Studying astrophysical reactions with low-energy RI beams -- the projects at CRIB

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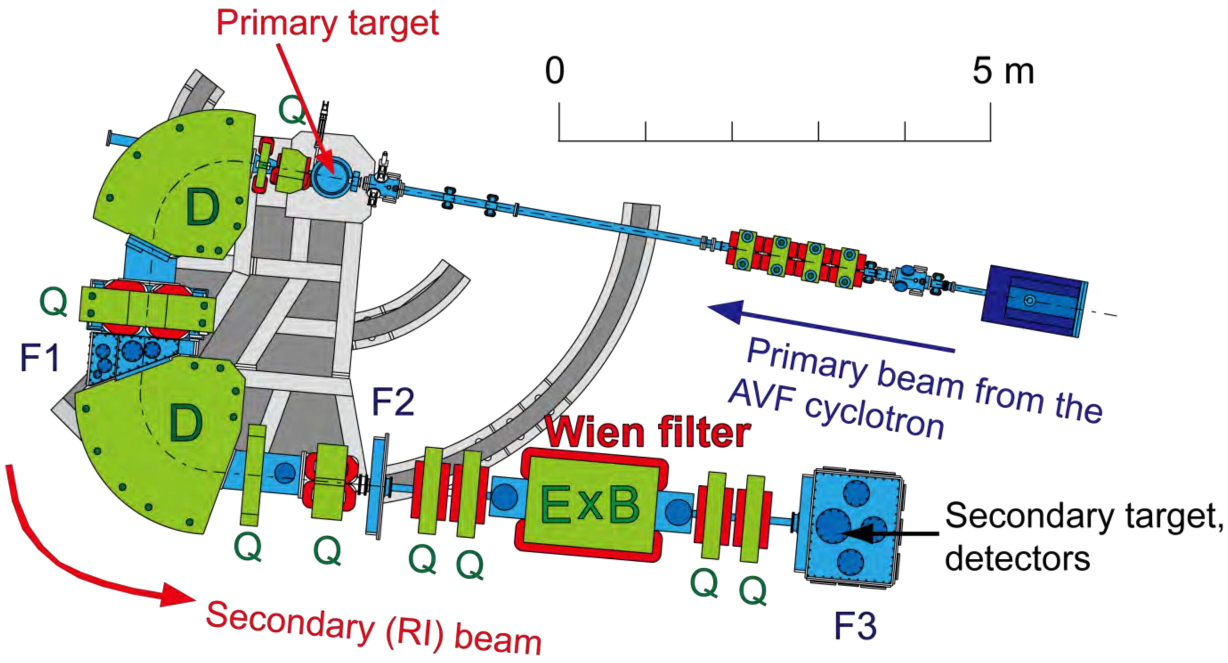
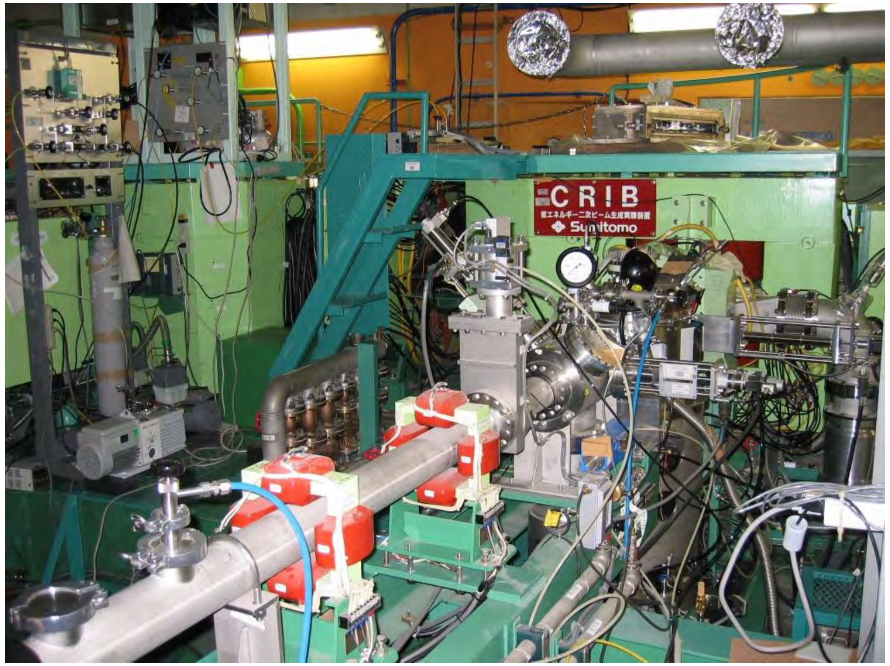
CRIB – Low energy RI beam separator of CNS

- CNS Radio-Isotope Beam separator , operated by CNS (Univ. of Tokyo), located at RIBF (RIKEN Nishina Center), in Japan.
  - 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.

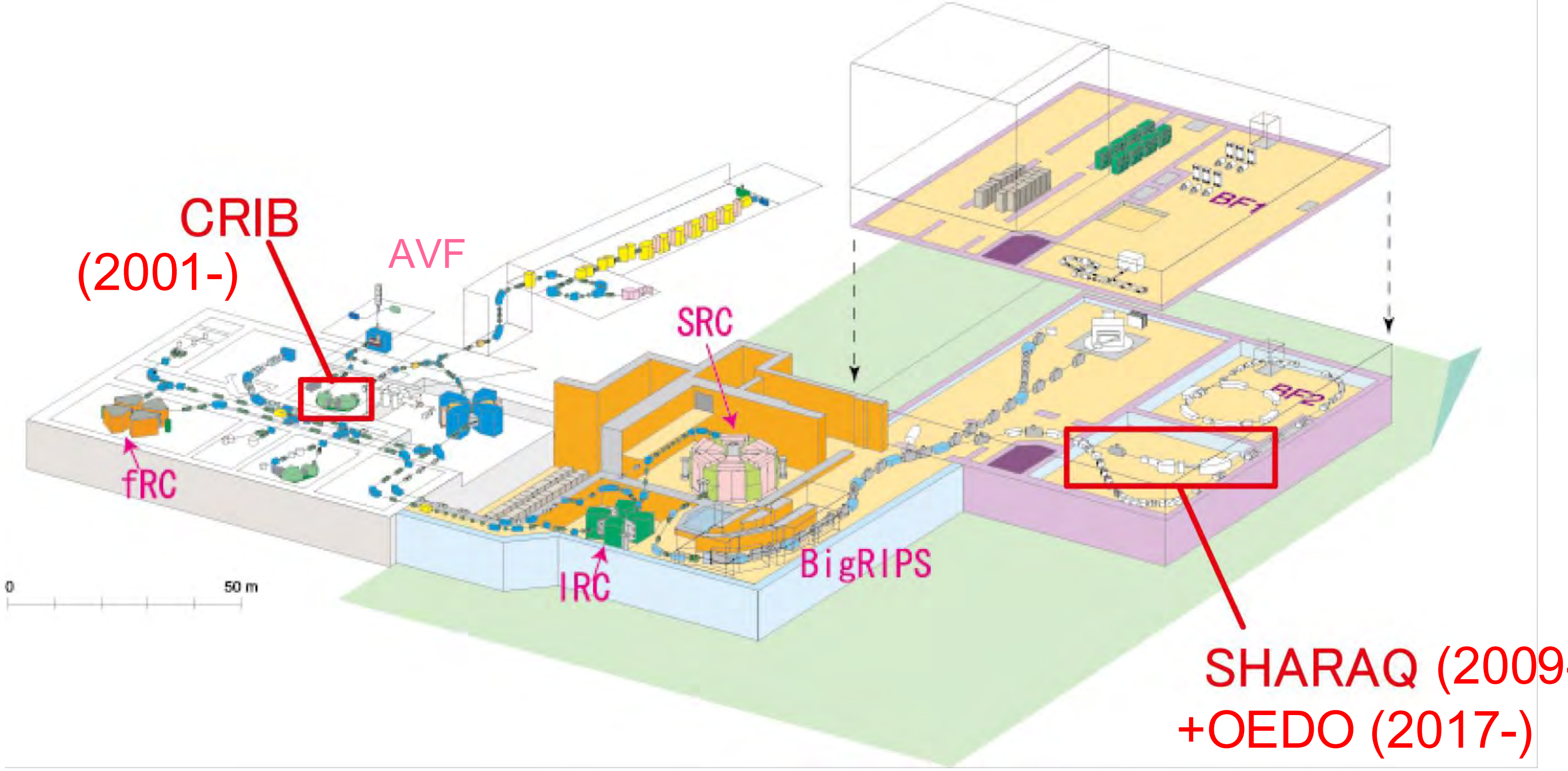




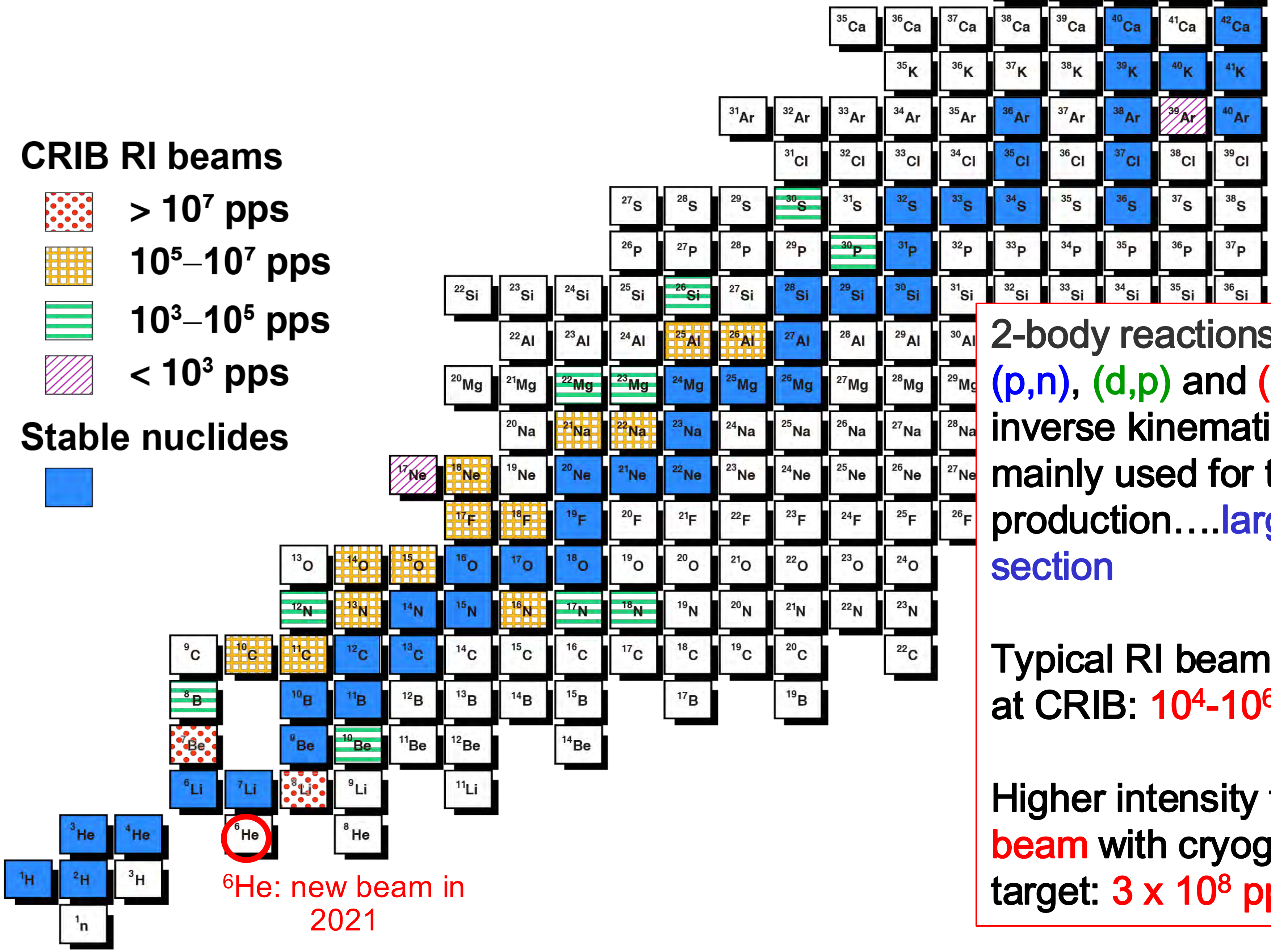
CRIB/OEDO in RIBF

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



Talk by Li Jiatai tomorrow



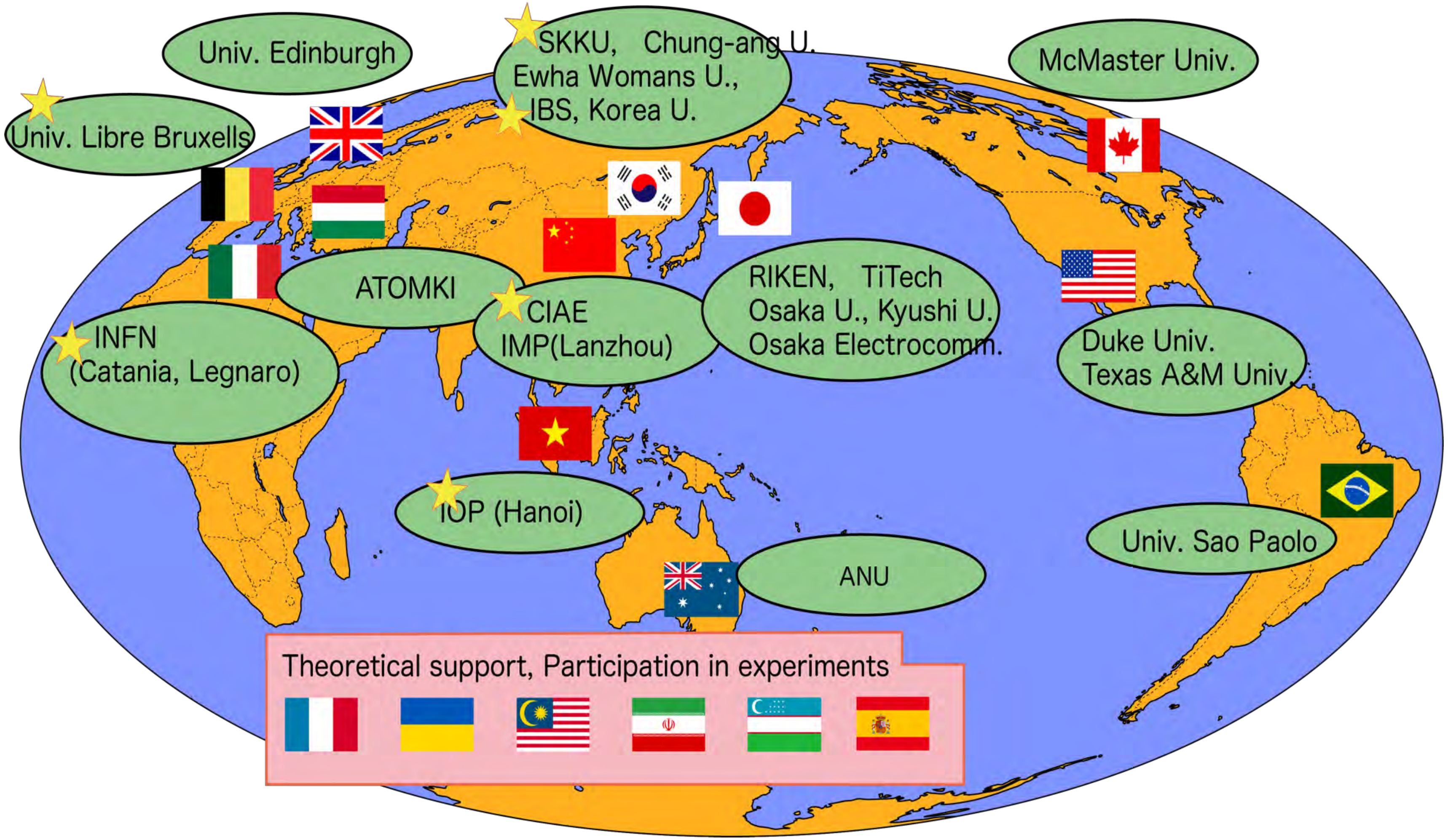
2-body reactions such as (p,n), (d,p) and (^{3}He,n) in inverse kinematics are mainly used for the production….large cross section

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

- Country/institutes that collaborated with us at CRIB (showing only core institutes of the proposed experiments):



Today's main topic: studying (α,p) reactions on RI

- There are (α,p) reactions relevant in astrophysics.

- Some are from RI to RI (e.g., $^{14}O(\alpha,p)^{17}O$), posing a challenge in directly measuring their rates, due to the limitation of RI beam intensity (typically 10^5 pps).

- Approaches:

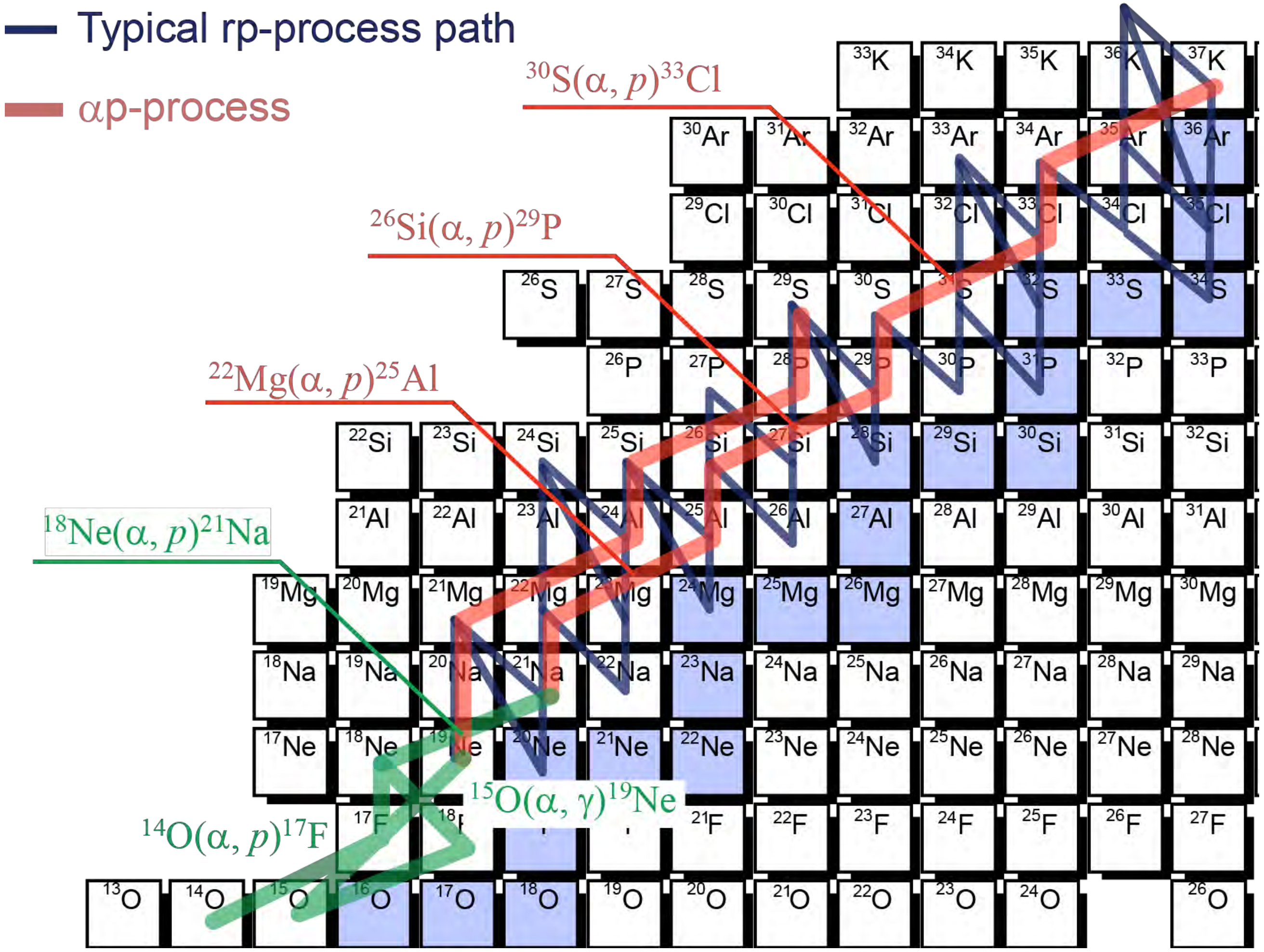
  1) Measure the cross section at high energy, and extrapolate it down to low energies…is the extrapolation reliable?

  2) Study resonance parameters and evaluate the reaction rates with those…can we obtain all necessary information, incl. Γ_α?

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.



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

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

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

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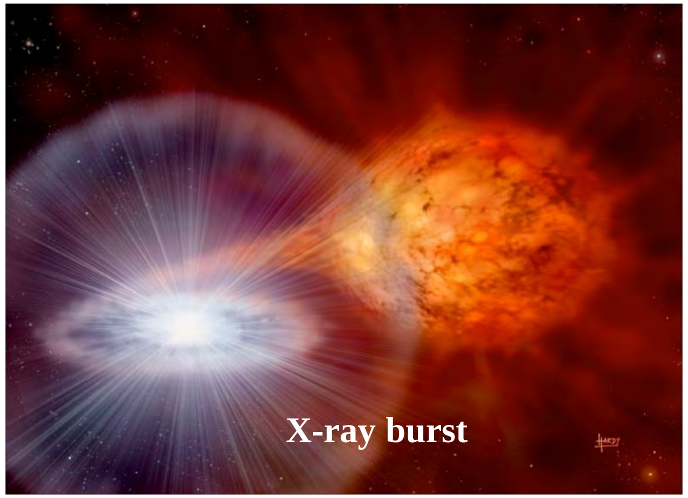
[10]*SUPA, School of Physics & Astronomy, University of Edinburgh, Edinburgh EH9 3FD, United Kingdom*
[11]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[12]*College of Nuclear Science and Technology, Beijing Normal University, Beijing 100875, China*

THE UNIVERSITY OF TOKYO

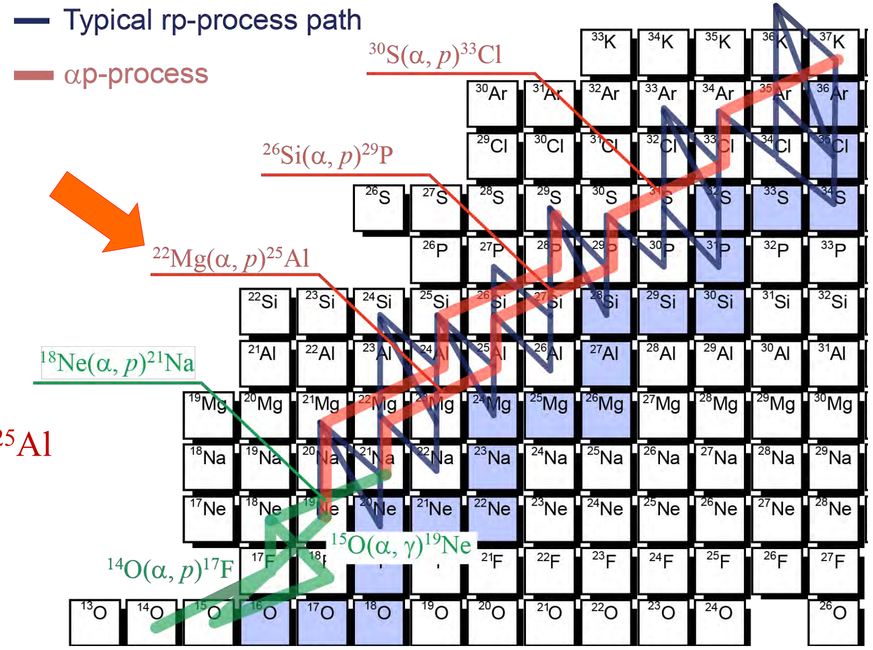
^{22}Mg(α,p) in Type I X-ray bursts



^{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.

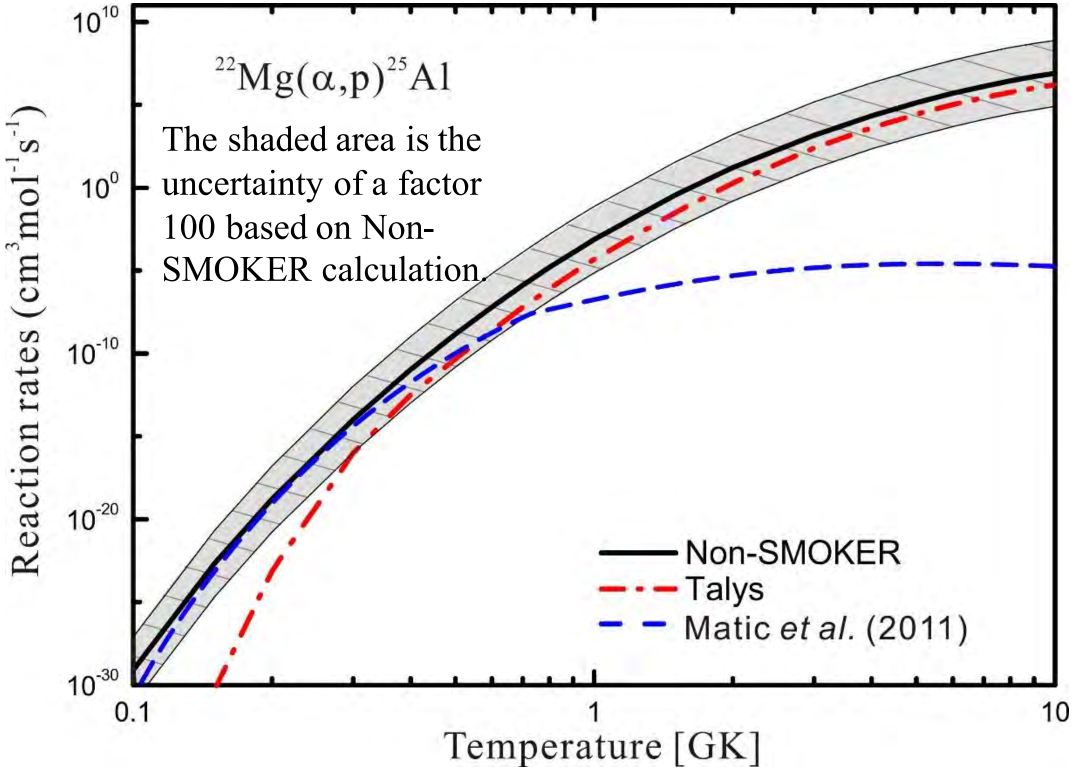
The Astrophysical Journal, 830:55 (20pp), 2016 October 20

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] $M^{(i)}_{LC}$ in units of 10^{38} erg s^{-1}.

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



Large difference between the experiment and theoretical calculation.

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

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.
The reaction was 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)

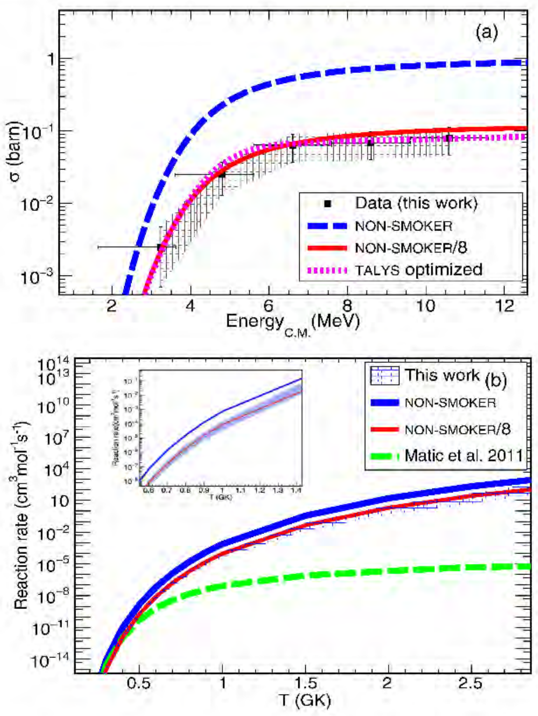


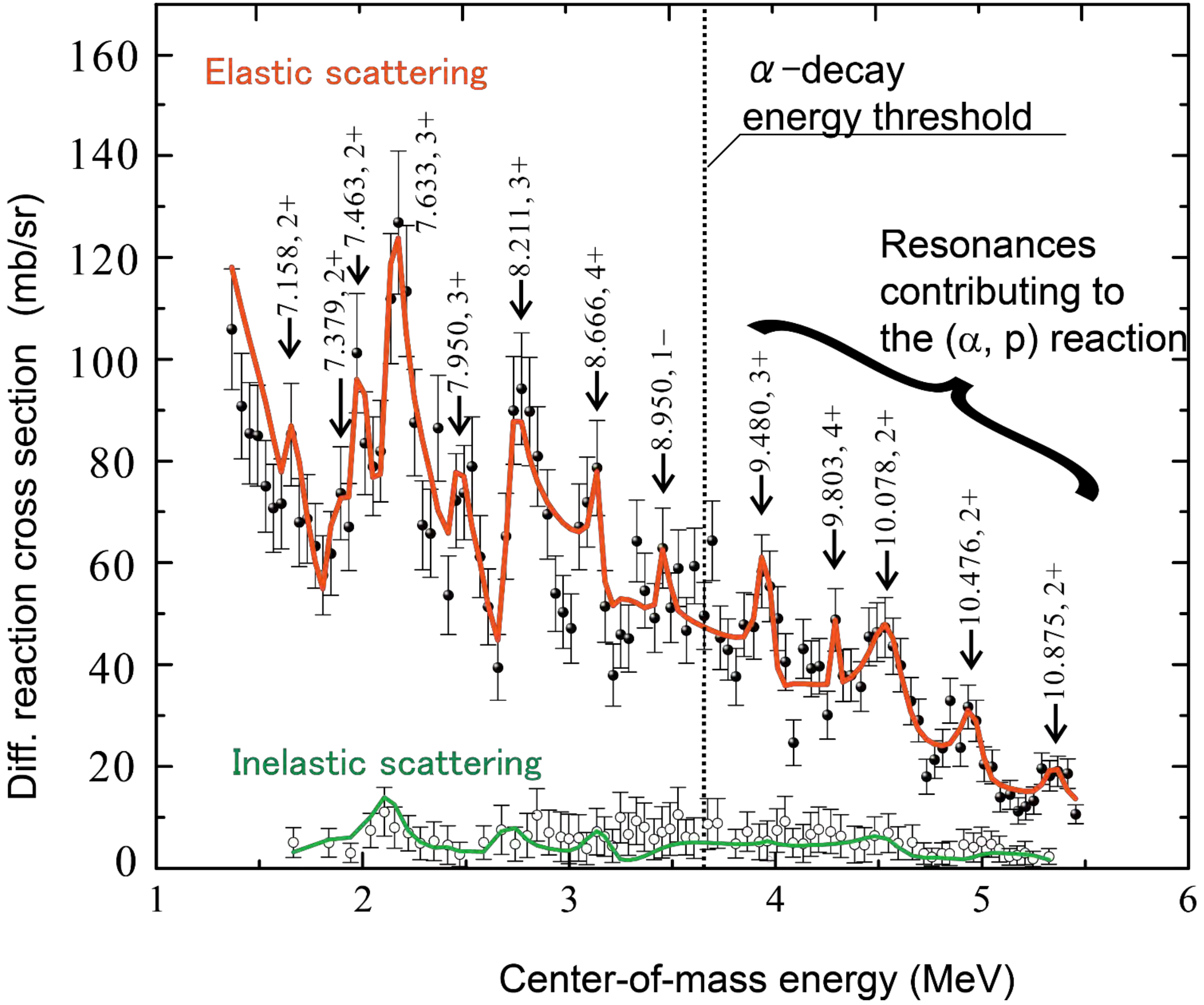
FIG. 3. Panel (a) shows the experimental cross sections obtained in the present work over a range of center-of-mass energies covered (black). For all the points, the cross section weighted energy is shown, which is the reason why horizontal error bars for the two lowest energy points are asymmetric. 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].

^{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.



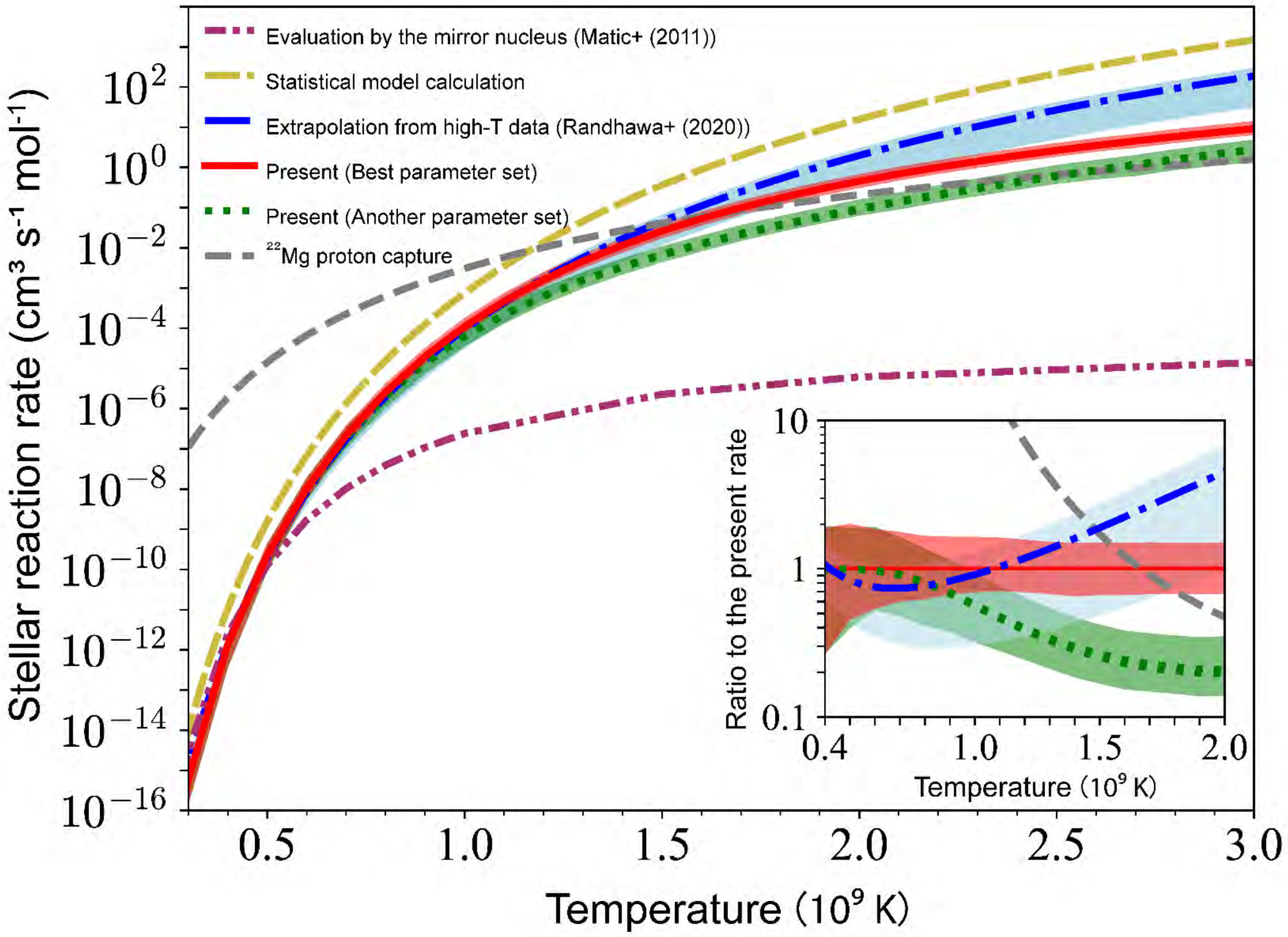
Updated $^{22}Mg(\alpha,p)$ reaction rate

Red curve …our new rate (resonant reaction rate)

Blue curve… MSU 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 (Dr. Lam Yi Hua)

→ Improved reproducibility of the observational data.

^{22}Mg(α,p) makes a significant effect.

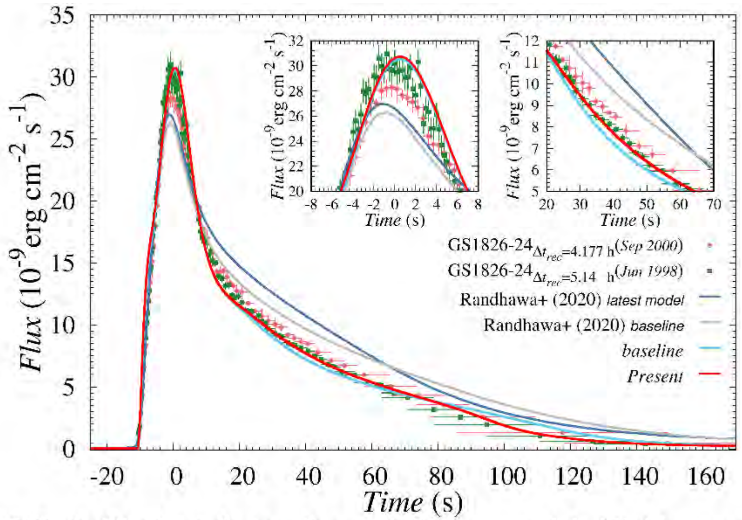


FIG. 3. The best fit *baseline* and *Present* modeled lightcurves to the observed lightcurve of epoch *Jun 1998*, and the best fit Randhawa *et al.* [22] lightcurves to epoch *Sep 2000*. The magnified lightcurves at the burst peak and t=20–70 s are shown in the left and right insets, respectively.

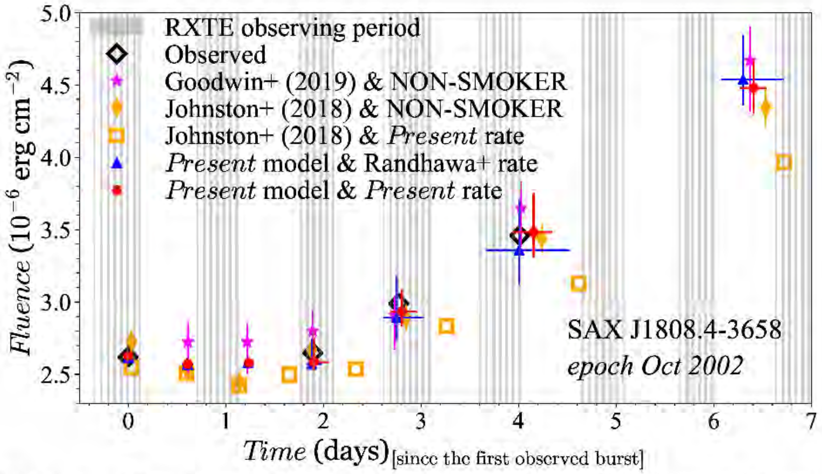


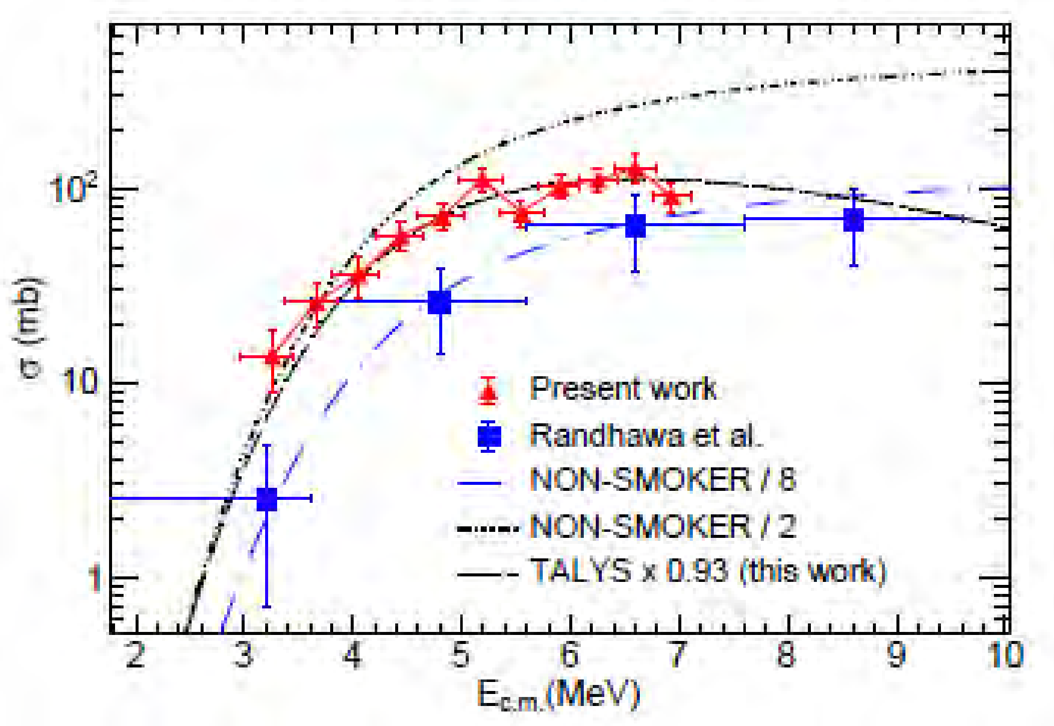
FIG. 4. The bursts' fluences (integration of flux over time) and times for SAX J1808.4-3658 burster, based on the RXTE observation [4], Johnston *et al.* [8] and Goodwin *et al.* [9] models, and present calculations. Johnston *et al.* [8] model is adopted to study the present and Randhawa *et al.* rates.

Helium abundance in the accreting envelope seems to be essential

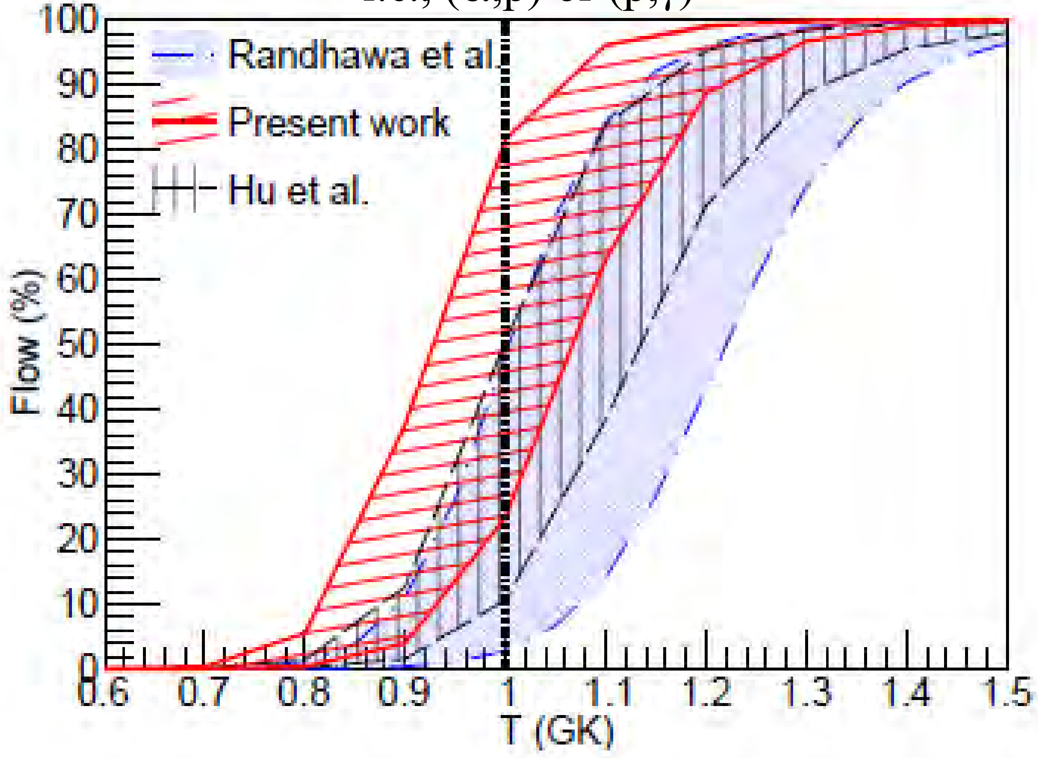
New publication

- Jayatissa et al., Phys. Rev. Lett. (2023).

New direct measurement at ANL, Factor 3-4 enhanced rate?



Flow ratio into the αp-process
i.e., (α,p) or (p,γ)



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

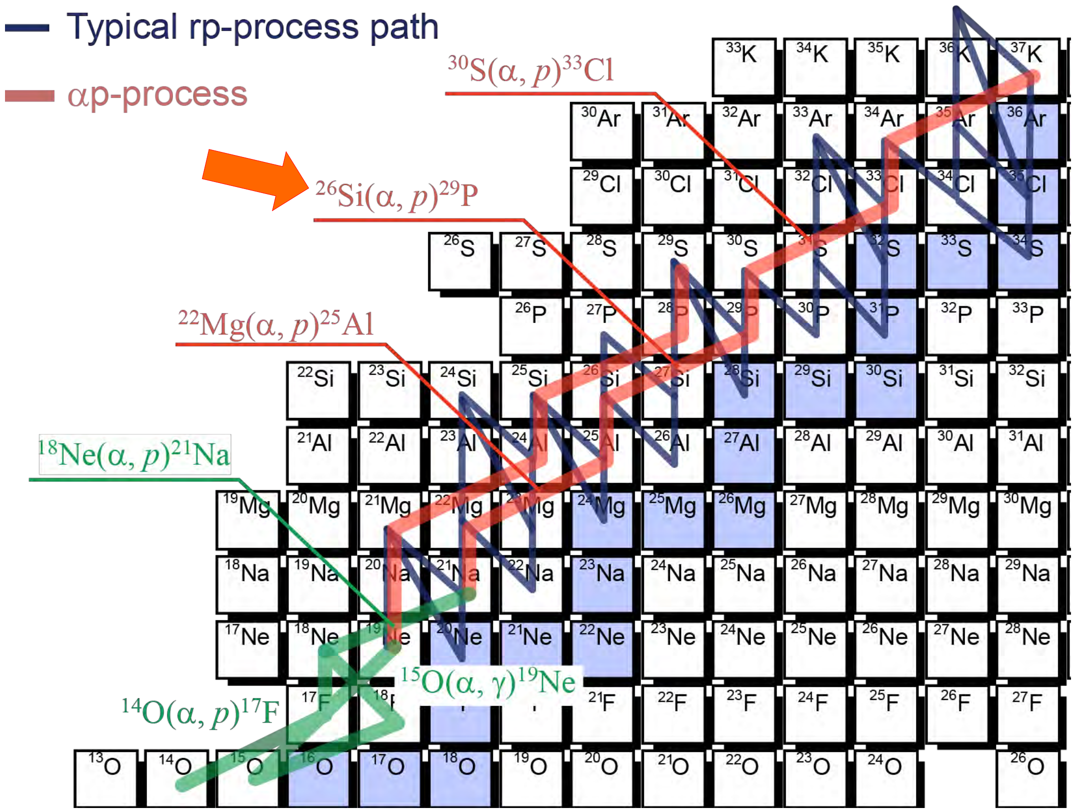


Table 1
Reactions that Impact the Burst Light Curve in the Single-zone X-Ray Burst Model

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

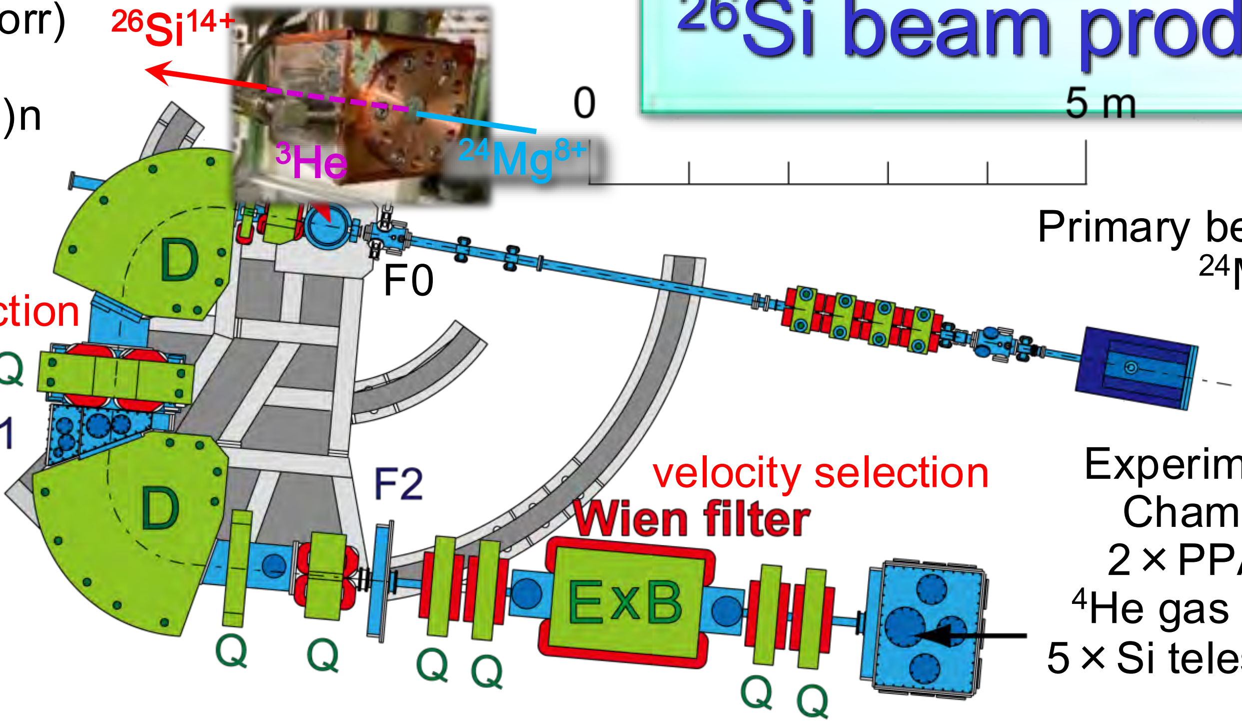
Table 2
Reactions that Impact the Burst Light Curve in the Multi-zone X-ray Burst Model

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).

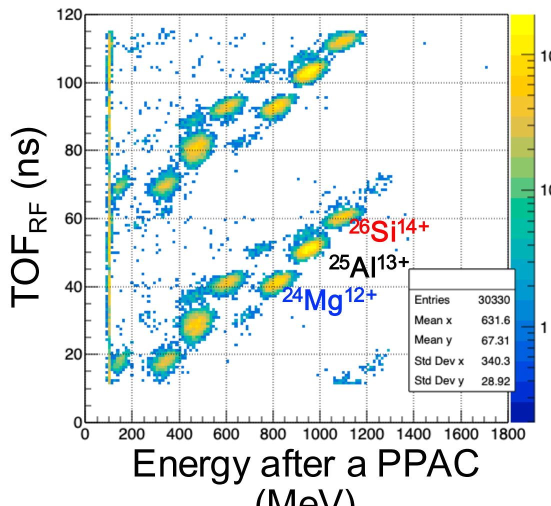
- The $^{26}Si(\alpha,p)^{29}P$ reaction has a <u>high sensitivity on the light curve</u>

^{26}Si beam production at CRIB

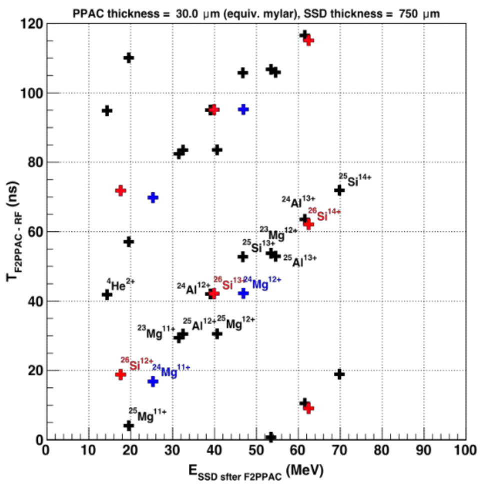


PID at F2 (ΔE vs TOF$_{RF}$)

Measurement

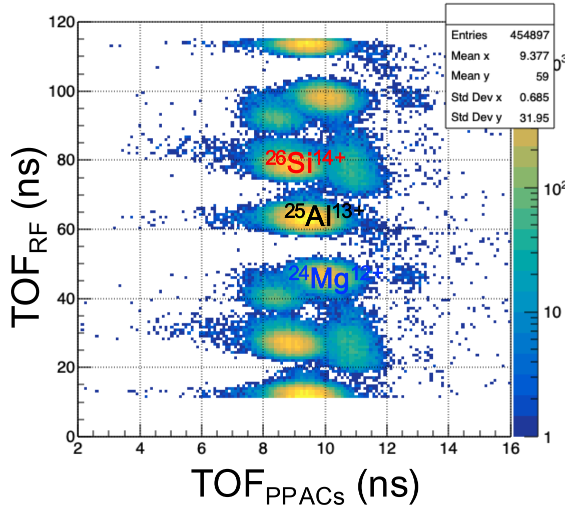


Simulation

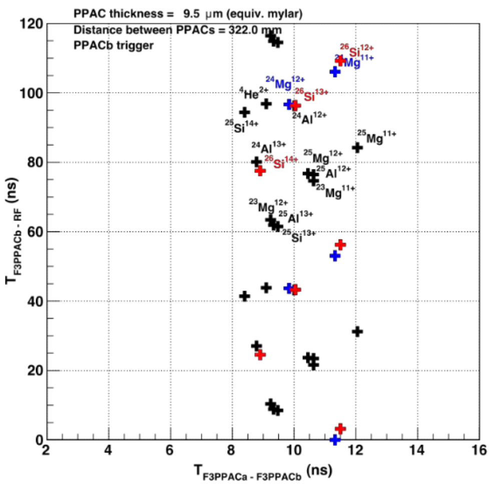


PID at F3 (TOF$_{PPACs}$ vs TOF$_{RF}$)

Measurement



Simulation



Collaboration/ beamtime

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,

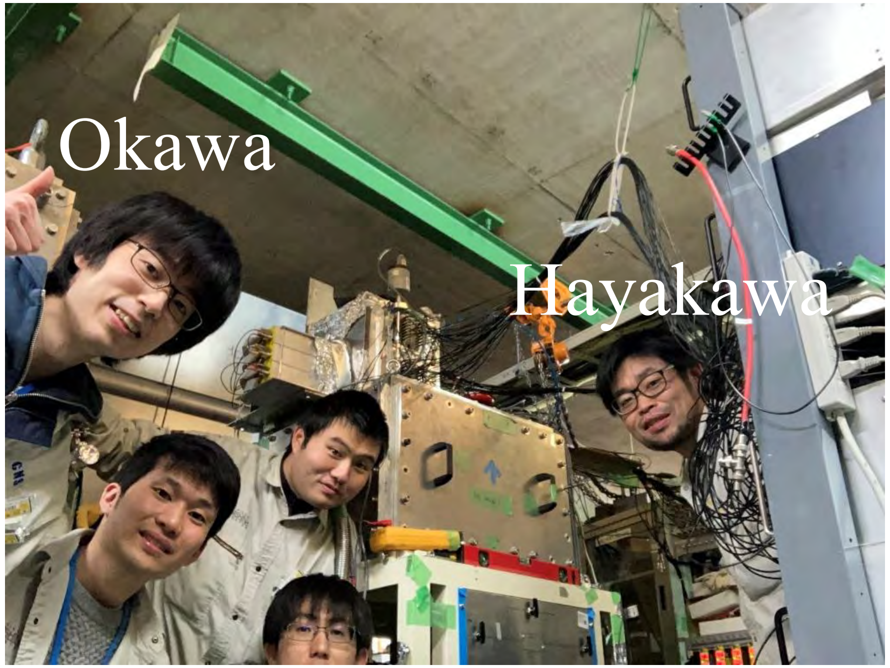
CNS: S. Hayakawa, K. Okawa, N.R. Ma, H. Shimizu H. Yamaguchi, Q. Zhang, T. Chillery, S. Hanai, N. Imai, J. Li, S. Michimasa, R. Yokoyama,

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 (Jan. 2022).

Foreign collaborators could not come to Japan from due to COVID19 restriction (border closed again in Dec. 2021)

Domestic collaborators from Osaka U. and CNS

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

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

→ Now their theses (Ph. D, Master) were completed, publications in preparation.

$^{14}O(\alpha,p)^{17}F$ Experiment, performed in 2023

Collaboration: IBS-CENS (Korea), Texas A&M (U.S.), CNS (Japan), SKKU (Korea), INFN (Italy) and others:

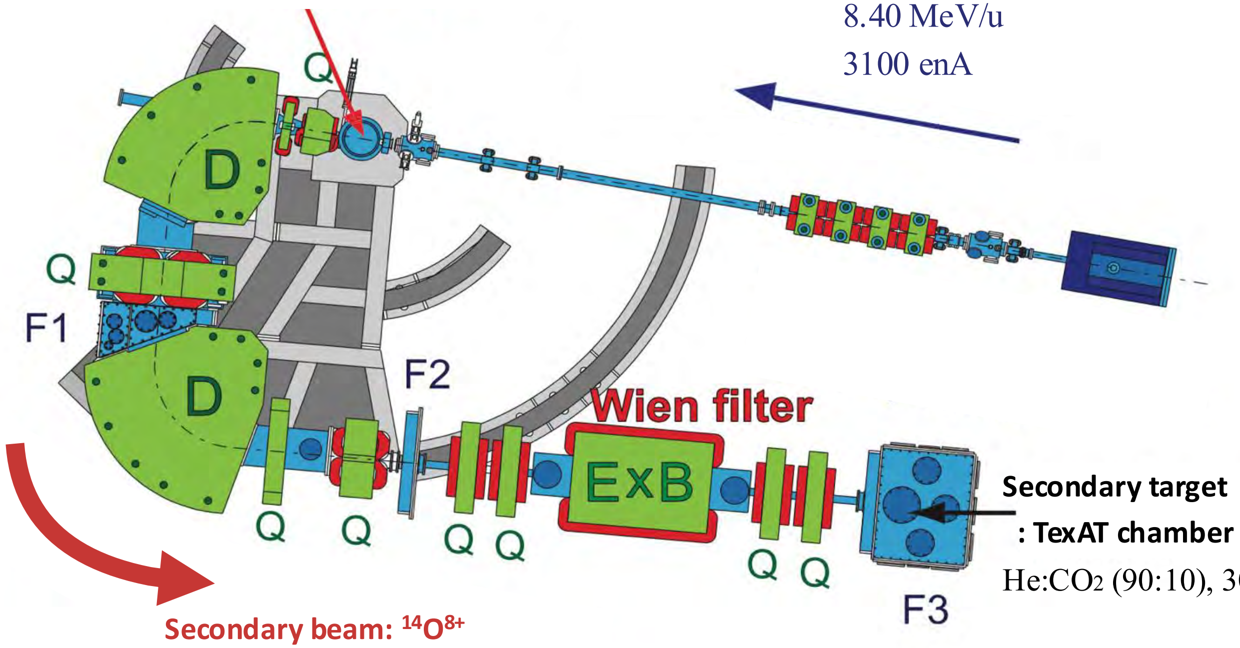
40 participants with 11 nationalities.

F0 target: H_2 gas (90K, 80 mm, ~500 Torr)

Primary beam: $^{14}N^{6+}$

8.40 MeV/u

3100 enA



Secondary target

: TexAT chamber

He:CO_2 (90:10), 300 Torr

Secondary beam: $^{14}O^{8+}$

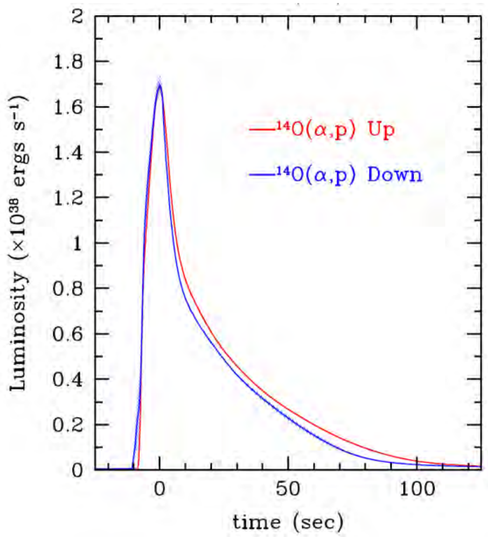
4.66 MeV/u

→ ~3 MeV/u, 10^5 pps after thin scintillator

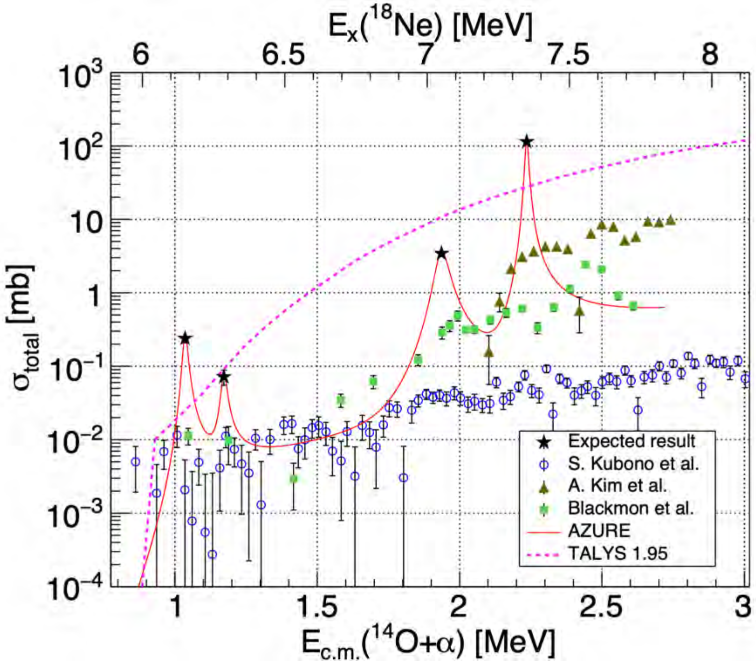
TexAT chamber

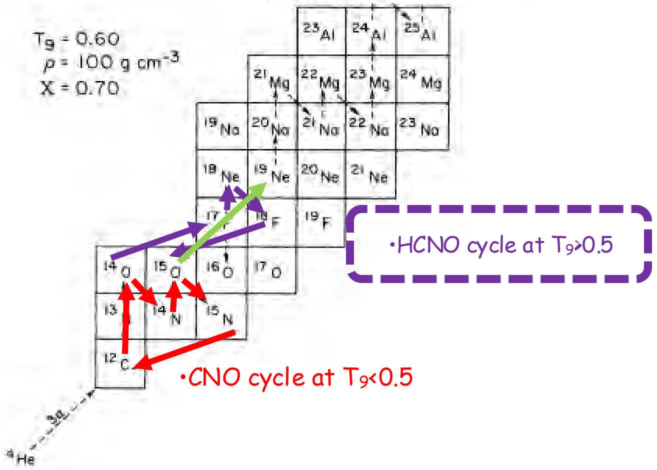
$^{14}O(\alpha,p)^{17}F$ reaction

- One of the important (α, p) reactions in X-ray bursts
- Possible break-out path from the hot CNO cycle to the rapid proton burning (rp-process).

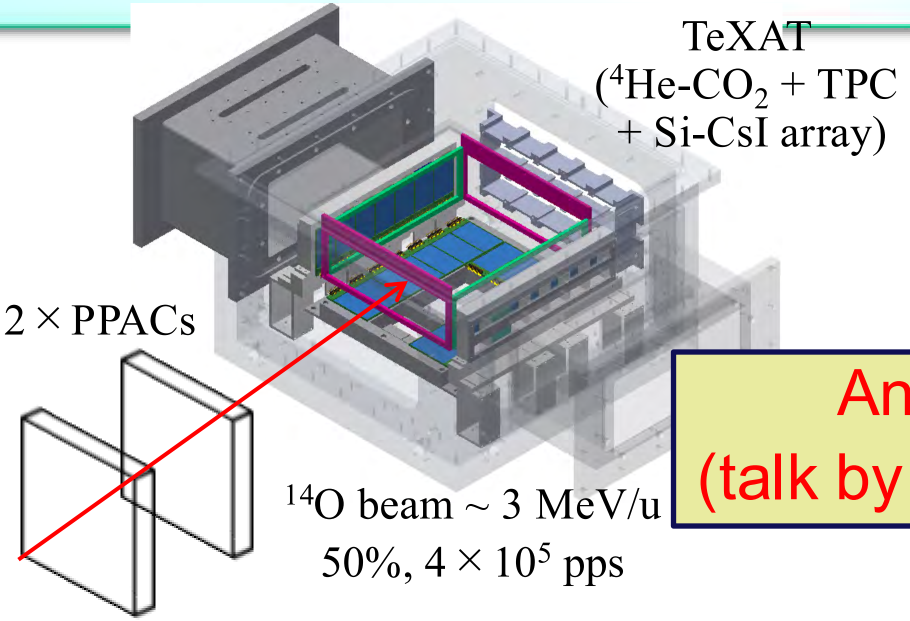


- Large uncertainty
  - Previous cross section measurements at high energy range (2 MeV ≤ E_{cm} ≤ 2.8 MeV) show large disagreements.
  - Data at low energy range (1 MeV ≤ E_{cm} ≤ 1.5 MeV) with large error bars have to be confirmed by another study.

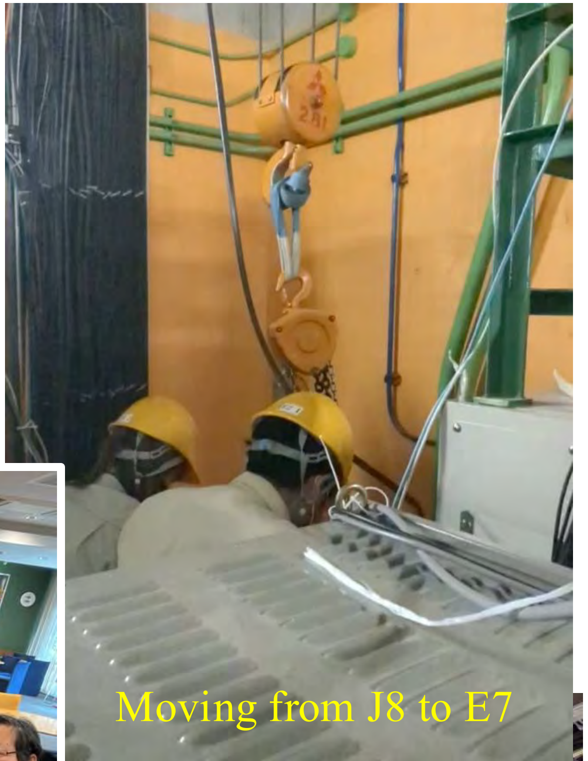




$^{14}O(\alpha,p)^{17}F$: Run

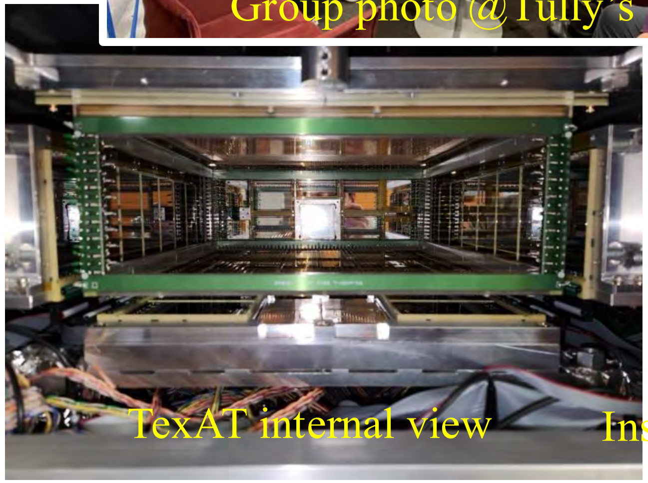



Preparation @J8
inside a cleanroom


Moving from J8 to E7

Analysis in progress
(talk by Tony Ahn later today).


Group photo @Tully's

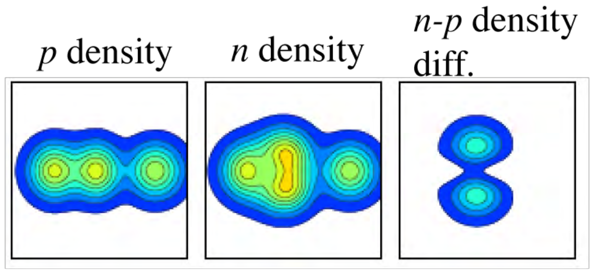

TexAT internal view

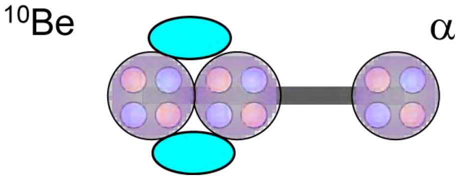

Installing TexAT to the CRIB line @E7

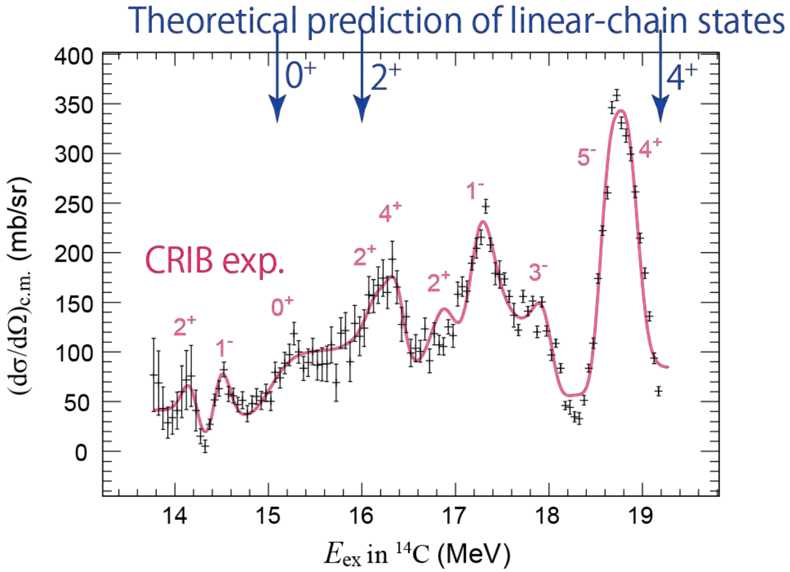
Another topic at CRIB: α clusters and linear chain

^{14}C ($^{10}Be+\alpha$)

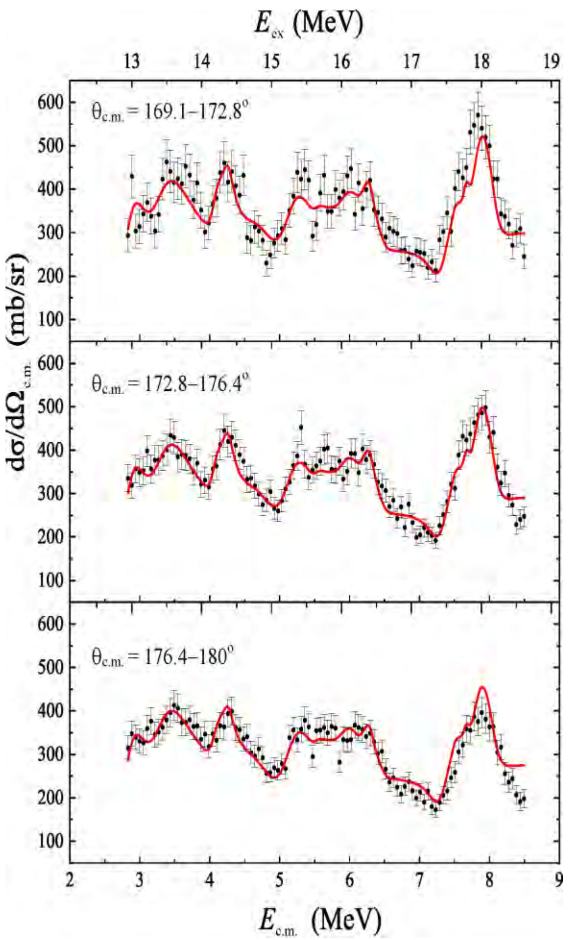
Suhara & En'yo, PRC 2010 and 2011:







^{14}O ($^{10}C+\alpha$)



Nice agreement between exp. and theory for the (0^+, 2^+, 4^+) states.

^{14}C: *H. Yamaguchi et al., Phys. Lett. B (2017).*

^{14}O: *N.R. Ma, M. Sferrazza et al, Phys Rev. C (2024).*

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.
- Successful international collaborations mainly on nuclear astrophysics:
  - (α, p) reactions in high-temperature environments $^{22}Mg(\alpha, p)$, $^{26}Si(\alpha, p)$, $^{14}O(\alpha, p)$, $^{13}N(\alpha, p)$
    - resonant scattering with TTIK.
    - direct measurement using a static or an active target.
  - Alpha cluster study $^{10}C+\alpha$, $^{26}Si+\alpha$

- Visit CRIB webpage for more information. http://www.cns.s.u-tokyo.ac.jp/crib/crib-new/