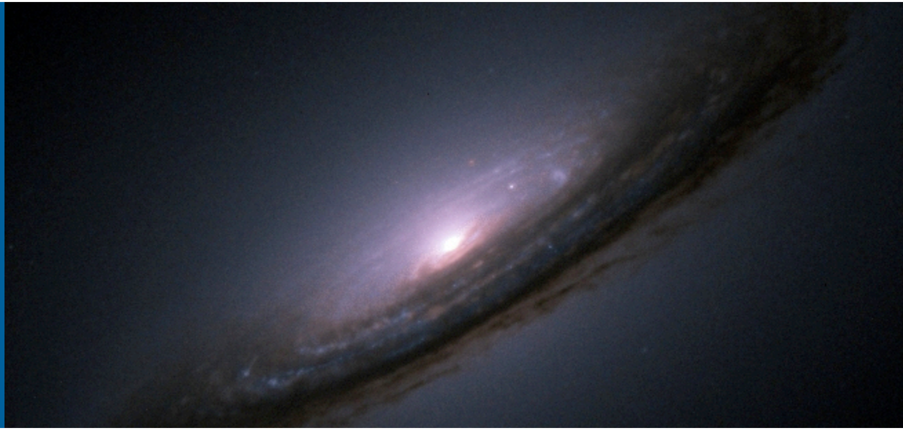
DIRECT REACTIONS WITH EXOTIC BEAMS 2022

Direct measurement of the $^{22}Mg(\alpha,p)^{25}Al$ reaction using MUSIC relevant for Type I X-ray bursts

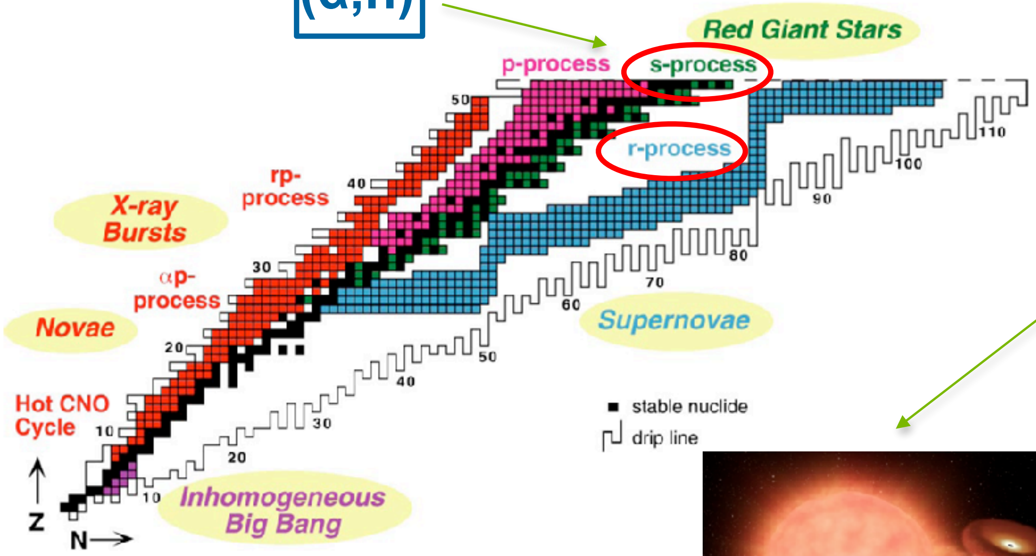


Heshani Jayatissa
Argonne National Laboratory

June 28, 2022
Santiago de Compostela, ES

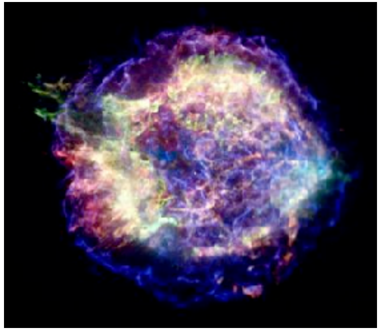
Alpha-induced reactions for nuclear astrophysics

(α,n)



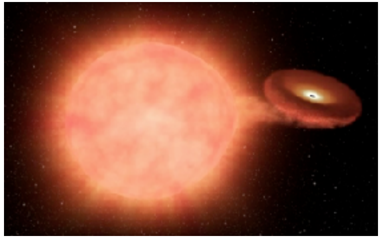
(α,γ)

(α,p)



Core-Collapse supernovae

Credit: NASA



Type 1a supernovae

X-ray Bursts

Importance of (α,p) reactions for X-ray bursts

Before the XRB:

H is burnt via the hot CNO cycle ⟶ powered by 3α reaction ⟶ thermonuclear runway

During the XRB:

Breaks out of the hot CNO cycle via alpha-capture reactions
^{15}O(α,γ)^{19}Ne & ^{18}Ne(α,p)^{21}Na

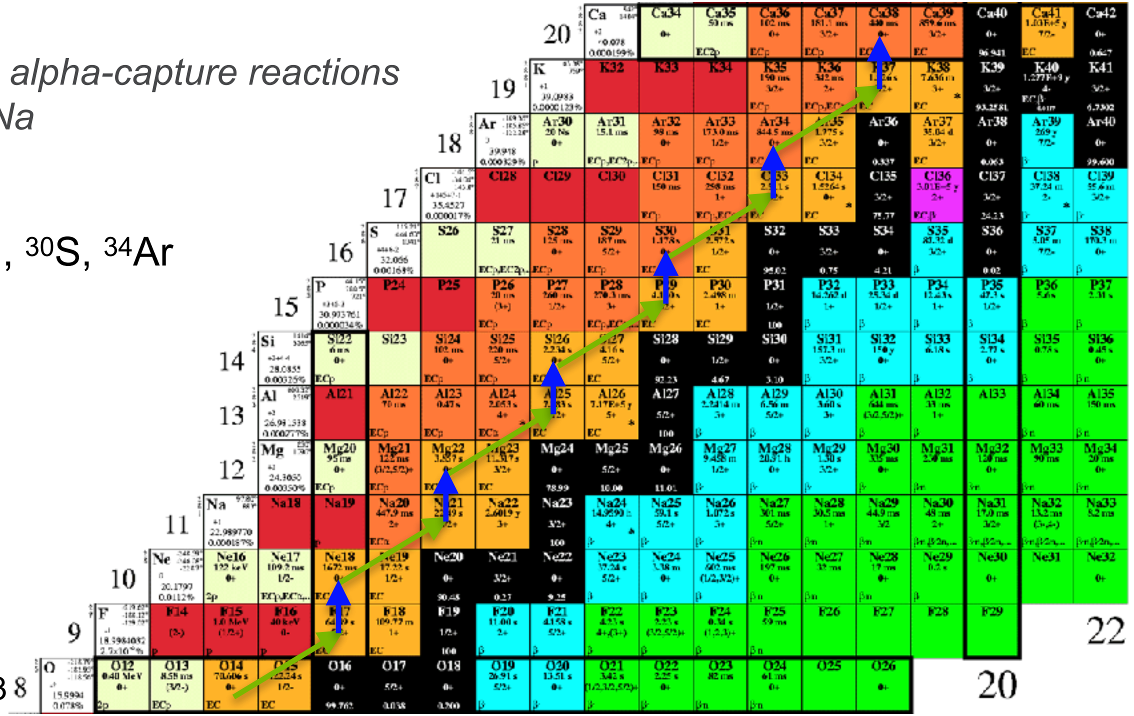
A few waiting point nuclei : ^{22}Mg, ^{26}Si, ^{30}S, ^{34}Ar

^{22}Mg

β - decay

^{22}Mg(p,γ)^{23}Al

^{22}Mg(α,p)^{25}Al



Importance of XRB models

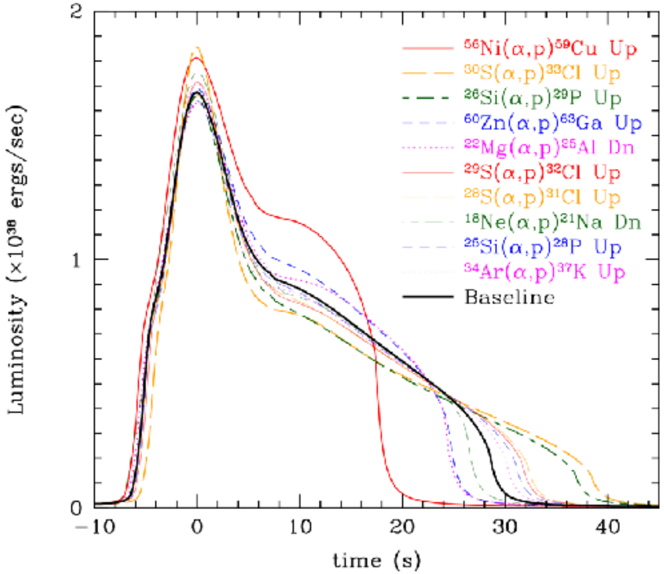
- Comparisons between XRB models and observed light curves allows to constrain elements of neutron stars:
  - Composition
  - Mass-Radius ratio
  - Compactness
  - Accretion rate
  - Accretion-based heating

- Models also allow predictions of the XRB ashes which alters the composition of the neutron star crust.

- XRB models are sensitive to nuclear physics inputs such as reaction rates.

XRB SENSITIVITY STUDY

Cyburt et al. (2016)



R. H. Cyburt et al. (2016)

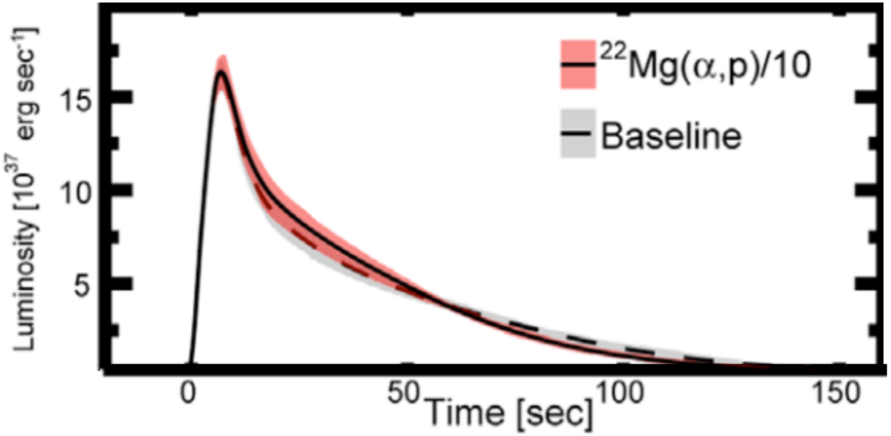
Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	$^{15}O(\alpha, \gamma)^{19}Ne$	D	16	1
2	$^{56}Ni(\alpha, p)^{59}Cu$	U	6.4	1
3	$^{59}Cu(p, \gamma)^{60}Zn$	D	5.1	1
4	$^{61}Ga(p, \gamma)^{62}Ge$	D	3.7	1
5	$^{22}Mg(\alpha, p)^{25}Al$	D	2.3	1
6	$^{14}O(\alpha, p)^{17}F$	D	5.8	1
7	$^{23}Al(p, \gamma)^{24}Si$	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
11	$^{12}C(\alpha, \gamma)^{16}O$	U	2.1	2
12	$^{26}Si(\alpha, p)^{29}P$	U	1.8	2
13	$^{17}F(\alpha, p)^{20}Ne$	U	3.5	2
14	$^{24}Mg(\alpha, \gamma)^{28}Si$	U	1.2	2
15	$^{57}Cu(p, \gamma)^{58}Zn$	D	1.3	2
16	$^{60}Zn(\alpha, p)^{63}Ga$	U	1.1	2
17	$^{17}F(p, \gamma)^{18}Ne$	U	1.7	2
18	$^{40}Sc(p, \gamma)^{41}Ti$	D	1.1	2
19	$^{48}Cr(p, \gamma)^{49}Mn$	D	1.2	2

SENSITIVITY STUDY

Meisel et al. (2019)

Studied the impact of the 19 reactions identified by Cyburt et al. in model-observation comparisons for for XRBs

- ☆ $^{15}O(\alpha,\gamma)$
- ☆ $^{23}Al(p,\gamma)$
- $^{14}O(\alpha,p)$
- $^{18}Ne(\alpha,p)$
- $^{22}Mg(\alpha,p)$
- $^{24}Mg(\alpha,\gamma)$
- $^{59}Cu(p,\gamma)$
- $^{61}Ga(p,\gamma)$



Reaction rate of $^{22}Mg(\alpha,p)$ from theoretical Hauser-Feshbach was divided by a factor of 10 to assess the light curve impact.

This effects the XRB light curve tail due to the enhancement of hydrogen burning early in the burst via $^{22}Mg(p,\gamma)^{23}Al(p,\gamma)^{24}Si$

Indirect measurement using $^{28}Si(p,t)^{26}Si$

A. Matic et al. (2011)

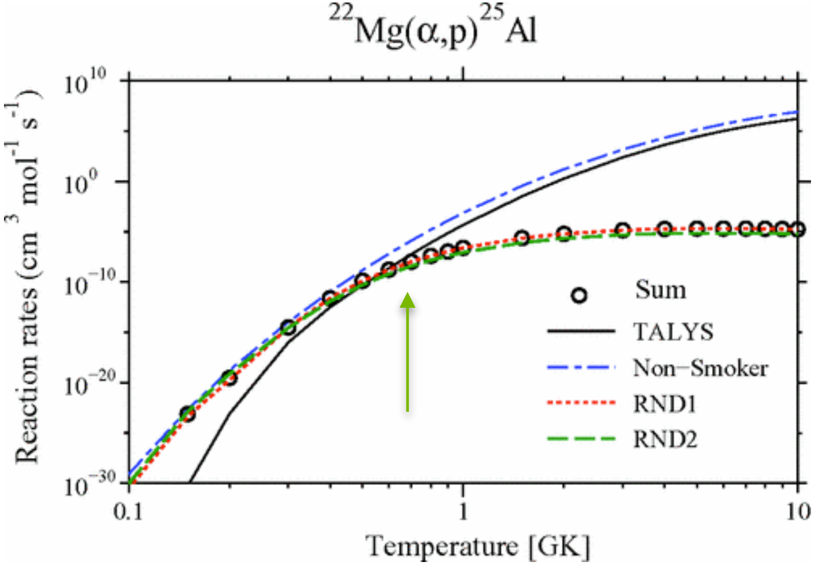
TABLE III. The adopted S_α and spin values and resonance strengths for the four resonances in the $^{22}Mg(\alpha,p)^{25}Al$ reaction.

E_x (^{26}Si) (MeV)	E_{res} (MeV)	J^π	S_α	J	Mirror[a] $\omega\gamma$ (eV)	J	RND1[b] $\omega\gamma$ (eV)	J	RND2[b] $\omega\gamma$ (eV)
9.316	0.152	$[4^+]$	0.015	4	5.81×10^{-37}	1	6.22×10^{-35}	4	5.81×10^{-37}
9.605	0.441	$[2^+]$	0.037	2	1.20×10^{-14}	1	6.66×10^{-15}	0	1.98×10^{-14}
9.762	0.598	$[5^-]$	0.007	5	3.72×10^{-13}	5	3.72×10^{-13}	2	1.23×10^{-10}
9.903	0.739	$[0^+]$	0.037	0	5.14×10^{-08}	0	5.14×10^{-08}	1	1.79×10^{-08}

[a] Spin and resonance strength for the mirror assignments.
[b] Spin and resonance strength for the randomly generated spins of states.

PRC 84, 025801 (2011)

- Observed 4 resonances in ^{26}Si above alpha threshold.
- Uncertainty in spin-parities of the measured states and the lack of resonance data above E_x = 10 MeV
- Reaction rate for $^{22}Mg(\alpha,p)$ is significantly lower than predicted by HF calculations for T > 0.7 GK.

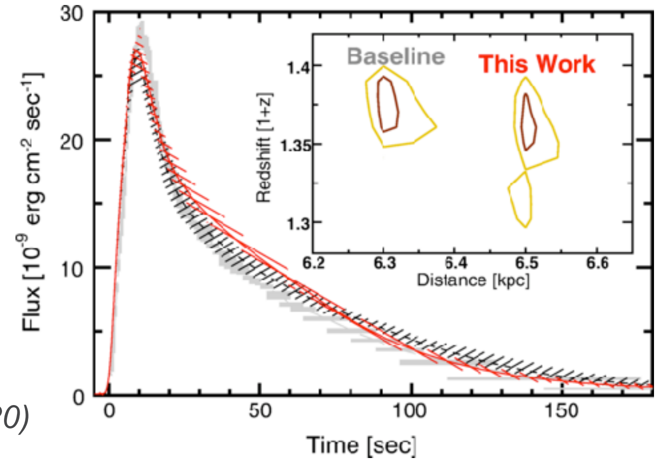


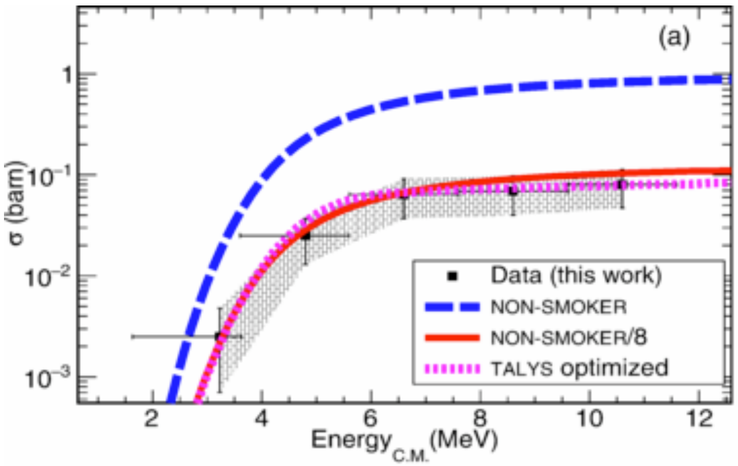
First direct measurement

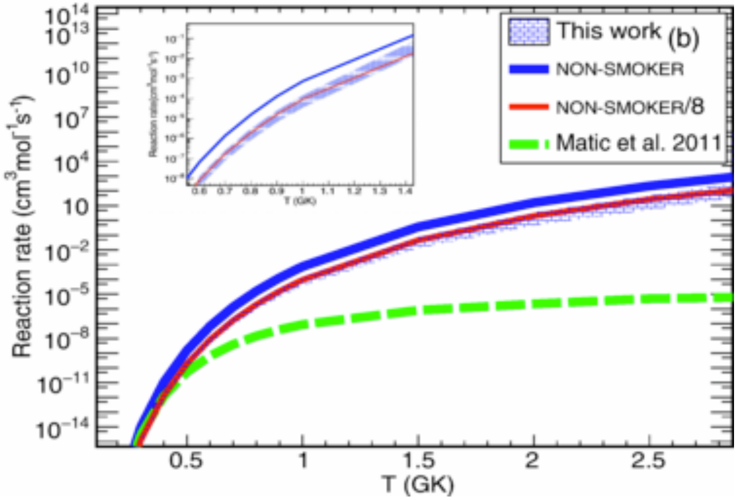
J. S. Randhawa et al. (2020)

^{22}Mg 5 MeV/u on He:CO_2 gas target in AT-TPC

Reaction CS is in agreement with theoretical Hauser-Feshbach cross sections using NON-SMOKER divided by a factor of 8 !!



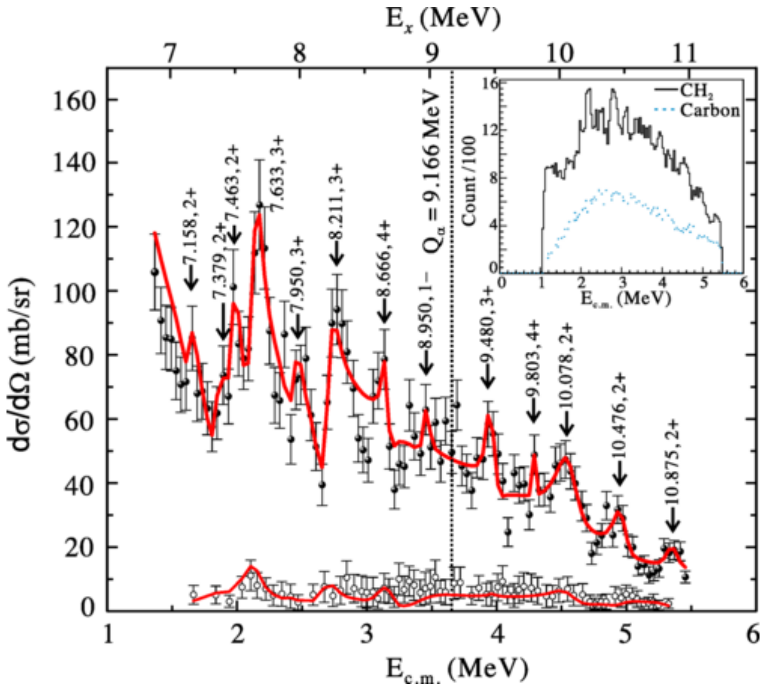


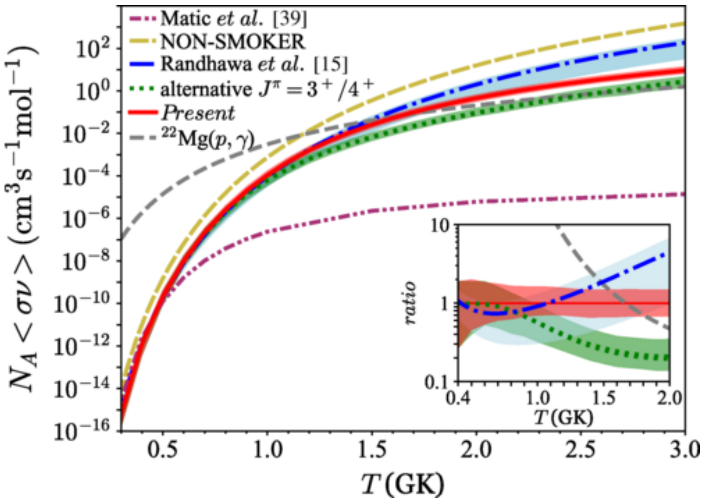


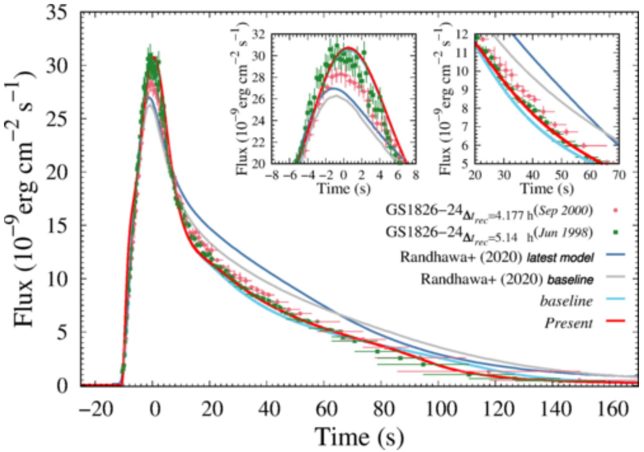
PRL 125, 202701 (2020)

(In)elastic scattering using ^{25}Al + p

J. Hu et al. (2021)





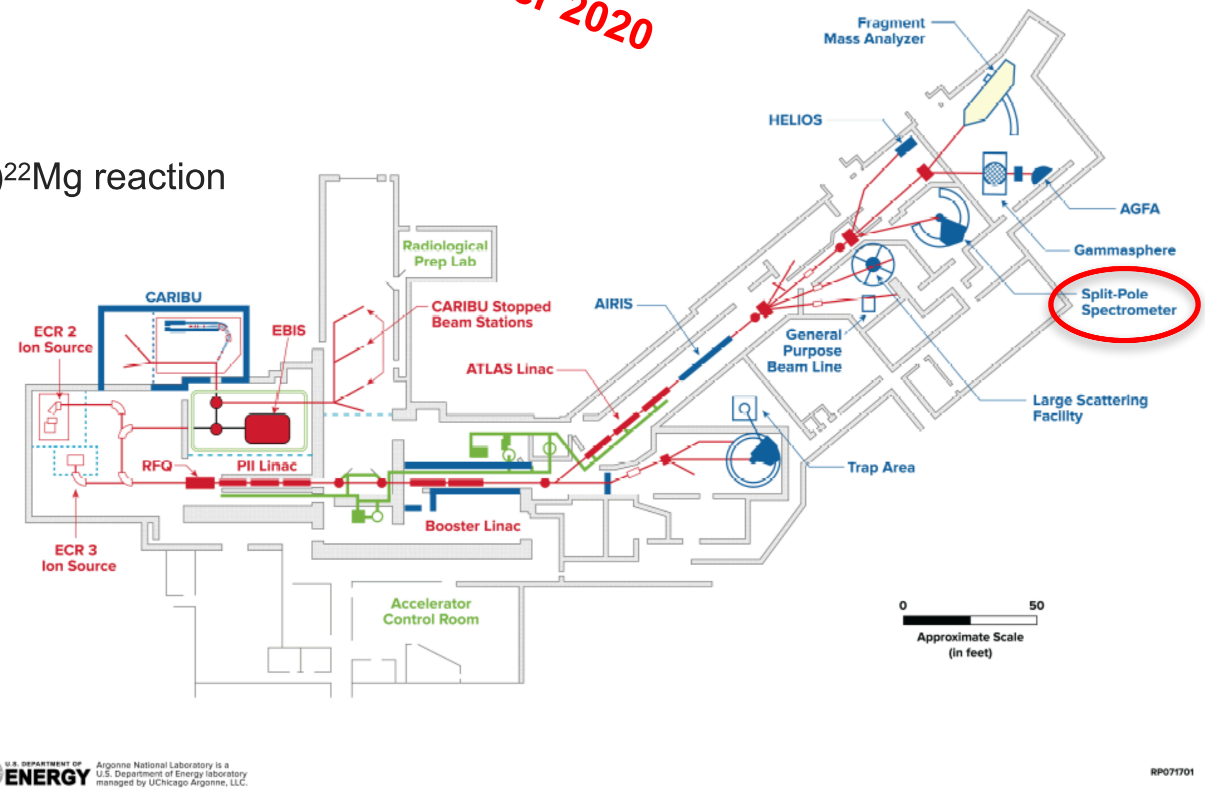


PRL 127, 172701 (2021)

Experiment details

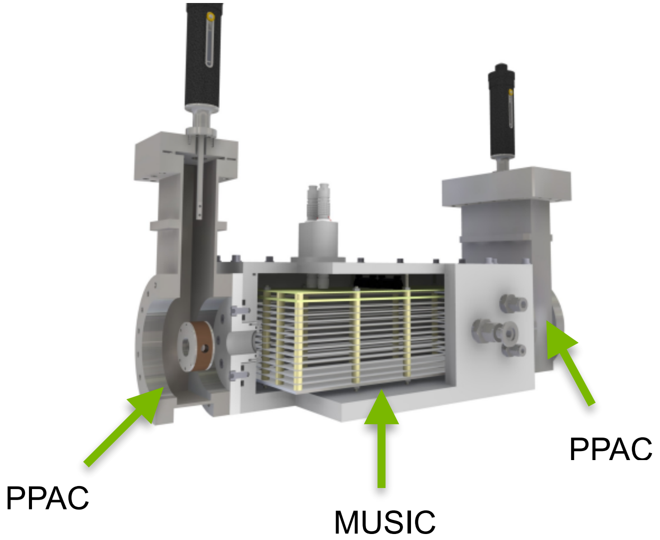
- Primary beam - ^{20}Ne
- ^{22}Mg created through ^{20}Ne(^{3}He,n)^{22}Mg reaction
- 74 MeV secondary ^{22}Mg beam
- Beam intensity ~150-200 pps
- Pure He gas target at 400 torr

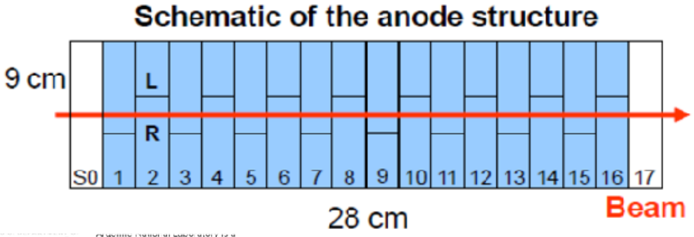
December 2020



MUSIC detector

MUlti-Sampling Ionization Chamber





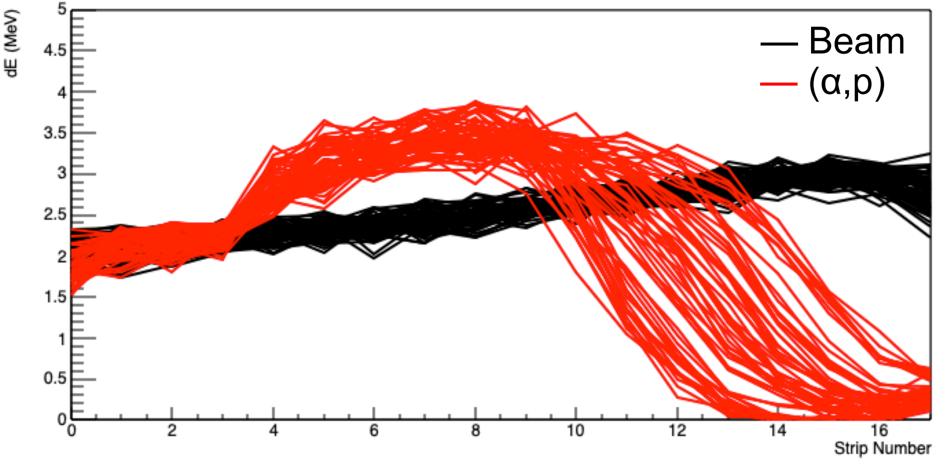
- Active target detector
- MUSIC offers a high efficiency due to the segmented anode structure.

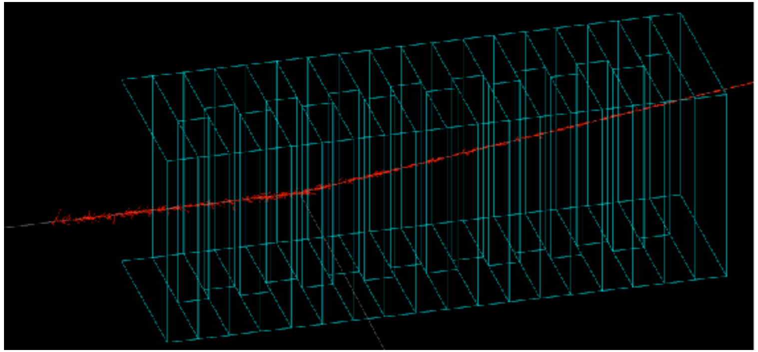
  This allows to measure a wide energy range with just a single beam energy.
- MUSIC is self-normalizing.

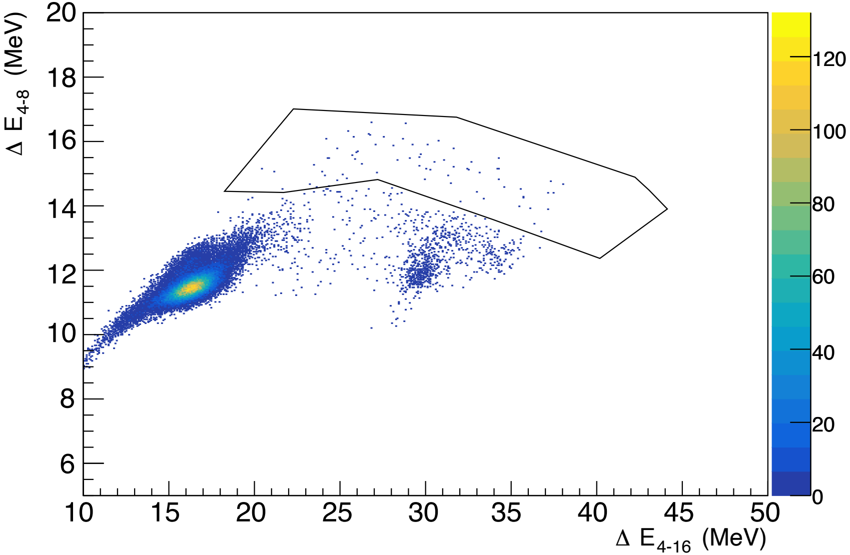
  Absolute normalization can be obtained with no additional monitor detectors.
- Gases: ^{4}He, ^{20,22}Ne, Ar, CH_4, etc
- Pressures: 150 - 760 Torr

Particle identification

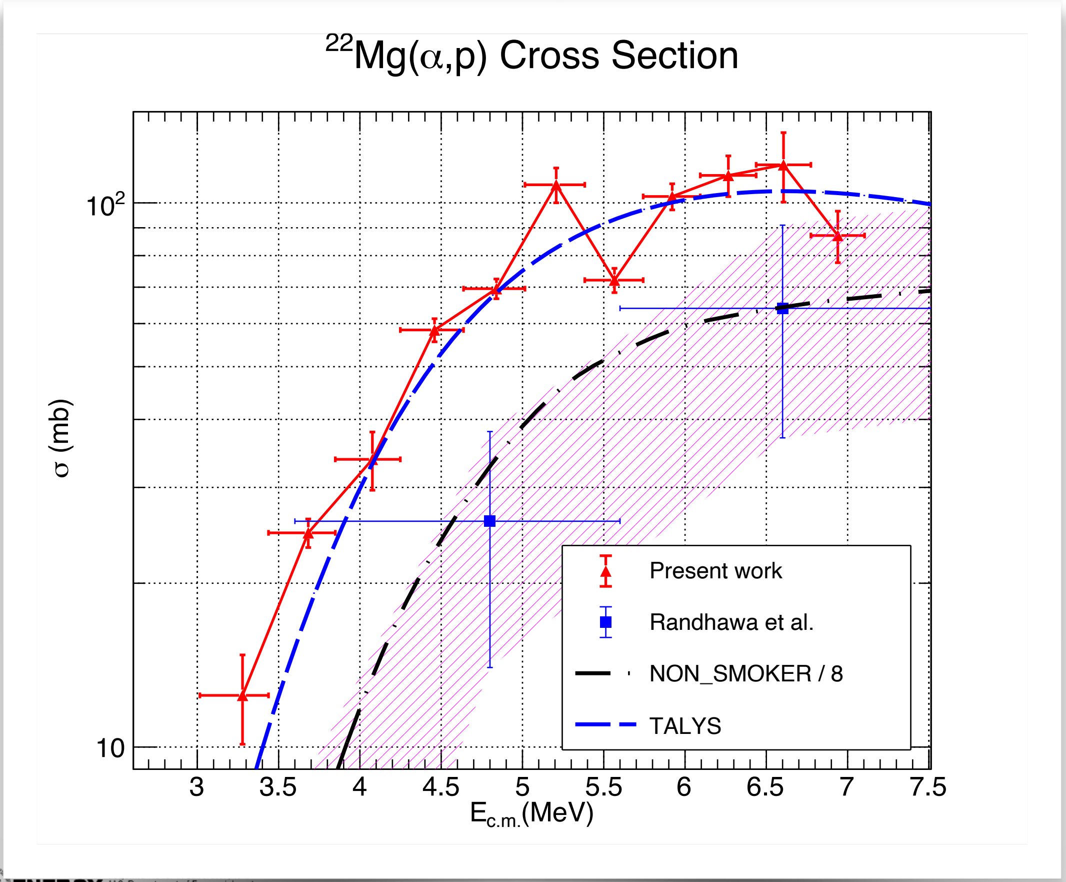
Events occurring in Strip 4 of MUSIC





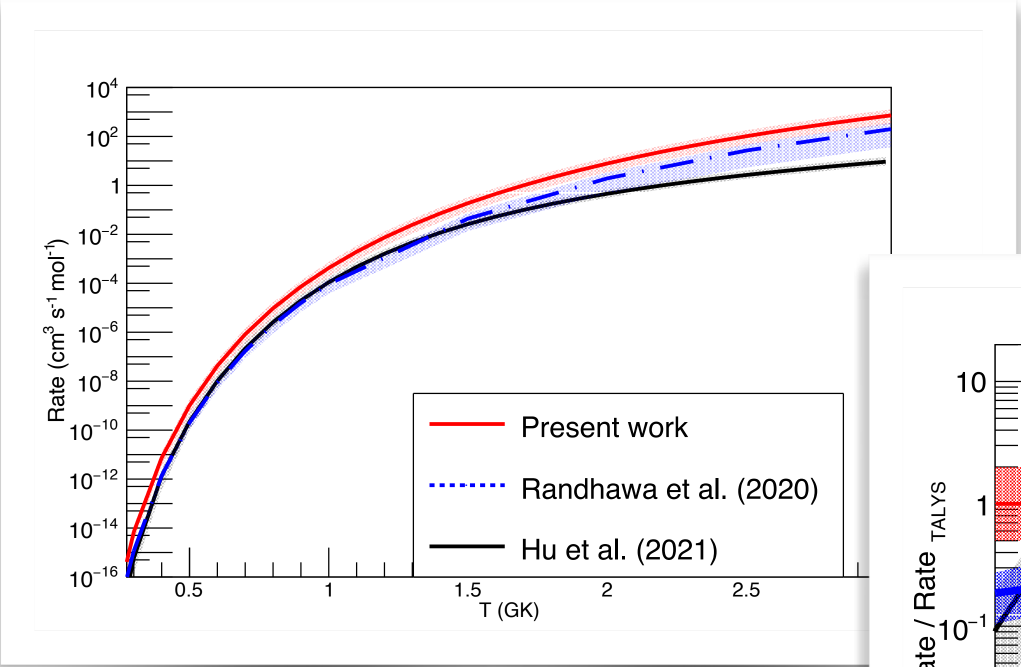


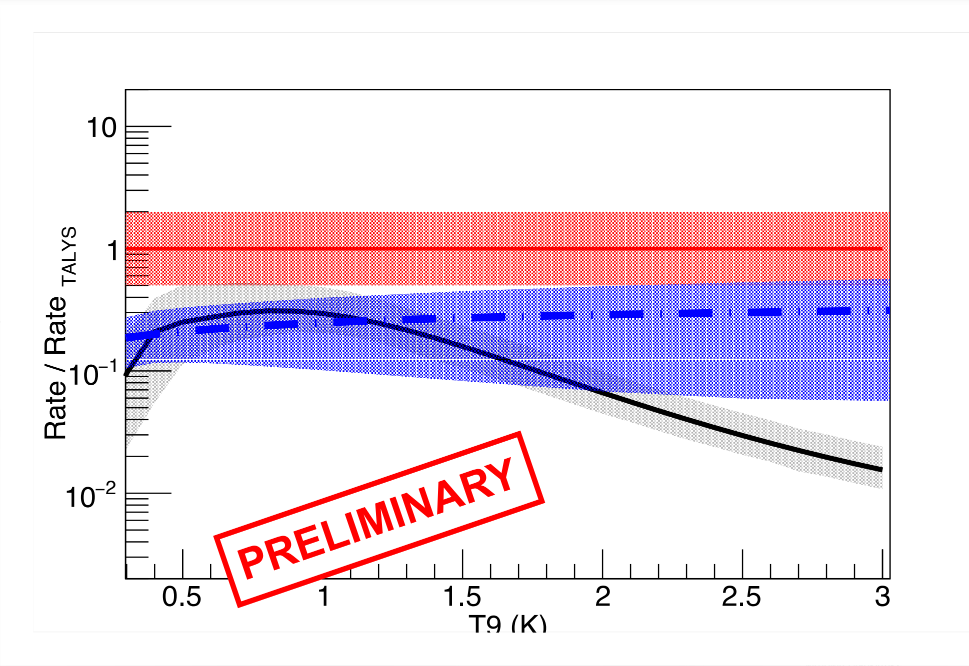
Total reaction cross section



- TALYS calculations performed by P. Mohr using McFadden & Satchler α-OMPs .
- Experimental CS are in good agreement with theoretical TALYS CSs within a factor of 2.
- Total reaction cross sections from the present work are higher than those of Randhawa et al. (2020)

Reaction rate comparison





SUMMARY

- A direct measurement of the $^{22}Mg(\alpha,p)^{25}Al$ reaction was performed using MUSIC at ATLAS.
- Total reaction cross sections are presented.
- Total reaction cross section is in good agreement with TALYS predictions within a factor of 2.
- Astrophysical implications are currently under investigation.

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THANK YOU