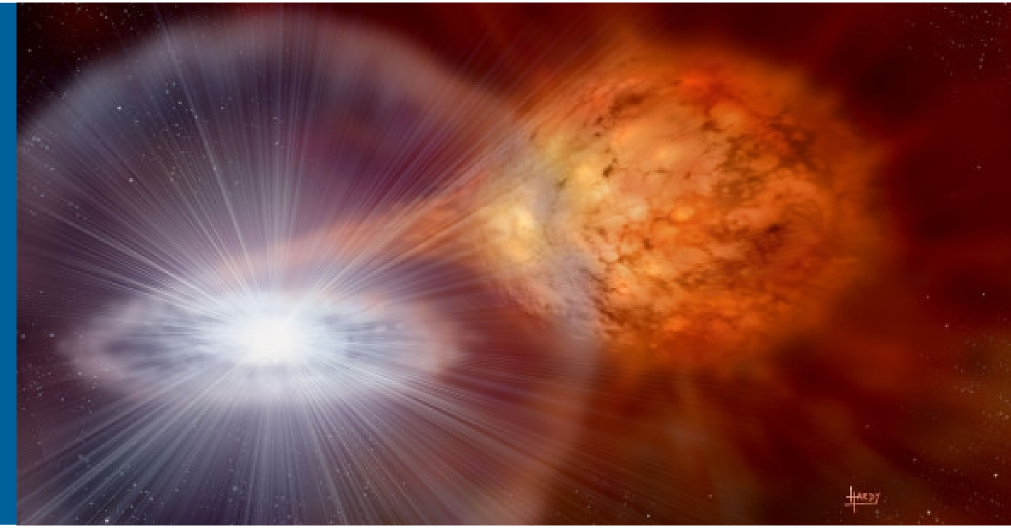
SOTANCP4 2018

STUDY OF α-PARTICLE INDUCED REACTIONS USING THE MUSIC DETECTOR



MELINA AVILA
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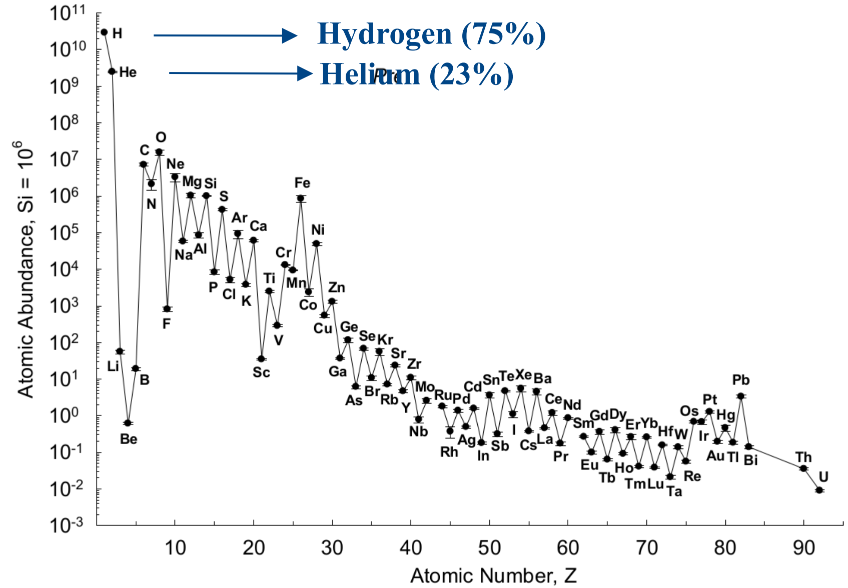
May 15 2018
Galveston TX

OUTLINE

- Motivation: Why α-induced reactions are important?
- Experimental techniques to study important nuclear reactions
- Recent results and perspectives
- Summary

α-INDUCED REACTIONS

Why are they relevant?



Lodders, et al., 2009. Landolt Börnstein, New Series, Vol. VI/4B, Chap. 4.4, J.E. Trümper (ed.), Berlin, Heidelberg, New York: Springer Verlag, p. 560 630.

Helium is the second most abundant element in the universe!

Rates of some (α,p) and (α,n) reactions are important input parameters for various astrophysical processes.

(α,p)

- X-ray burst.
- Classical novae
- Supernovae: Radioactive ^{44}Ti production

(α,n)

- s-process: Important neutron sources.
- r-process in neutrino-driven winds

X-RAY BURSTS

Type I X-ray bursts

- Explosive hydrogen-helium burning arising from thermonuclear ignition in the envelope of a neutron star in close binary systems.

- Most common thermonuclear explosions in the Galaxy.

Discovery

- They were first observed by the Astronomical Netherlands Satellite (ANS) in 1975.

- Within a year of the discovery more than 20 bursting sources were discovered

- 110 Sources known so far (The Multi-INstrument Burst ARchive (MINBAR) data base https://burst.sci.monash.edu/sources)

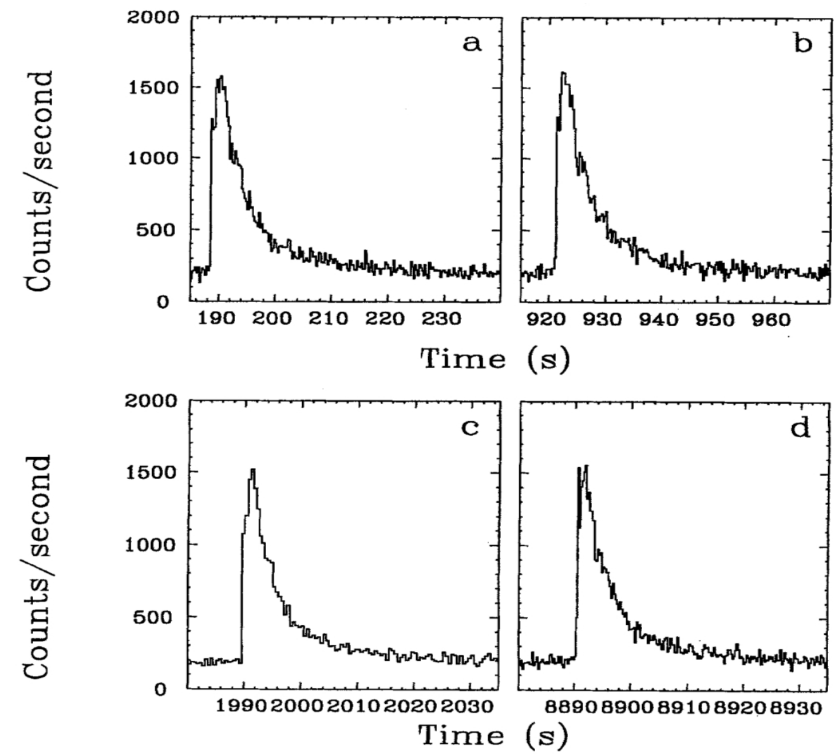
TYPE I X-RAY BURSTS OBSERVABLES

Light curves properties

- Peak luminosity ~10^{38} erg s^{-1}
- Burst duration 10-100 s
- Fast rise time ~ 0.5-10 s
- Decay time ~ 10-100 s
- No cataclysmic event recurrence rate: hours to days

Accumulation of accreted matter for hours - Unstable nuclear burning for seconds

Four of seven burst observed with EXOSAT in Aug 19 1985 during 20 hr observation



W.H.G Lawin et al. 1993

TYPE I X-RAY BURSTS OBSERVABLES

Light curves properties

Provide unique information regarding the fundamental properties of the neutron star. Can be used to constrain the mass, radius and spin frequency of a neutron star.

The X-ray light curves depend on many parameters:

- Nature of the companion star (H/He ratio)
- Accretion rate
- Surface properties (heat transport)
- Neutrinos (cooling)
- Turbulence in the explosions
- Rotation, …
- Nuclear physics

no complete understanding yet!

NUCLEAR PHYSICS IN TYPE I X-RAY BURSTS

NUCLEOSYNTHESIS IN TYPE I X-RAY BURSTS

Burst ignition

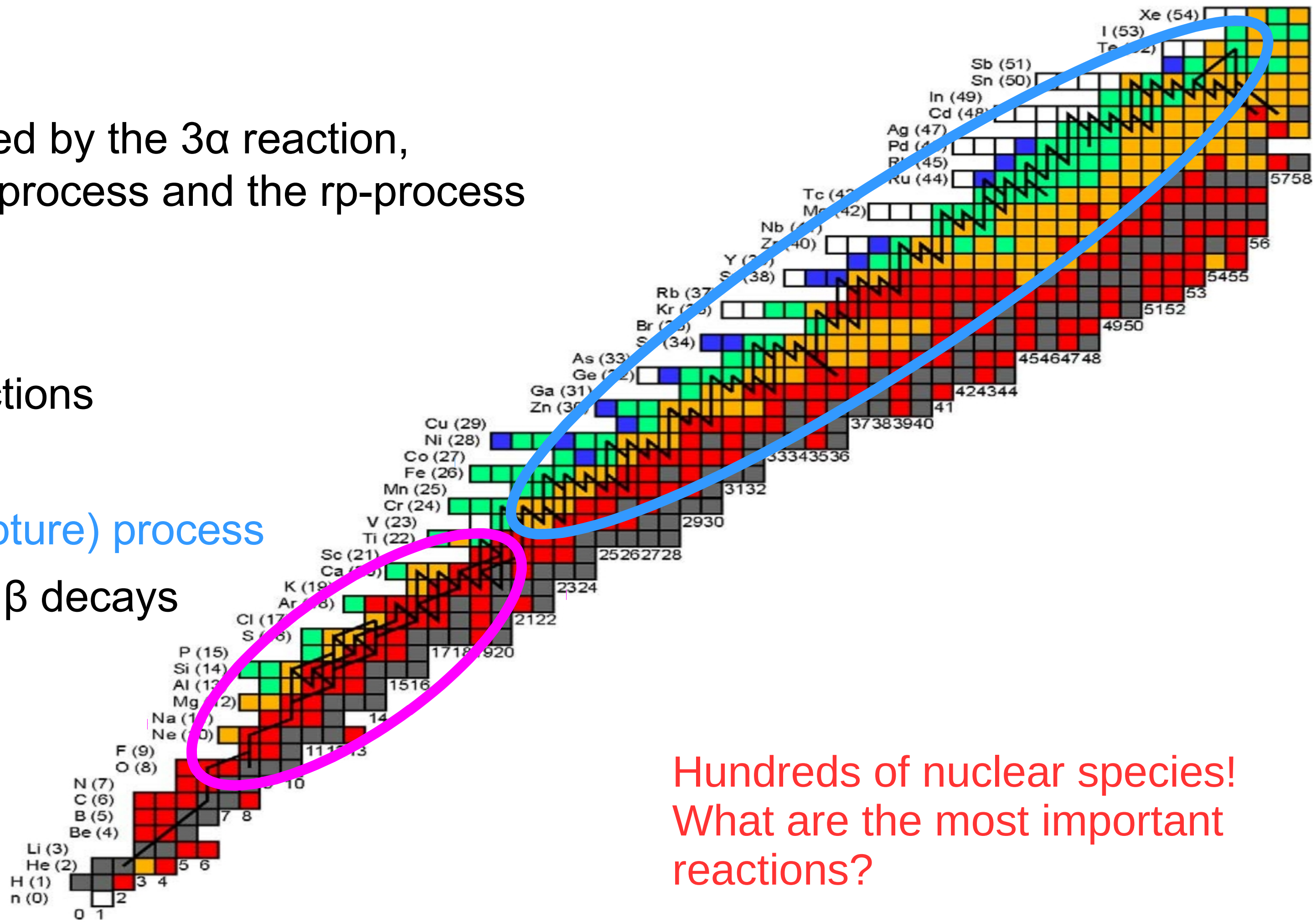
The burst is powered by the 3α reaction, followed by the αp-process and the rp-process

- αp process

  (α,p) and (p,γ) reactions

- rp (rapid proton capture) process

  (p,γ) reactions and β decays



Hundreds of nuclear species!
What are the most important reactions?

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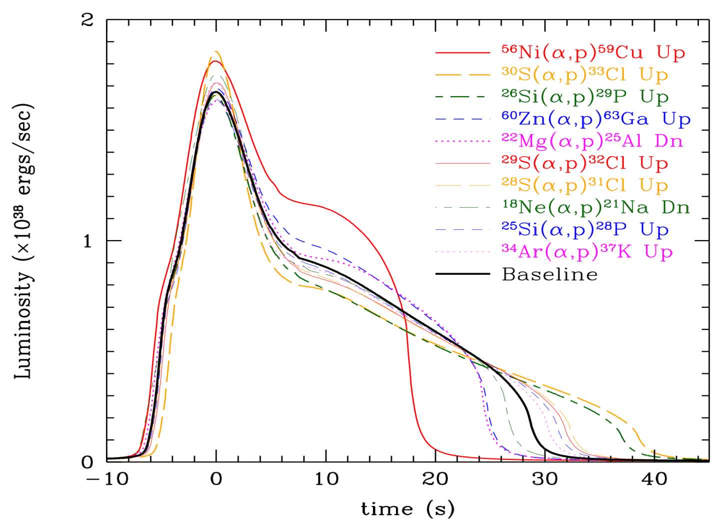
SENSITIVITY STUDIES

Identify key nuclear reactions

Sensitivity study using self-consistent X-ray burst models that account for the coupling between nuclear energy generation and the astrophysical conditions.

R.H. Cyburt et al., ApJ **830**, 55 (2016)

- Relevant (α,p) reactions in the single-zone model



- Relevant reactions in the multi-zone model

Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	^{15}O(α, γ)^{19}Ne	D	16	1
2	^{56}Ni(α, p)^{59}Cu	U	6.4	1
3	^{59}Cu(p, γ)^{60}Zn	D	5.1	1
4	^{61}Ga(p, γ)^{62}Ge	D	3.7	1
5	^{22}Mg(α, p)^{25}Al	D	2.3	1
6	^{14}O(α, p)^{17}F	D	5.8	1
7	^{23}Al(p, γ)^{24}Si	D	4.6	1
8	^{18}Ne(α, p)^{21}Na	U	1.8	1
9	^{63}Ga(p, γ)^{64}Ge	D	1.4	2
10	^{19}F(p, α)^{16}O	U	1.3	2
11	^{12}C(α, γ)^{16}O	U	2.1	2
12	^{26}Si(α, p)^{29}P	U	1.8	2
13	^{17}F(α, p)^{20}Ne	U	3.5	2
14	^{24}Mg(α, γ)^{28}Si	U	1.2	2
15	^{57}Cu(p, γ)^{58}Zn	D	1.3	2
16	^{60}Zn(α, p)^{63}Ga	U	1.1	2
17	^{17}F(p, γ)^{18}Ne	U	1.7	2
18	^{40}Sc(p, γ)^{41}Ti	D	1.1	2
19	^{48}Cr(p, γ)^{49}Mn	D	1.2	2

Many (α,p) reactions!

SUMMARY OF IMPORTANT (α,p) REACTIONS

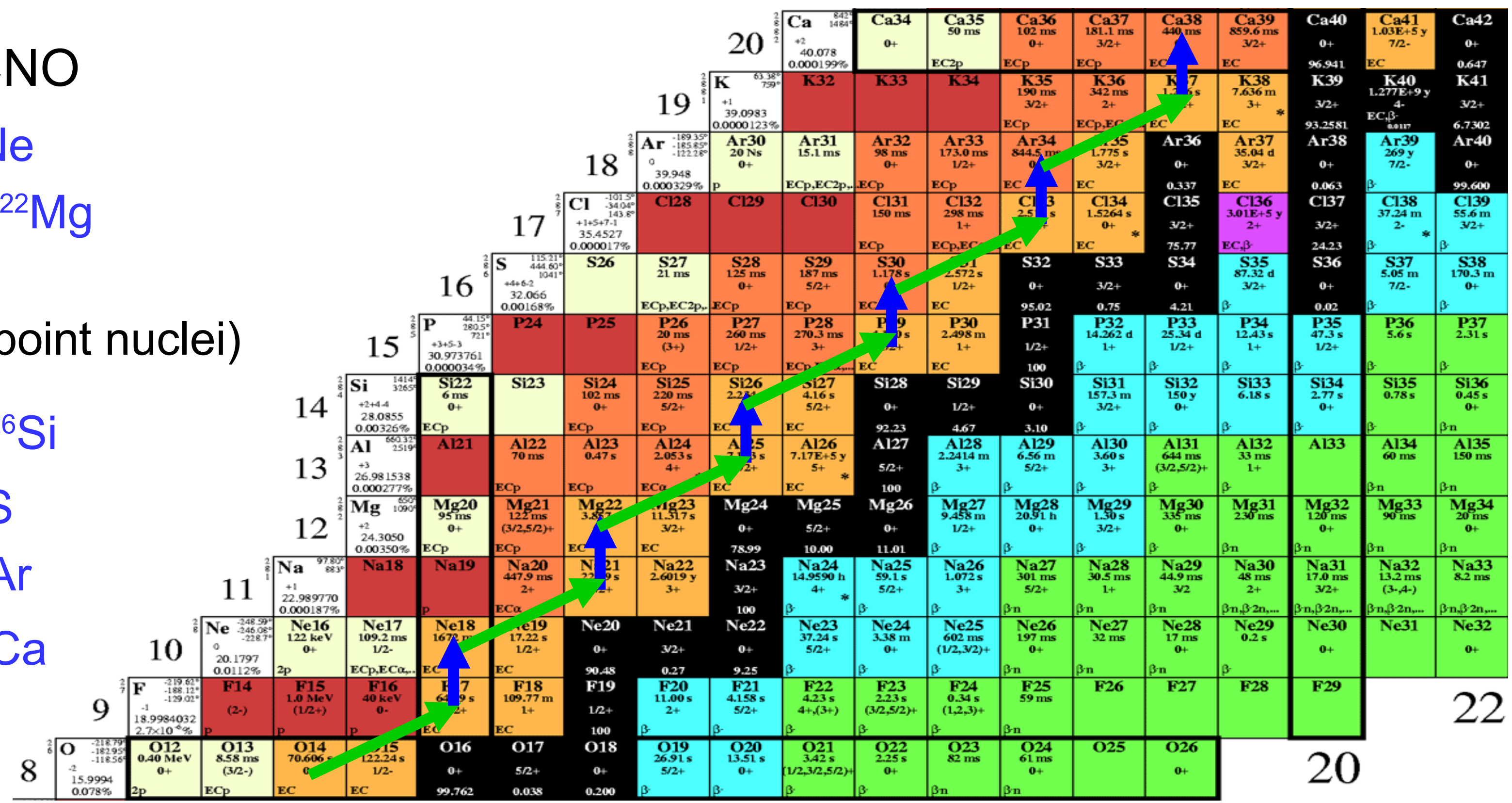
For A<34

Break-out from HCNO

- ^{14}O(α,p)^{17}F(p,γ)^{18}Ne
- ^{18}Ne(α,p)^{21}Na(p,γ)^{22}Mg

αp-process (waiting point nuclei)

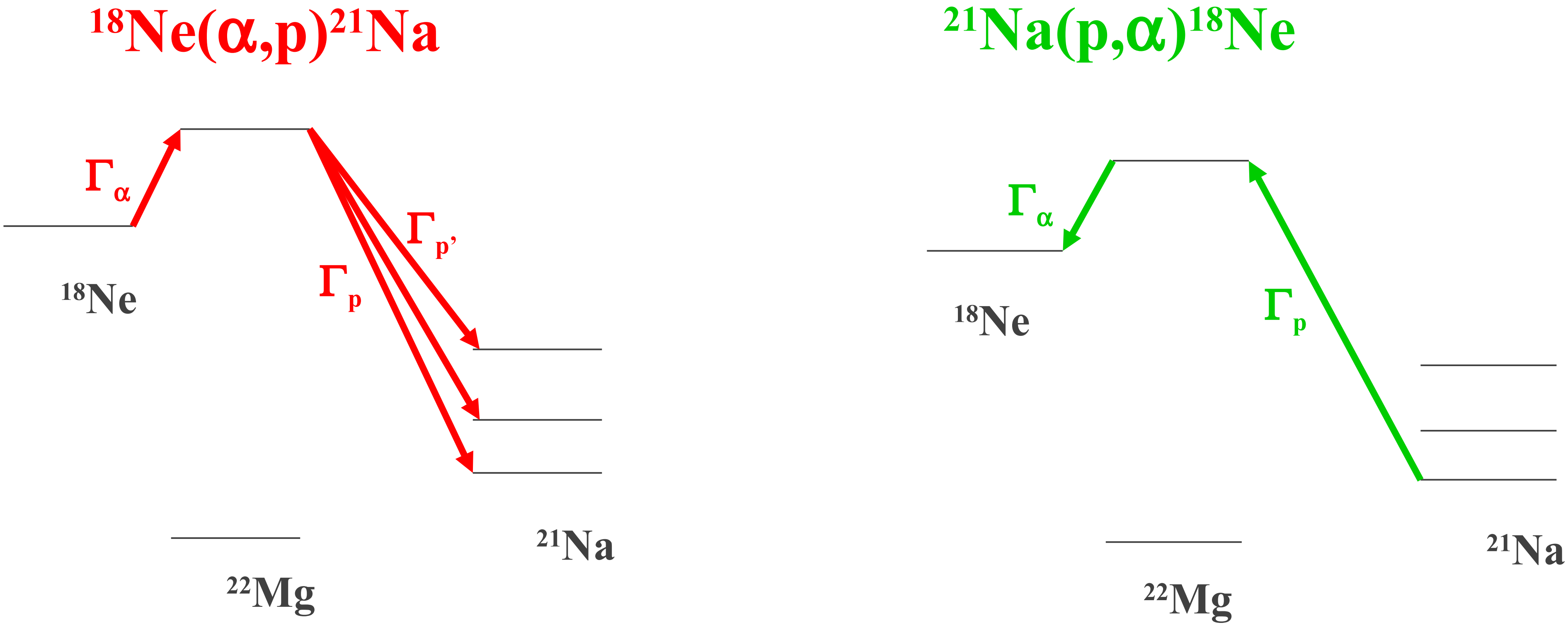
- ^{22}Mg(α,p)^{25}Al(p,γ)^{26}Si
- ^{26}Si(α,p)^{29}P(p,γ)^{30}S
- ^{30}S(α,p)^{33}Cl(p,γ)^{34}Ar
- ^{34}Ar(α,p)^{37}K(p,γ)^{38}Ca



These experiments require exotic beams!

STUDY OF (α,p) VIA THE TIME-INVERSE REACTION

Example for the $^{18}Ne(\alpha,p)^{21}Na$ reaction



Only ground state to ground state transition!

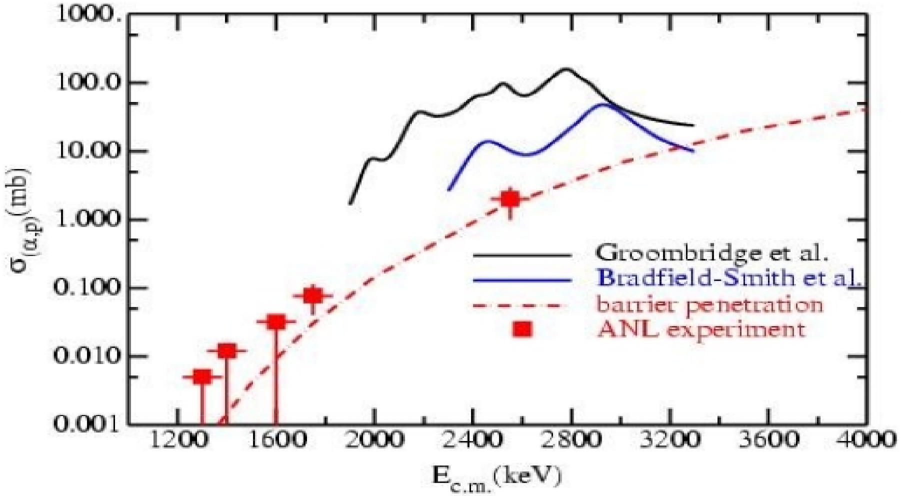
STUDY OF (α,p) VIA THE TIME-INVERSE REACTION

The $^{18}Ne(\alpha,p)^{21}Na$ reaction

Used $^{21}Na(p,\alpha)^{18}Ne$ to study the break-out reaction $^{18}Ne(\alpha,p)^{21}Na$

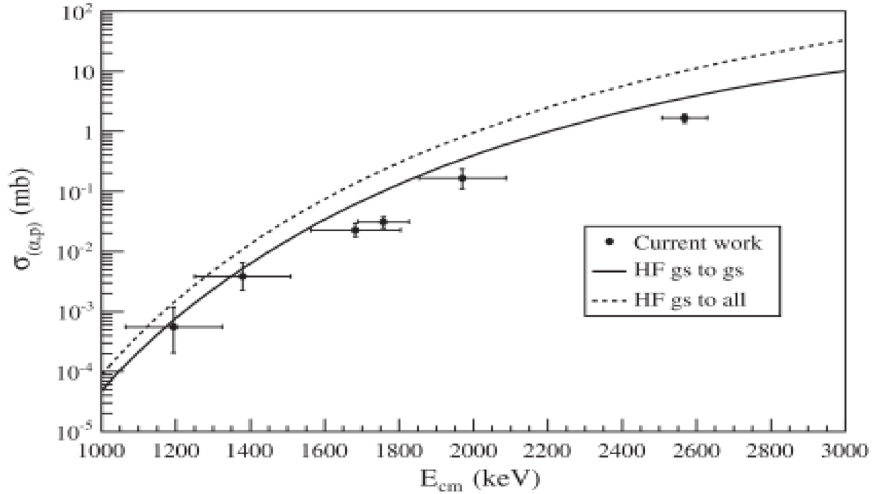
ANL

S. Sinha, et al., ANL Internal report 2004



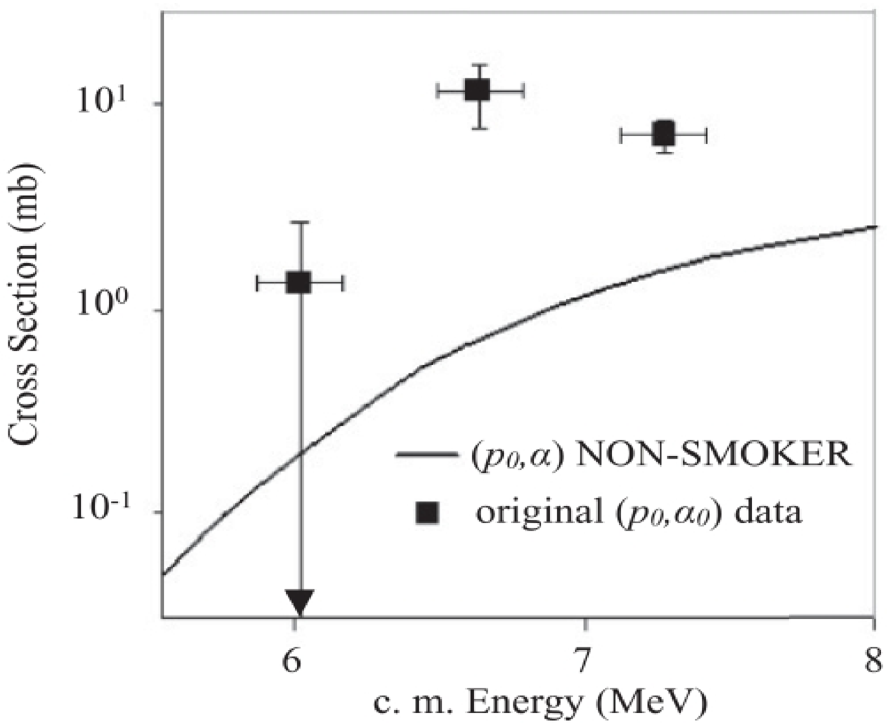
TRIUMF

P.J.C. Salter et al.,PRL 108, 242701 (2012)



STUDY OF (α,p) VIA THE TIME-INVERSE REACTION

The ^{30}S(α,p)^{33}Cl reaction



Used ^{33}Cl(p,α)^{30}S to study the ^{30}S(α,p)^{33}Cl reaction

ANL

C.M Deibel et al.,PRC 84, 045802 (2011)

Also measured:
^{29}P(p,α)^{26}Si
^{37}K(p,α)^{34}Ar
^{25}Al(p,α)^{22}Mg

C.M Deibel et al.,NICXI 56 (2010)

STUDY OF (α,p) VIA THE TIME-INVERSE REACTION

Limitations of previous measurements

- Only ground state to ground state transition
- Long time to measure a single energy point
- Difficult to tune the beam and to change energy
- Problems associated to low efficient detectors
- Uncertainties related to normalization of the cross section

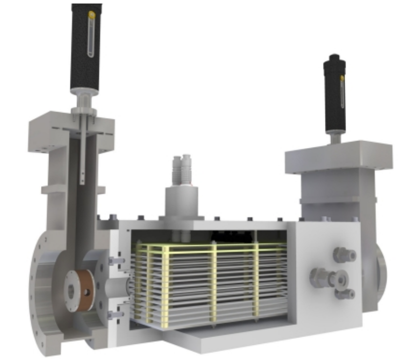
Most of current models and studies are based on theoretical Hauser-Feschbach reaction rates

Need of more intense radioactive beams and more efficient detectors!

MEASUREMENTS WITH THE MUSIC DETECTOR AT ANL

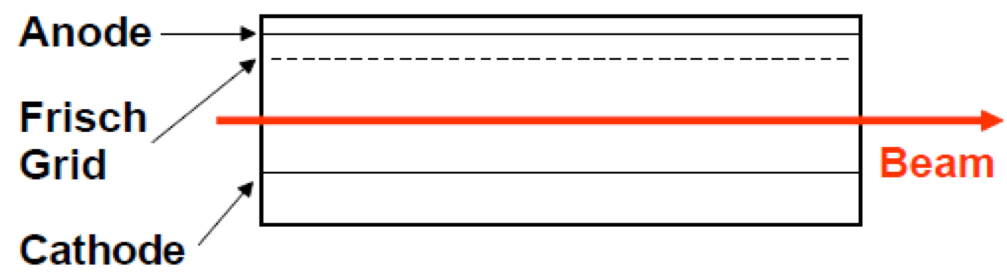
THE MUSIC DETECTOR

Multi-Sampling Ionization Chamber

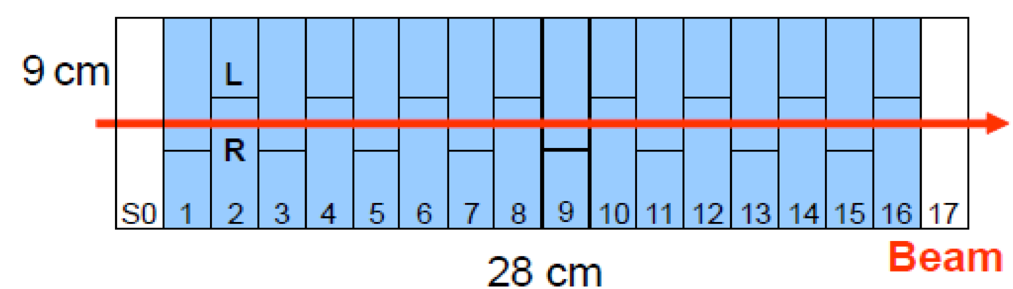


MUSIC is an active target detector in where the counting gas serves as target and detector gas

- Highly efficient because segmented anode allows to measure large energy range with a single energy beam
- Self normalizing: No additional monitors for absolute normalization
- Counting gases: He, CH_4, Ne, Ar
- 34 channels
- Counting rate ~ 5 KHz



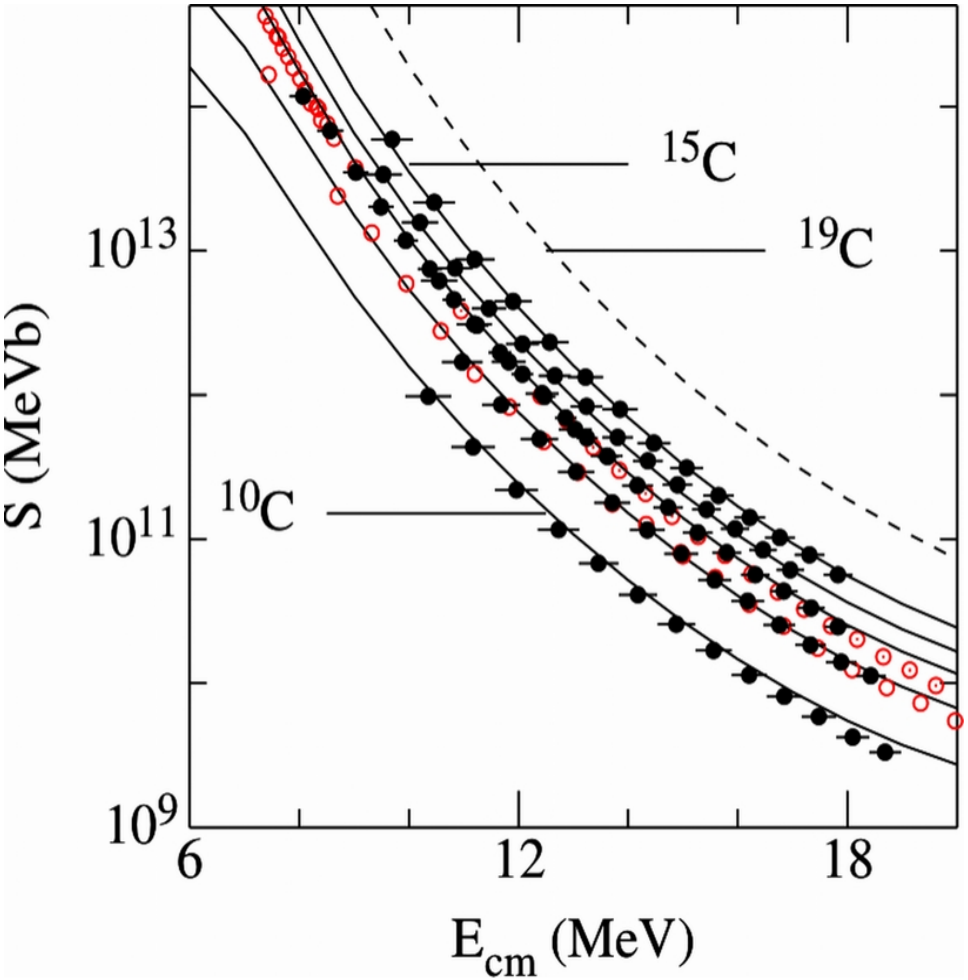
Schematic of the anode structure



THE MUSIC DETECTOR

Fusion reactions: $^{12}C+^{10,12,13,14,15}C$

- Measured S factor at 12 energies with one beam energy
- Good agreement with theory

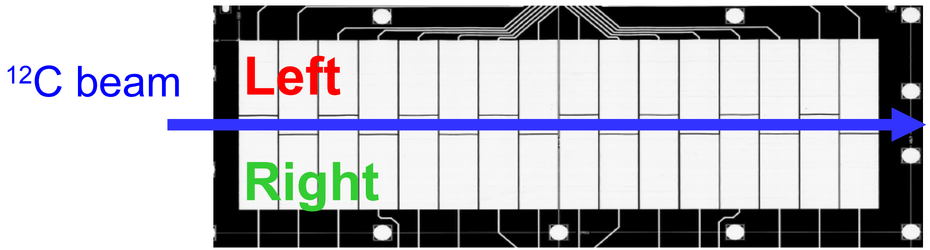


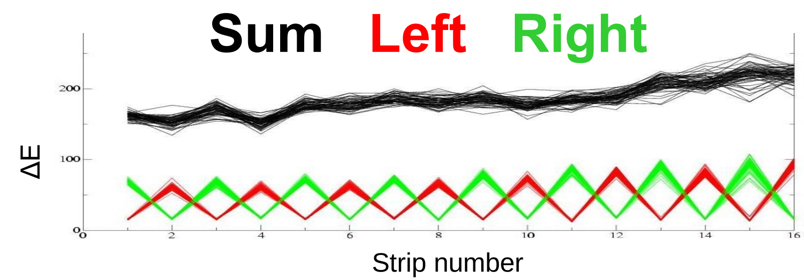
P. F.F Carnelli et al., PRL 112, 192701 (2014)

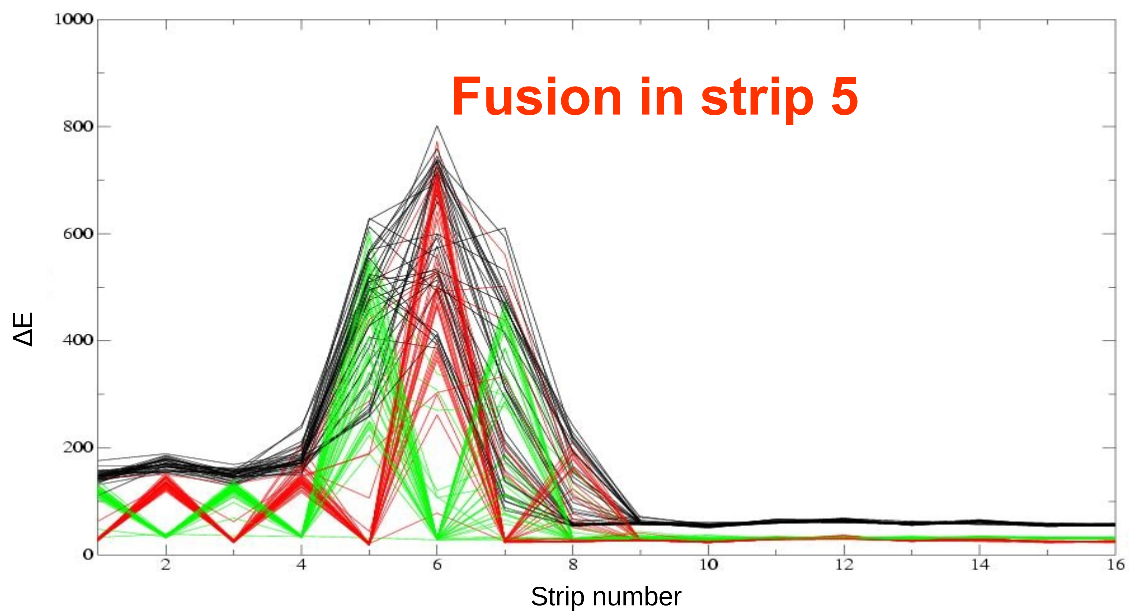
THE MUSIC DETECTOR

Event-by-event analysis

Example: $^{12}C + ^{12}C$ fusion







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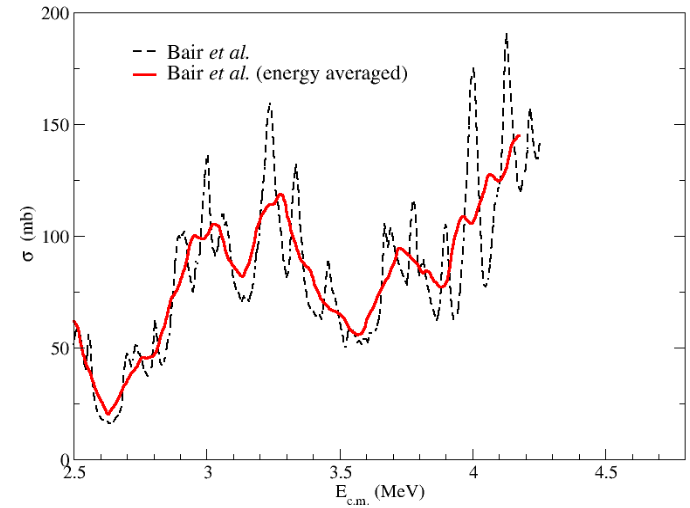
THE MUSIC DETECTOR

Calibration of the technique

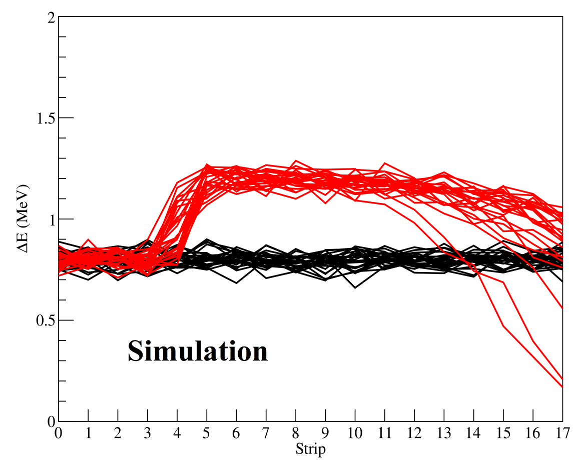
- Chose the $^{17}O(\alpha,n)^{20}Ne$ reaction that has been measure before
- (α,p) is energetically forbidden
- Simulations showed is possible

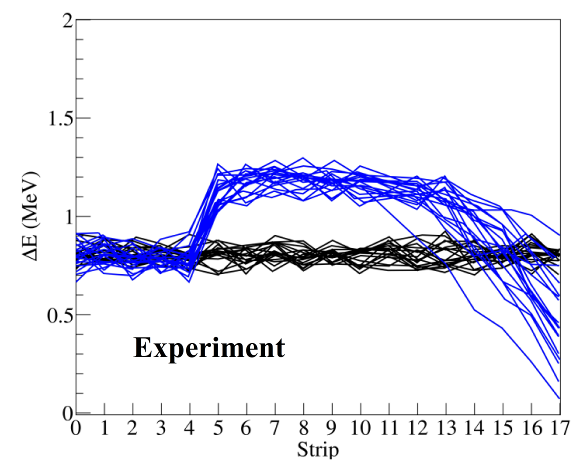


J.K. Bair, et al. Phys. Rev. C **7**, 1356 (1973)

Experimental information:

- ^{17}O energy: 34.8 MeV
- Gas pressure: 200 Torr
- Beam intensity: 5000 pps

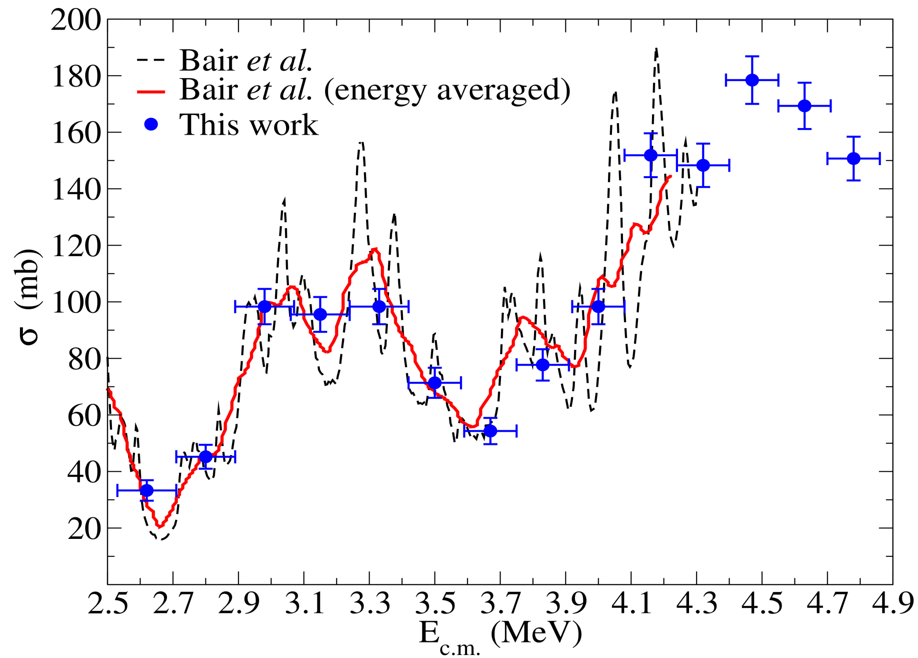




STUDY OF α-INDUCED REACTIONS WITH MUSIC

Calibration of the technique

The $^{17}O(\alpha,n)^{20}Ne$ reaction with MUSIC



Successfully measured (α,n) with MUSIC!

M.L. Avila et al., Nucl. Inst. and Meth. A, **859**, 63 (2017)

STUDY OF α-INDUCED REACTIONS WITH MUSIC

The $^{23}Na(\alpha,p)^{26}Mg$ and $^{23}Na(\alpha,n)^{26}Al$ reactions

- The $^{23}Na(\alpha,p)^{26}Mg$ reaction directly influences the production of ^{26}Al in massive stars
- Important proton source for the $^{25}Mg(p,\gamma)^{26}Al$

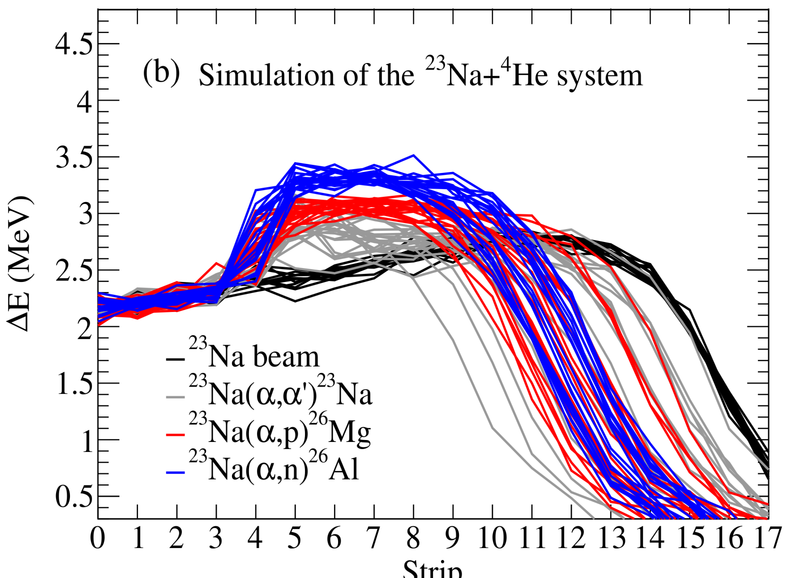
- The $^{23}Na(\alpha,n)^{26}Al$ reaction important for the production of ^{26}Al in massive stars
- $^{26}Al(n,\alpha)^{23}Na$ is one of the dominant destruction mechanisms of ^{26}Al

STUDY OF α-INDUCED REACTIONS WITH MUSIC

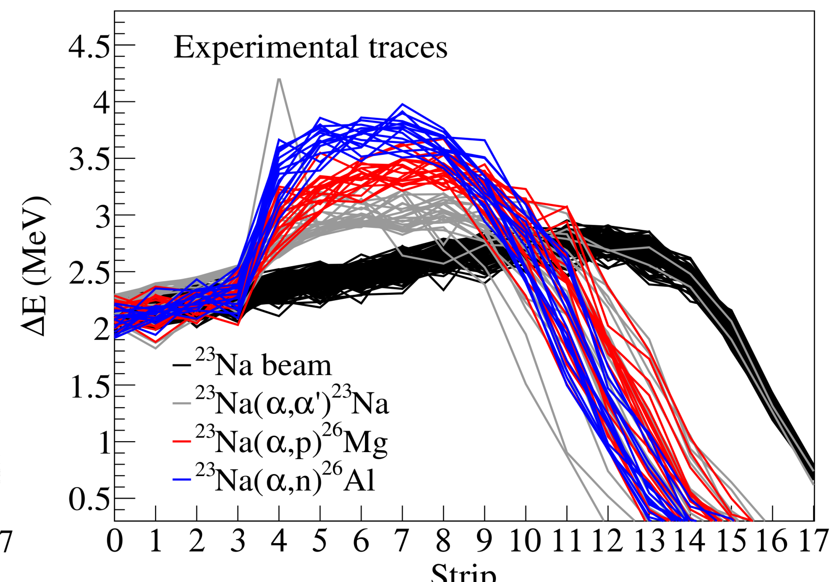
The ^{23}Na(α,p)^{26}Mg and ^{23}Na(α,n)^{26}Al reactions

- The experiment was performed in inverse kinematics
- Beam energies of 51.5 and 57.4 MeV
- Gas Pressure ~400 Torr

Simulation



Experiment



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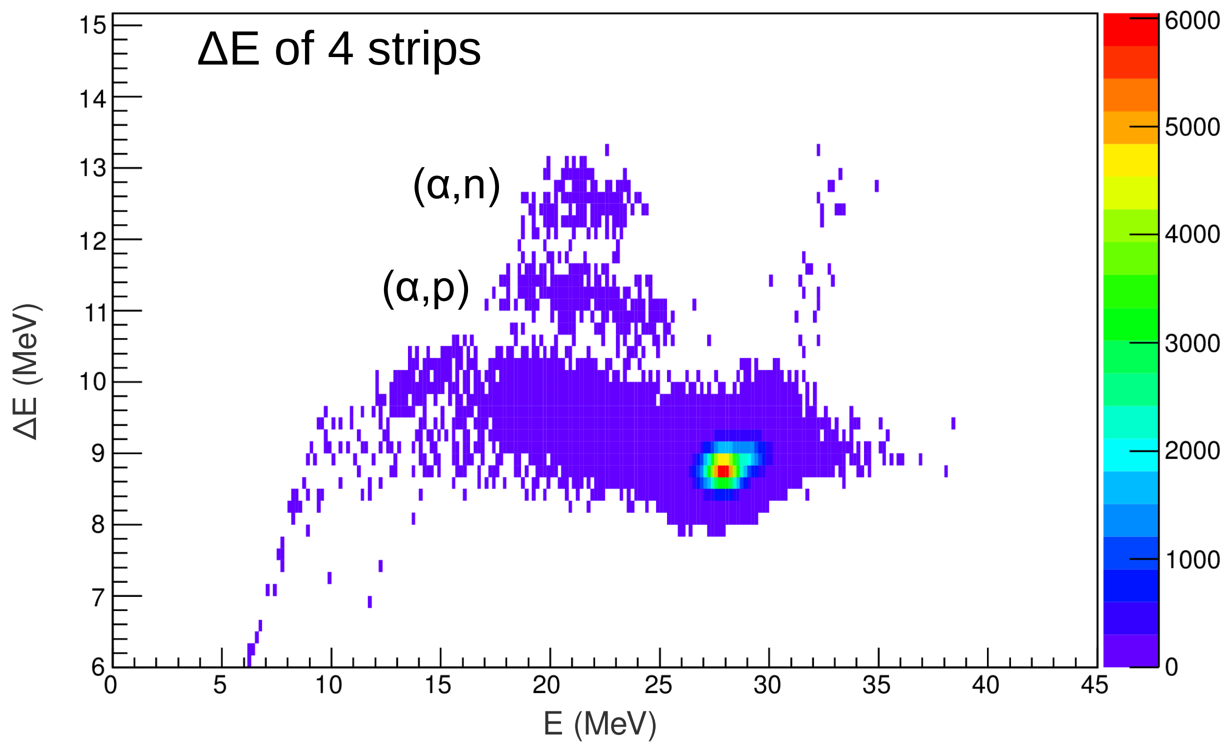
STUDY OF α-INDUCED REACTIONS WITH MUSIC

The $^{23}Na(\alpha,p)^{26}Mg$ and $^{23}Na(\alpha,n)^{26}Al$ reactions

Identification of events from different reactions occurring in strip 4



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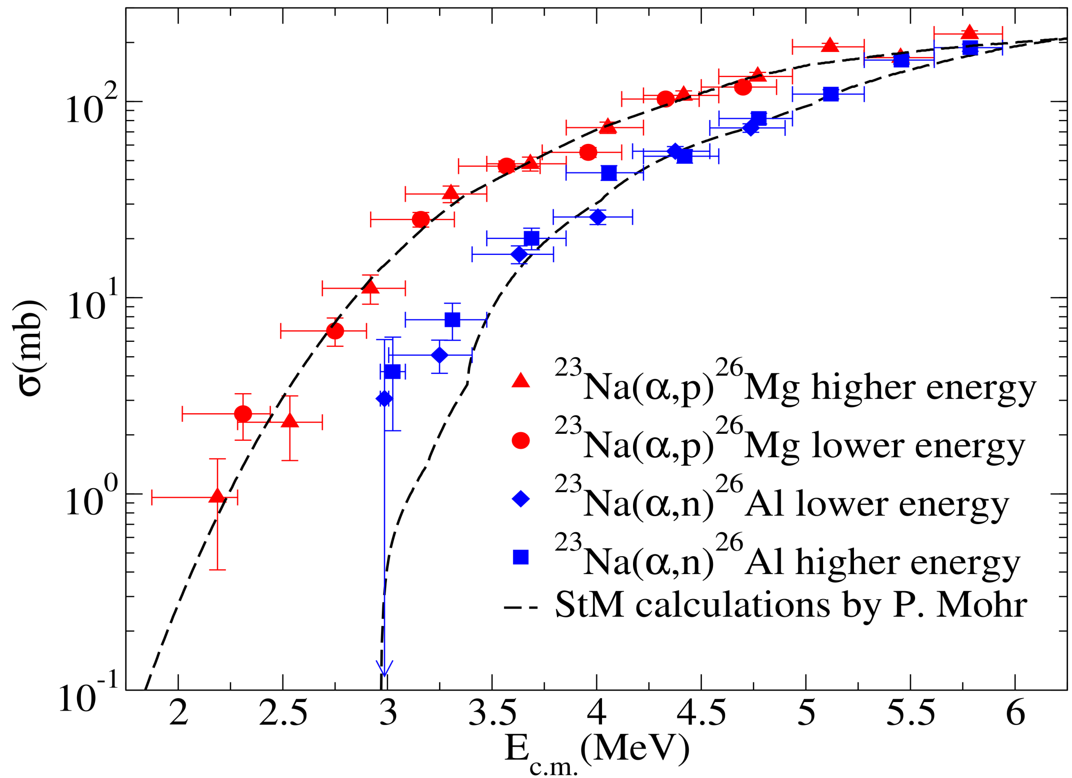
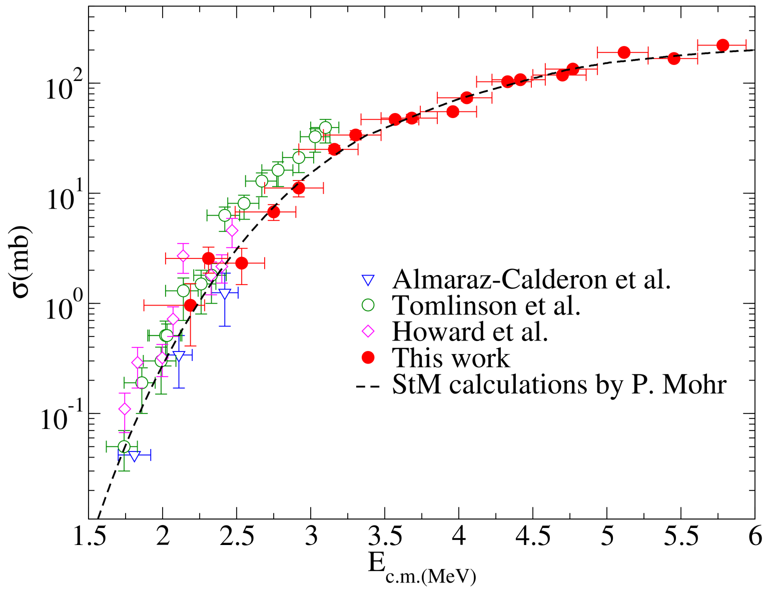


Measured (α,p) and (α,n) simultaneously in one day!

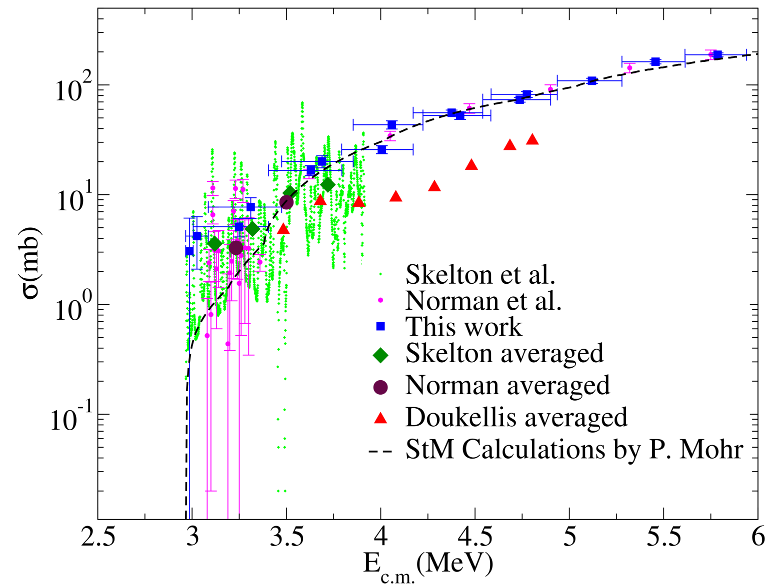
M. L. Avila et al., Phys. Rev. C 94, 065804 (2016)

STUDY OF α-INDUCED REACTIONS WITH MUSIC

The ^{23}Na(α,p)^{26}Mg and ^{23}Na(α,n)^{26}Al reactions



Our data agrees with previous measurements

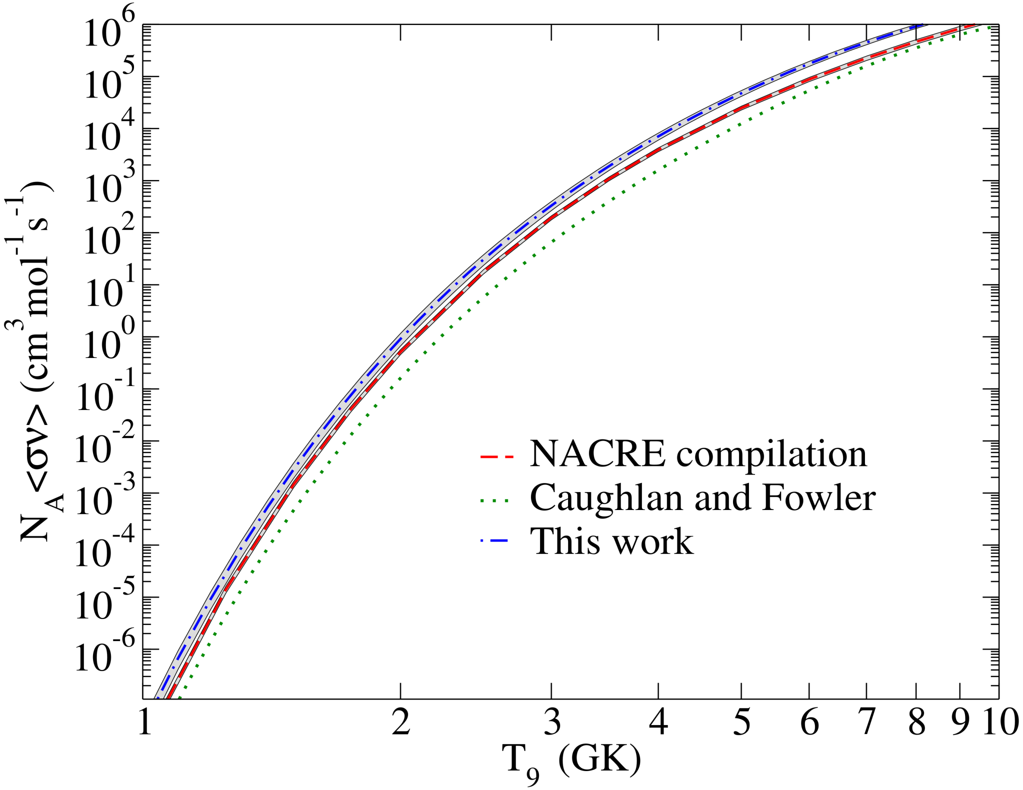


Our data agrees with Norman and Skelton but not Doukellis.

M. L. Avila et al., Phys. Rev. C 94, 065804 (2016)

STUDY OF α-INDUCED REACTIONS WITH MUSIC

The $^{23}Na(\alpha,n)^{26}Al$ reaction



Reaction rate is higher than the previously recommended

M. L. Avila et al., Phys. Rev. C 94, 065804 (2016)

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STUDY OF α-INDUCED REACTIONS WITH MUSIC

The $^{17}F(\alpha,p)^{20}Ne$ reaction

- Ranked as one of the most important reactions for type I X-ray affecting the light curve and the composition of the ashes.
- The primary reactions that affect the ^{44}Ti production in core collapse supernovae

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
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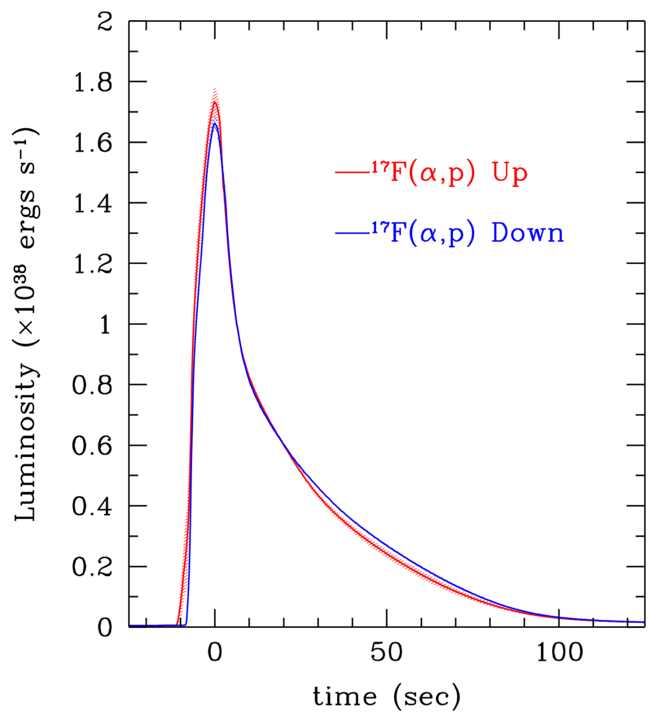
R.H. Cyburt et al., ApJ **830**, 55 (2016)



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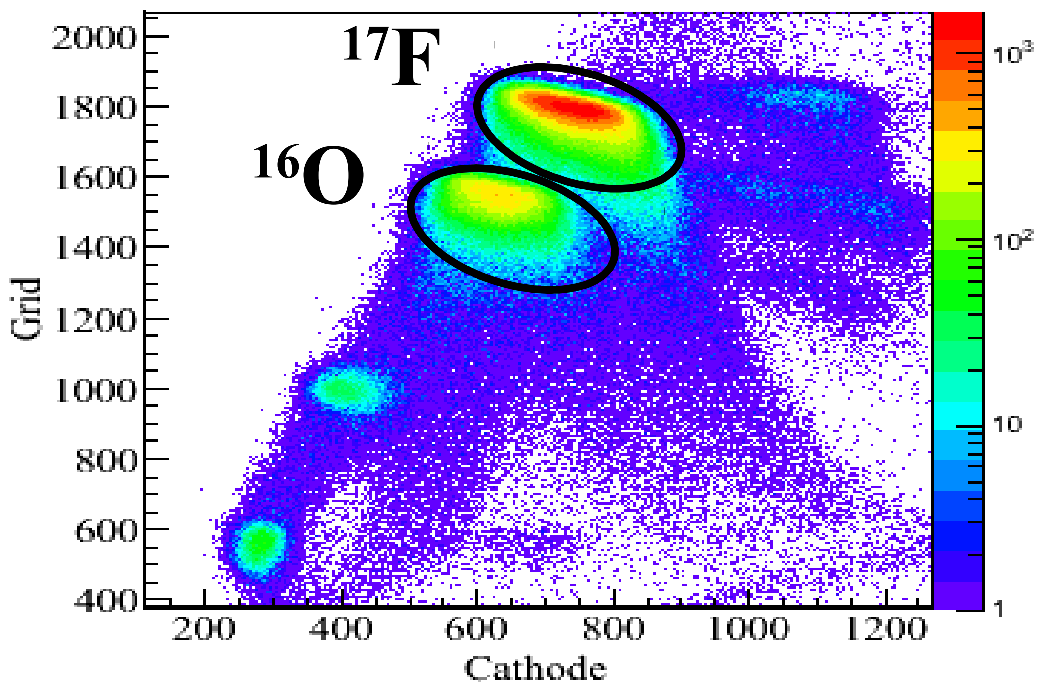
STUDY OF α-INDUCED REACTIONS WITH MUSIC

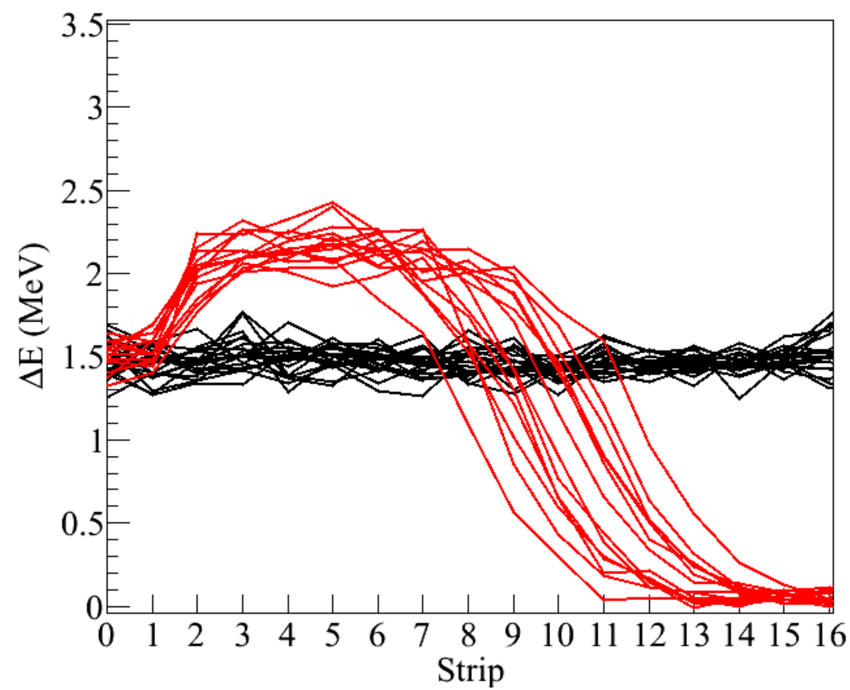
The $^{17}F(\alpha,p)^{20}Ne$ reaction

^{17}F produced using the in-flight technique via the reaction $^{16}O(d,n)^{17}F$

Particle ID



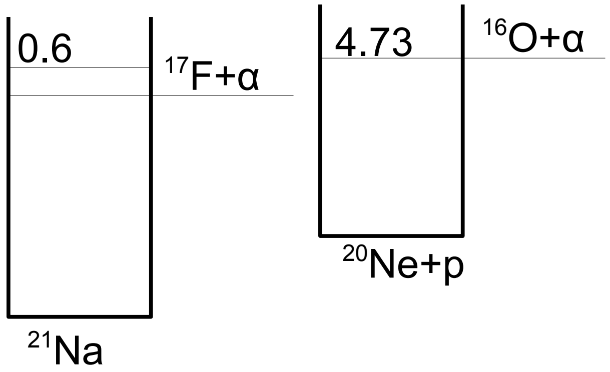
Experimental traces

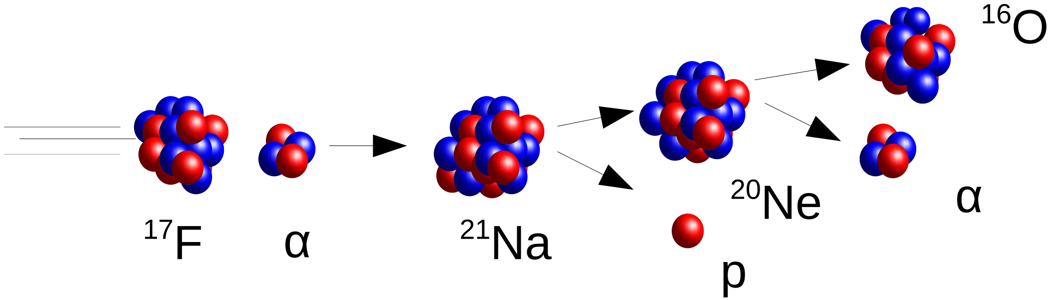


STUDY OF α-INDUCED REACTIONS WITH MUSIC

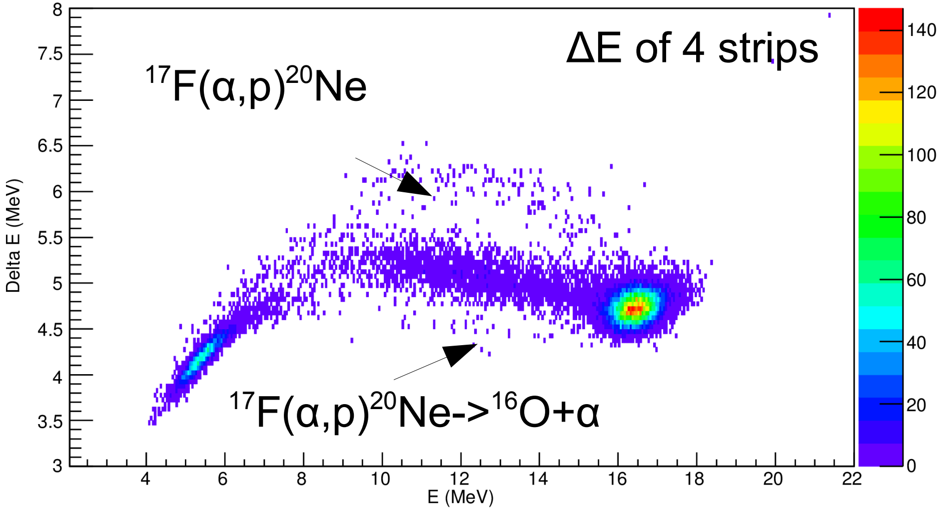
The $^{17}F(\alpha,p)^{20}Ne$ reaction

$^{20}Ne \rightarrow {}^{16}O+\alpha$ Q=4.13 MeV





Identification of events from different reactions occurring in strip 4



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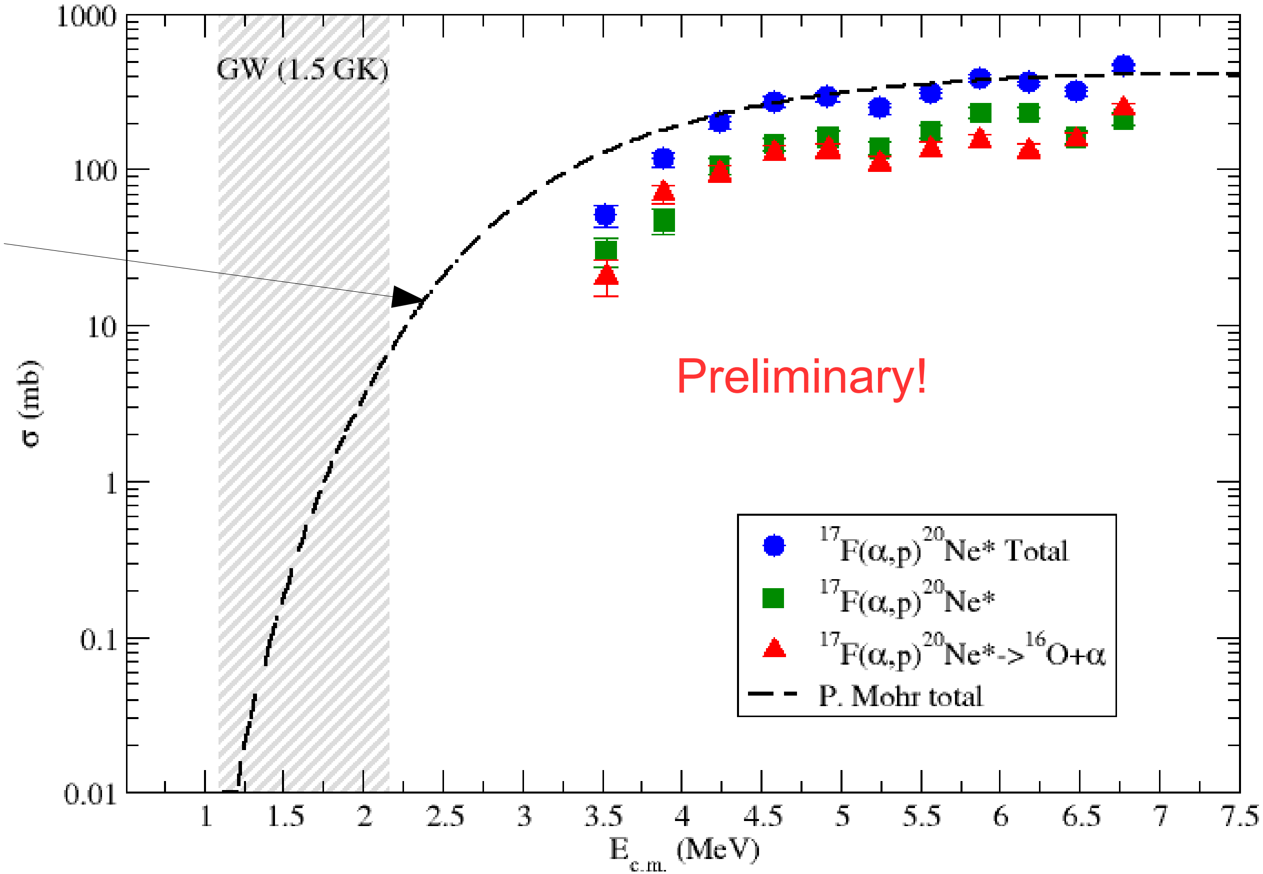
STUDY OF α-INDUCED REACTIONS WITH MUSIC

The $^{17}F(\alpha,p)^{20}Ne$ reaction

Have data at lower energy



PERSPECTIVE

Measurement of important reactions for X ray bursts

- MUSIC can be used for measuring many other (α,p) reactions
- Upcoming upgrades like the Argonne In-flight Radioactive Ion Separator (AIRIS) and later the Facility for Rare Isotope Beams (FRIB) will give us access to exotic beams
- New improvements will allow us to increase the rate and study smaller cross sections

SUMMARY

- Nuclear reaction rates of (α,n) and (α,p) reactions are crucial in many astrophysical scenarios
- Upcoming upgrades in facilities will give us access to exotic beams which will allow us to study more exotic reactions
- The high efficient detector MUSIC offers great possibilities of study for direct measurements with radioactive beams
- The MUSIC detector has been successfully use for (α,n) and (α,p) reactions, such as the astrophysically important ^{23}Na(α,p)^{26}Mg and ^{23}Na(α,n)^{26}Al reactions and ^{17}F(α,p)^{20}Ne.

COLLABORATORS

ANL

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THANK YOU!

Argonne NATIONAL LABORATORY