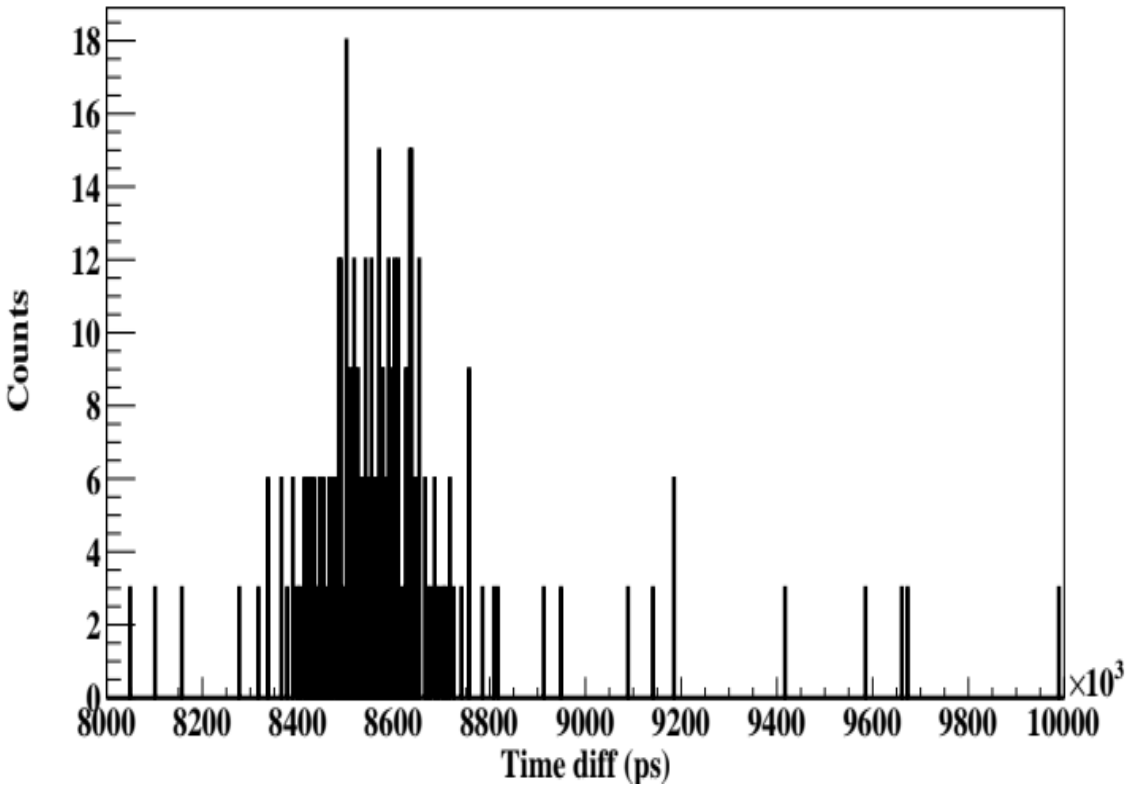


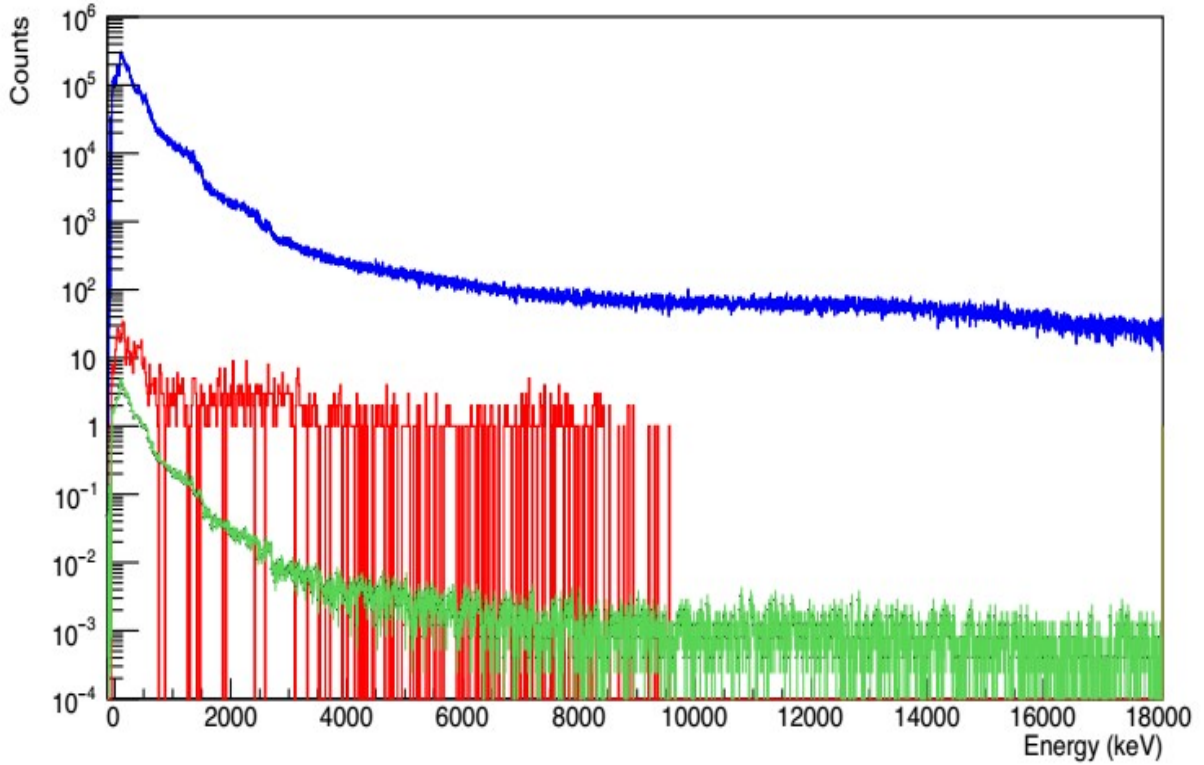


First campaign with the array included 7 detectors at θ = 90°

Second campaign with the array included 20 detectors

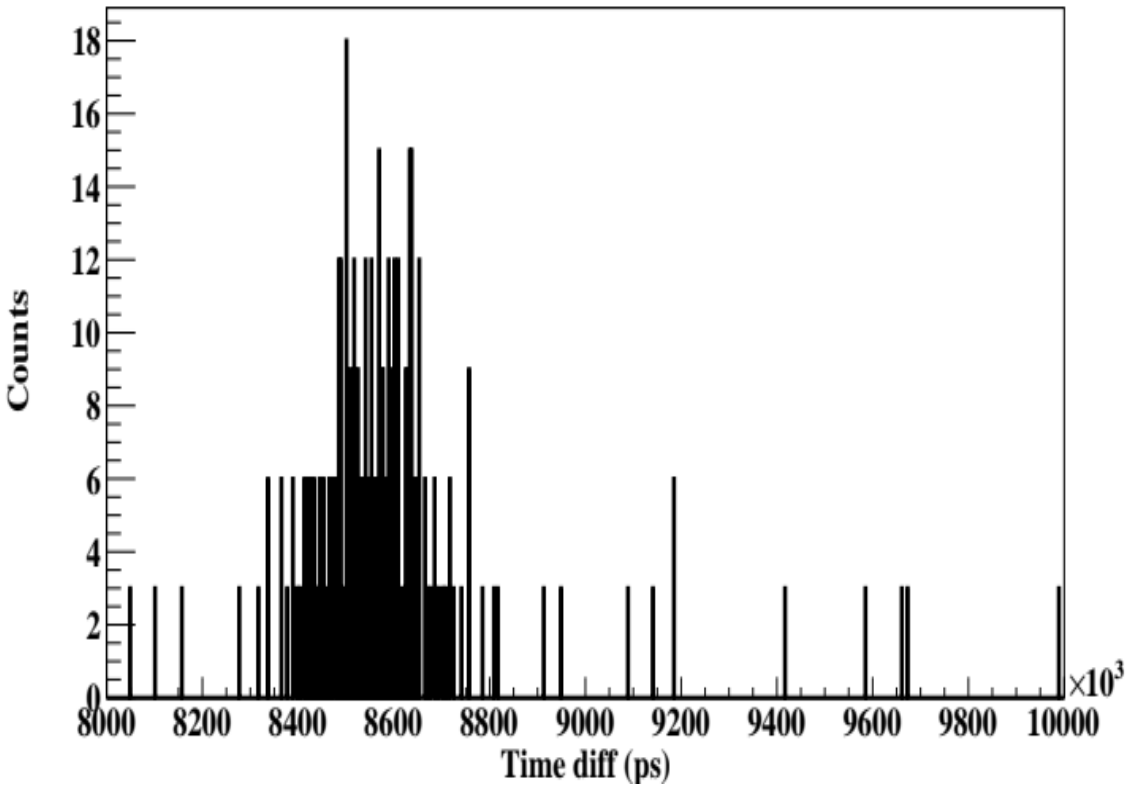
RESULTS: FIRST CAMPAIGN WITH GAMMA ARRAY

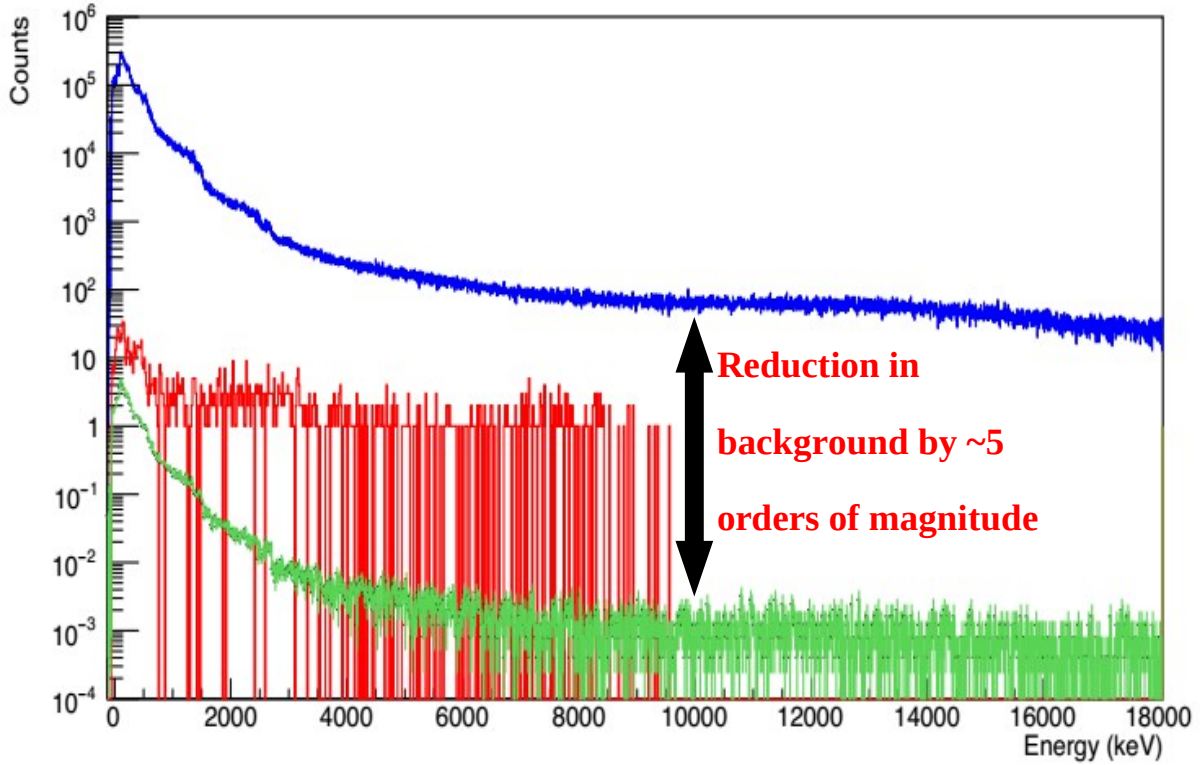




Time coincidence spectrum between the recoils and the gammas (left) and Energy spectrum of the whole gamma array after calibrating single NaIs spectrum and summing over all runs. The spectrum without coincidence is shown in blue and the spectrum resulted applying the coincidence analysis is shown in red. In green is the background for coincidences (right).

RESULTS: FIRST CAMPAIGN WITH GAMMA ARRAY





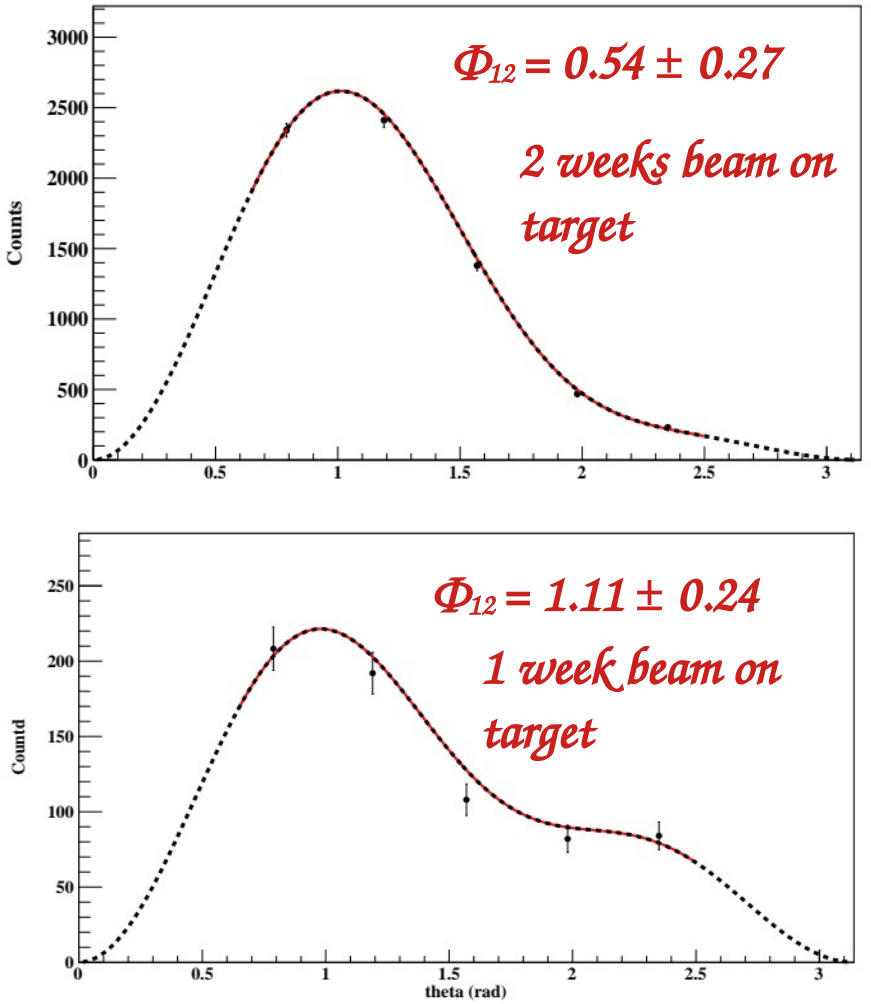
Time coincidence spectrum between the recoils and the gammas (left) and Energy spectrum of the whole gamma array after calibrating single NaIs spectrum and summing over all runs. The spectrum without coincidence is shown in blue and the spectrum resulted applying the coincidence analysis is shown in red. In green is the background for coincidences (right).

Conclusions

- The separator has been tuned to measure cross-sections down to E_{cm} = 1 MeV
- Absolute cross-section measurments with an uncertainity of ±10% till E_{cm} = 1.8 MeV.
- Set-up of the gamma-array to attain background free coincidence spectra with 20 NaI detectors

Conclusions

- **The separator has been tuned to measure cross-sections down to E_{cm} = 1 MeV**
- **Absolute cross-section measurments with an uncertainity of ±10% till E_{cm} = 1.8 MeV.**
- **Set-up of the gamma-array to attain background free coincidence spectra with 20 NaI detectors**

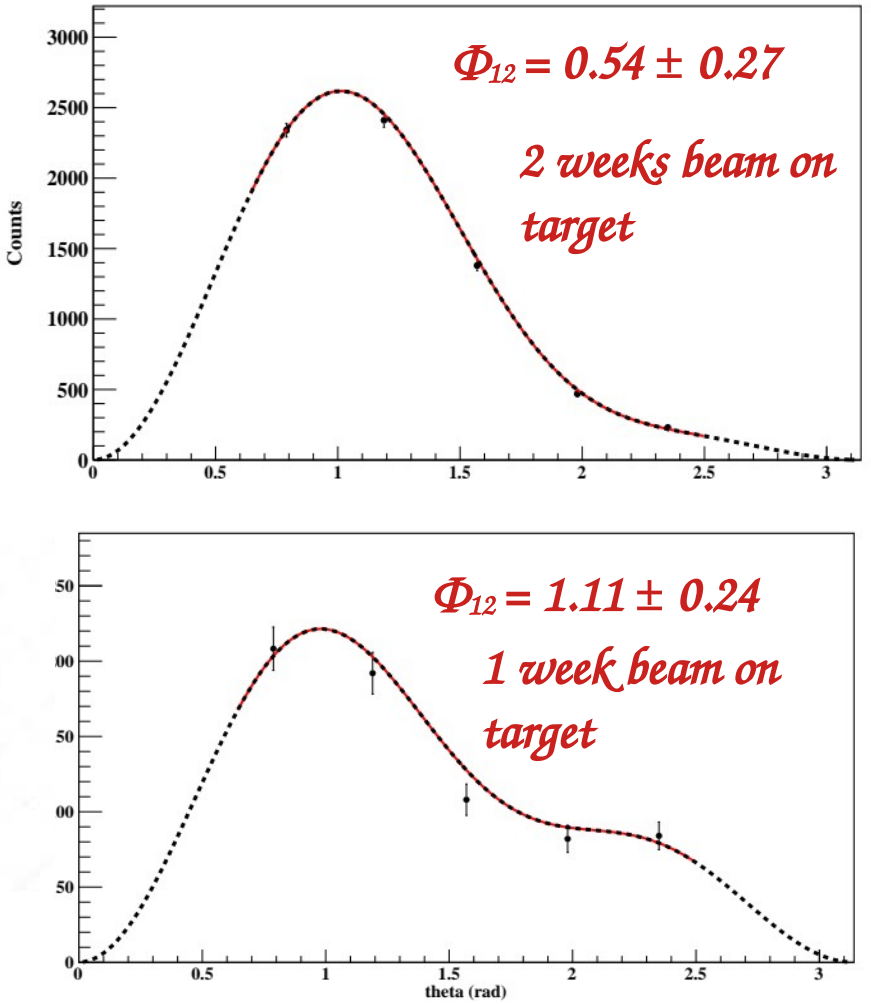


Monte-Carlo Simulated Angular Distibutions at E_{cm} = 2.42 MeV (top) and E_{cm} = 2.56 MeV (bottom)

Conclusions

- **The separator has been tuned to measure cross-sections down to E_{cm} = 1 MeV**
- **Absolute cross-section measurments with an uncertainity of ±10% till E_{cm} = 1.8 MeV.**
- **Set-up of the gamma-array to attain background free coincidence spectra with 20 NaI detectors**

- **Runs with longer statistics to attain angular distribution around E_{cm} = 2.42 MeV resonance**



Monte-Carlo Simulated Angular Distibutions at E_{cm} = 2.42 MeV (top) and E_{cm} = 2.56 MeV (bottom)

ERNA COLLABORATION

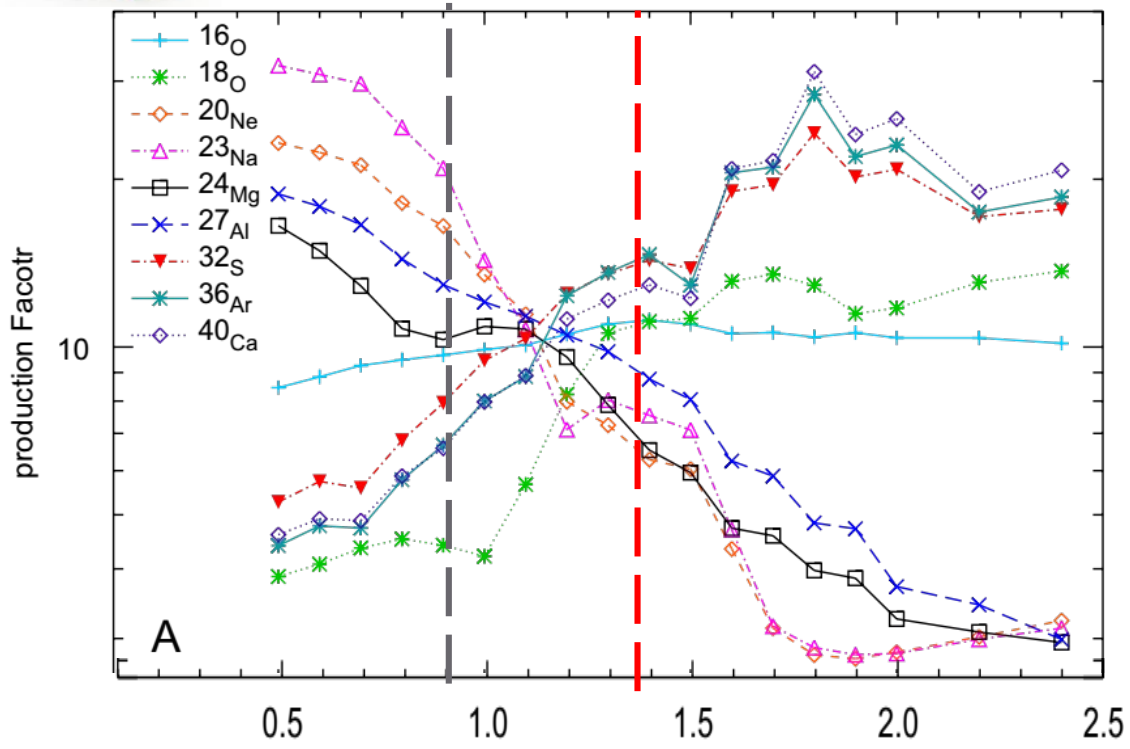
R. Buompane[1,2], A. Di Leva[3,2], L. Gialanella[1,2], K. Chakraborty[1,2], Samar[1,2], C. Santonastaso[4], A. Best[3,2],M. De. Cesare[5,2], F. Ercolano[3,2], A. Formicola[6], G. Imbriani[3,2], F. Marzaioli[1,2], C. M. Morone[7,8], G. Porzio[1,2], D. Rapagnani[3,2], R. P. Yadav[6], M. Romoli[2], O. Straniero[9,6]

[1]Dipartimento di Matematica e Fisica, Università della Campania "L. Vanvitelli", Caserta, Italy
[2]Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Napoli, Italy
[3]Dipartimento di Fisica "E. Pancini", Università di Napoli "Federico II", Napoli, Italy
[4]RIKEN Nishina Center, Wako, Saitama, Japan
[5]Dipartimento di Metodologie e Tecnologie per le Osservazioni e Misure, Centro Italiano Ricerche Aerospaziali, Capua, Italy
[6]Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Roma, Italy
[7]Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[8]Istituto Nazionale di Fisica Nucleare INFN - Sezione di Roma Tor Vergata, Roma, Italy
[9]INAF,Osservatorio Astronomico d'Abruzzo, Teramo, Italy

Questions: kajol.chakraborty@unicampania.it
Collaboration: lucio.gialanella@unicampania.it, raffaele.buompane@unicampania.it

Astrophysical Significance of $^{12}C(\alpha,\gamma)^{16}O$

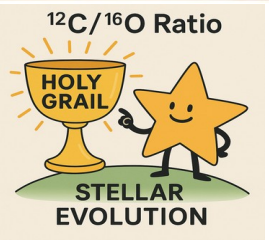
Reaction Rate of $^{12}C(\alpha,\gamma)^{16}O$

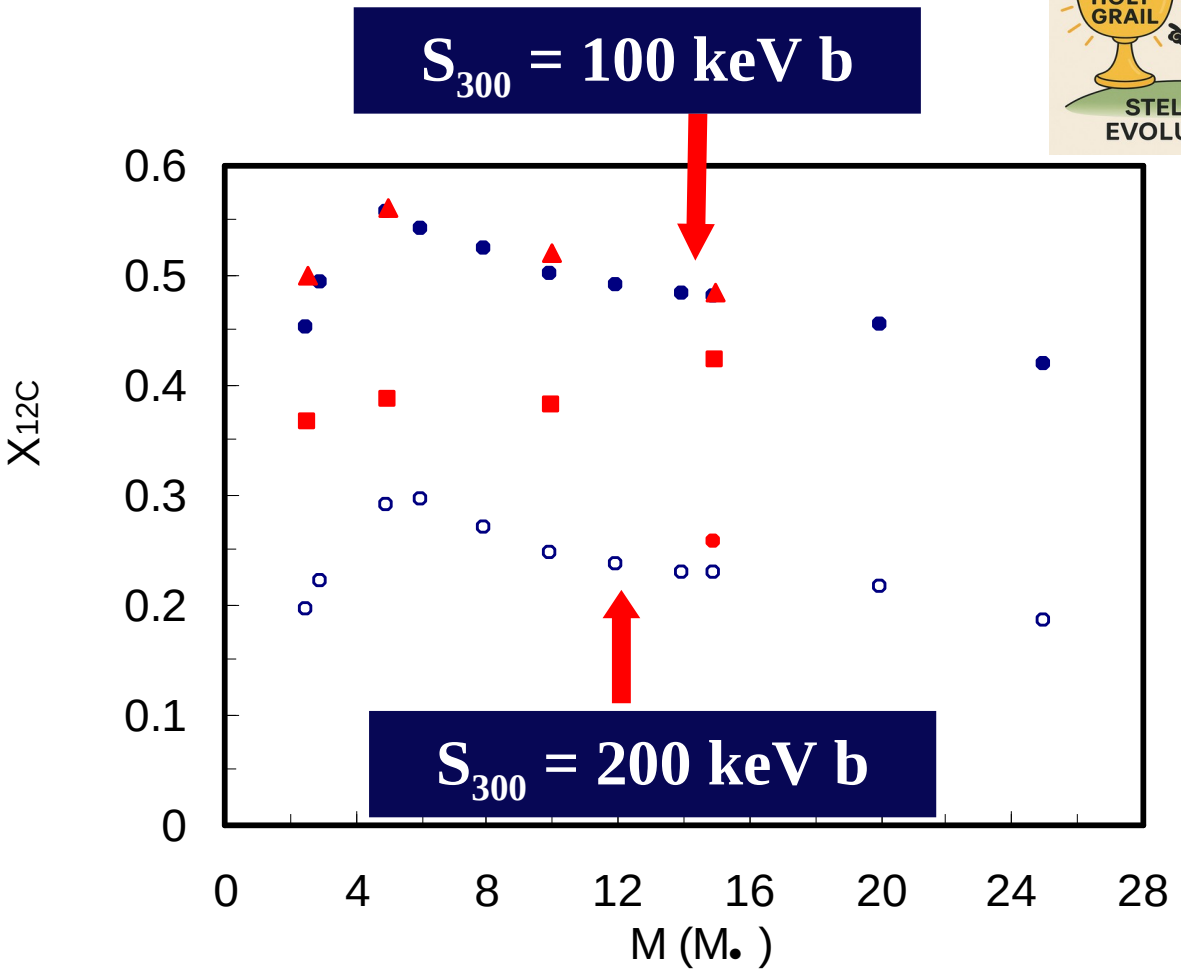


Multiplier on $^{12}C(\alpha,\gamma)^{16}O$ Rate (Buchmann 1996)

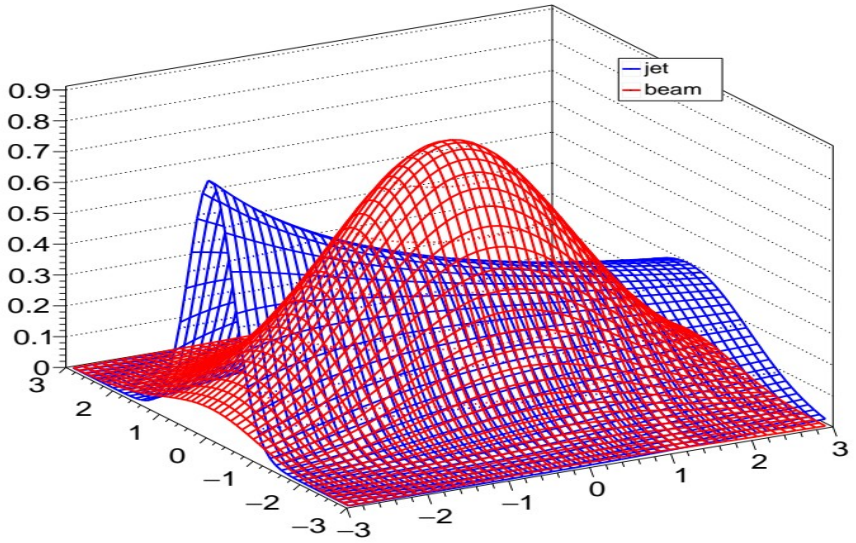
S_{300} = 170 ± 20 keV b

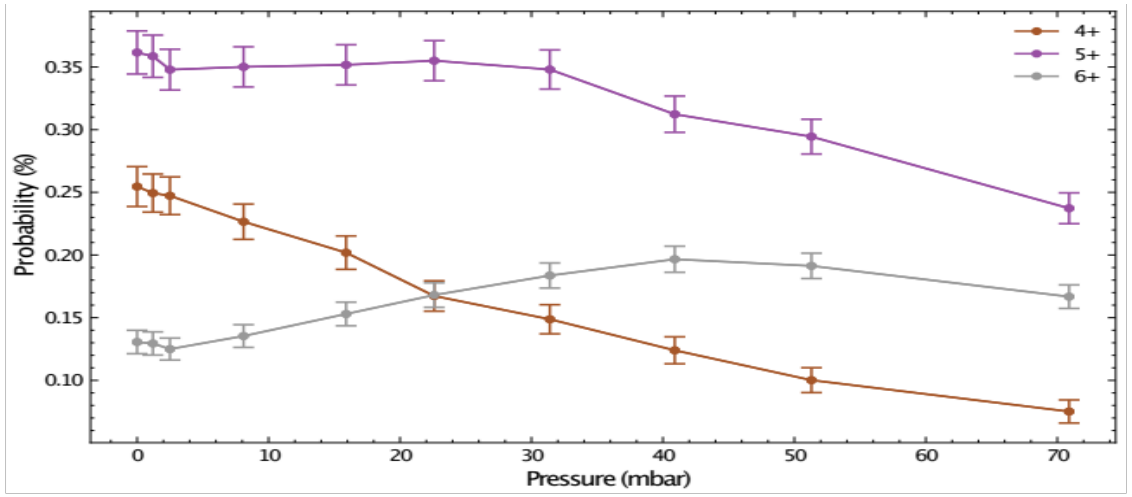
Direct Measurements are Necessary!!

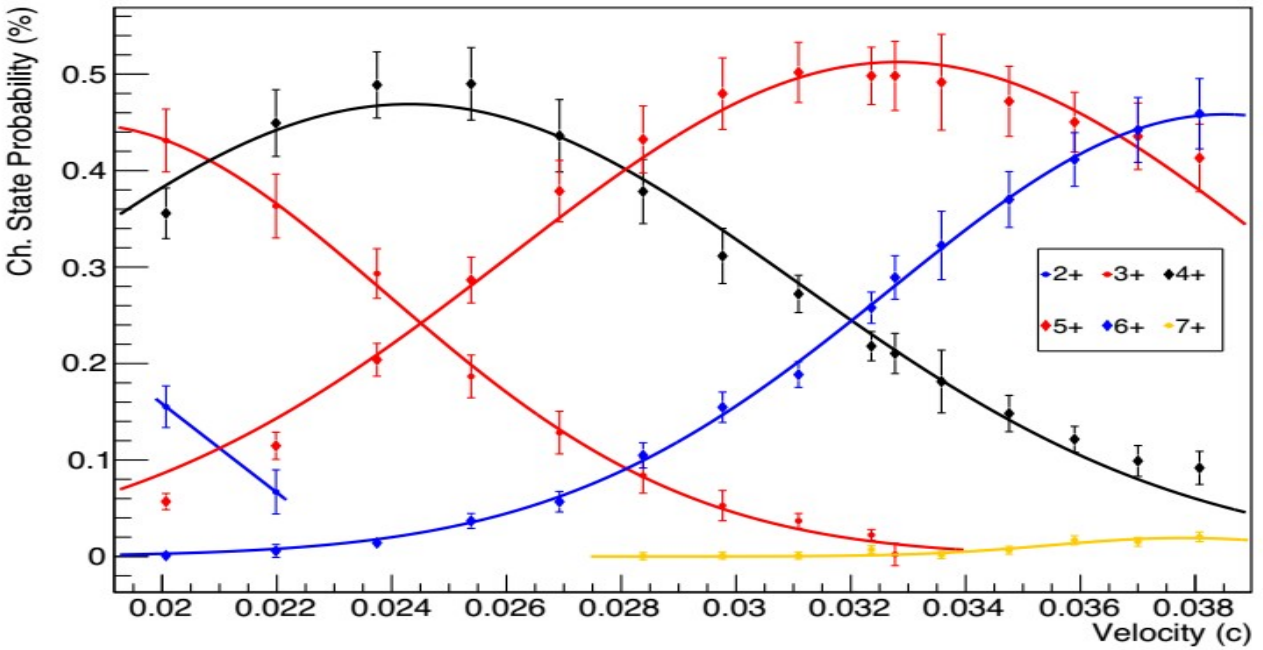




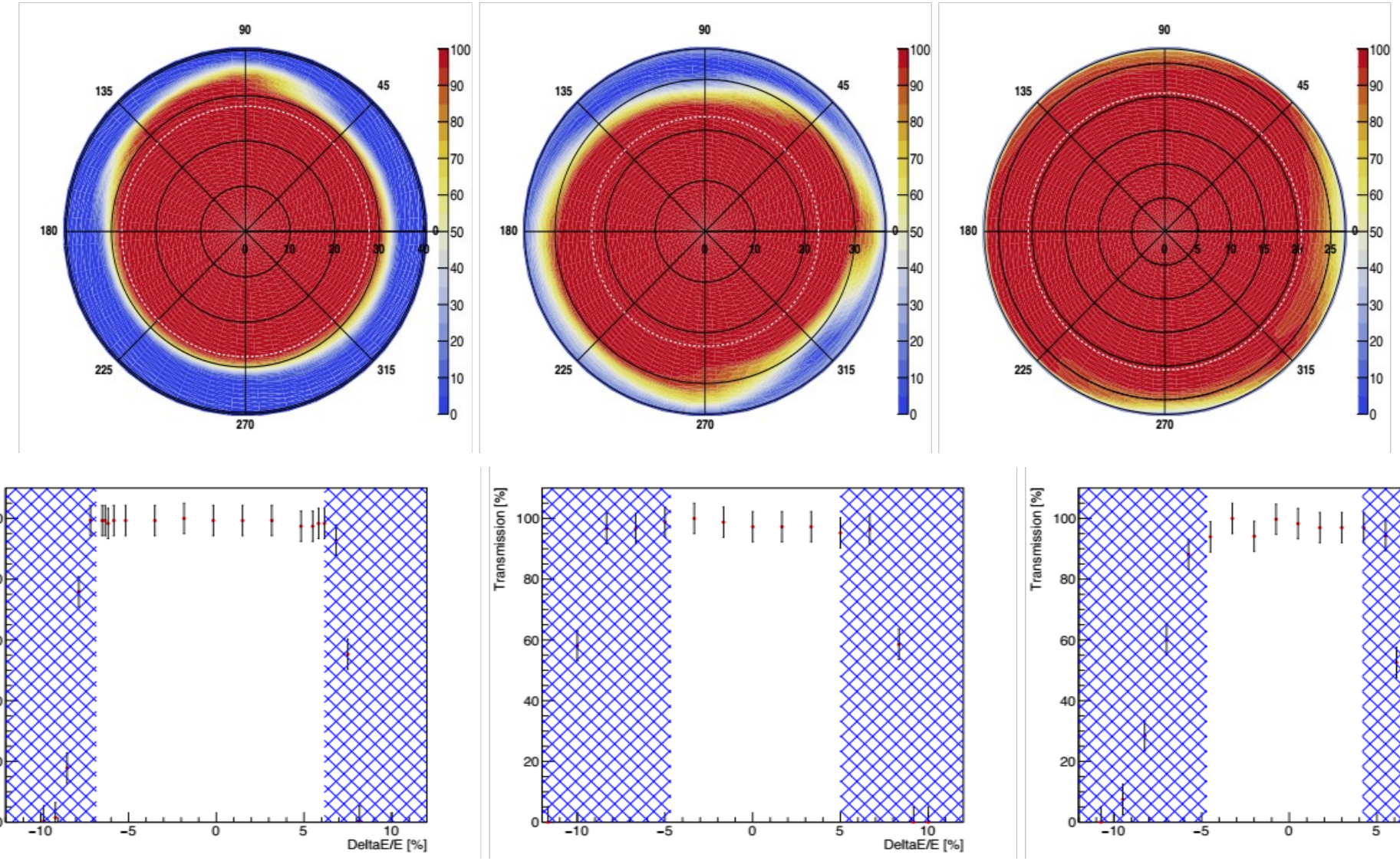
Woosley *et al.*, Physics Reports 442 (2007) 269
Buchmann *et al.*, The Astrophysical Journal (1996) 468
Imbriani *et al.*, The Astrophysical Journal (2001)


jet
beam
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
3
2
1
0
−1
−2
−3
−3
−2
−1
0
1
2
3

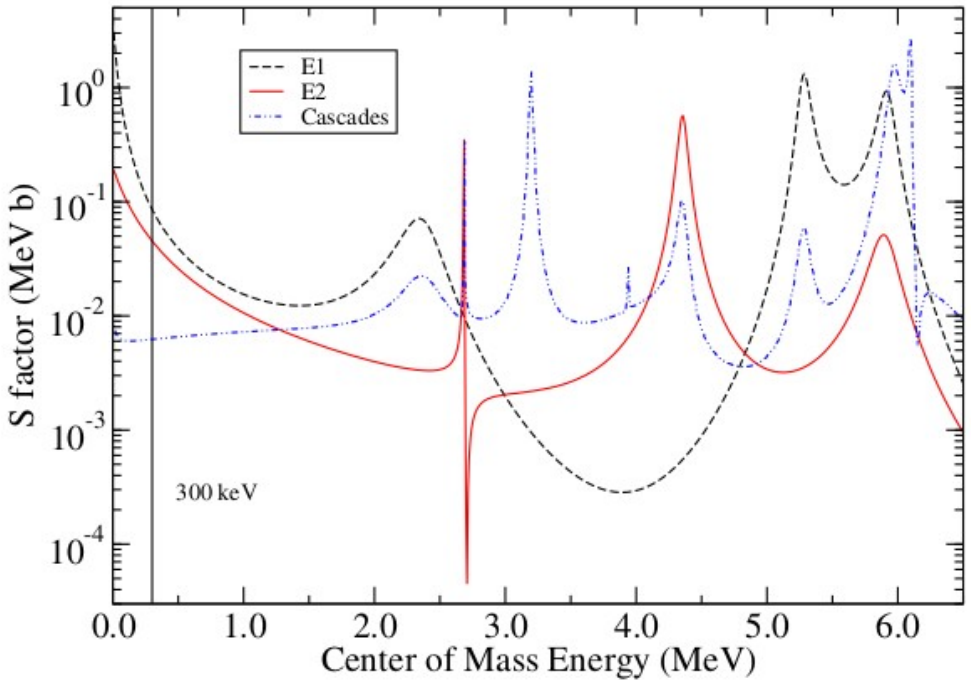

4+
5+
6+
Probability (%)
0.35
0.30
0.25
0.20
0.15
0.10
0
10
20
30
40
50
60
70
Pressure (mbar)

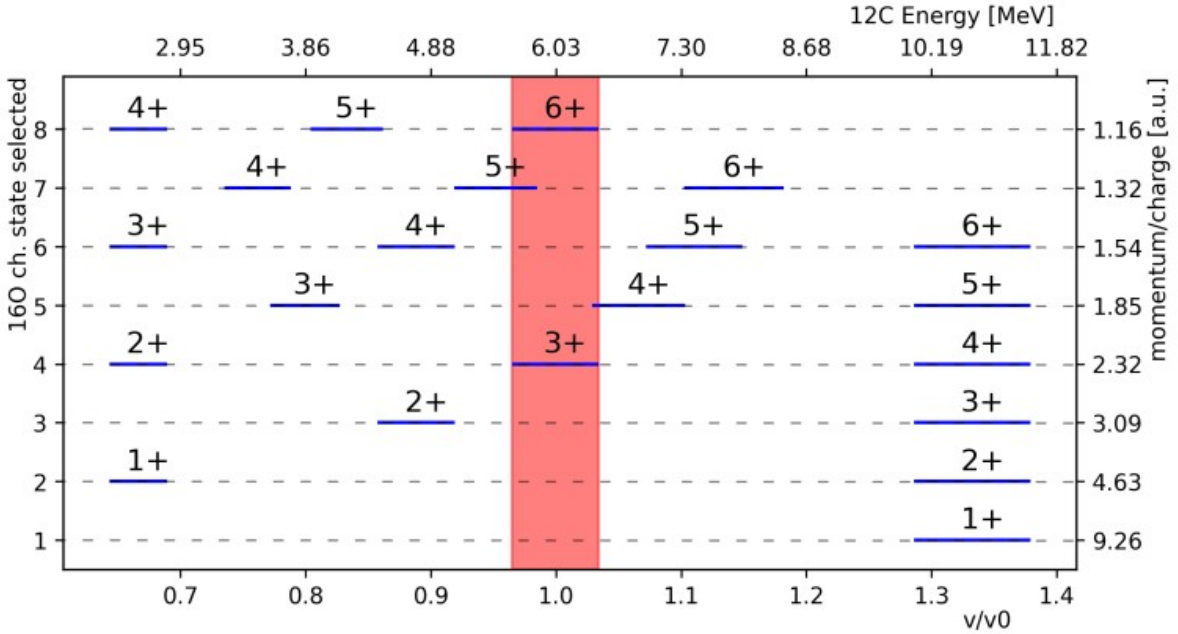

Ch. State Probability (%)
0.5
0.4
0.3
0.2
0.1
0
2+
3+
4+
5+
6+
7+
0.02
0.022
0.024
0.026
0.028
0.03
0.032
0.034
0.036
0.038
Velocity (c)

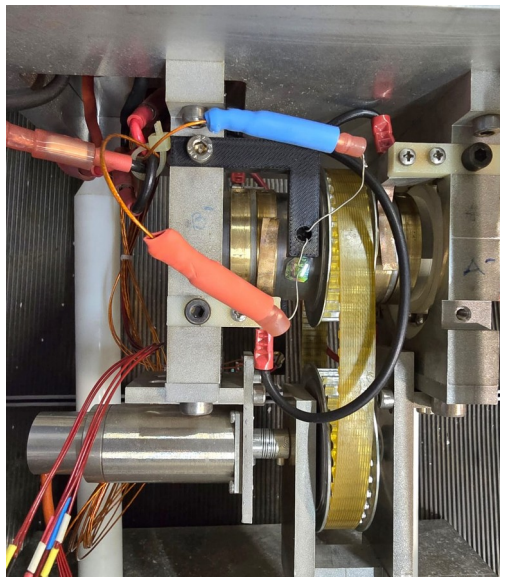
ANGULAR AND ENERGY ACCEPTANCE

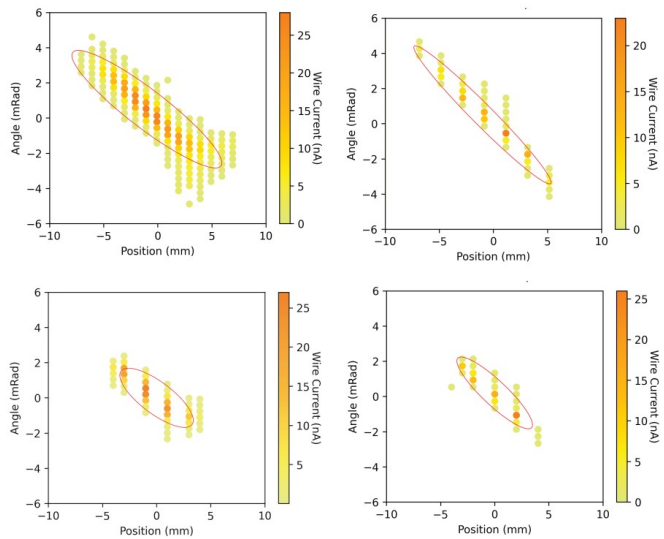


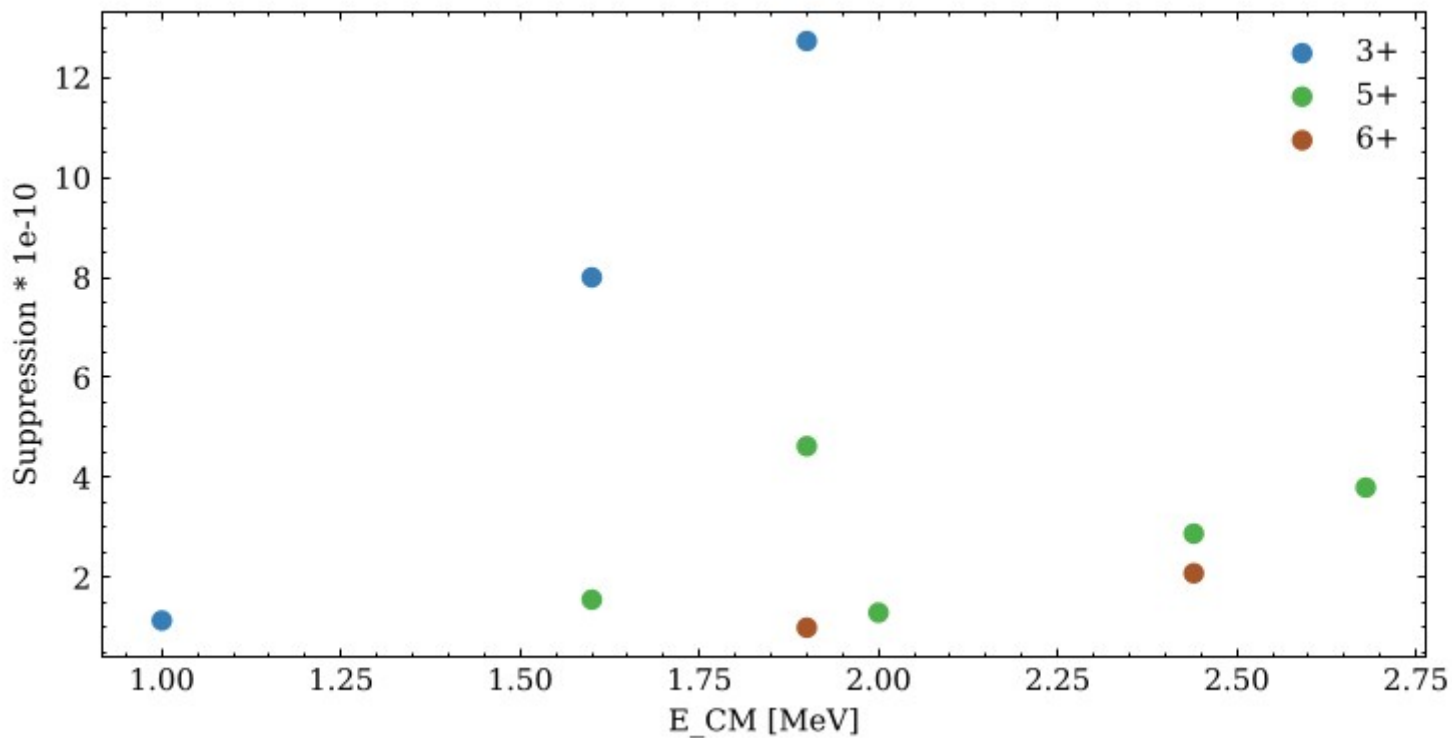
Angular (top panel) and Energy (bottom panel) acceptance of the separator at Ecm = 1 MeV, 2 MeV and 2.68 MeV

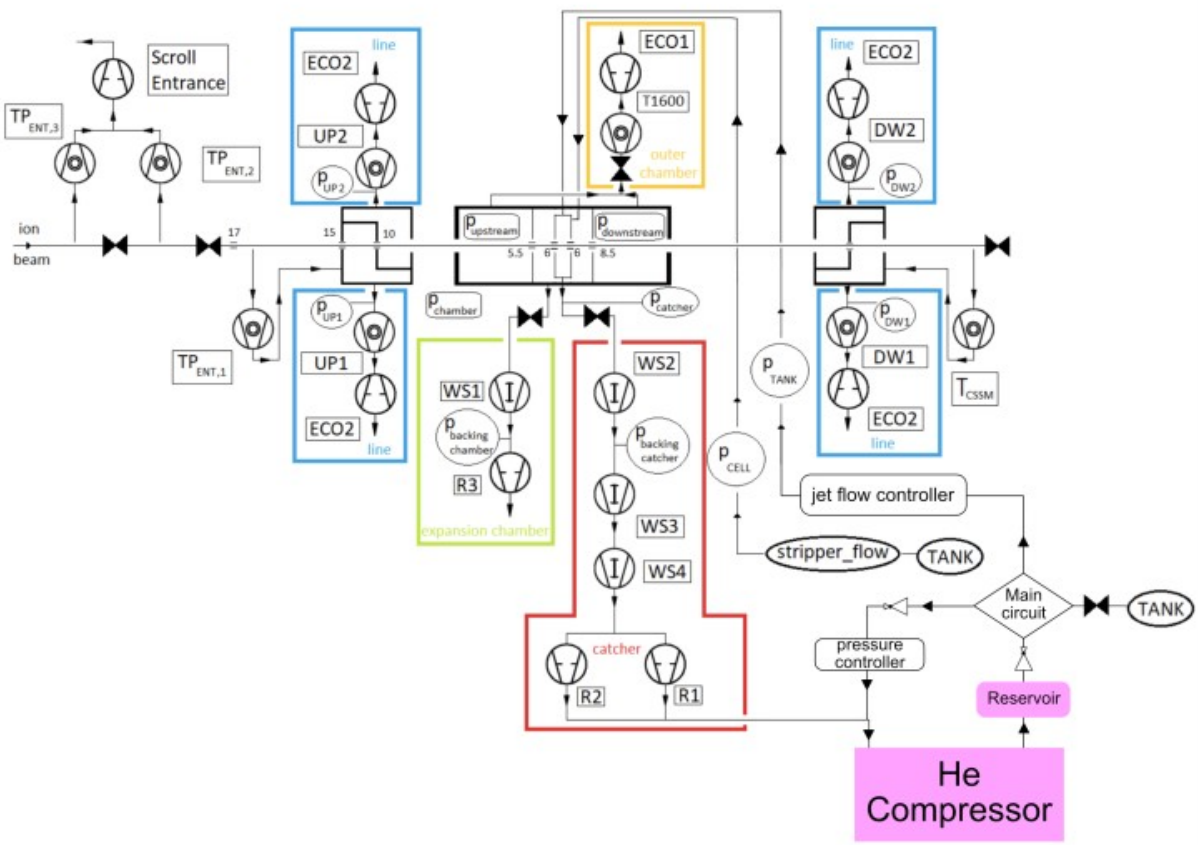

E1
E2
Cascades
300 keV
S factor (MeV b)
Center of Mass Energy (MeV)


12C Energy [MeV]
160 ch. state selected
momentum/charge [a.u.]
v/v0




Angle (mRad)
Position (mm)
Wire Current (nA)


Suppression * 1e-10
12
10
8
6
4
2
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
E_CM [MeV]
3+
5+
6+


Scroll
Entrance
TP ENT,3
TP ENT,2
TP ENT,1
ion
beam
17
15
10
line
ECO2
UP2
p UP2
UP1
p UP1
ECO2
line
ECO1
T1600
outer
chamber
p upstream
p downstream
5.5
6
6
8.5
p chamber
p catcher
WS1
p backing chamber
R3
expansion chamber
WS2
p backing catcher
WS3
WS4
catcher
R2
R1
p CELL
p TANK
line
ECO2
DW2
p DW2
p DW1
DW1
ECO2
line
T CSSM
jet flow controller
stripper_flow
TANK
Main
circuit
TANK
pressure
controller
Reservoir
He
Compressor