X線バーストにおける重要不安定核反応の実験的検証
Experimental investigation of relevant unstable-nucleus reactions in X-ray bursts

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Topics

- Experimental evaluation of reactions from an unstable nucleus (RI) to another RI relevant for X-ray bursts ⇒ still challenging, due to the limited intensity of RI beams.

Two recent examples at CRIB (RI beam separator of U-Tokyo):

◆ ^{22}Mg(α, p)^{25}Al reaction study with resonant scattering

Jun Hu, H. Yamaguchi et al., Phys. Rev. Lett. **127**, 172701 (2021).

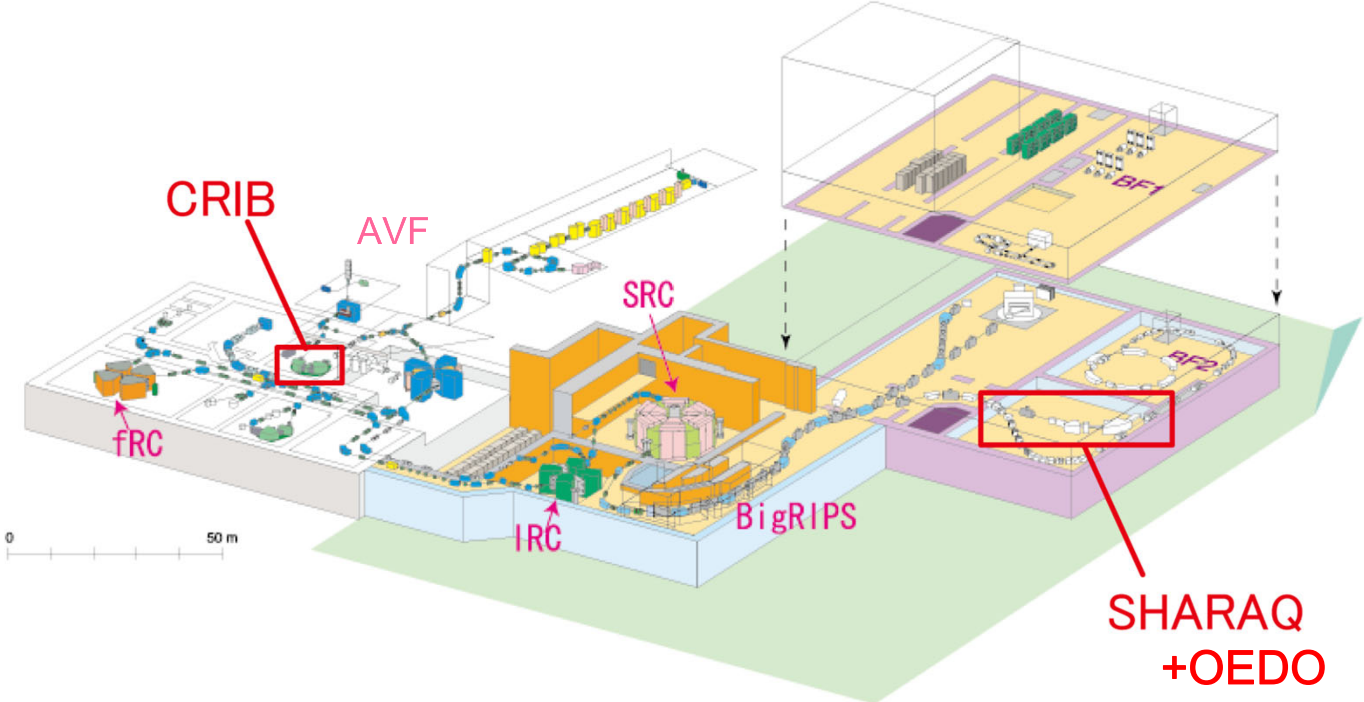
◆ ^{26}Si(α, p)^{29}P reaction study with direct measurement

Measurement performed in 2022, analysis in progress (K. Okawa's Ms thesis)

CRIB/OEDO in RIBF

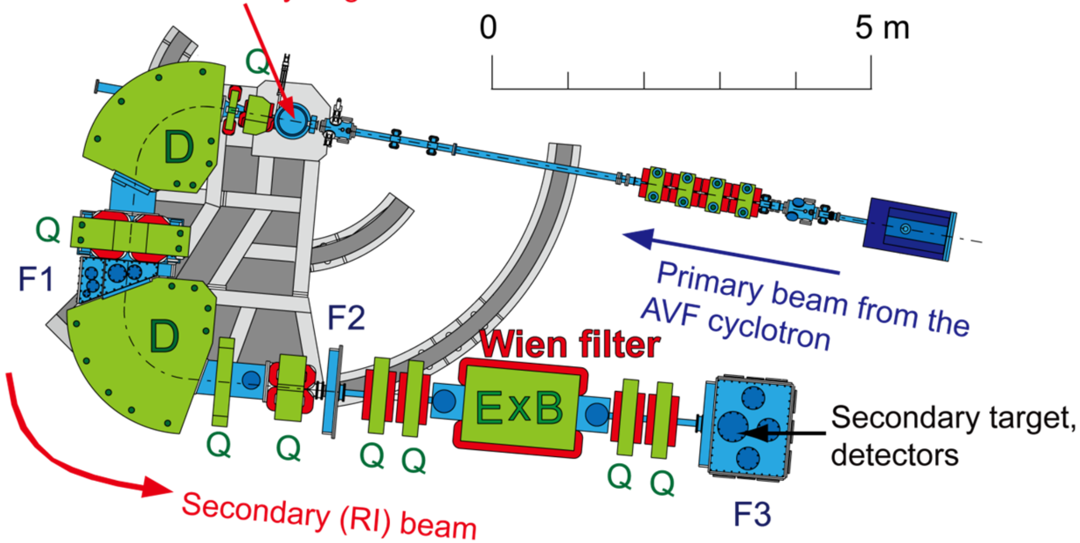
RI-beam apparatuses operated by CNS, the University of Tokyo at RIBF

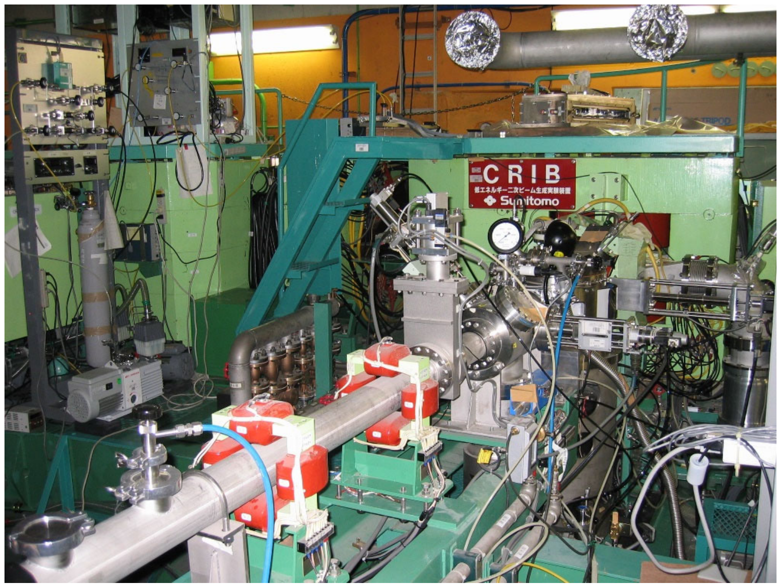
- CRIB: RI beam separator for low-mass, low-energy (<10 MeV/u) RI beams
- SHARAQ: high resolution spectrometer
- OEDO: new low-energy (20-50 MeV/u) beamline for exotic beams

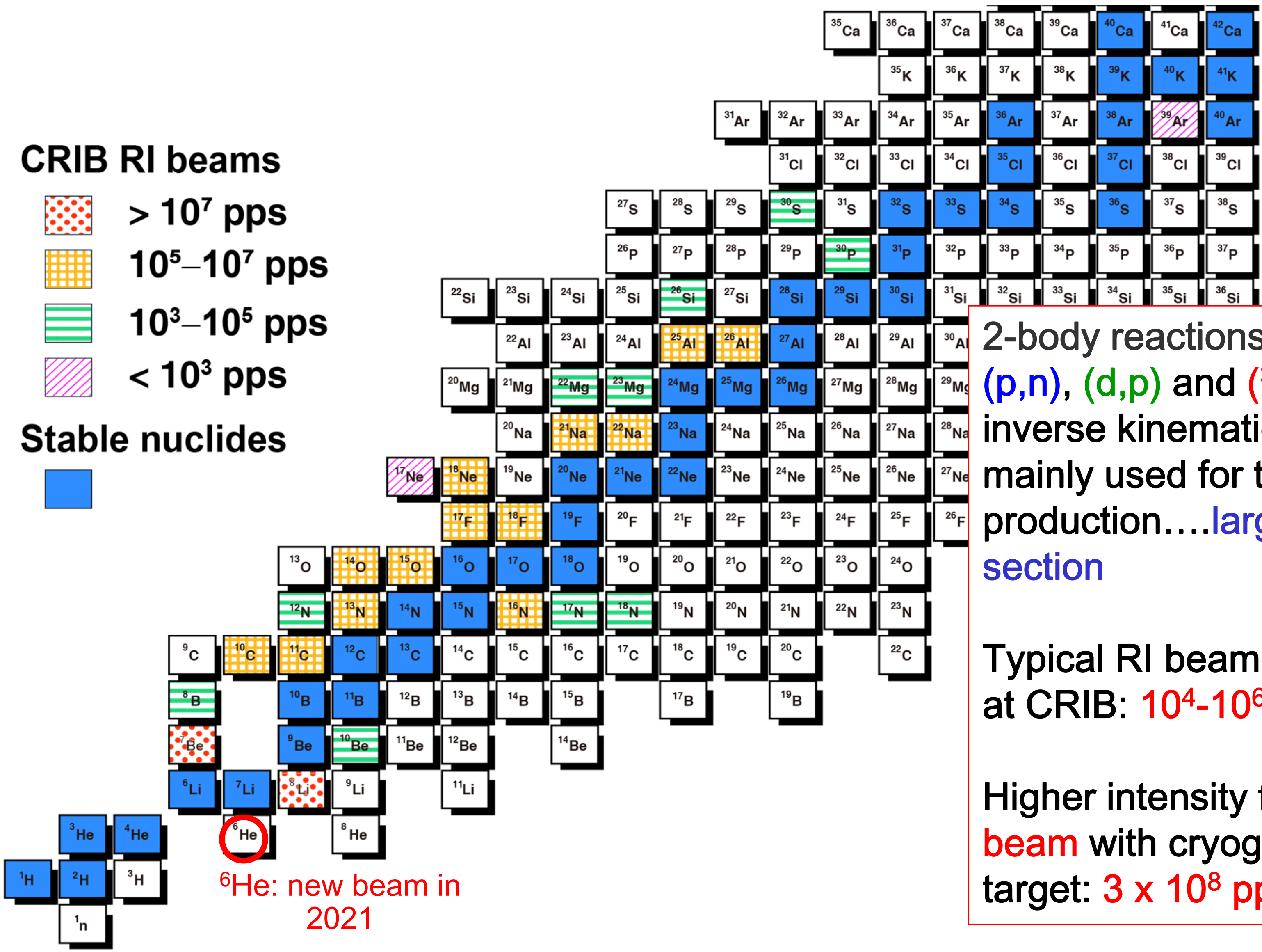


CRIB – Low energy RI beam separator of CNS

- CNS Radio-Isotope Beam separator , operated by CNS (Univ. of Tokyo), located at RIBF (RIKEN Nishina Center).
  - ◆ Low-energy(<10MeV/u) RI beams by in-flight method.
  - ◆ Primary beam from K=70 AVF cyclotron.
  - ◆ Momentum (Magnetic rigidity) separation by “double achromatic” system, and velocity separation by a Wien filter.







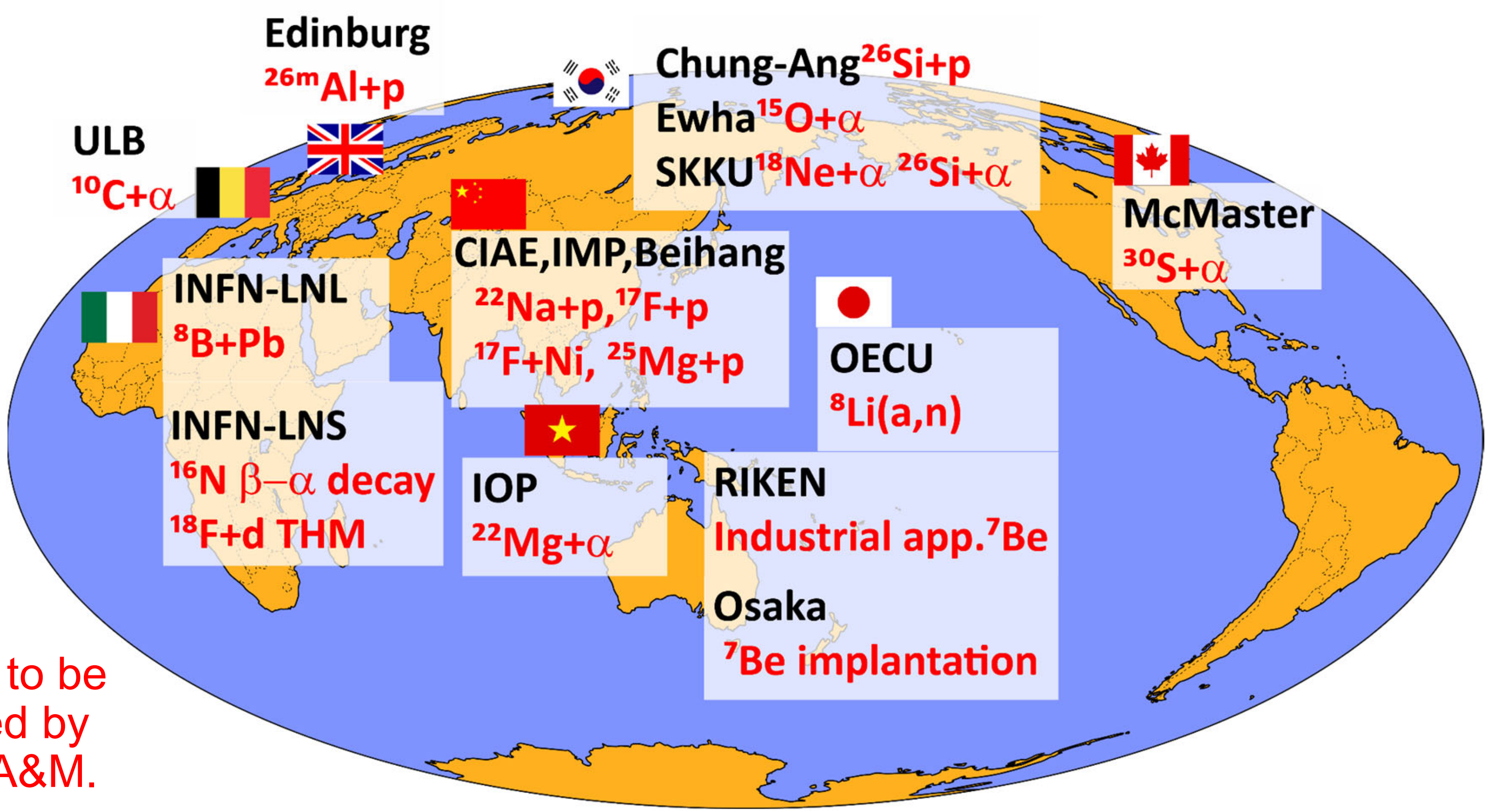
2-body reactions such as (p,n), (d,p) and (^{3}He,n) in inverse kinematics are mainly used for the production….large cross section

Typical RI beam intensity: at CRIB: 10^4-10^6 pps

Higher intensity for ^{7}Be beam with cryogenic H_2 target: 3 x 10^8 pps.

CRIB is collaborative

- Recent CRIB collaborators (only the main institutes that proposed an experiment are shown):

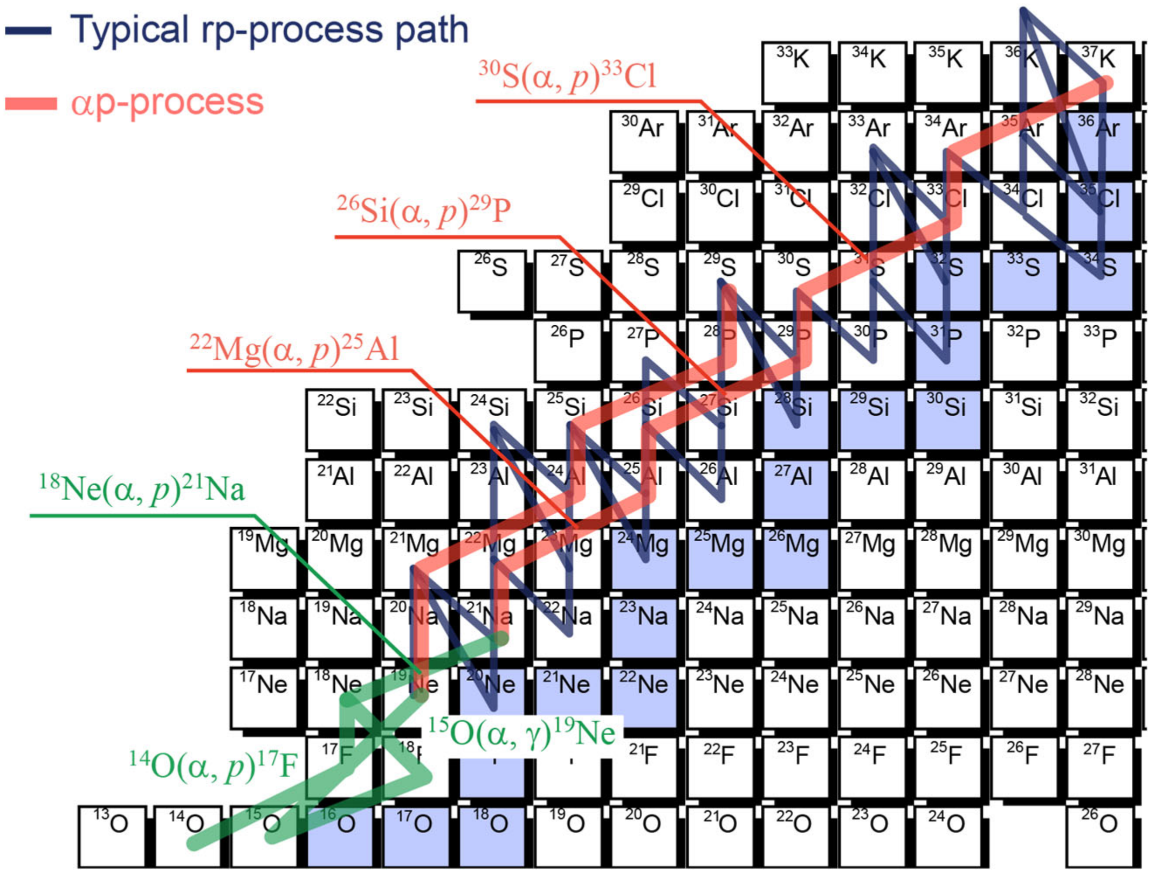


2023 Mar:
^{14}O+α experiment is to be performed, proposed by IBS(Korea)+Texas A&M.

Key α-induced reactions in X-ray bursts

- The "rp-process" in X-ray bursts (T_{max} can be 2-3 GK) takes a path including (α, p) reactions to skip sequential (p, γ) and β decays… the αp-process.

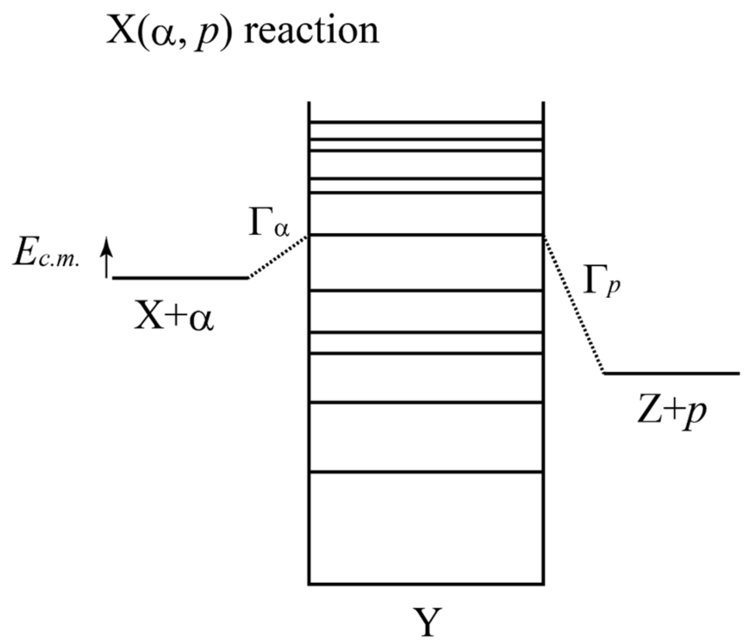
- Several key (α, γ) and (α, p) reactions, from an RI to another RI (i.e. difficult to study it experimentally) affect much to the X-ray light curve.



Typical situation

For those RI-to-RI astrophysical (α, p) reactions,

- Reaction rates are often dominated by resonant reactions.
- Most effective reactions are exothermic (positive Q-value). The p channel is located below the α channel and $\Gamma_\alpha << \Gamma_p$
- Resonances just above the α threshold are most relevant; $E_{c.m.}$ is small in stellar reactions, ~1 MeV order at T=1 GK.



Study of resonance parameters

The Breit-Wigner formula:

$$\sigma(E) = \pi ƛ^2 \frac{2\boxed{J}+1}{(2J_1+1)(2J_2+1)}(1+\delta_{12})\frac{\boxed{\Gamma_a}\boxed{\Gamma_b}}{(E-\boxed{E_0})^2+(\boxed{\Gamma}/2)^2}$$

$ƛ$: de Broglie wavelength

J_1, J_2, J : spins of projectile, target, excited state in the compound nucleus

δ_{12} : 1 for identical particles, 0 otherwise

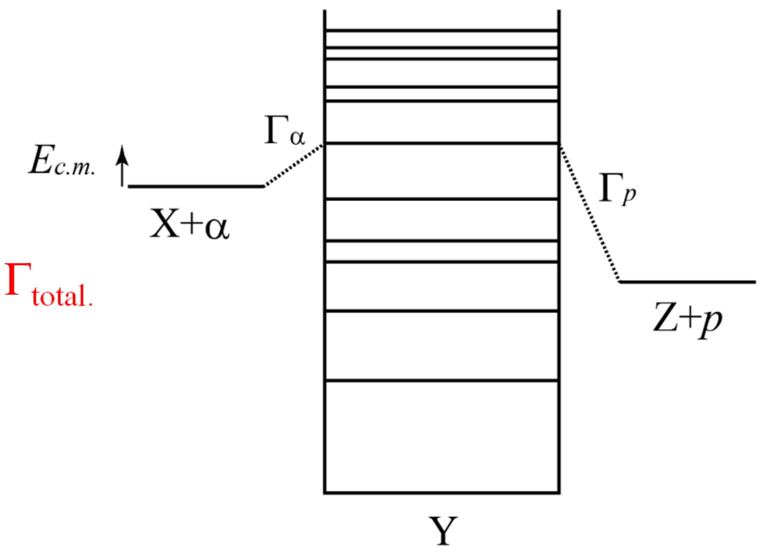
Γ_a, Γ_b : Widths of entrance and exit channels

is telling us the resonant reaction cross section σ is known by the resonance parameters: E_r, J^π, decay widths Γ_{α}, Γ_p, and Γ_{total}.

- In the typical case, $\Gamma_\alpha << \Gamma_p \sim \Gamma_{total}$

this implies the effect of Γ_α is greater than Γ_p.

X(α, *p*) reaction



Resonant scattering from inverse reaction channel

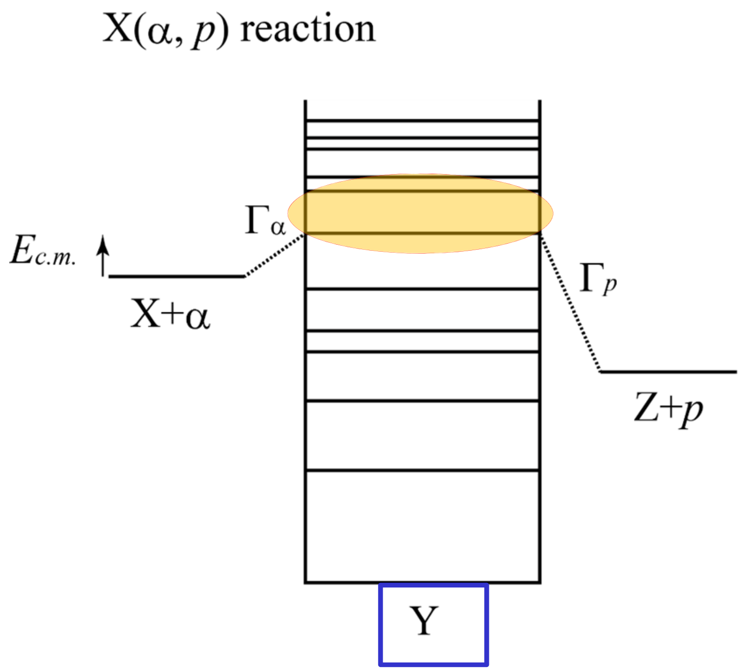
- Resonant scattering…A good method to observe resonances with a high cross section (even feasible with RI beams). Resonance parameters can be determined by R-matrix analysis.

We can study resonances in Y via

X+α scattering (α-resonant scattering)

or inversely,

Z+p scattering (proton resonant scattering)



- X+α…the scanned energy is quite low. The most relevant resonances (at Gamow energy) are buried under Rutherford scattering and hardly seen.
- Z+p…Thanks to the lower threshold energy, we can observe relevant resonances, and determine E_r, J^π, and Γ_p, (but no Γ_α). "Resonant scattering from inverse reaction channel".

Our recent publication on ^{22}Mg(α, p): One application of the "resonant scattering from inverse reaction channel"

PHYSICAL REVIEW LETTERS **127,** 172701 (2021)

Advancement of Photospheric Radius Expansion and Clocked Type-I X-Ray Burst Models with the New ^{22}Mg$(\alpha,p)^{25}$Al Reaction Rate Determined at the Gamow Energy

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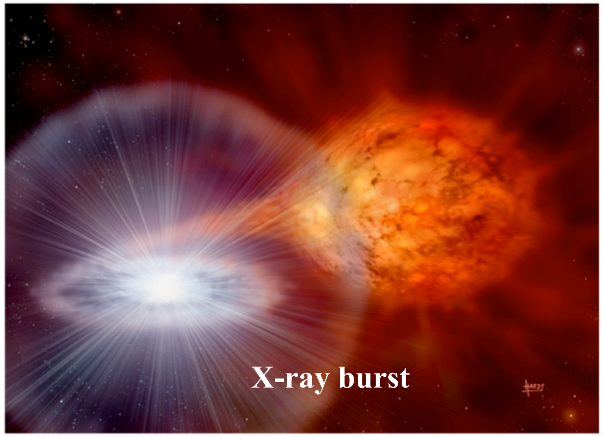
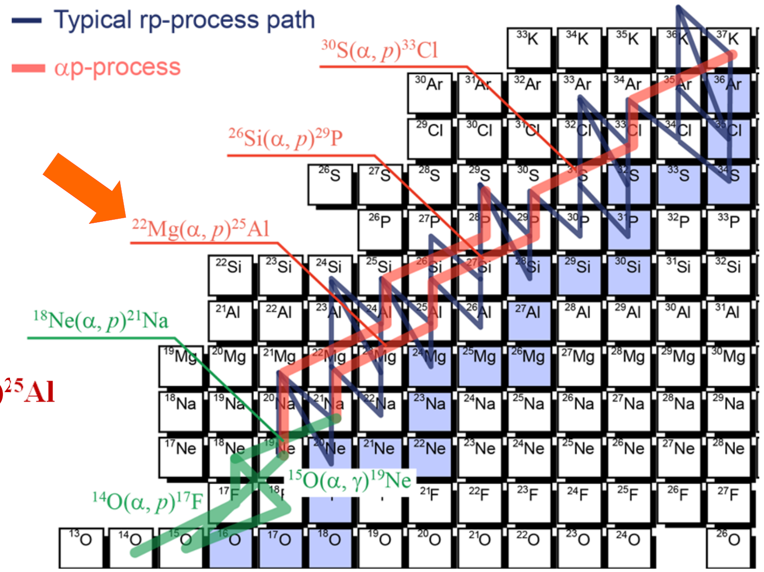
^{22}Mg(α, p) in Type I X-ray bursts



^{14}O(α,p)^{17}F(p,γ)^{18}Ne(α,p)^{21}Na(p,γ)^{22}Mg(α,p)^{25}Al

(p,γ)^{26}Si(α,p)^{29}P(p,γ)^{30}S(α,p)^{33}Cl(p,γ)^{34}Ar(α,p)

^{37}K(p, γ)^{38}Ca(α,p)^{41}Sc



R. Cyburt et al.

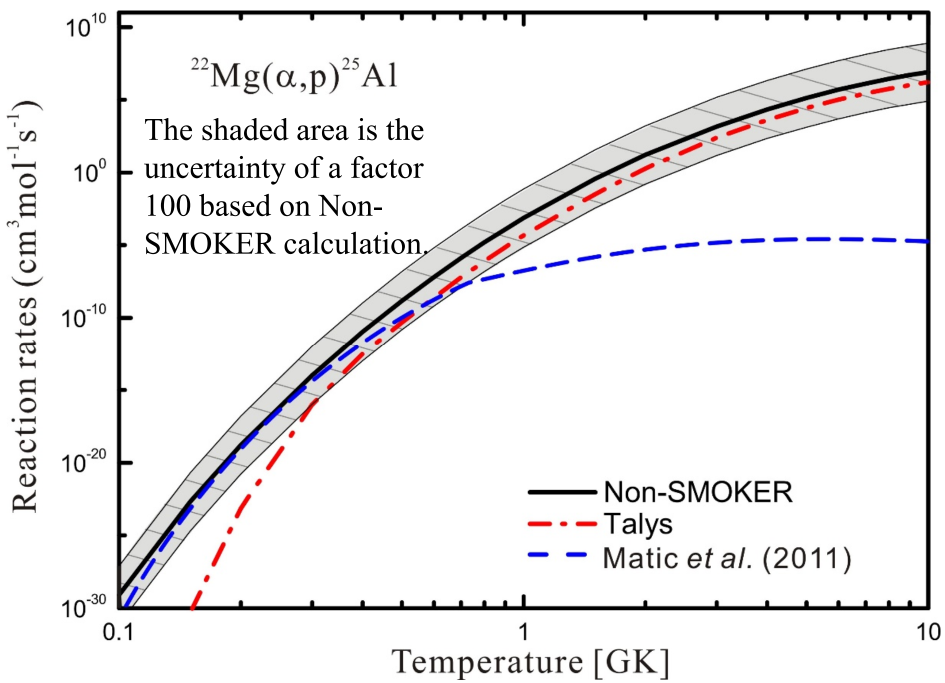
The Astrophysical Journal, 830:55 (20pp), 2016 October 20

Table 2
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(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	3.8	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

Notes.
[a] Up (U) or down (D) variation that has the largest impact.
[b] $M^{(i)}_{l,C}$ in units of 10^{38} erg s^{-1}.

Status of $^{22}Mg(\alpha,p)^{25}Al$ astrophysical reaction rate evaluation (as of 2018)



The $^{22}Mg(\alpha,p)^{25}Al$ reaction rate as a function of the temperature for the Hauser-Feshbach predictions TALYS and non-SMOKER

Large difference between the experimental and theoretical calculations.

Direct measurement of ^{22}Mg(α,p) at MSU

Randhawa et al., Phys. Rev. Lett (2020):
First direct measurement of ^{22}Mg(α, p).

NSCL; ~5 MeV/u (broad?) ^{22}Mg beam 900 cps, reaction measured with AT-TPC.

Data points only at energies corresponding to $T >$ 2.6 GK (cf. most relevant T range they claim: below 1 GK).

Reaction rate evaluated by extrapolation down to the stellar energy with a statistical-model (NON-SMOKER) calculation. Reliable?

PHYSICAL REVIEW LETTERS **125,** 202701 (2020)

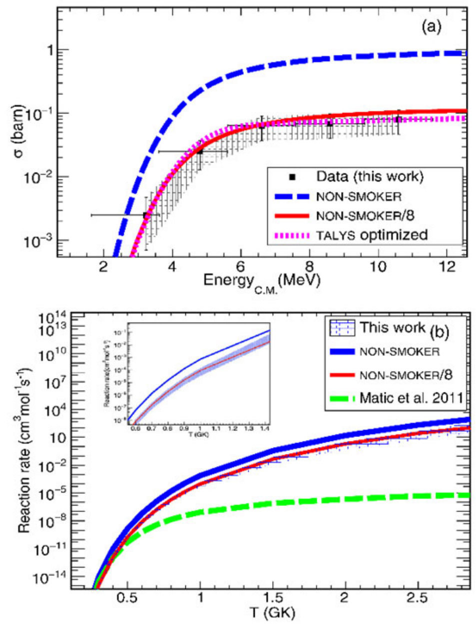
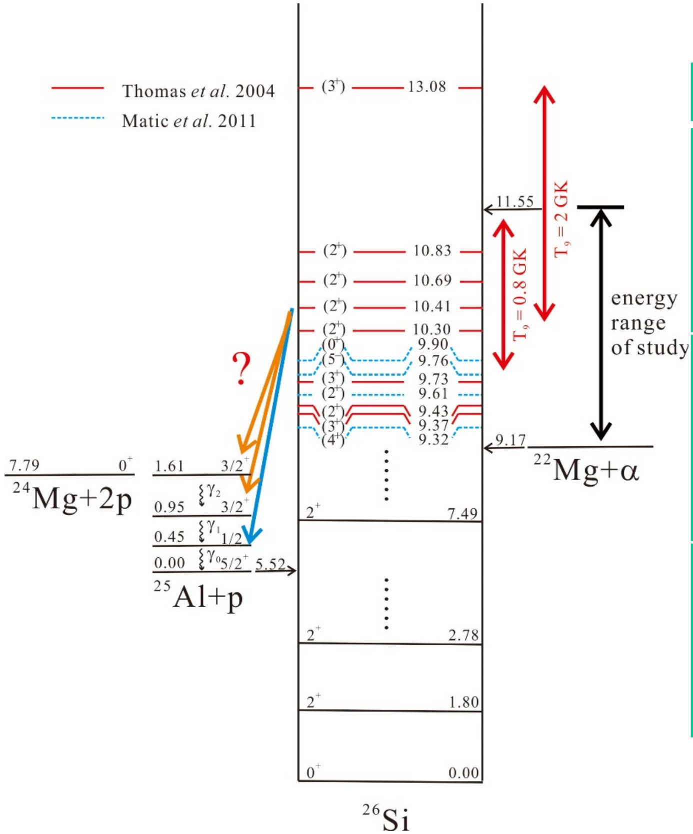


FIG. 3. Panel (a) shows the experimental cross sections obtained in the present work over a range of center-of-mass energies covered (black). For all the points, the cross section weighted energy is shown, which is the reason why horizontal error bars for the two lowest energy points are asymmetric. Panel (b) shows the reaction rate comparison of the current work to different model predictions and to the previous measurement by Matic *et al.* [11].

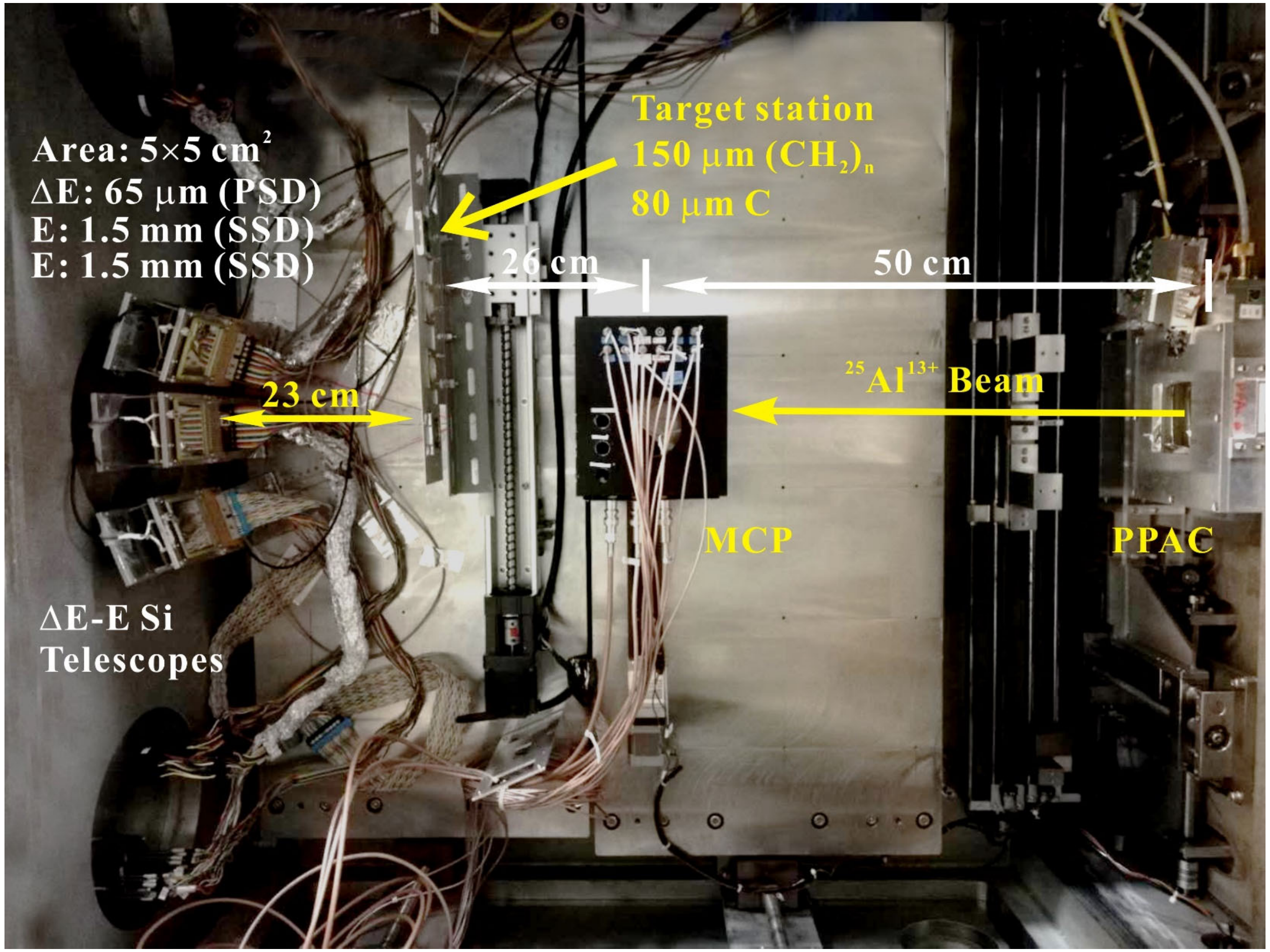
Status of resonance studies



Experimental technique	E_{res}	J^{π}	Γ_{p0}	$\Gamma_{p'}$	Γ_{α}
β-delayed proton measurement of ^{26}P Thomas et al. 2004	Ex>10 MeV	– Shell model calculation	–	–	–
^{28}Si(p,t)^{26}Si Matic et al. 2011	Ex<10 MeV	– Analog state assignment	–	–	–
^{25}Al+p scattering measurement above the α threshold of ^{26}Si (present work)	Covering the relevant range, Ex=9-11 MeV	R-Matrix fitting	^{25}Al (p, p)^{25}Al	^{25}Al (p, p′)^{25}Al	–

Experimental Setup at F3 focal plane

^{25}Al beam: 2 x 10^5 pps, 80% purity

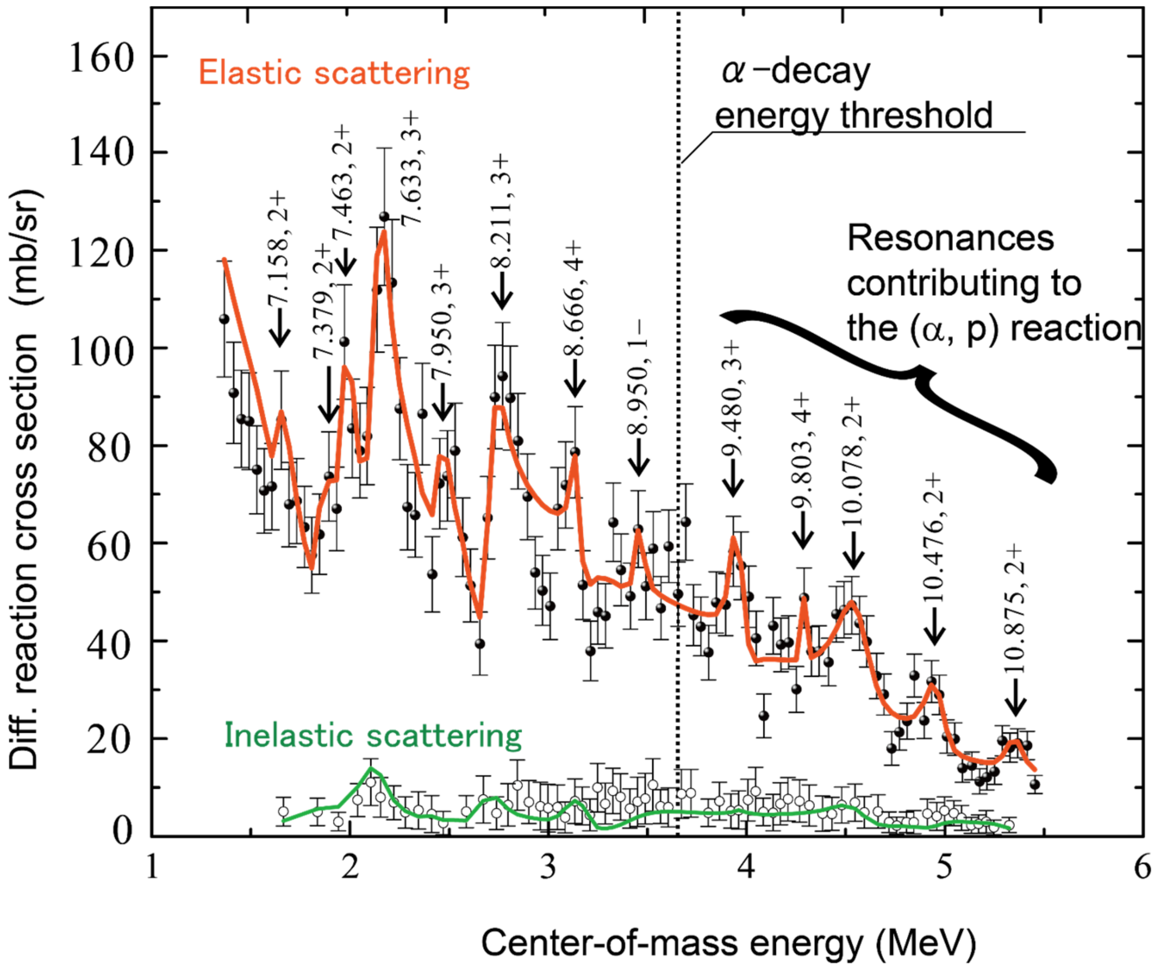


^{25}Al RI beam at CRIB, (142 ± 1) MeV, 2 x 10^5 pps, 80% purity.

Resonances in ^{26}Si are scanned by proton resonant scattering of ^{25}Al+ p … exit channel of ^{22}Mg(α, p).

The spin parities of 5 states above the α threshold were determined for the first time … reaction rate evaluated with parameters of those resonances (E, J^{π}, Γ_p).

Γ_α were not known from the measurement, and evaluated with the spectroscopic factor of the mirror ^{26}Al nucleus by Matic et al.



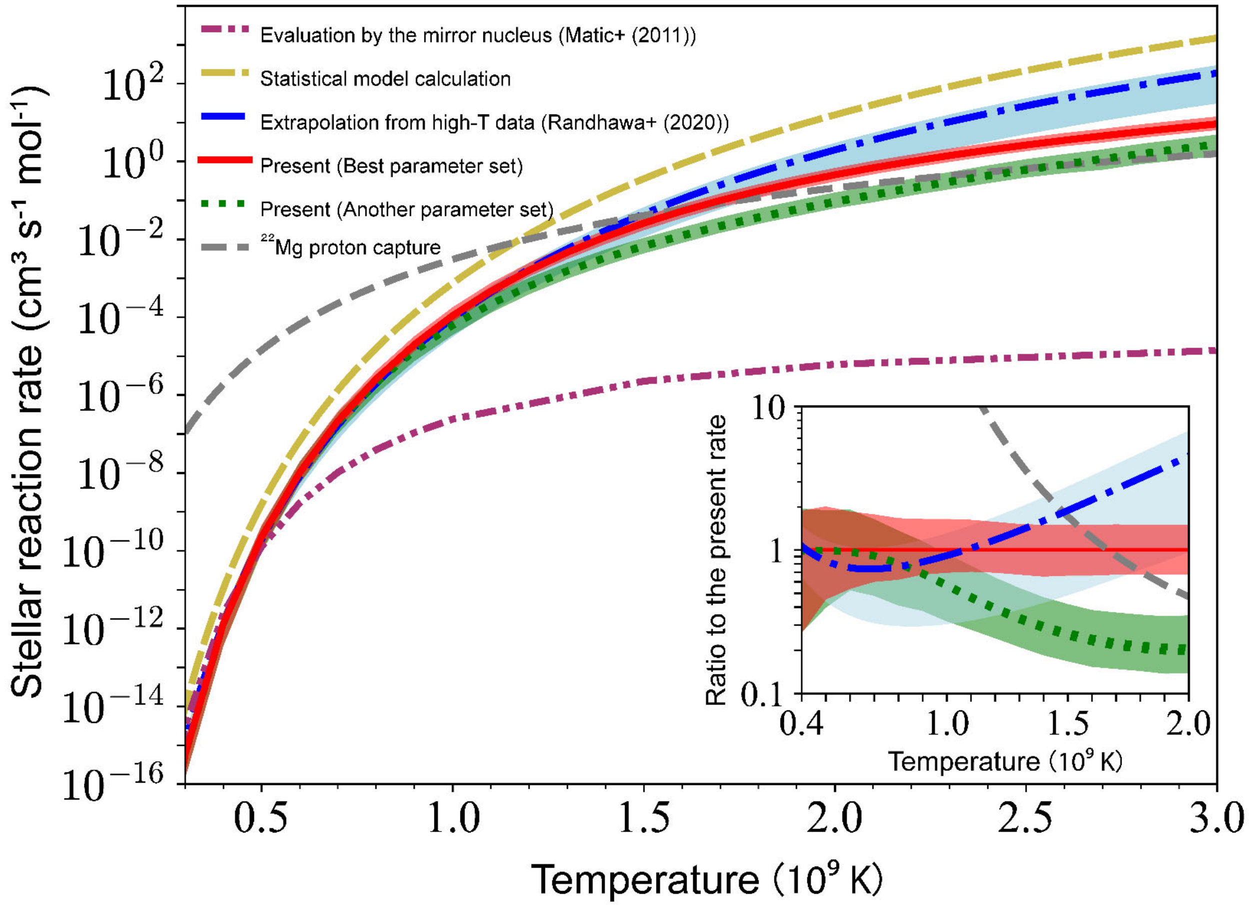
Updated $^{22}Mg(\alpha,p)$ reaction rate

Red curve …our new rate (resonant reaction rate)

Blue curve… MSU latest work (extrapolation)

These two are not too much different for the X-ray burst temperature.

Our uncertainty is mostly smaller than MSU, even though the error associated with extrapolation with statistical model calculation is not included in their evaluation.



X-ray burst simulations

Light curves with a new XRB model (by Dr. Lam Yi Hua)

→ Improved reproducibility of the observational data (GS1826-24, SAXJ1808.4-3658). ^{22}Mg(α,p) produces a visible effect.

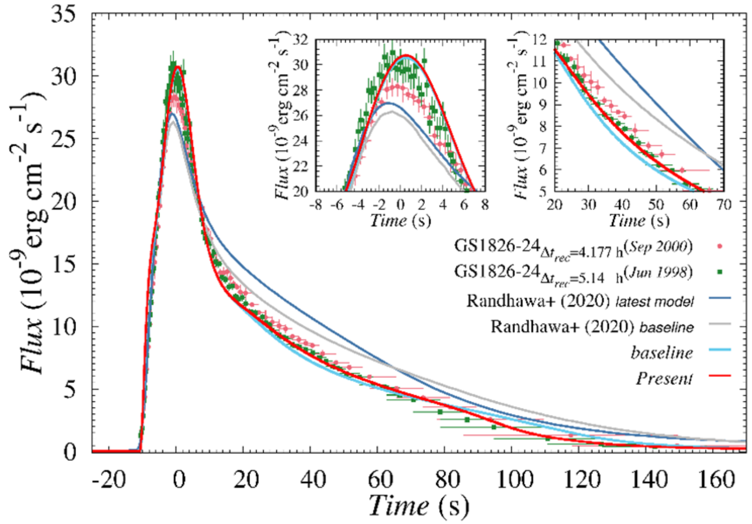


FIG. 3. The best fit *baseline* and *Present* modeled lightcurves to the observed lightcurve of epoch *Jun 1998*, and the best fit Randhawa *et al.* [22] lightcurves to epoch *Sep 2000*. The magnified lightcurves at the burst peak and t=20–70 s are shown in the left and right insets, respectively.

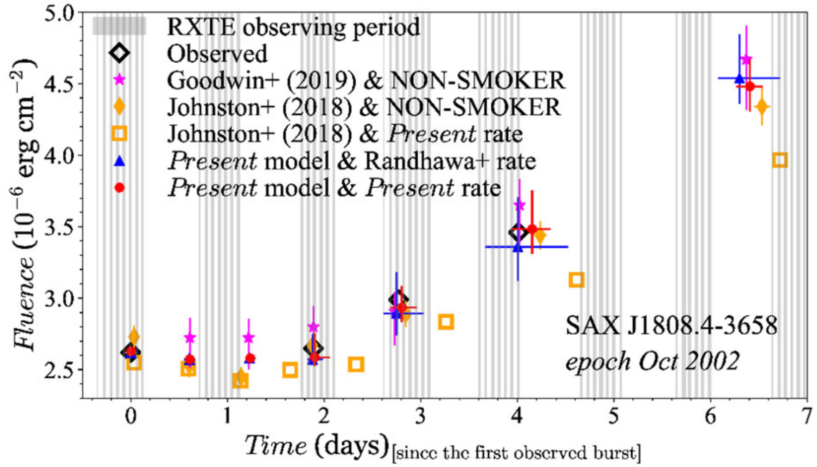


FIG. 4. The bursts' fluences (integration of flux over time) and times for SAX J1808.4-3658 burster, based on the RXTE observation [4], Johnston *et al.* [8] and Goodwin *et al.* [9] models, and present calculations. Johnston *et al.* [8] model is adopted to study the present and Randhawa *et al.* rates.

Helium abundance in the accreting envelope seems to be essential

The $^{26}Si(\alpha,p)^{29}P$ reaction

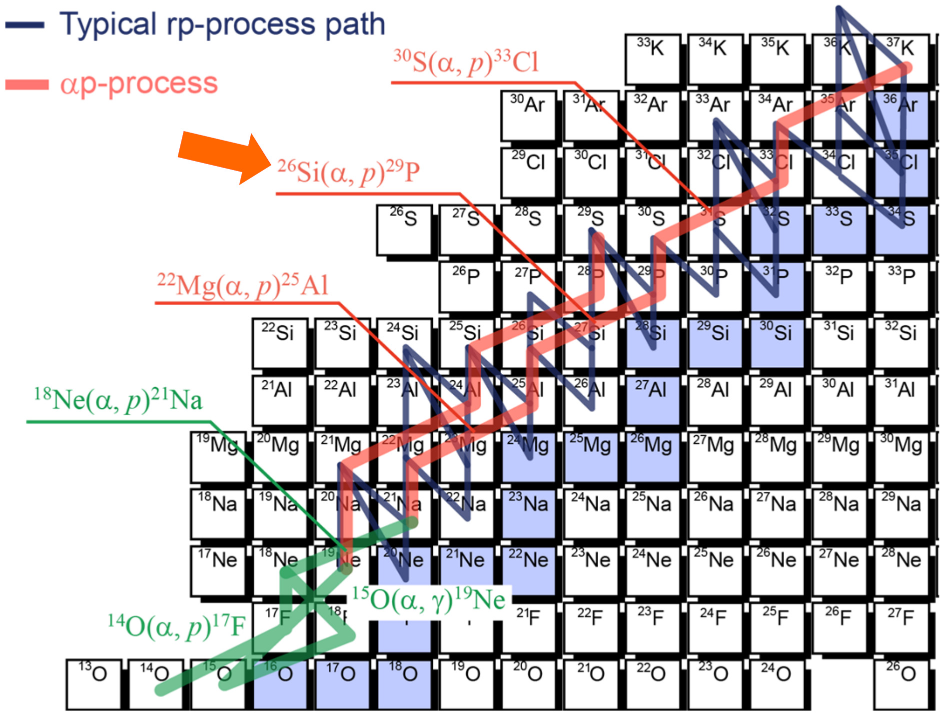


Table 1
Reactions that Impact the Burst Light Curve in the Single-zone X-Ray Burst Model

Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	$^{56}Ni(\alpha, p)^{59}Cu$	U	12.5	1
2	$^{59}Cu(p, \gamma)^{60}Zn$	D	12.1	1
3	$^{15}O(\alpha, \gamma)^{19}Ne$	D	7.9	1
4	$^{30}S(\alpha, p)^{33}Cl$	U	7.8	1
5	$^{26}Si(\alpha, p)^{29}P$	U	5.3	1
6	$^{61}Ga(p, \gamma)^{62}Ge$	D	5.0	1
7	$^{23}Al(p, \gamma)^{24}Si$	U	4.8	1
8	$^{27}P(p, \gamma)^{28}S$	D	4.4	1

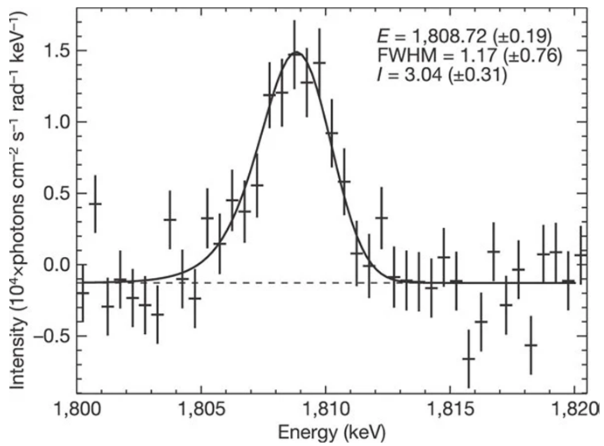
Table 2
Reactions that Impact the Burst Light Curve in the Multi-zone X-ray Burst Model

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
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

•R.H. Cyburt *et al.*, Astrophys. J. **830**, 55 (2016).

- The $^{26}Si(\alpha,p)^{29}P$ reaction has a high sensitivity on the light curve

Effect on the ^{26}Al abundance



R. Diehl et al., Nature **439**, 45 (2006)

- The galactic 1.808 MeV gamma ray of ^{26}Al
  - ◆ Evidence of the ongoing process of the nucleosynthesis
  - ◆ Doppler shift of the line => rotation of the Galaxy

- The ^{26}Si(α,p)^{29}P reaction has also sensitivity on the abundance of ^{26}Al

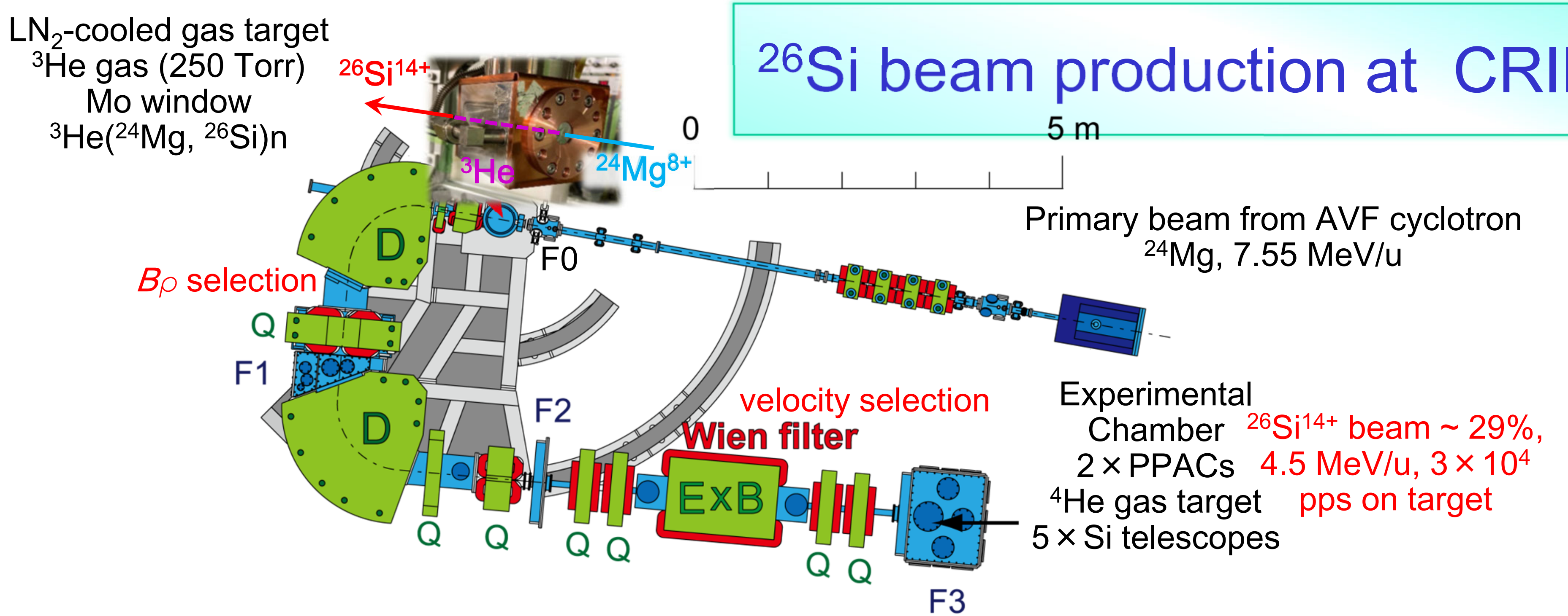
TABLE 3

SAME AS TABLE 1, BUT FOR MODEL F08 (FISKER ET AL. 2008)

Reaction	Isotope	10	0.1
^{12}C(p, γ) ^{13}N	^{12}C	0.41	...
^{12}C(α, γ)^{16}O	^{12}C	0.42	...
	^{16}O	3.27	0.36
	^{20}Ne	3.03	0.42
	^{24}Mg	2.40	...
^{16}O(α, γ)^{20}Ne	^{16}O	0.11	8.36
^{20}Ne(α, γ)^{24}Mg	^{20}Ne	0.10	9.84
^{22}Mg(α, p)^{25}Al	^{25}Mg	...	8.81
	^{27}Al	...	2.23
^{24}Mg(p, γ) ^{25}Al	^{25}Mg	3.02	0.43
^{24}Mg(α, γ)^{28}Si	^{24}Mg	0.18	4.16
	^{25}Mg	0.24	4.10
^{25}Al(α, p)^{28}Si	^{25}Mg	0.22	2.36
^{26g}Al(p, γ)^{27}Si	^{27}Al	2.71	0.40
^{26g}Al(α, p)^{29}Si	^{26}Mg	...	2.34
	^{26g}Al	0.08	2.38
	^{27}Al	0.40	...
^{26}Si(α, p)^{29}P	^{26g}Al	0.08	...
	^{27}Al	0.23	...
^{27}Al(α, p)^{30}Si	^{27}Al	0.32	...
^{27}Si(α, p)^{30}P	^{27}Al	0.30	...
^{28}Si(α, γ)^{32}S	^{28}Si	0.43	...
	^{32}S	3.73	0.37

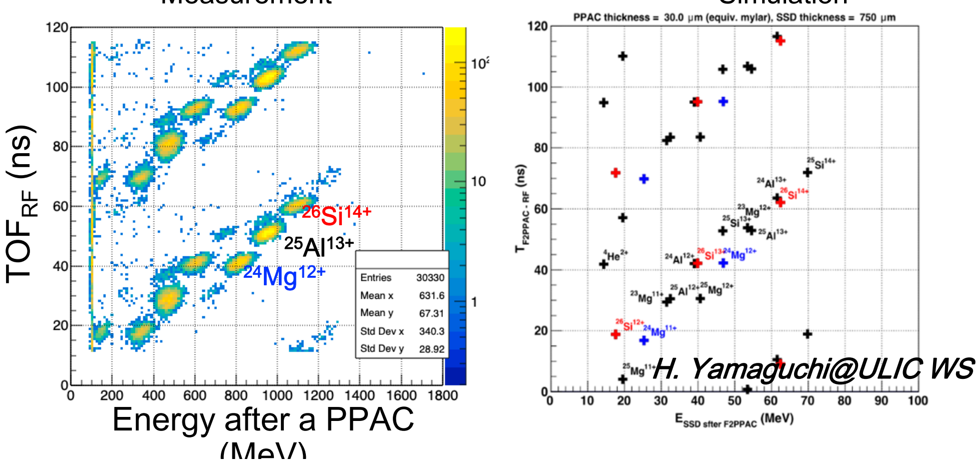
Parikh *et al.*, Astrophys. J. Suppl. Ser. **178**, 110 (2008)

^{26}Si beam production at CRIB



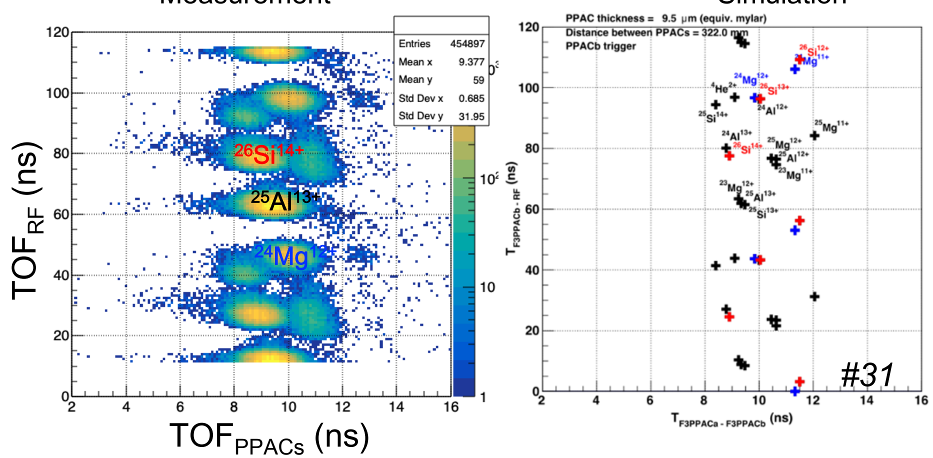
PID at F2 (ΔE vs TOF$_{RF}$)

Measurement Simulation



PID at F3 (TOF$_{PPACs}$ vs TOF$_{RF}$)

Measurement Simulation



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#31

Thick target in inverse kinematics + ^{26}Si beam

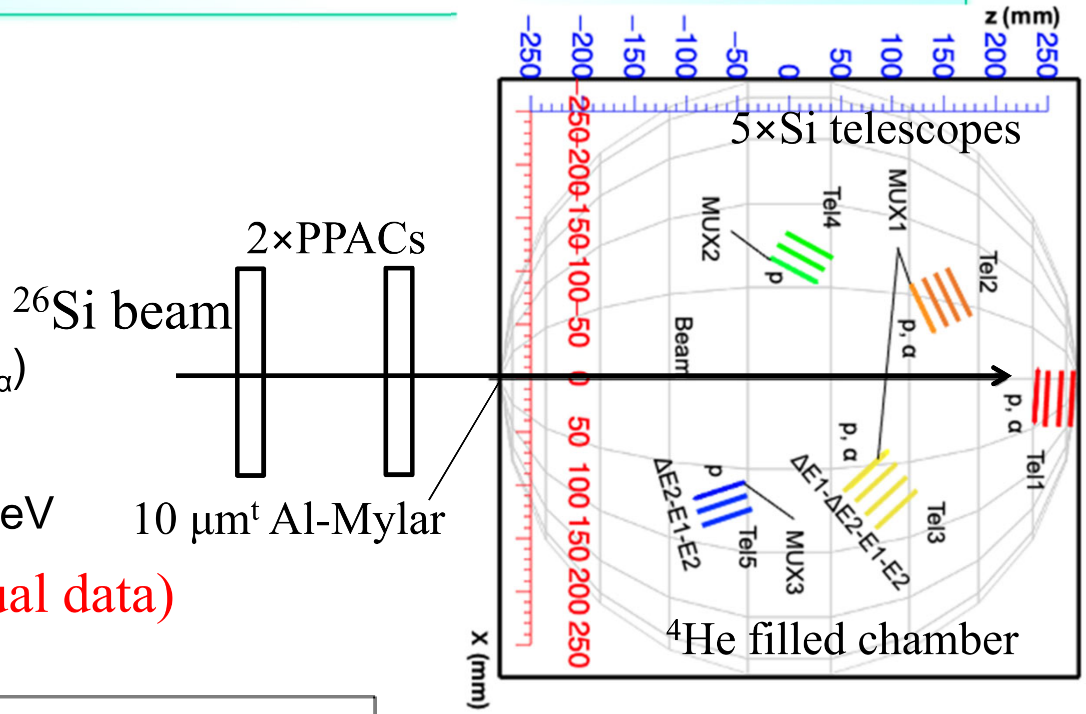
TTIK scan, $E_{c.m.}$ up to 7.3 MeV

α resonant scattering measurement

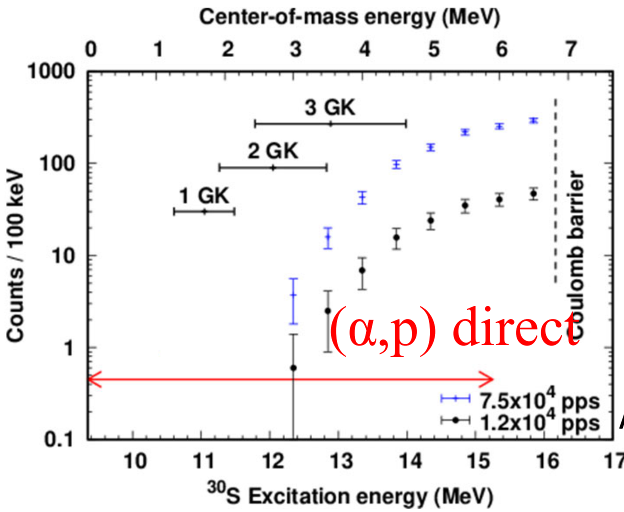
- α resonances, α clustering structure
- R-matrix analysis → to determine Γ_α
  (<< Γ_p, dominant in $\langle\sigma_R v\rangle \propto \Gamma_\alpha\Gamma_p / \Gamma_{tot} \sim \Gamma_\alpha$)

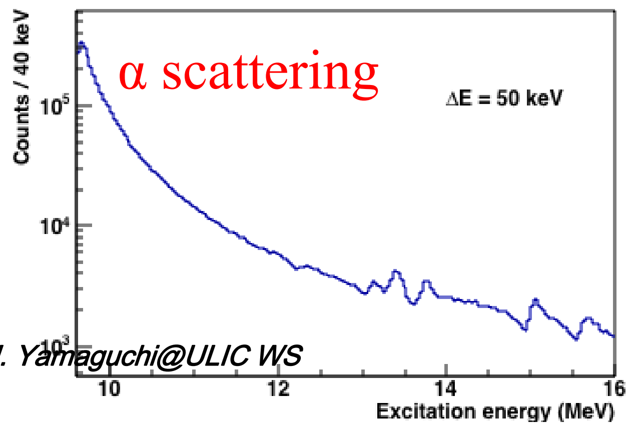
(α,p) reaction direct measurement

- Reasonable statistics down to $E_{c.m.} \sim$ 3 MeV



Yield estimation (not actual data)





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Collaboration/ beamtime

CNS: S. Hayakawa, K. Okawa, N.R. Ma, H. Shimizu H. Yamaguchi, Q. Zhang,
T. Chillery, S. Hanai, N. Imai, J. Li, S. Michimasa, R. Yokoyama

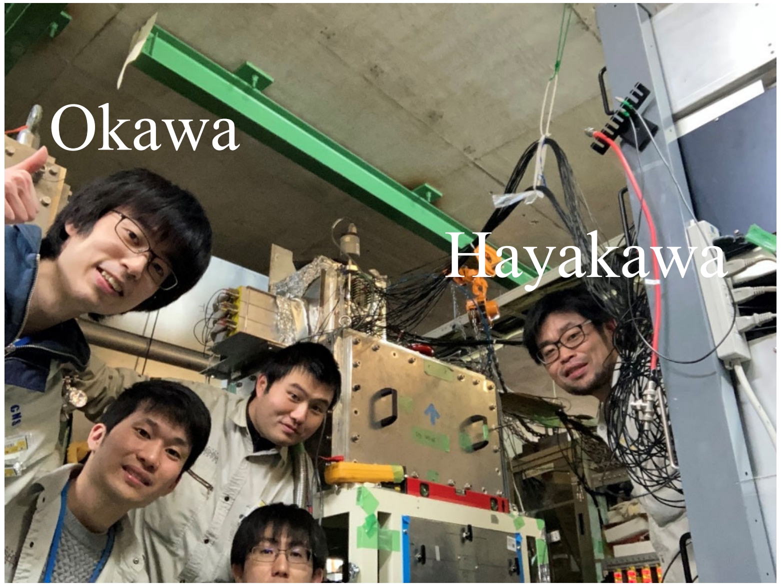
SKKU: K.Y. Chae, M.J. Kim, N.N. Duy, G.M. Gu, C.H. Kim, S.H. Kim, M.S. Kwag,
N.K. Uyen,

IBS: S.M. Cha, D. Kim

Osaka: S. Adachi, T. Furuno, K. Sakanashi, T. Kawabata

ELI-NP: D. Kahl, O. Sirbu

RIKEN: S. Kubono



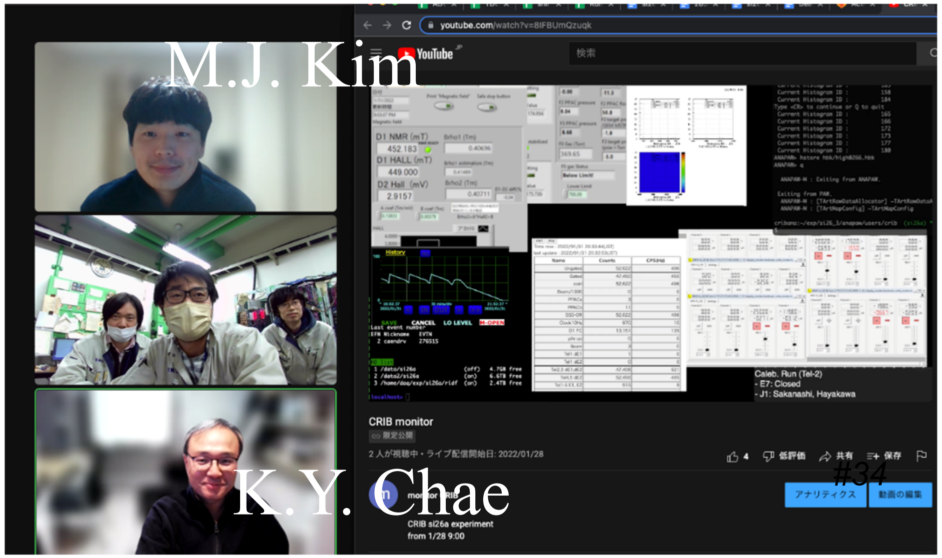
The first CRIB main experiment after COVID.

Foreign collaborators could not come to Japan from due to COVID19 restriction

Domestic collaborators from Osaka U. and CNS

Online communication during the machine time (Zoom + Slack + YouTube live)

Graduate students working on analysis (Okawa, M.J. Kim)



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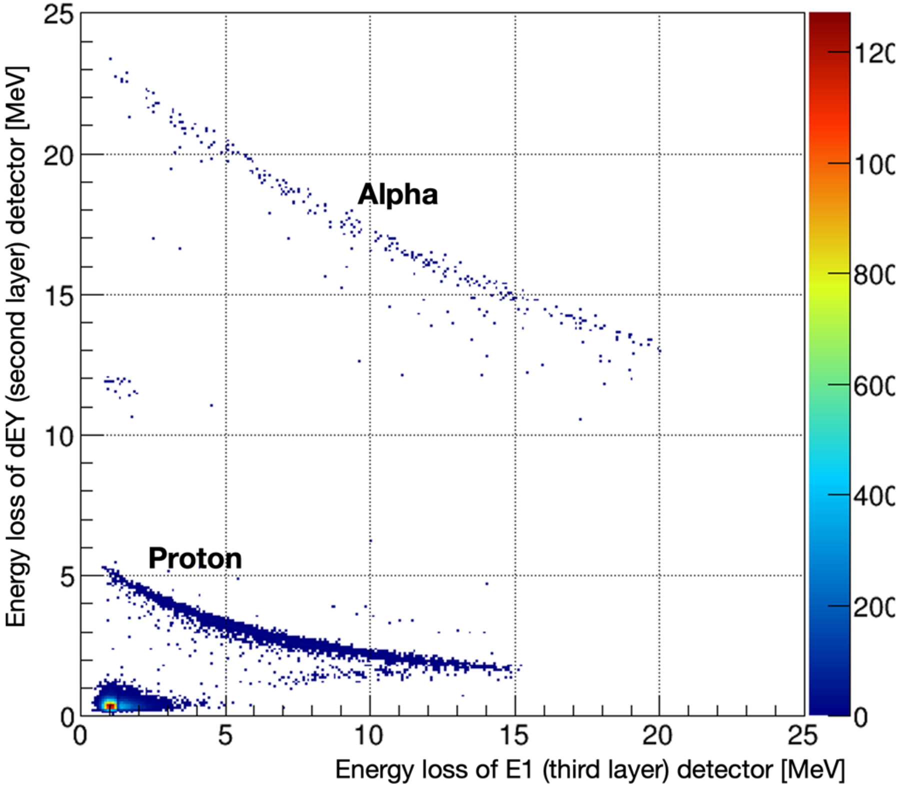
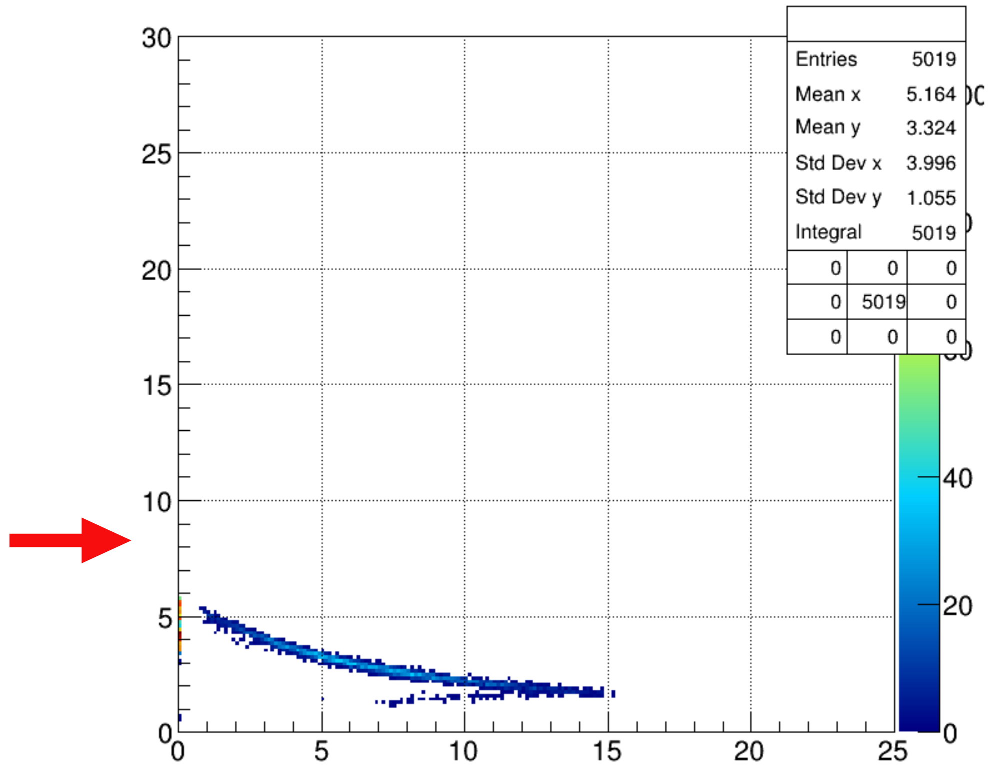
Proton event selection

α and p were clearly identified. Selected proton events as candidates of (α,p) reaction products

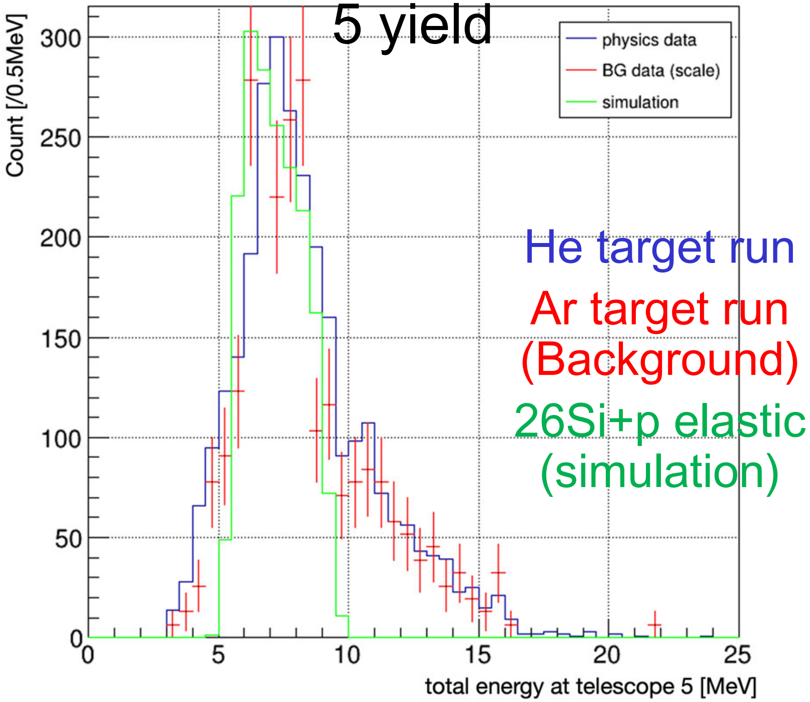




Background from the elastic scattering of ^{26}Si + p

- **Low energy (<10 MeV) proton events were likely to be elastic scattering at the window (Mylar $C_{10}H_8O_4$)** → consistent with a Monte Carlo calculation

•Example: Telescope 5 yield

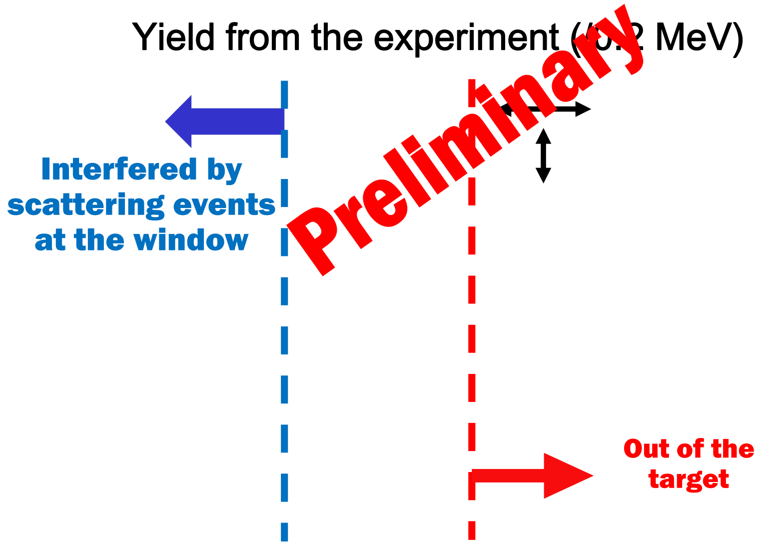


- However, **spectra of the He-target run and Ar-target background run are still similar in 10 – 15 MeV region.**

Evaluated the yield of the (α,p) reaction by **subtracting all proton events from the background events**

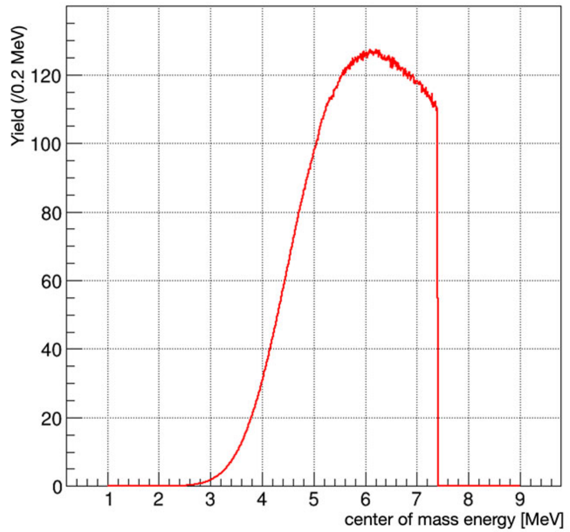
Yield compared with calculation

Yield from the experiment (/0.2 MeV)



[Spectrum concealed in the uploaded slides]

Simulation with NON-SMOKER cross section



- **The subtracted yield was lower than theoretical yield by over one order of magnitude**
  - **Experiment: ~ 5 events vs calculation: ~ 120 events, per 0.2 MeV, around 7.0 MeV**

Summary

- CRIB is an RI beam facility in RIBF operated by CNS, the University of Tokyo, providing low-energy (<10MeV/u) in-flight RI beams with high intensity and purity.
- Unique studies with low-energy RI beams have been made. Recent highlights are:
  - ^{22}Mg(α, p) reaction study with the resonant scattering method

    →Reaction rate updated with the resonant reaction evaluation. Implication to the X-ray burst light curve was discussed.
  - ^{26}Si(α, p) reaction study with the direct measurement.

    →The preliminary result shows the yield seems to be more than factor 10 lower than the theoretical calculation.
- We welcome new collaborators and new ideas. Please contact with me if you have any idea.
- Visit CRIB webpage for more information. http://www.cns.s.u-tokyo.ac.jp/crib/crib-new/