Production and Application of the low-energy RI beams at CRIB

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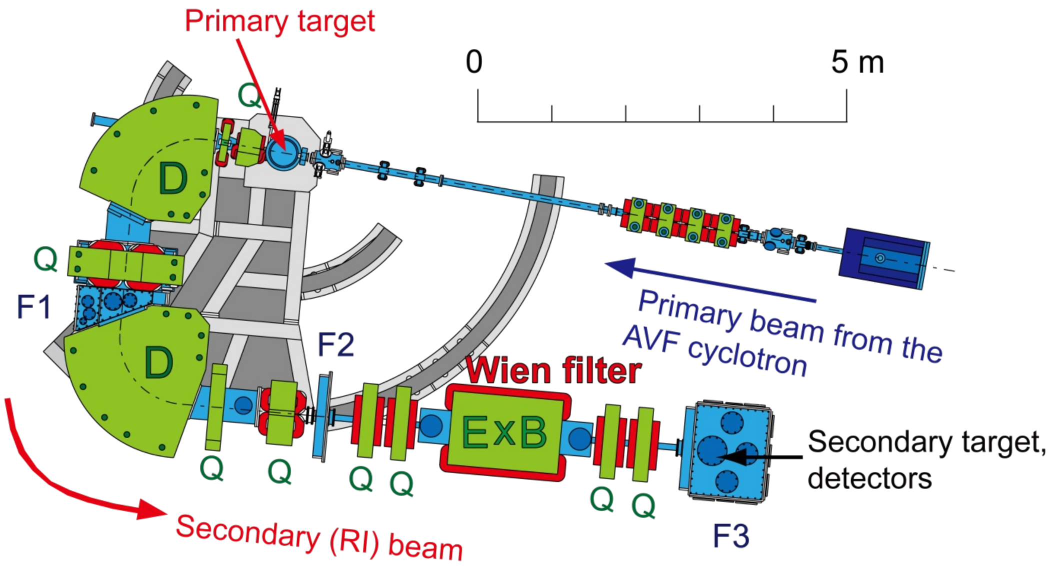
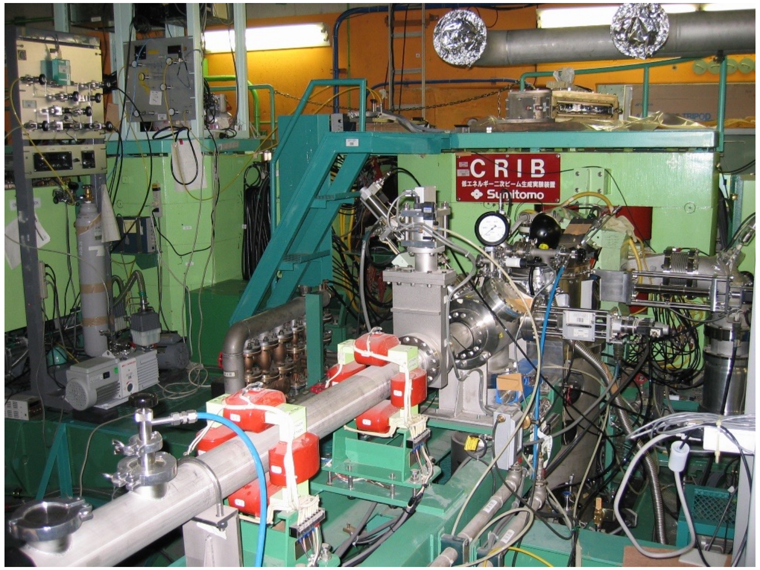
CRIB – Low energy RI beam separator of CNS

- 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.

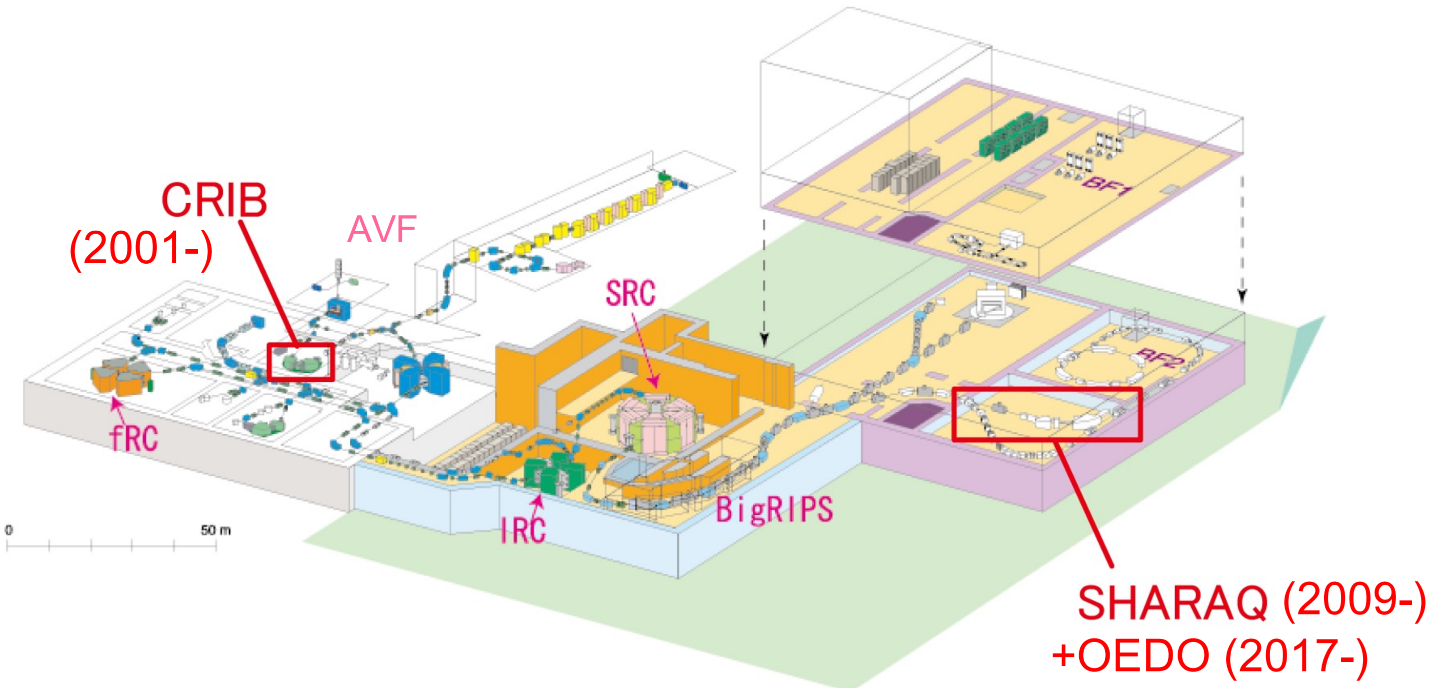


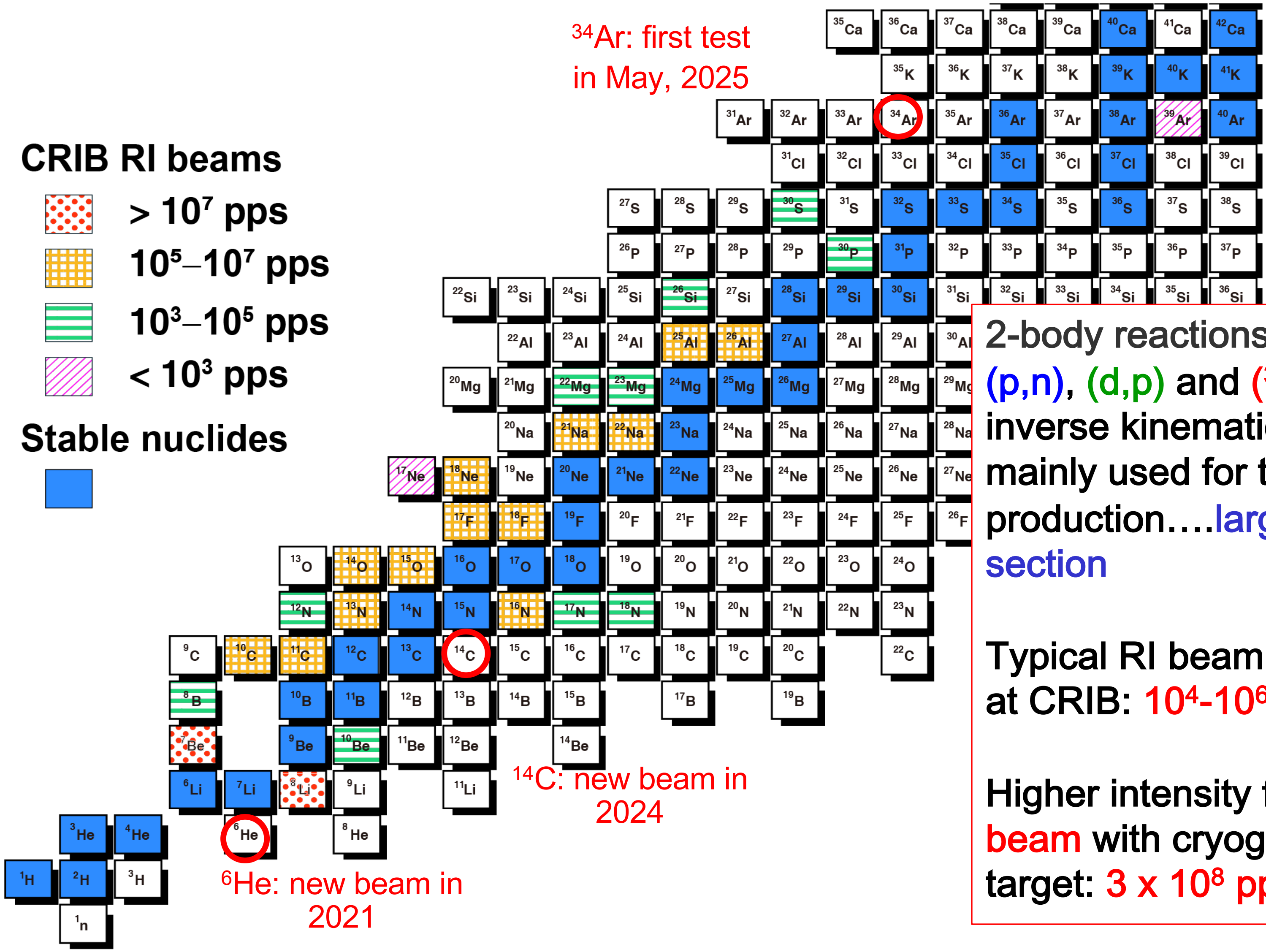


CRIB in RIBF

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



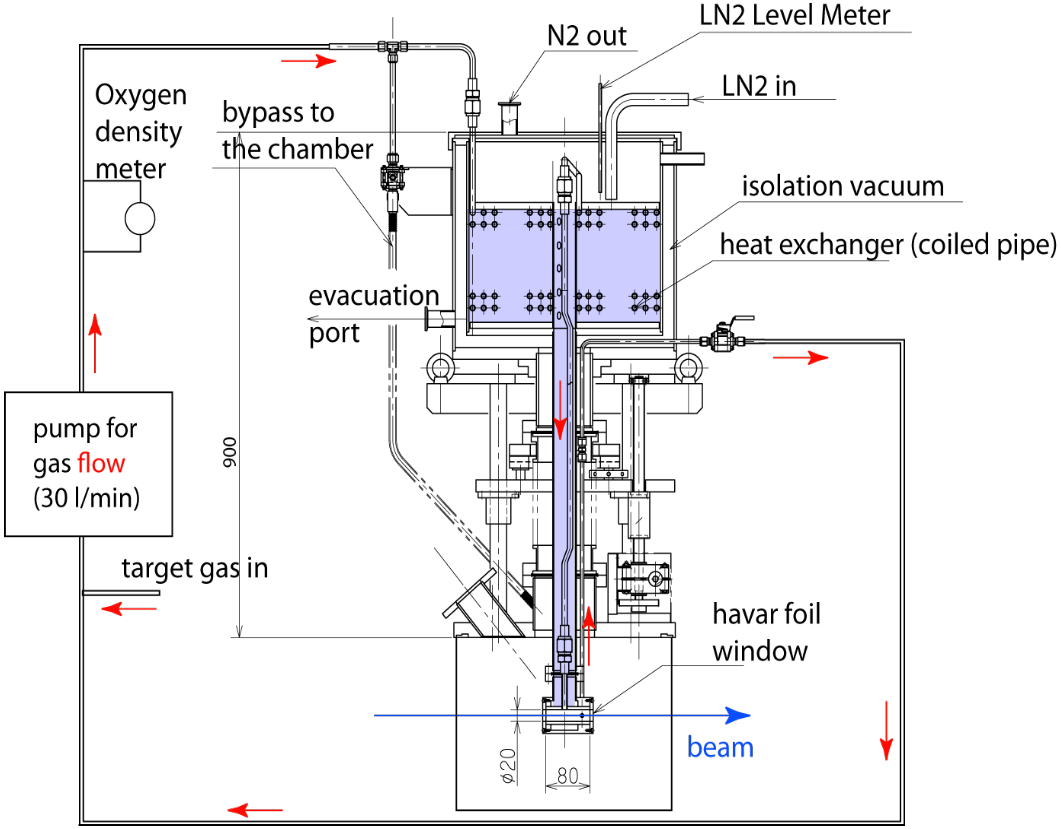


2-body reactions such as (p,n), (d,p) and (^{3}He,n) in inverse kinematics are mainly used for the production….large cross section

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.

Cryogenic target for the RI beam production



- Gas cell: 80-mm long, Sealed with thin Havar foils (2.5 μm x2). Can hold gas at ~1 atm.
- Lq. N_2 cooling (automatic refill), T~90 K

  to improve the cooling efficiency and the target thickness.
- Forced target gas flow (>30 l/min) to have a better cooling, and to avoid target thickness reduction by the high-current beam.

H. Yamaguchi et al., NIMA (2008)

^{34}Ar beam production test (May 12-14, 2025)

Primary beam:

8.3 MeV/u $^{32}S^{11+}$, max. 84 pnA.

Target:

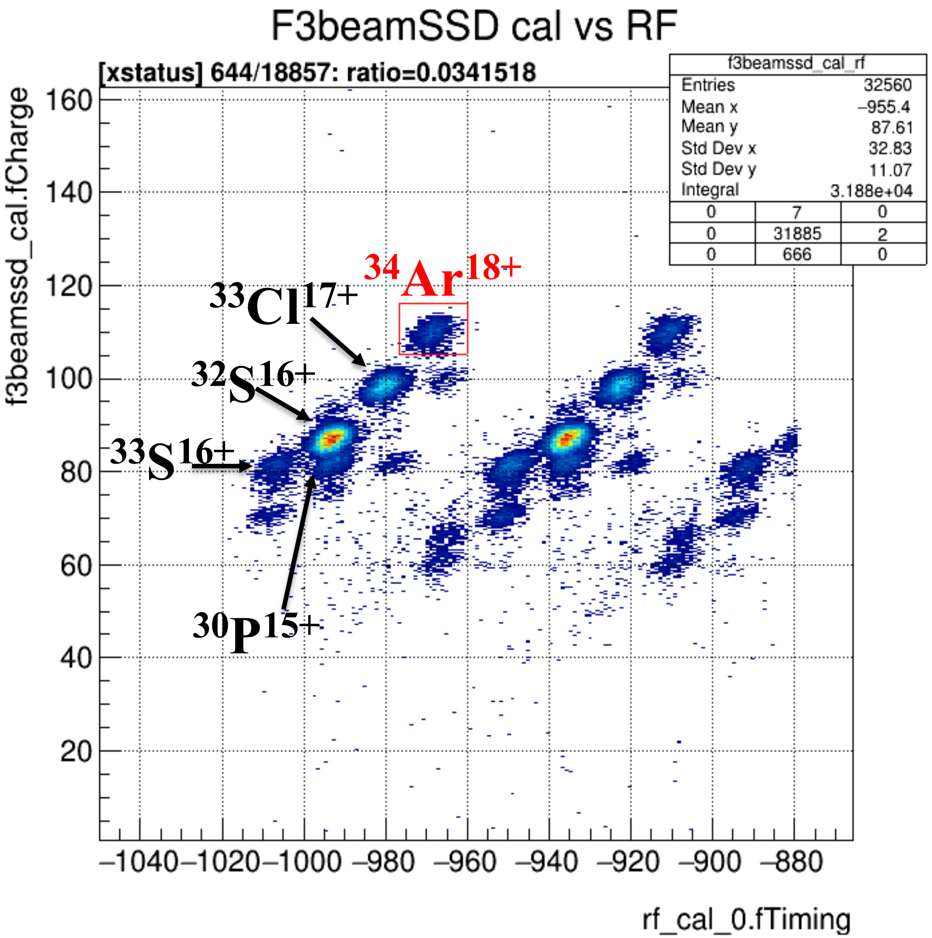
LN_2-cooled ^{3}He Gas, 300Torr, 80 mm.

Reused (contaminated) gas with limited amount.

Secondary beam:

$^{34}Ar^{18+}$, 110 MeV (3.2 MeV/u), max purity: 6.8%, achieved max intensity: 2.5×10^3 pps.

We may expect ~5×10^3 pps, if we can use a pure and thicker gas target in the main measurement.

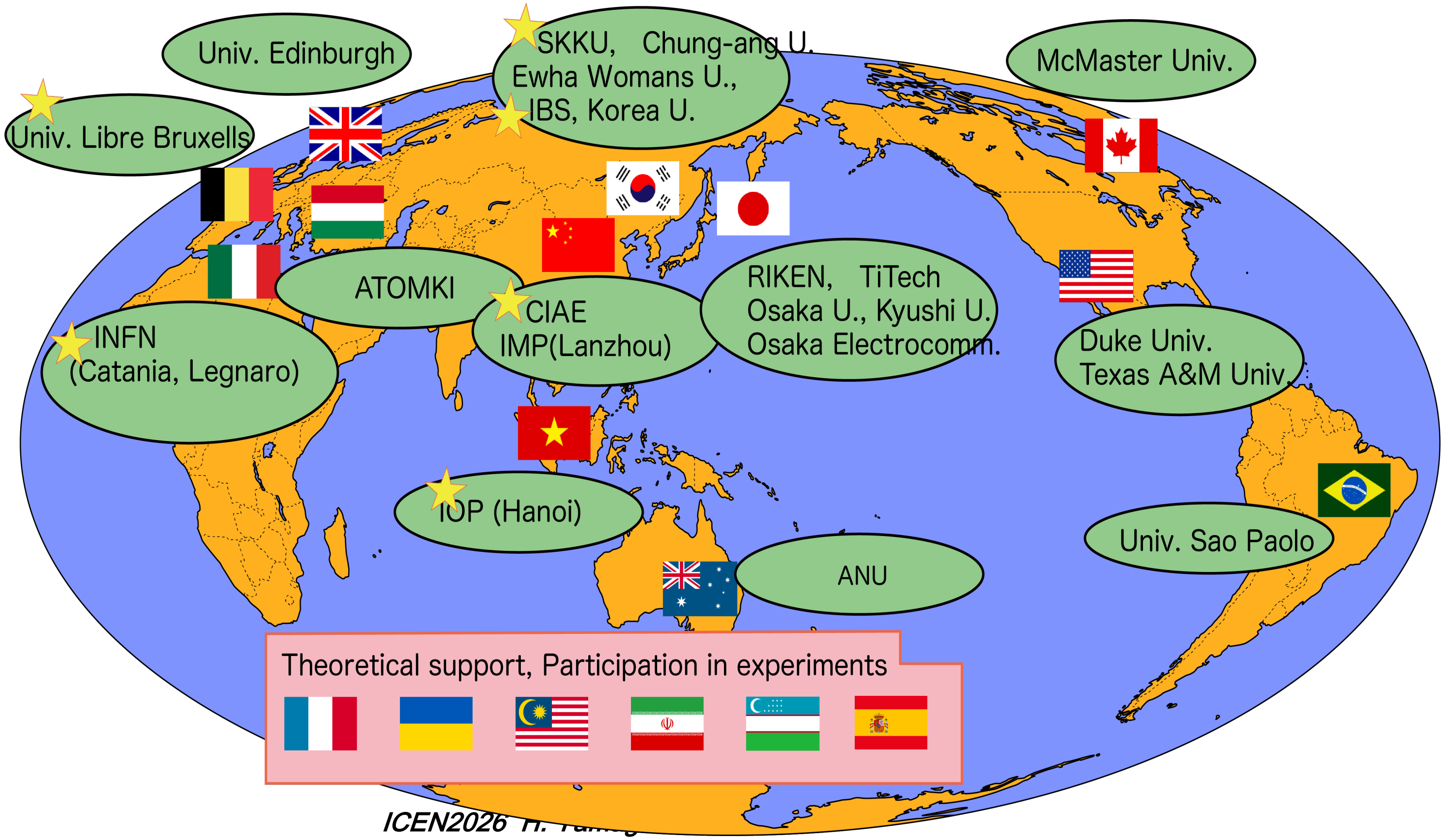


Cf.) Browne et al., PRL 2023 (NSCL exp.)

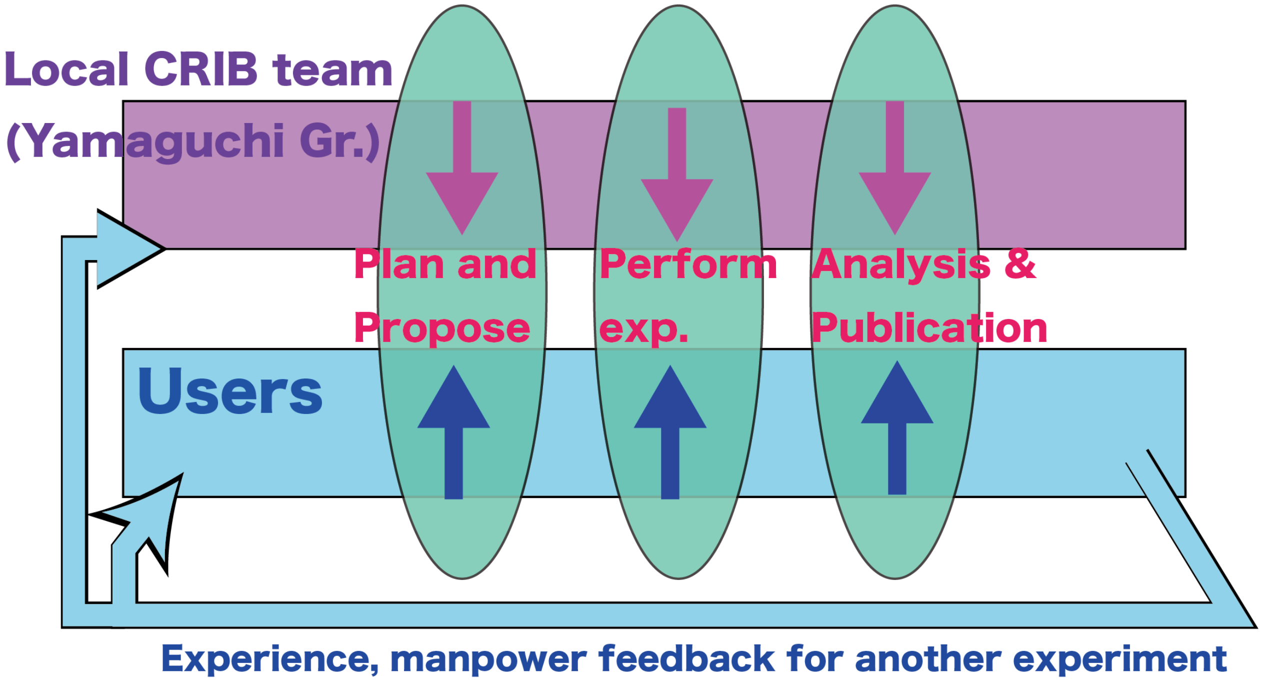
$E_{c.m.}$=5.9 and 5.6 MeV at the center of the target. Total beam intensities on target ranged between ~(2–8) x 10^3 pps in total, 60% of them are ^{34}Ar. No event-by event ID of the beam particle, and Ar/Cl were not separated.

CRIB is collaborative

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



Collaboration scheme



CRIB is collaboration-based facility:

- CRIB local members are collaborators in every CRIB experiment.
- The local team works with the users in all stage of the experimental projects

…We are not just "the beam provider" and "customers".

Physics

- Nuclear astrophysics
  - ◆RI-involved astrophysical reactions

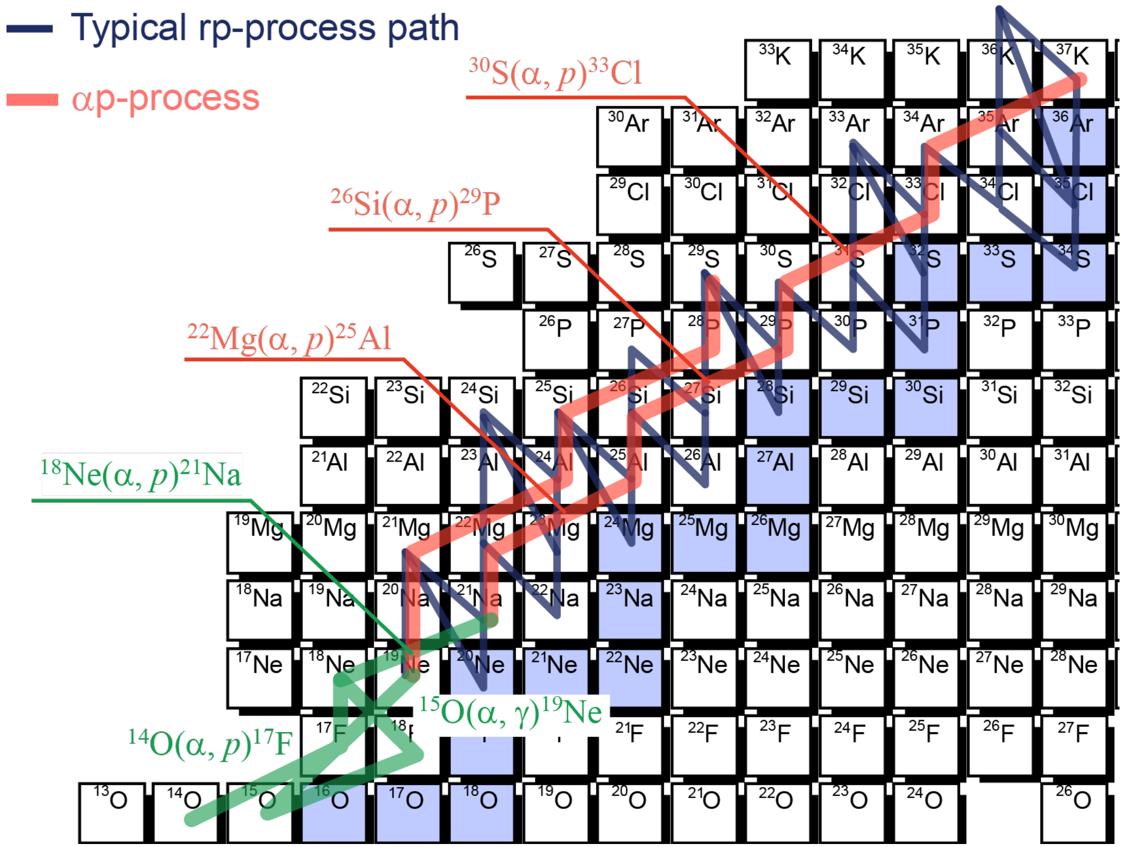
    Stellar sites: Big-bang nucleosynthesis, X-ray bursters, Supernovae, etc.
- Nuclear-clustering
  - ◆Mirror symmetry
  - ◆Linear-chain cluster states
- Nuclear reactions
  - ◆Reaction mechanism
  - ◆Halo nuclei

Key α-induced reactions in X-ray bursts

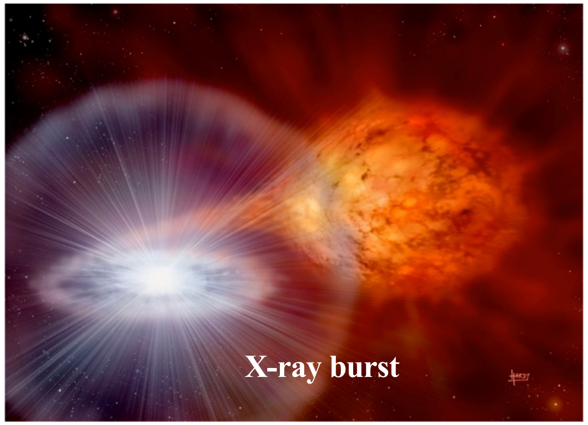
- The "rp-process" in X-ray bursts ($T_{\max}$ can be 2-3 GK) takes a path including (α, p) reactions to skip sequential (p, γ) and β decays… the αp-process.

- Many key (α, γ) and (α, p) reactions, from an RI to another RI (i.e. difficult to study it experimentally) which may affect much to the X-ray bursts.

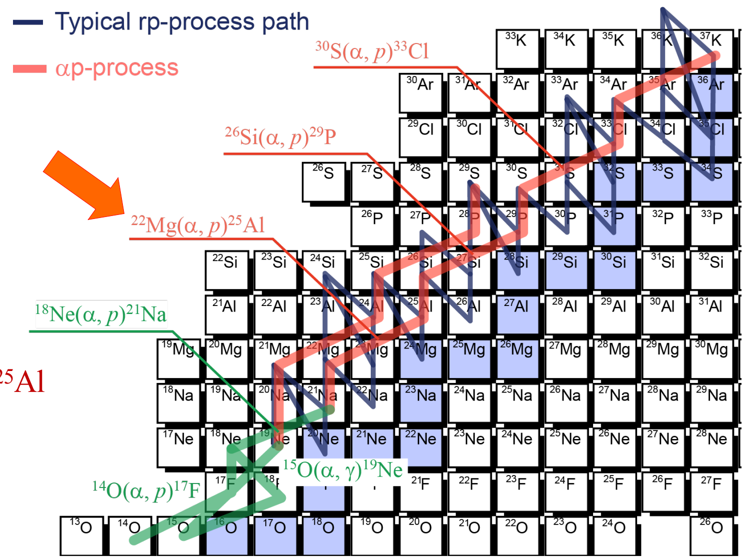
- Good matching with CRIB beams…MeV-order energy, A=10-40 mass region, proton rich RI.



^{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	[illegible]
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}.

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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)

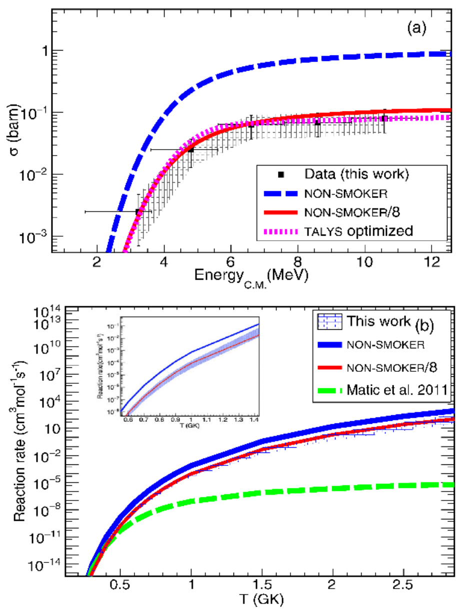


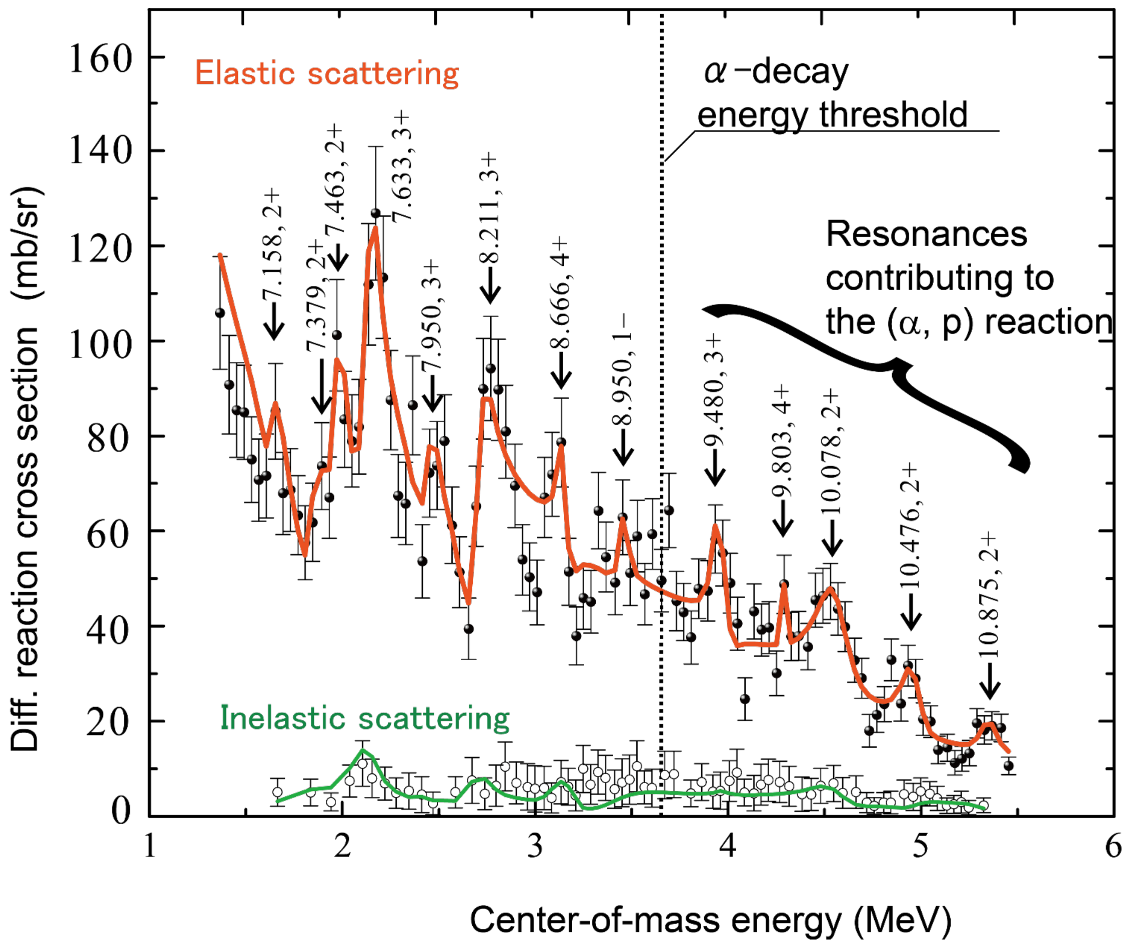
FIG. 3. Panel (a) shows the experimental cross sections obtained in the present work over a range of center-of-mass energies covered (black). For all the points, the cross section weighted energy is shown, which is the reason why horizontal error bars for the two lowest energy points are asymmetric.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



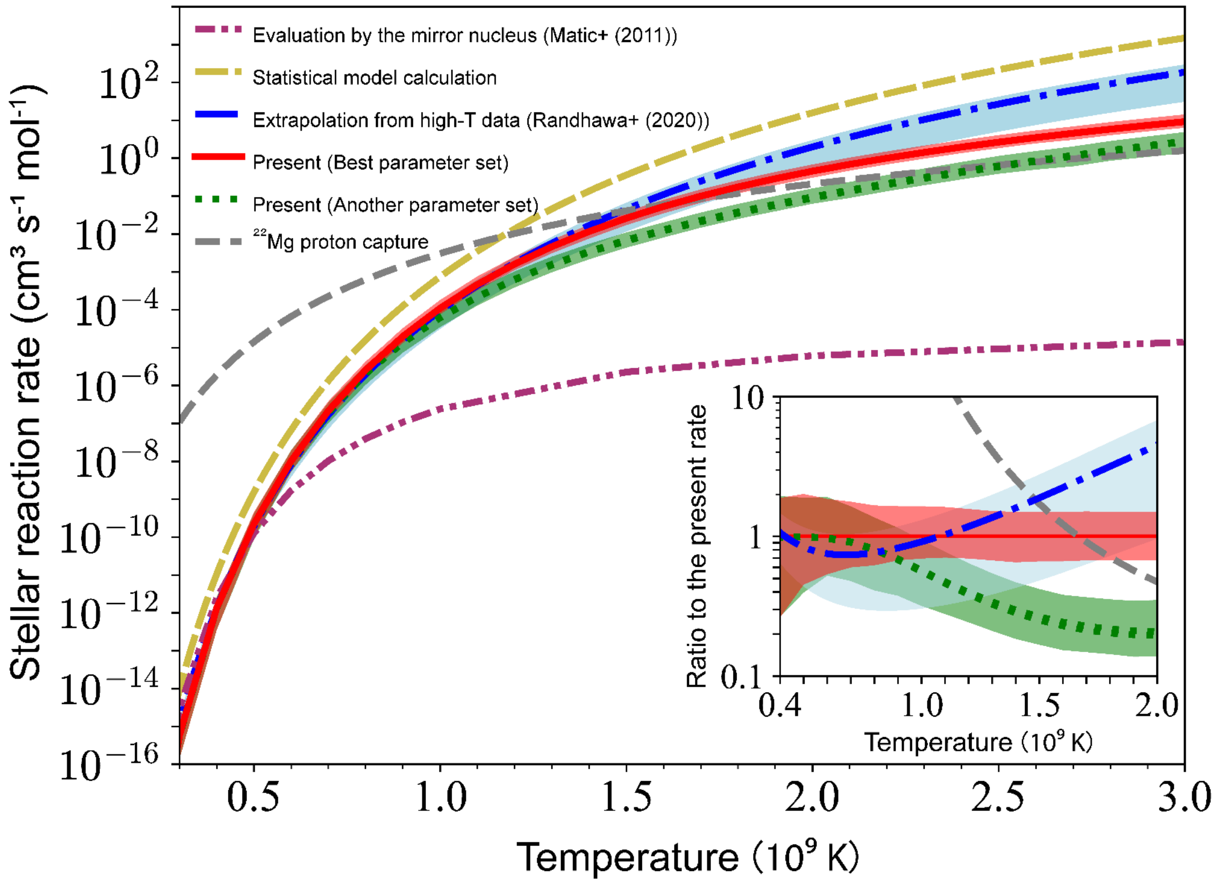
Updated ^{22}Mg(α,p) reaction rate

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.

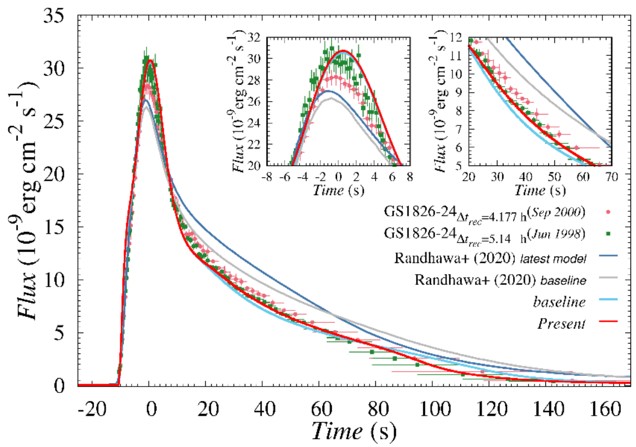


FIG. 3. The best fit *baseline* and *Present* modeled lightcurves to the observed lightcurve of epoch *Jun 1998*, and the best fit Randhawa *et al.* [22] lightcurves to epoch *Sep 2000*. The magnified lightcurves at the burst peak and t=20–70 s are shown in the left and right insets, respectively.

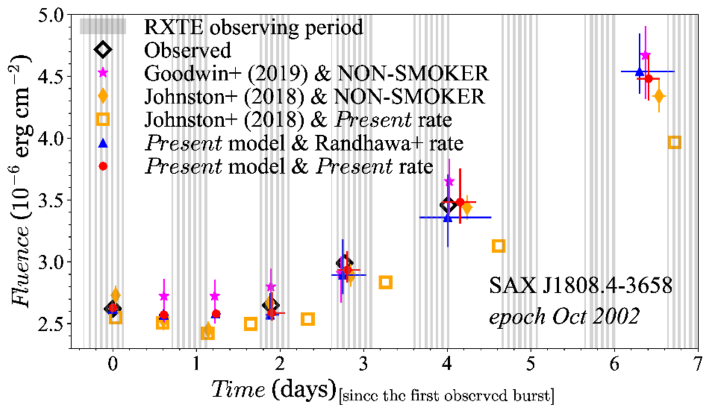


FIG. 4. The bursts' fluences (integration of flux over time) and times for SAX J1808.4-3658 burster, based on the RXTE observation [4], Johnston *et al.* [8] and Goodwin *et al.* [9] models, and present calculations. Johnston *et al.* [8] model is adopted to study the present and Randhawa *et al.* rates.

Helium abundance in the accreting envelope seems to be essential

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

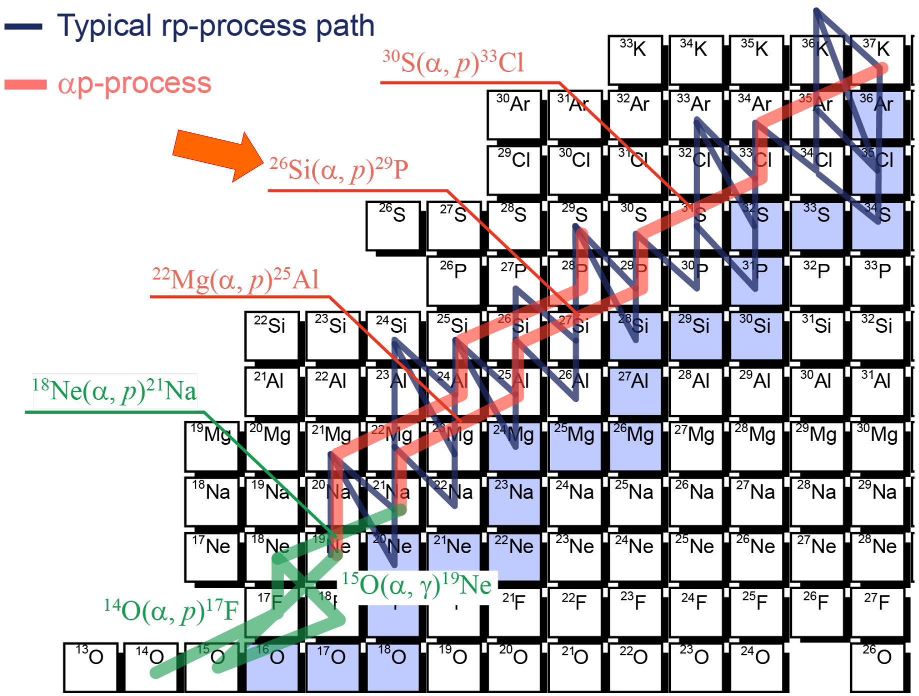


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Table 1
Reactions that Impact the Burst Light Curve in the Single-zone X-Ray Burst Model

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

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

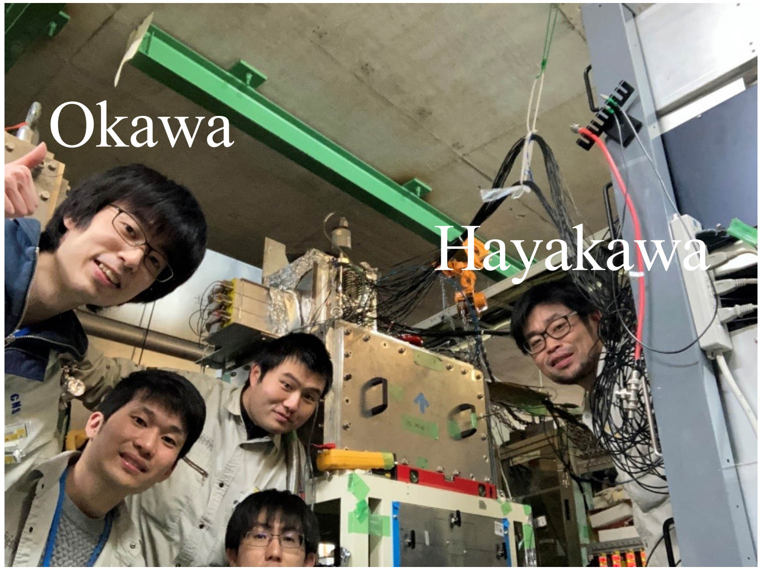
SKKU: K.Y. Chae, M.J. Kim, N.N. Duy, G.M. Gu, C.H. Kim, S.H. Kim, M.S. Kwag, N.K. Uyen,

IBS: S.M. Cha, D. Kim

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

ELI-NP: D. Kahl, O. Sirbu

RIKEN: S. Kubono



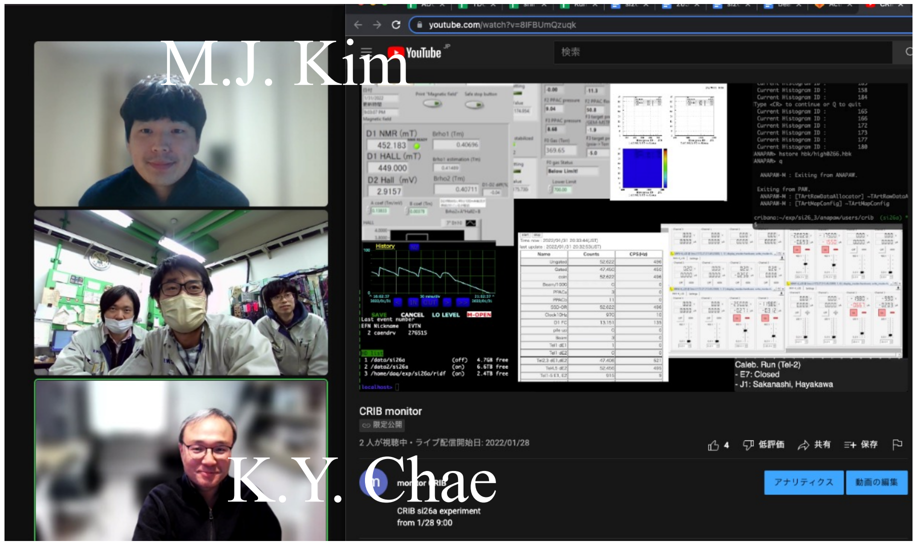
The first CRIB main experiment after COVID (Jan. 2022).

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)

Analysis by graduate students:
M.J. Kim's Ph.D thesis, K. Okawa's Ms. Thesis.



More (α, *p*) direct measurements

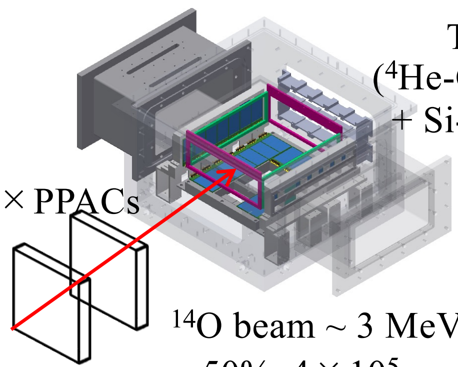
<u>Direct measurement of the $^{14}O(\alpha, p)^{17}F$ reaction with the Texas Active Target detector</u>

(S. Ahn, D. Kim, IBS, Mar 11 - 25, 2023)

Measurement of $^{14}O(\alpha,p)$ astrophysical reaction with a 4×10^5 pps low-energy ^{14}O beam at CRIB.

Texas Active Target (TexAT) transpoted from Texas.

40 participants with 10 nationalities.



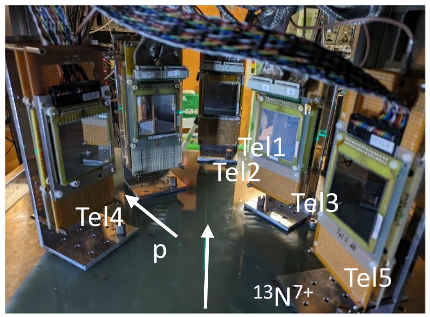
<u>Studying supernova nucleosynthesis with CRIB: Measurement of the $^{13}N(\alpha, p)^{16}O$ reaction</u>

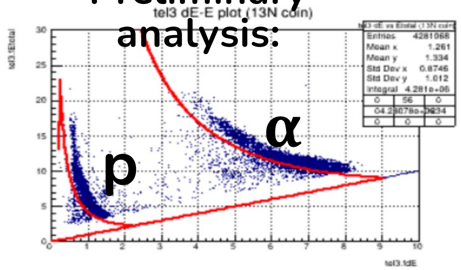
(A. Psaltis, Duke Univ., Jun 6-15, 2024)

$^{13}N(\alpha, p)^{16}O$: reaction relevant in supernovae.

^{13}N beam produced at ~1×10^6 pps, 90% purity, thick-target method measurement was performed.

28 participants from 5 countries. 🇯🇵🇺🇸🇰🇷🇮🇹🇧🇪





What can we do at RAON?

- Assuming KoBRA can be regarded as a "Super CRIB", we can extend our research in a more advanced form.
  - ◆ RI beam: higher intensity and variety of nuclides
  - ◆ Wider energy range
  - ◆ Low neutron background (the production target is behind the wall)
  - ◆ High efficiency with the Active target

Today I propose two ideas, based on the beam development status at KoBRA:

- ^{8}Li(α,n) famous reaction for the inhomogenius big-bang model, may need neutron measurements.
- ^{21}Na(α,p) RI-involving astrophysical reaction in explosive stellar environments.

^{8}Li(α,n)^{11}B reaction

Slides by Y. Mizoi

Standard Big Bang Model

$\Updownarrow$

Inhomogeneous Big Bang Model

$\underline{^{7}\mathrm{Li}(\mathrm{n},\gamma)^{8}\mathrm{Li}(\alpha,\mathrm{n})^{11}\mathrm{B}(\mathrm{n},\gamma)^{12}\mathrm{B}(\mathrm{decay})^{12}\mathrm{C}}$

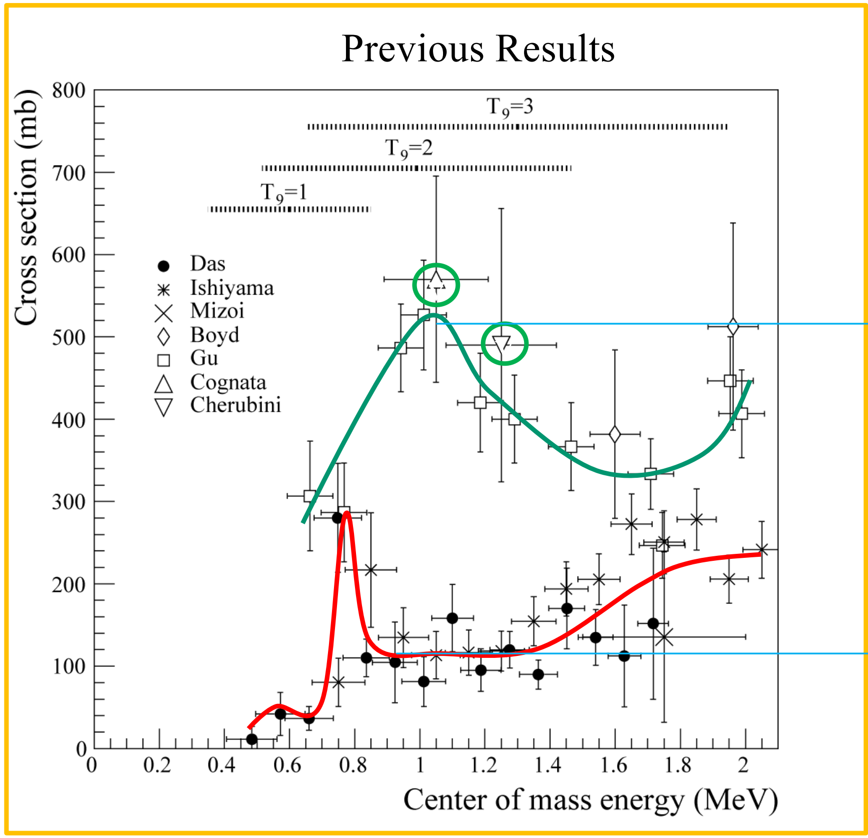
J. H. Applegate, C. J. Hogan, and R. J. Scherrer, Astrophys. J. 329, 572 (1988).
R. A. Malaney and W. A. Fowler, Astropys. J. 333, 14 (1988).
T. Kajino and R. N. Boyd, Astrophys. J. 359, 267 (1990).

Core-Collapse Supernovae

M. Terasawa *et al*., Astrophys. J. 562, 470 (2001).
T. Sasaqui *et al*., Astrophys. J. 645, 1345 (2006).

n-rich nucleosynthesis
^{8}Li ($T_{1/2}$ = 840 ms)

Astrophysical $^{8}Li(\alpha,n)^{11}B$ Reaction



Only neutron detection

("inclusive")

Only ^{11}B detection

Both ^{11}B and neutron detection ("exclusive")

A criticism for the exclusive measurement: low-energy neutrons were under the threshold of the detector?

big difference !

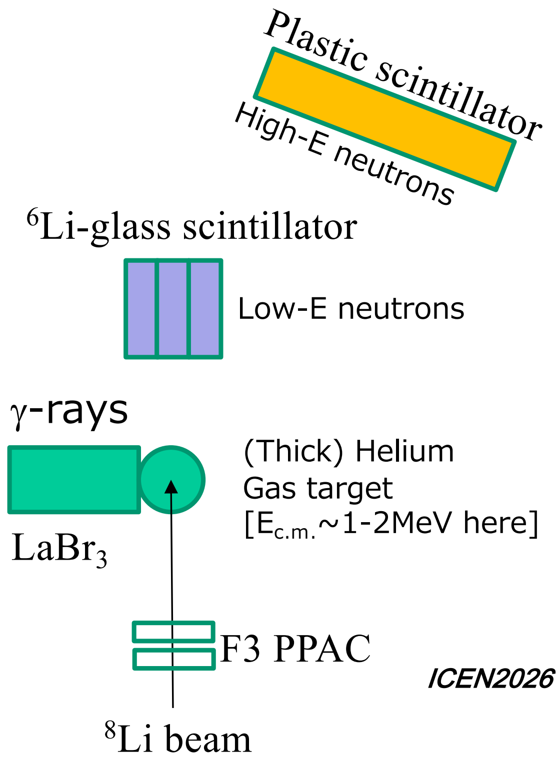
There had been no measurement detecting γ-rays from $^{11}B^*$.

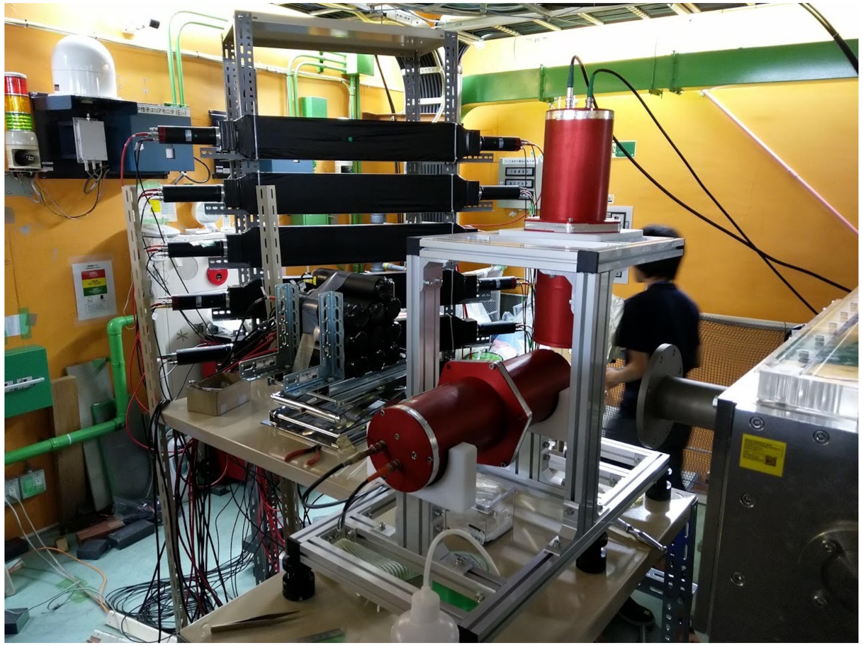
Measurement of $^{8}Li(\alpha,n)^{11}B$ at CRIB (in collaboration with Y. Mizoi)

2018 Sep. 14-20, experiment at CRIB

300 kHz ^{8}Li beam@F3 PPAC (6 MeV/u, 250 particle nA ^{7}Li on 1.9 mg/cm^{2} D_2-gas target)

Top View of Experimental Setup





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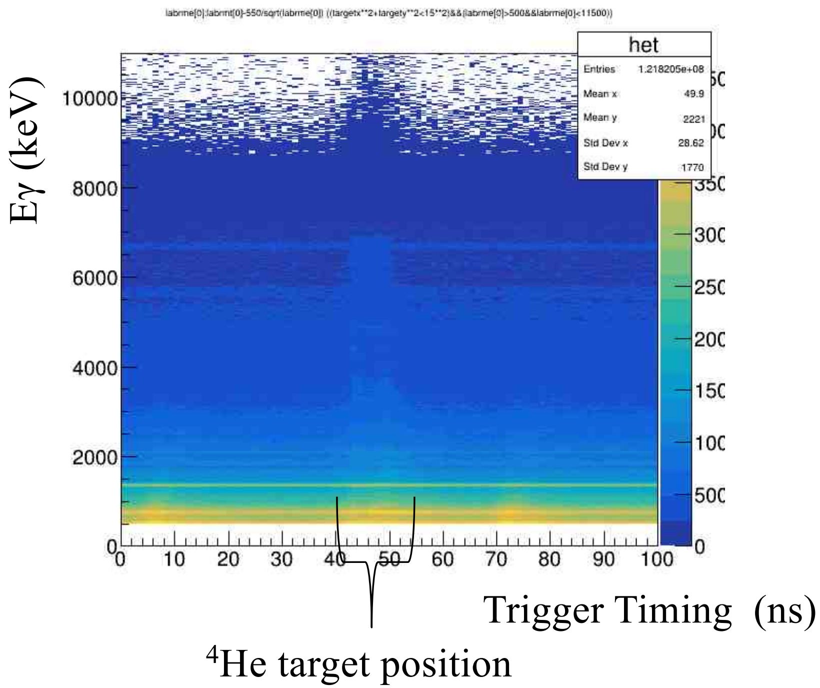
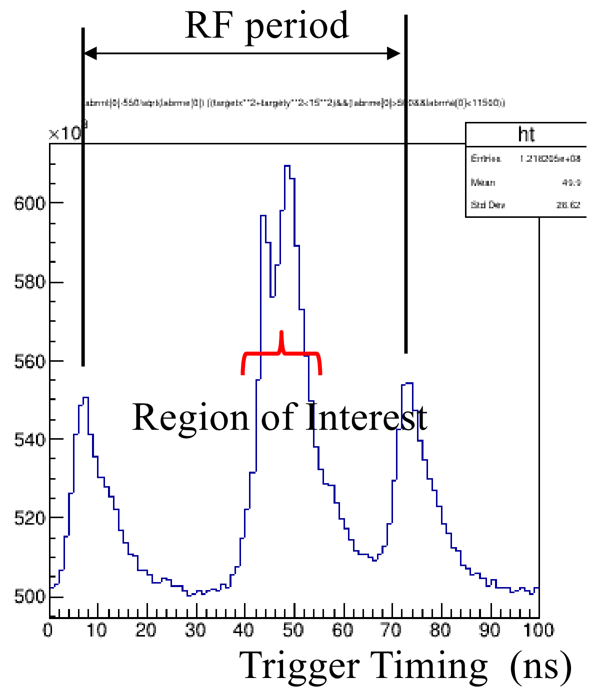
CRIB data of ^{8}Li(α,n)^{11}B





Astrophyisical ^{21}Na(α,p) reaction measurement

RAON: RI beam+ATOM-X

Strong setup for direct charged-particle reaction measurements.

^{21}Na beam experiment would be possible?

^{21}Na(α,p)…one reaction in the explosive stellar burning process, also relevant for meteoritic abundance anomaly.

At CRIB, ^{21}Na(α,p) cross section was evaluated with the widths determined by ^{21}Na+a resonant scattering, but there are discrepancies with the statistical model calculation and time-reverse (a,p_0) reaction measurement.

Dam Nguyen Binh's thesis, U-Tokyo

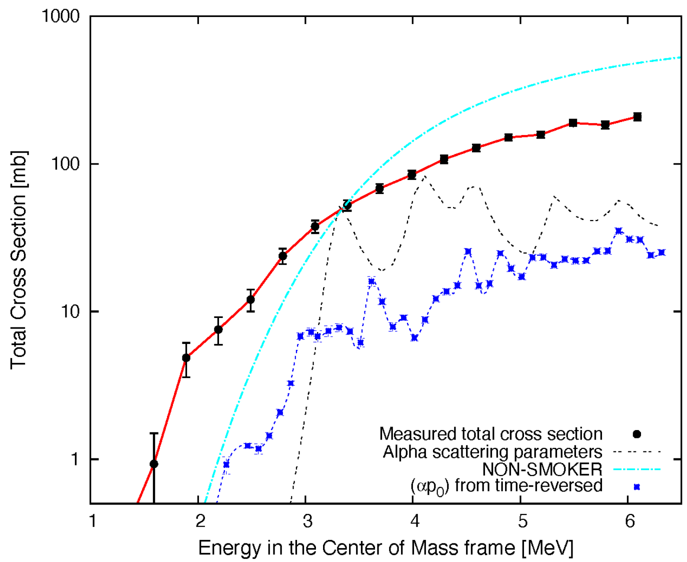


Figure 4.5: The total cross sections of the ^{21}Na$(\alpha,p)^{24}$Mg reaction measured directly, calculated using the resonant information obtain by the alpha scattering measurement, and the cross section calculated by the NON-SMOMKER web code [76].

Summary

- CRIB is a low-energy RI beam separator of CNS, the University of Tokyo.
- Intimate international collaboration is essential for efficient operation of the RI beam separator.
- Developments:

RI beam production target, Wien filter, Active target, Silicon detector array

- Experiments with various methods:
  - Alpha/proton resonant scattering
  - Astrophysical reaction measurement by direct/indirect measurements
  - Reaction mechanism study

  →More interesting results are to come
- Accumulated knowledge and experience should be useful for future experiments at RAON-KoBRA.