The 29th International Nuclear Physics Conference, INPC 2025

Direct Measurements of Key Reactions in Nuclear Astrophysics at CENS

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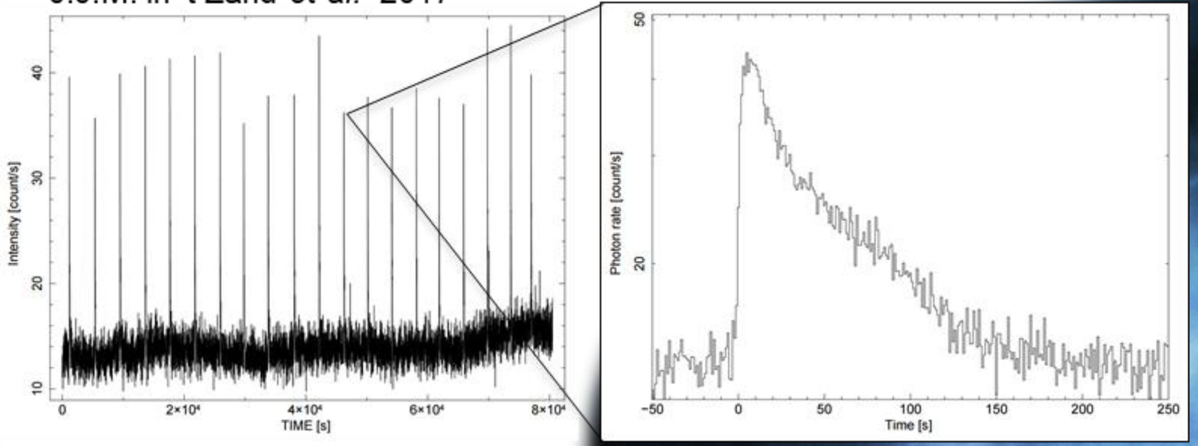
Institute for Basic Science
(CENS/IBS)
on behalf of CENS Astro-boys
05/29/2025

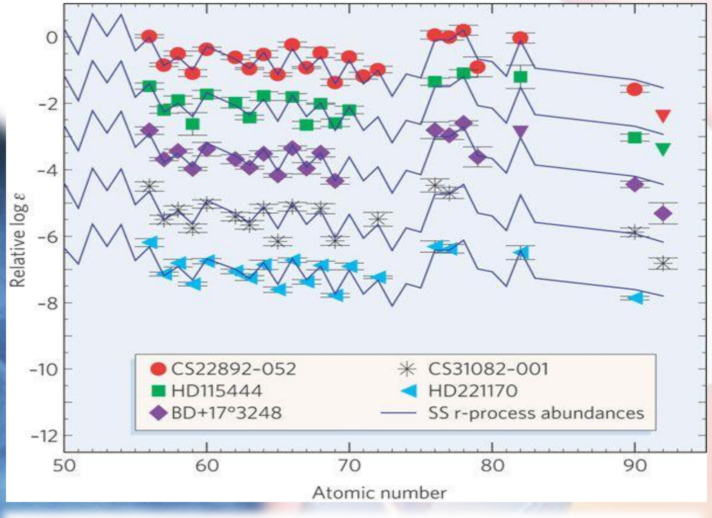
INPC 2025
May 25-30, 2025
DCC, Daejeon, Korea

Astrophysical Observables

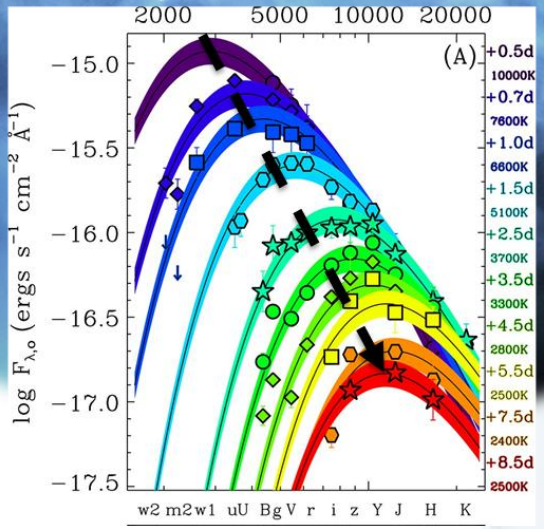
J.J.M. in 't Zand *et al.* 2017



Observed light curves of X-ray burst

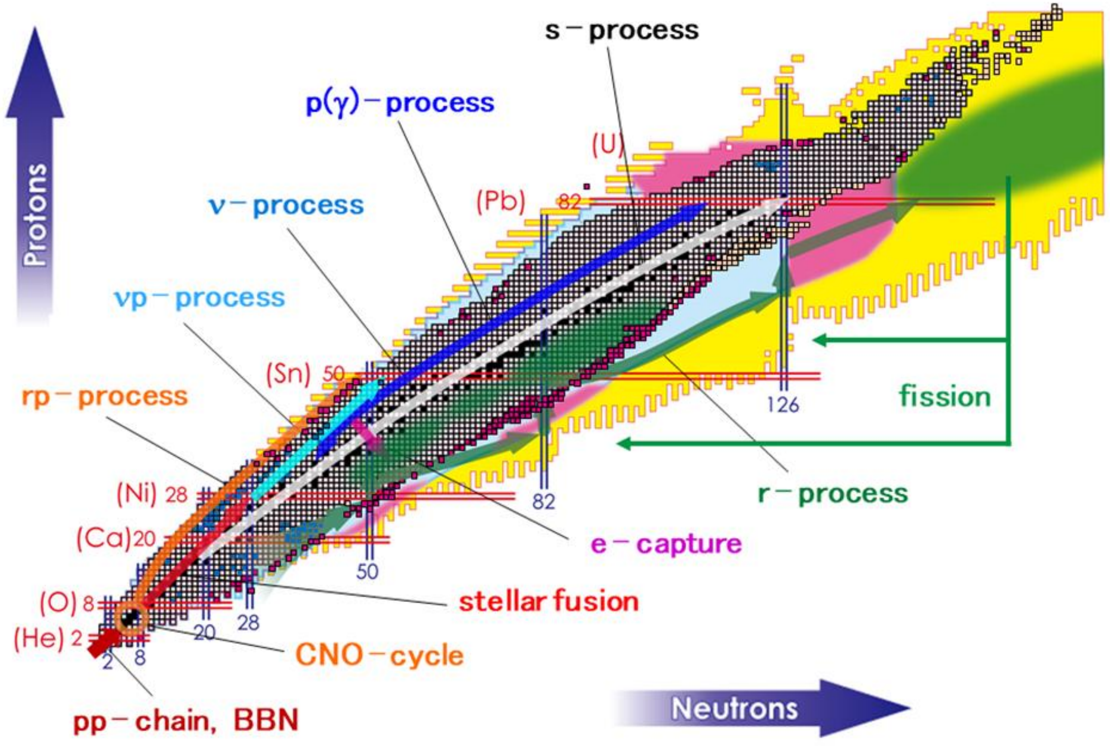


Abundances in metal poor r-stars
J.J. Cowan and C. Sneden, *Nature* 440, 1151 (2006)

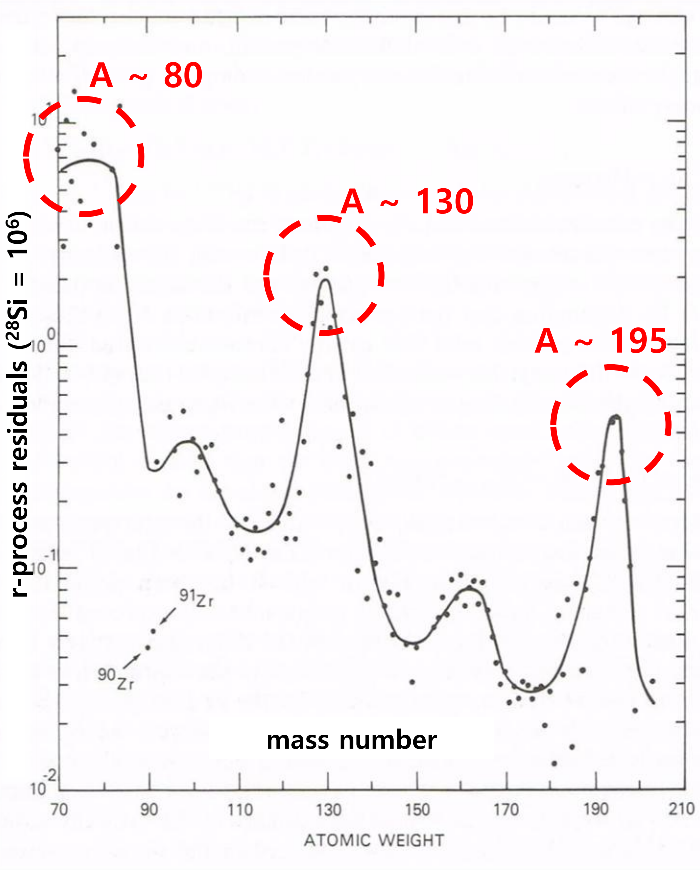


Kilo Nova/GW Observations
Drout *et al.* 2017

Nucleosynthesis Processes



Nuclear chart and the major nucleosynthetic processes in the universe
X. Tang *et al.*, *Association of Asia Pacific Physical Societies* 31, 19 (2021)

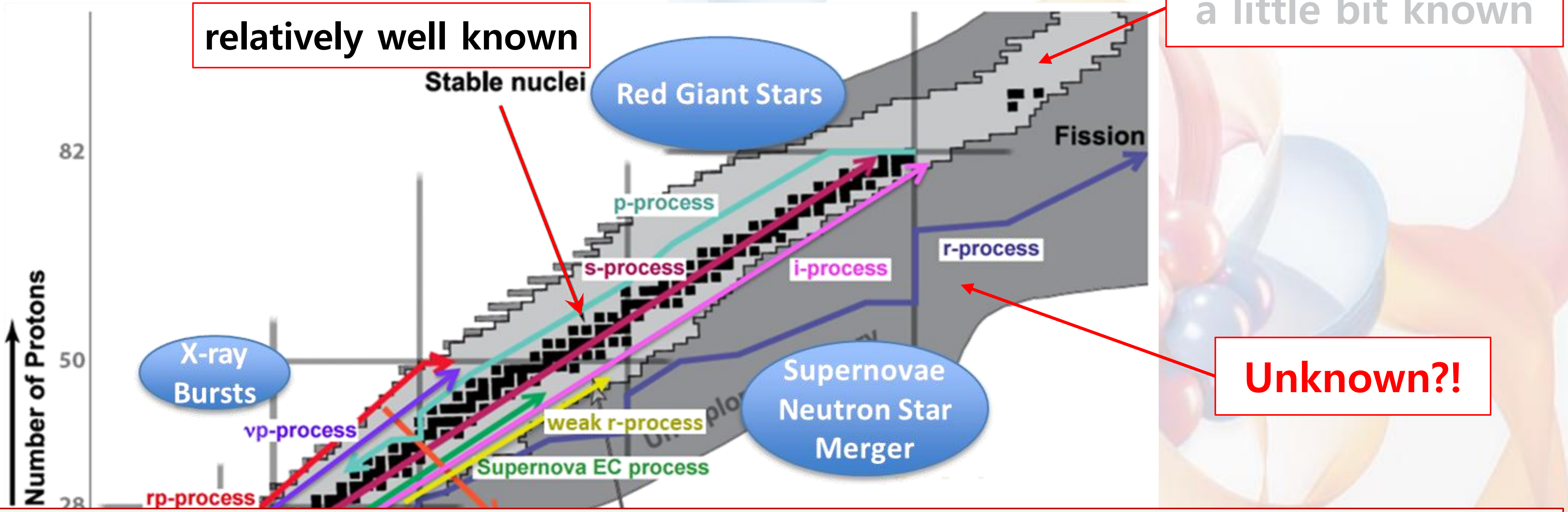


Calculated r-process yields for solar abundance patterns
F. Kappeler *et al. Rep. Prog. Phys.* 52 945 1989

❖ Nucleosynthesis process can explain the observation.
→ **Nuclear Physics plays an important role!**

What do we need to study?

❖ **Properties of Nuclei: mass, Q-value, $T_{1/2}$, P_n, level densities, reaction rates, level structure, magic number and drip line**

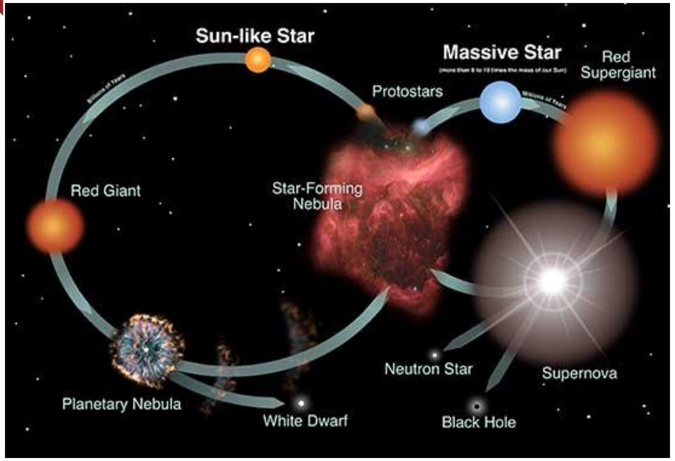


➔ **How can we study them?**

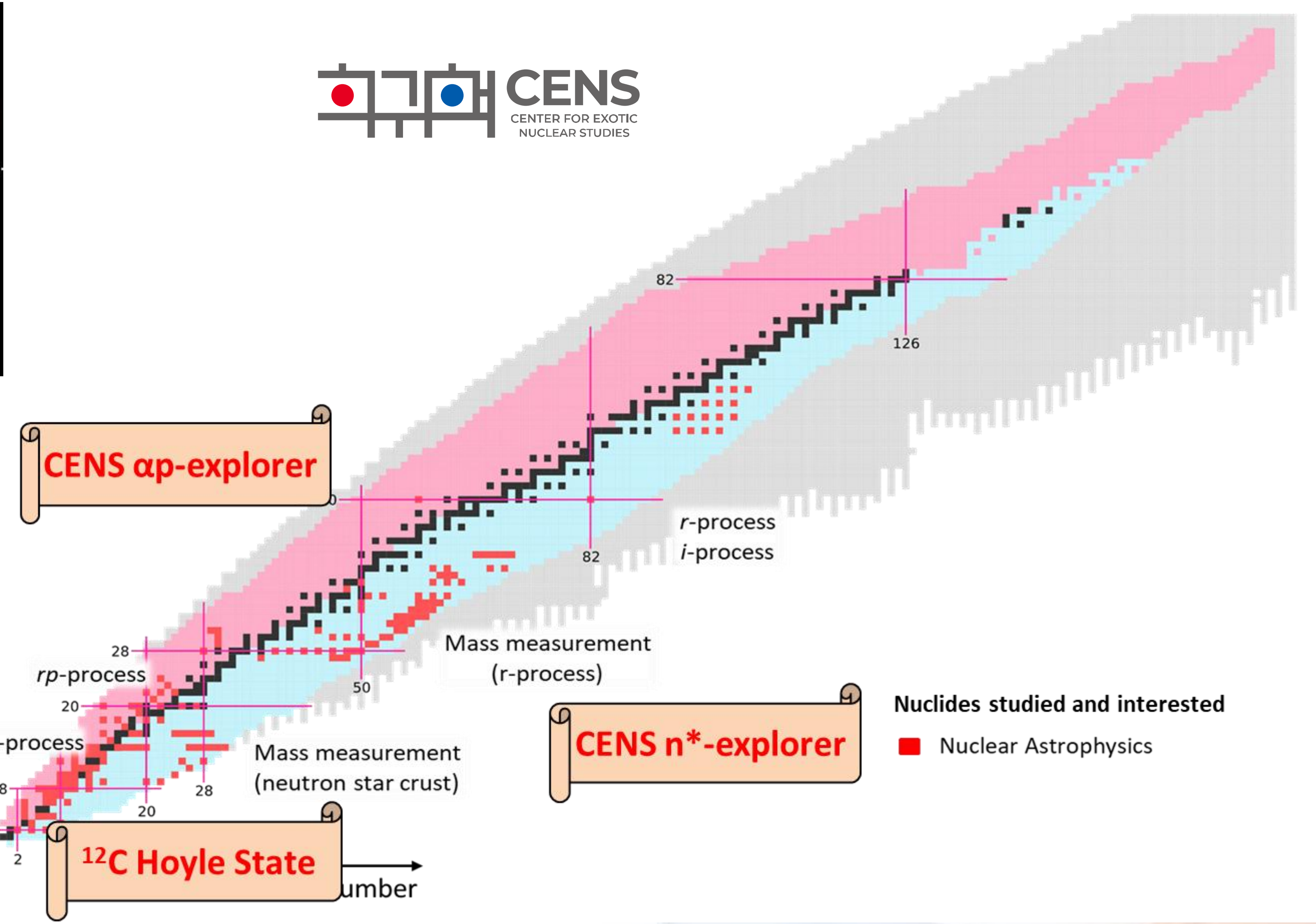
1. **Indirect techniques** for constraining neutron-capture reactions (optical potential and γ-ray strength function).
2. **Direct measurements** of explosive hydrogen and helium burning reactions at or near the astrophysical energies using recoil separators, active targets, or gas targets.
3. **Direct reaction-rate measurements for charged particle reaction rates** of importance to heavy element nucleosynthesis in the weak r-, p-, and νp-processes.

Schematic overview of the nuclear processes on nuclear chart
H. Schatz, 2016

Astrophysically important nuclei on CENS Nuclear Chart

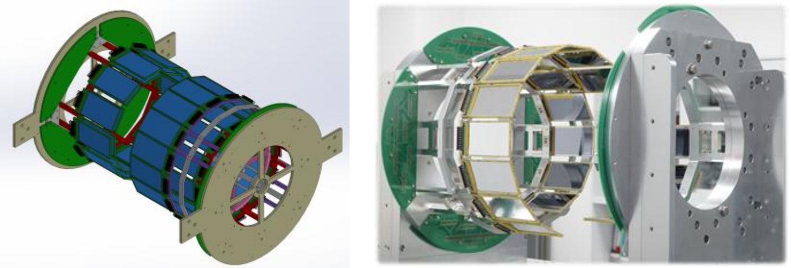


Credit: NASA and the Night Sky Network



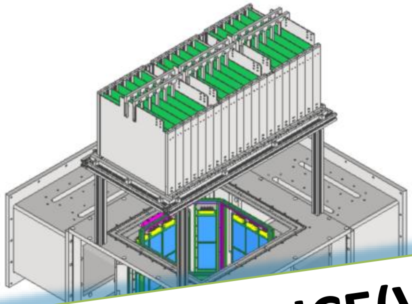
CENS Detector Developments (selected)

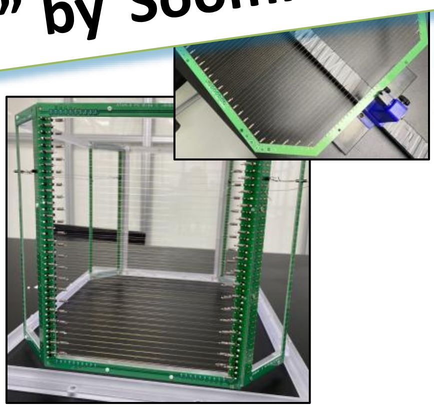
[STARK]



Silicon Telescope Array for Reactions in inverse Kinematics

[AToM-X]



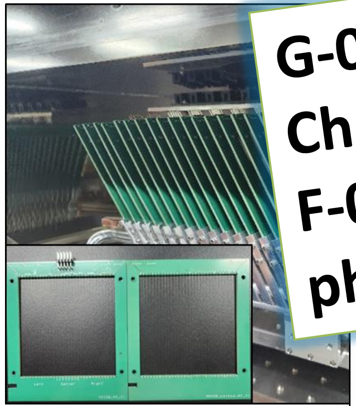


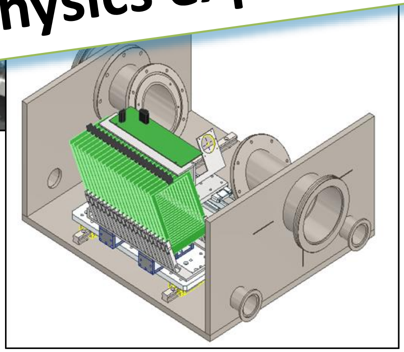
Active target TPC for Multiple nuclear eXperiments

[JETTSTAR]

gas JET Target system for nuclear STructure and Astrophysical Research

[VOICE]



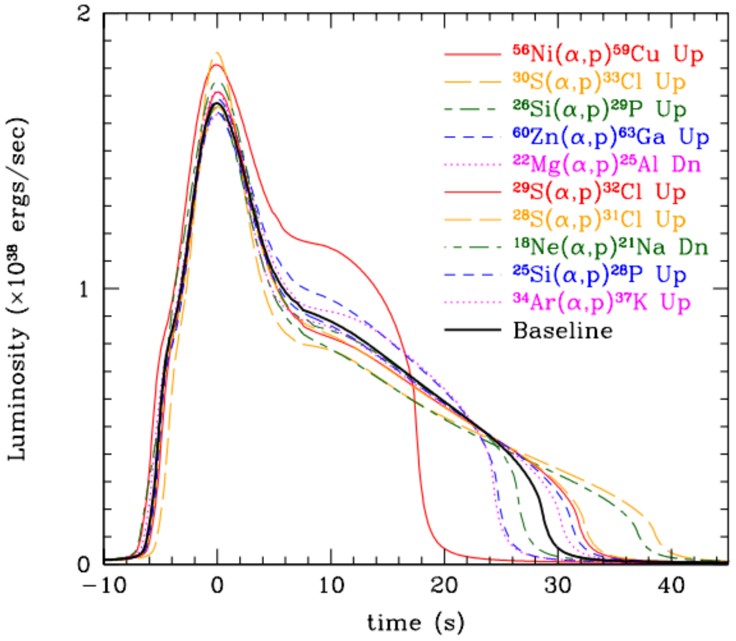


Vertically Oriented wire Ionization Chamber with sEgmentations

G-04 "Development status of VOICE(Vertically Oriented-wire Ionization Chamber with sEgmentation)" by Minju Kim

F-07 "Development of a new active target TPC for multiple nuclear physics experiments" by Soomi Cha

CENS *αp*-explorer Project



Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	^{56}Ni(α, p)^{59}Cu	U	12.5	1
2	^{59}Cu(p, γ)^{60}Zn	D	12.1	1
3	^{15}O(α, γ)^{19}Ne	D	7.9	1
4	^{30}S(α, p)^{33}Cl	U	7.8	1
5	^{26}Si(α, p)^{29}P	U	5.3	1
6	^{61}Ga(p, γ)^{62}Ge	D	5.0	1
7	^{23}Al(p, γ)^{24}Si	U	4.8	1
8	^{27}P(p, γ)^{28}S	D	4.4	1
9	^{63}Ga(p, γ)^{64}Ge	D	3.8	1
10	^{60}Zn(α, p)^{63}Ga	U	3.6	1
11	^{22}Mg(α, p)^{25}Al	D	3.5	1
12	^{56}Ni(p, γ)^{57}Cu	D	3.4	1
13	^{29}S(α, p)^{32}Cl	U	2.8	1
14	^{28}S(α, p)^{31}Cl	U	2.7	1
15	^{31}Cl(p, γ)^{32}Ar	U	2.7	1
16	^{35}K(p, γ)^{36}Ca	U	2.5	2
17	^{18}Ne(α, p)^{21}Na	D	2.3	2
18	^{25}Si(α, p)^{28}P	U	1.9	2
19	^{57}Cu(p, γ)^{58}Zn	D	1.7	2
20	^{34}Ar(α, p)^{37}K	U	1.6	3
21	^{24}Si(α, p)^{27}P	U	1.4	3
22	^{22}Mg(p, γ)^{23}Al	D	1.1	3
23	^{65}As(p, γ)^{66}Se	U	1.0	3
24	^{14}O(α, p)^{17}F	U	1.0	3
25	^{40}Sc(p, γ)^{41}Ti	D	0.9	3
26	^{34}Ar(p, γ)^{35}K	D	0.8	3
27	^{47}Mn(p, γ)^{48}Fe	D	0.8	3
28	^{39}Ca(p, γ)^{40}Sc	D	0.8	3

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

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

- **Key Research Question:**
  1. direct measurements of key (*α,p*) reaction cross sections which important for *αp*-process *and* *p*-process.

- **Methods:**
  1. Thick Target in Inverse Kinematics (TTIK) using TexAT_v2, AToM-X or VOICE
  2. (*α,p*) Reaction in Inverse Kinematics using JENSA, CryoSTAR or JETTSTAR with STARK

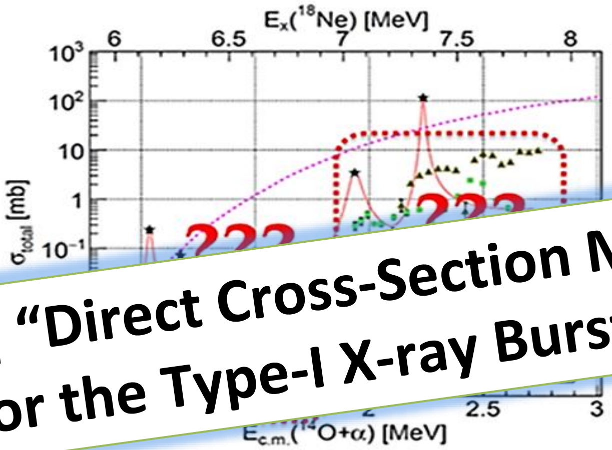
Direct measurement of $^{14}O(\alpha,p)^{17}F$ cross section at CRIB/CNS

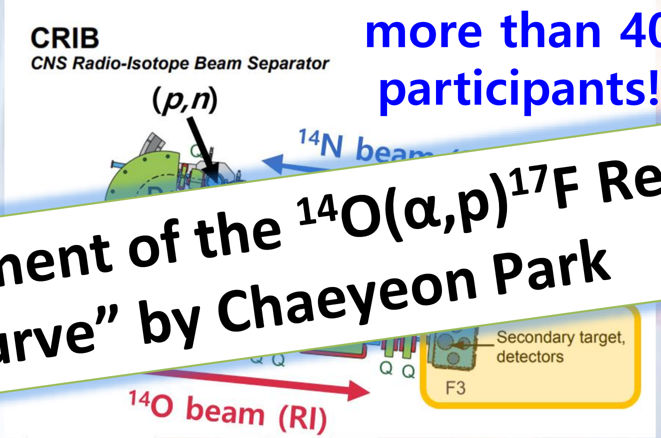
R. H. Cyburt *et al.* 2016

Rank	Reaction	Type	Sensitivity
1	$^{15}O(\alpha,\gamma)^{19}Ne$	D	16
2	$^{56}Ni(\alpha,p)^{59}Cu$	U	6.4
3	$^{59}Cu(p,\gamma)^{60}Zn$	D	5.1
4	$^{61}Ga(p,\gamma)^{62}Ge$	D	3.7
5	$^{22}Mg(\alpha,p)^{25}Al$	D	2.3
6	$^{14}O(\alpha,p)^{17}F$	D	5.8
7	$^{23}Al(p,\gamma)^{24}Si$	D	4.6
8	$^{18}Ne(\alpha,p)^{21}Na$	U	1.8
9	$^{63}Ga(p,\gamma)^{64}Ge$	D	1.4
10	$^{19}F(p,\alpha)^{16}O$	U	1.3

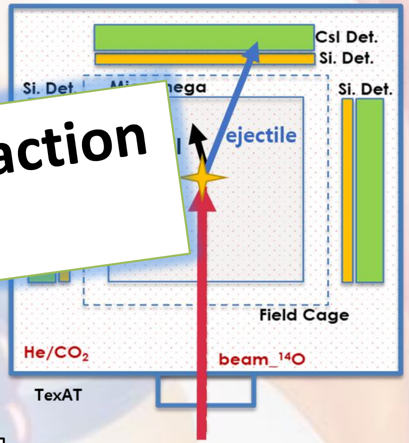
Reactions that impact the burst light curve in the multi-zone X-ray burst

- "A direct measurement of the $^{14}O(\alpha,p)^{17}F$ reaction with the Texas Active Target detector" approved by RIKEN PAC (2020)
- Beam time was very hard to get due to the Covid-19. We performed the experiment in Mar. 2023.

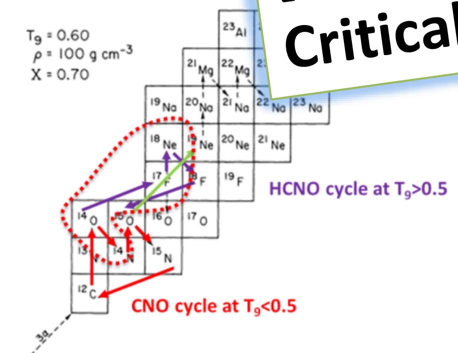




more than 40 participants!

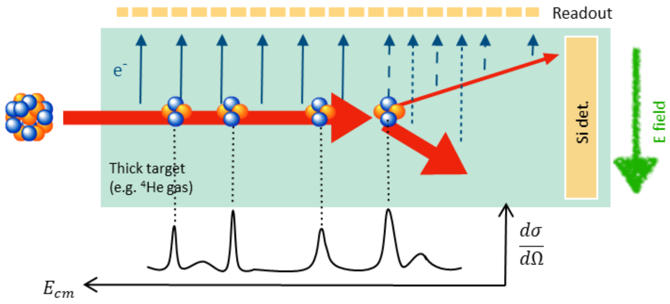


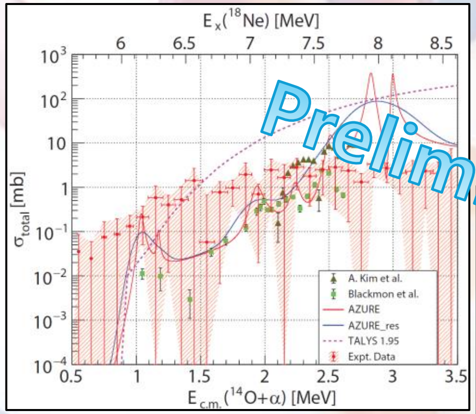
[PA5-NA] "Direct Cross-Section Measurement of the $^{14}O(\alpha,p)^{17}F$ Reaction Critical for the Type-I X-ray Burst Light Curve" by Chaeyeon Park

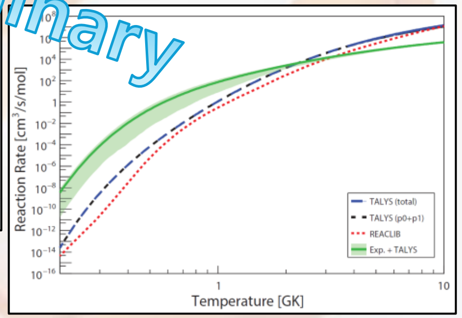


R. K. Wallace and S. E. Woosley, Astro. J. Suppl. Ser. 45, 389 (1981)

Previous measured data and calculated total cross sections of $^{14}O(\alpha,p)$ reaction



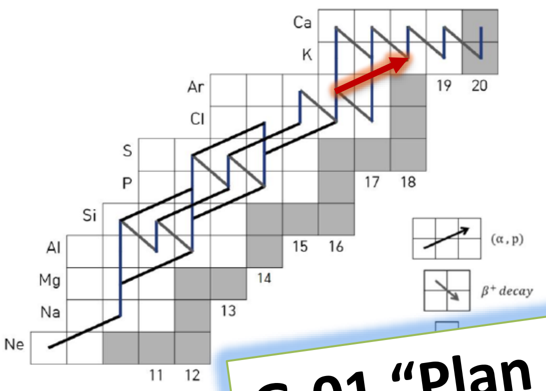


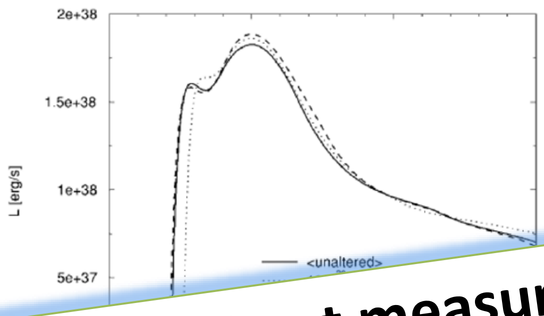


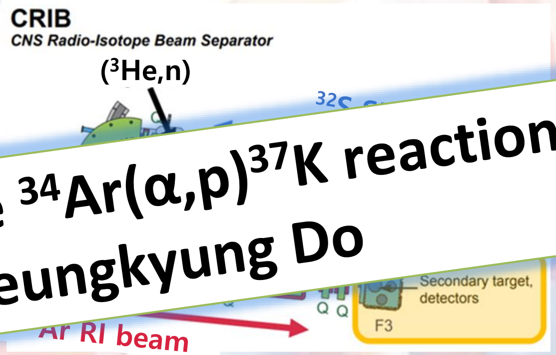
Direct measurement of ^{34}Ar(α,p)^{37}K cross section at CRIB/CNS

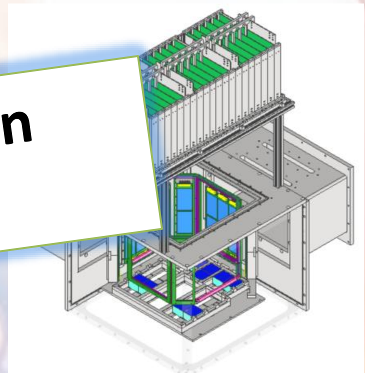
Motivation: a key reaction for understanding the luminosity curve of the double peak and nucleosynthesis mechanism in X ray bursts.

^{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



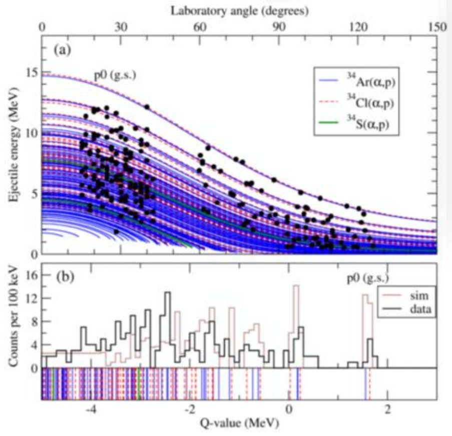




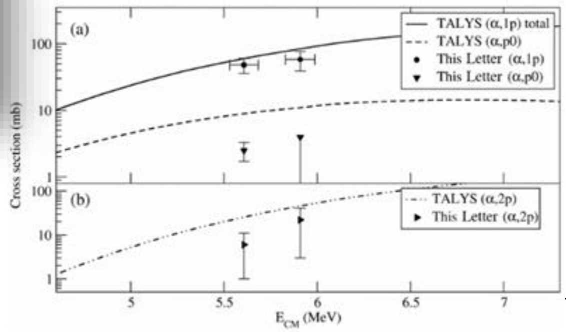


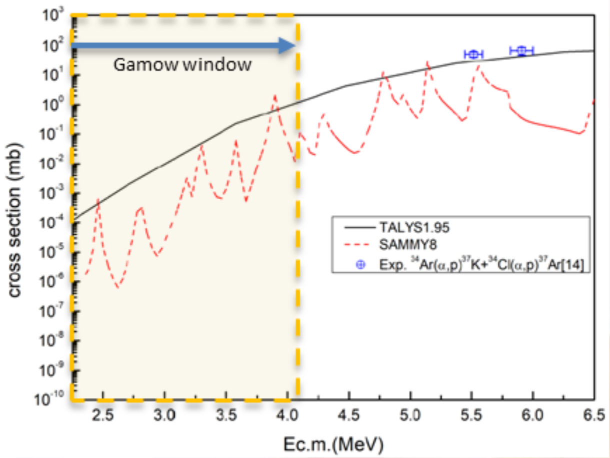
G-01 "Plan for the direct measurement of the ^{34}Ar(α,p)^{37}K reaction in Gamow window using AToM-X at CRIB" by Seungkyung Do

(Left) Nuclear fl... (Middle) Compu... ...ble peak structure observed during X-ray burst



J. Browne *et al.*, PRL 130, 212701 (2023)



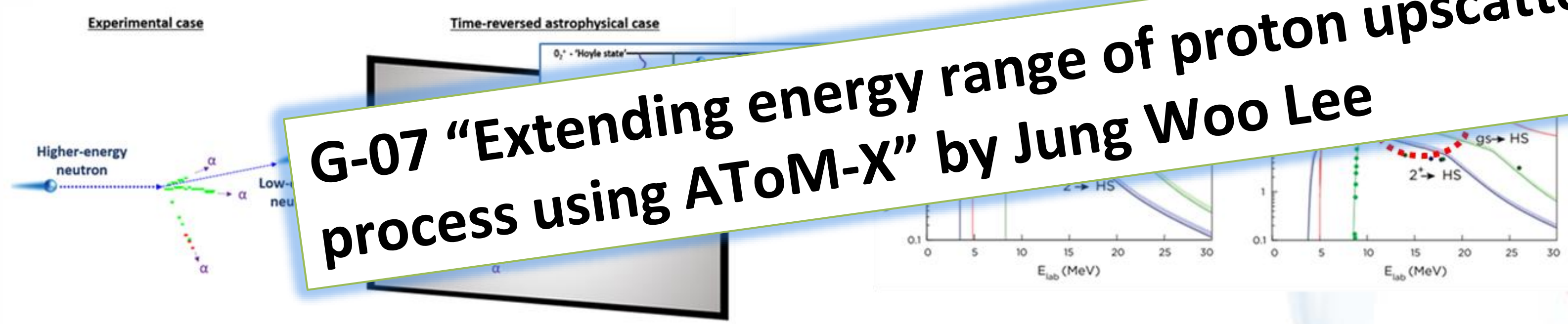


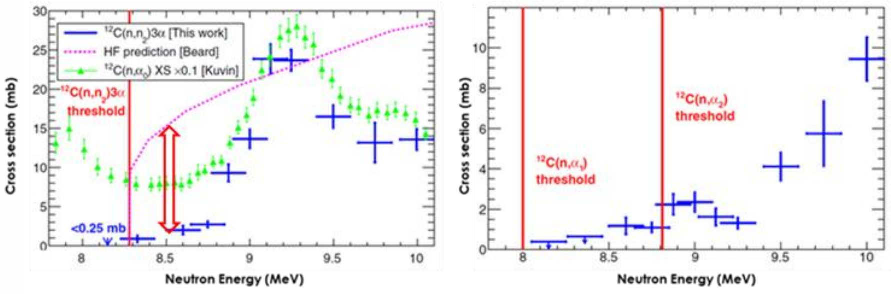
Proposed by A. Kim at Korea Univ. and K. I. Hahn

Study of enhancements from neutron/proton upscattering

- High-density environment, large neutron enhancements at low temperature (≈0.2 GK)
- No data on gs→HS of n-upscattering from 8 to 16 MeV, higher E data deviate from Hauser-Feshbach (HF) OMP predictions
- The measured cross sections are significantly suppressed near the threshold in comparison to HF predictions.
- At these low temperatures, where previously the neutron enhancement factor was predicted to be greater than 100, the enhancement is instead small, of the order of unity.
- No data on gs→HS of p-upscattering above 12 MeV → experimental study using an active target TPC, AT... X.
- A test experiment using 10^7 pps proton beam at PKU performed using another activ...

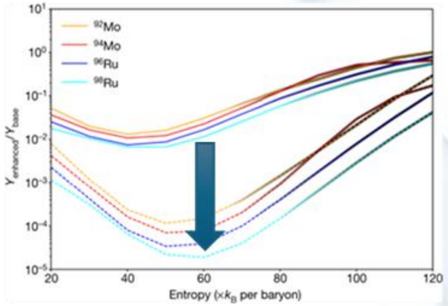
G-07 "Extending energy range of proton upscattering in the triple-alpha process using AToM-X" by Jung Woo Lee

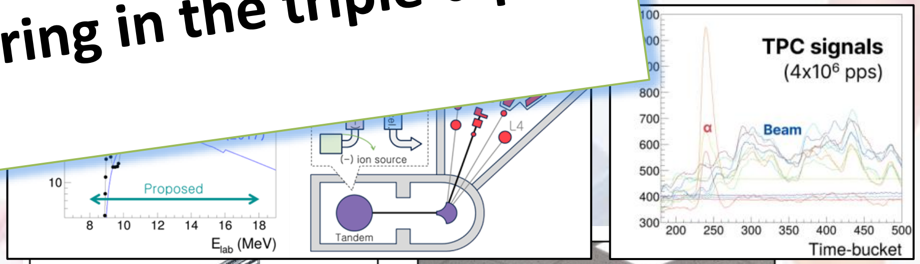


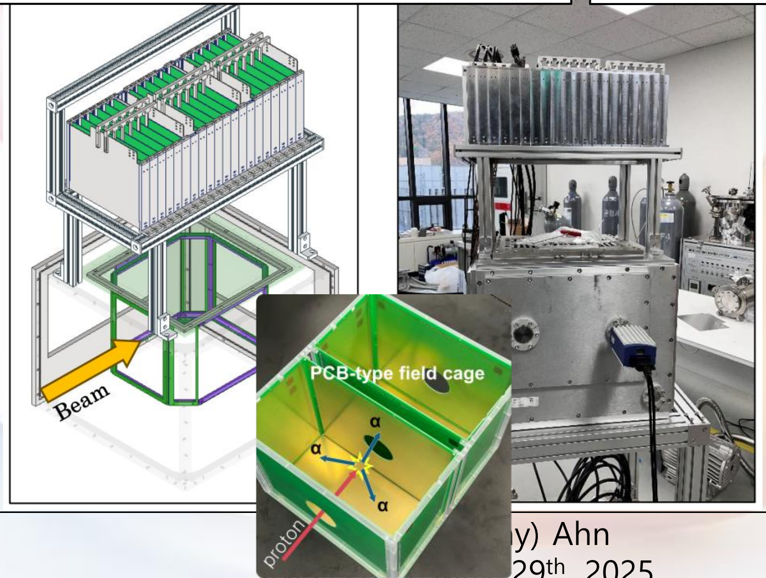


J. Bishop *et al.*, Nat.Commun. **13** (2022) 2151.

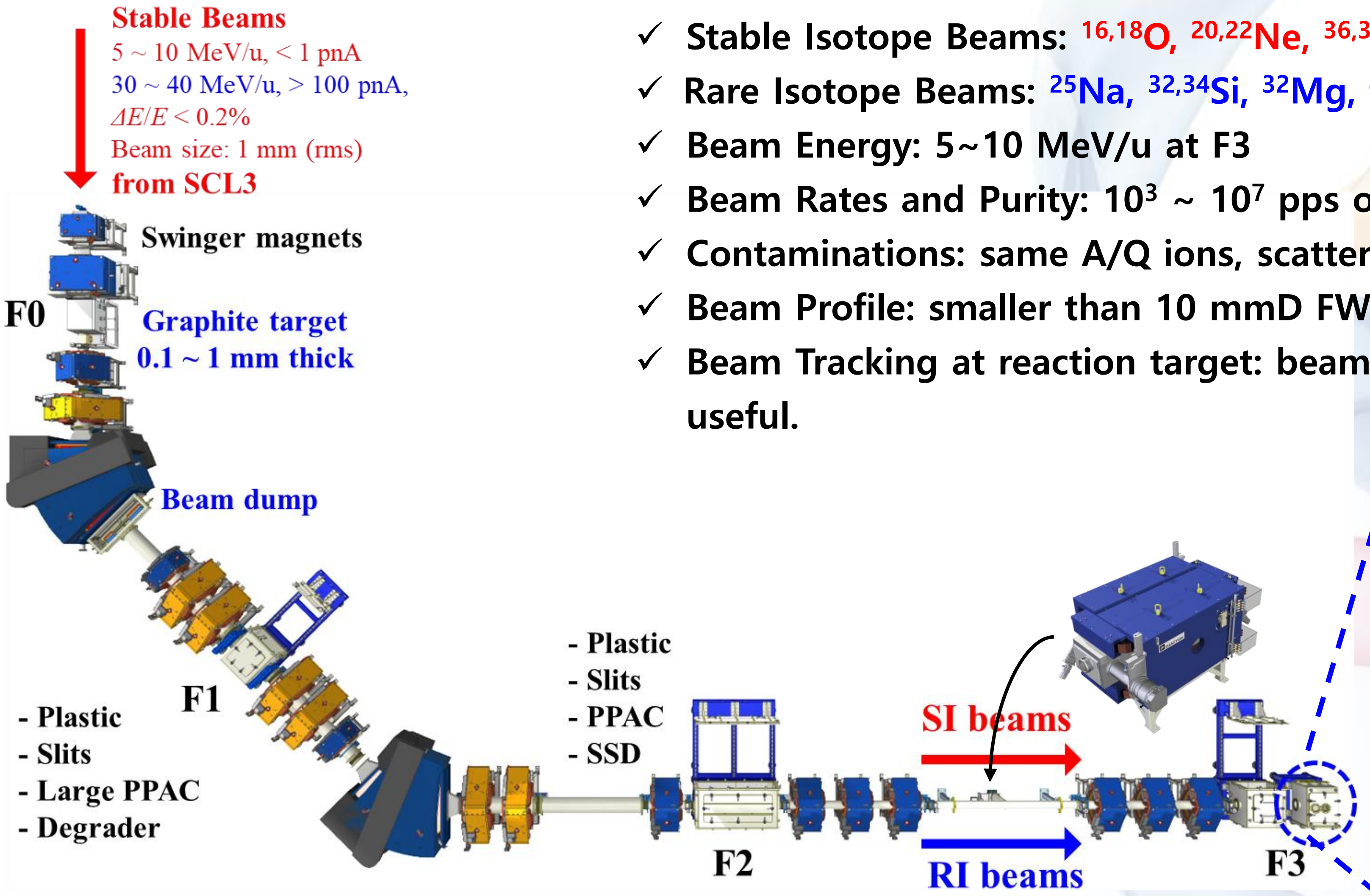
S. Jin *et al.*, Nature **588**, (2020) 57.







Stable/Rare Isotope Beams at KoBRA, RAON



- ✓ Stable Isotope Beams: ^{16,18}O, ^{20,22}Ne, ^{36,38,40}Ar, ^{86}Kr
- ✓ Rare Isotope Beams: ^{25}Na, ^{32,34}Si, ^{32}Mg, ^{45,47}Ca and many more…
- ✓ Beam Energy: 5~10 MeV/u at F3
- ✓ Beam Rates and Purity: 10^3 ~ 10^7 pps of more than 90% pure beam
- ✓ Contaminations: same A/Q ions, scattered light ions
- ✓ Beam Profile: smaller than 10 mmD FWHM (It is okay for AT-TPC)
- ✓ Beam Tracking at reaction target: beam monitor or TPC detector will be useful.

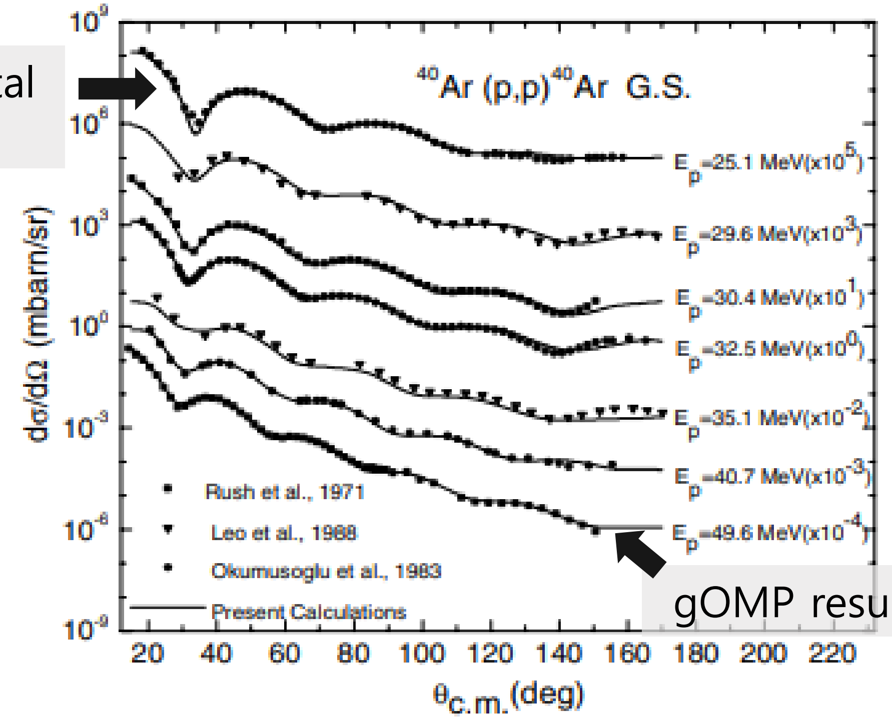
CENS detector systems
- STARK
- AToM-X
- ASGARD
- CryoSTAR+STARK
- JETTSTAR+STARK
- $LaBr_3$ detectors
- Decay Spectroscopy Station
- VOICE

M. Kwag, CENS-KoBRA Collaboration Meeting (2019)

Optical Model Potential Study of ^{40}Ar + p elastic scattering

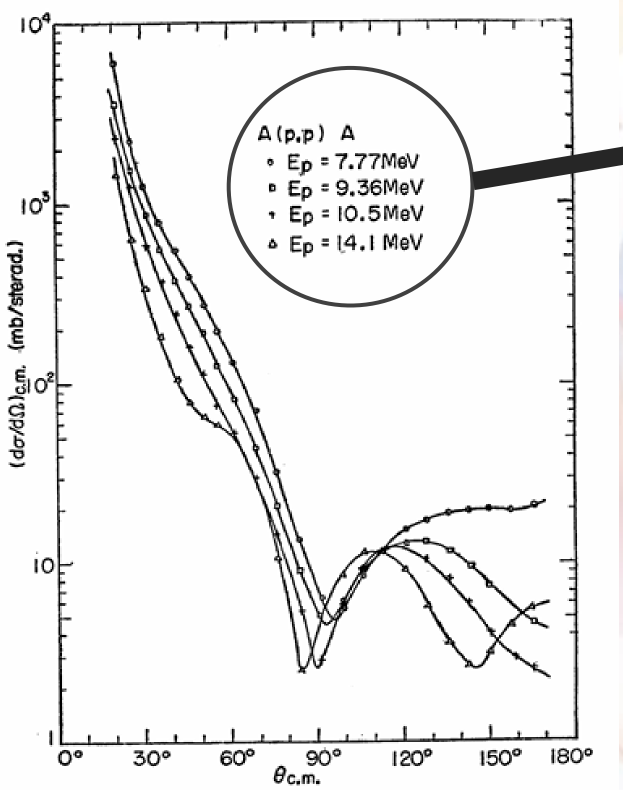
- Optical model potential (OMP) parameters are required to predict cross-section for each energy.
- Lack of optical model parameters at low energies, especially near the Coulomb barrier.

Experimental data



gOMP results

N. T. Okumuşoğlu et al., Phys. Rev. C 75, 034616 (2007).

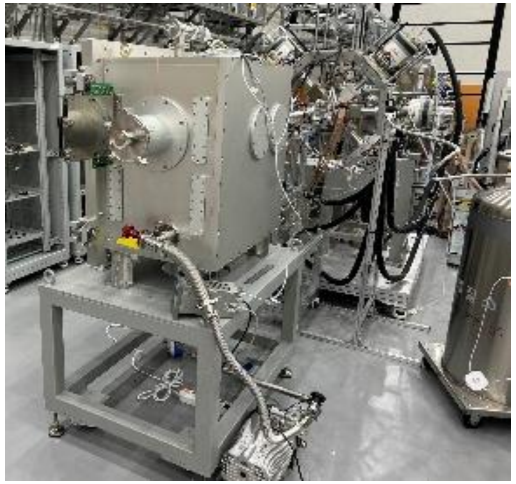


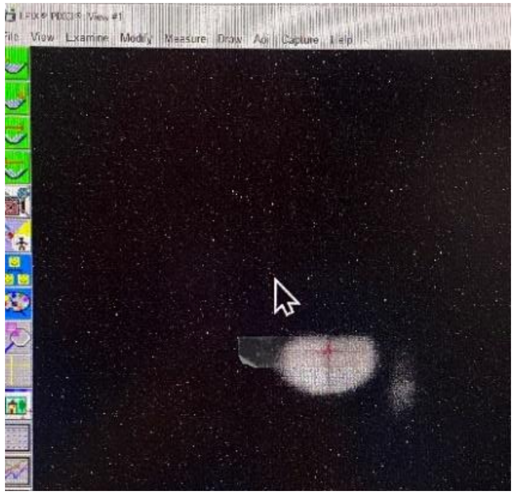
At lower energies, No gOMP parameters were obtained. (E_p < 7 MeV)
No data available near the Coulomb barrier. (V_c = 4.1 MeV)

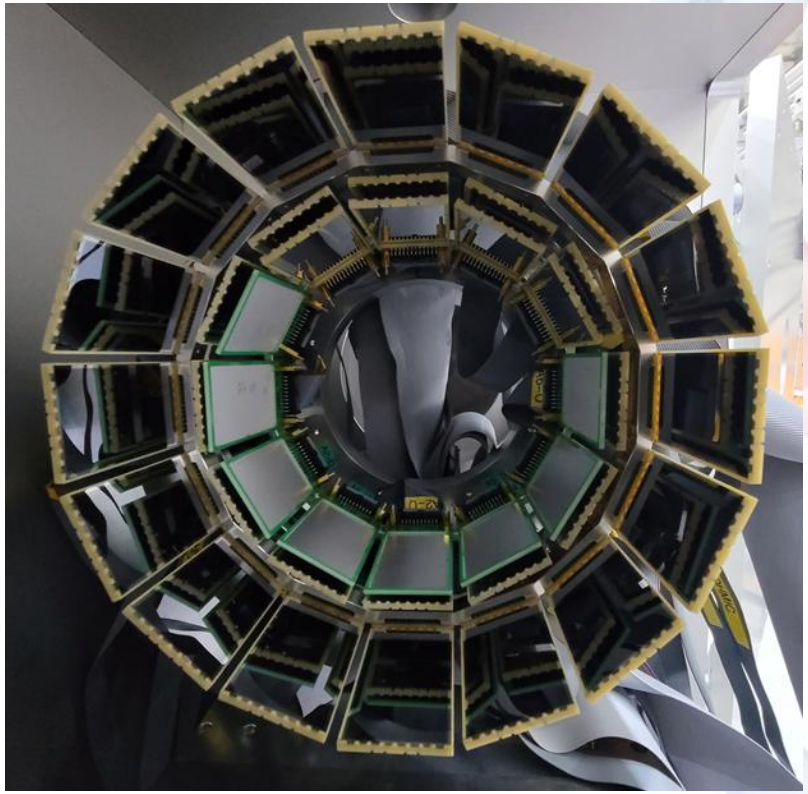
[Main Goal] Compare the global optical models with the experimental data in low energy region and extract OMP parameters.

Experimental setup photos

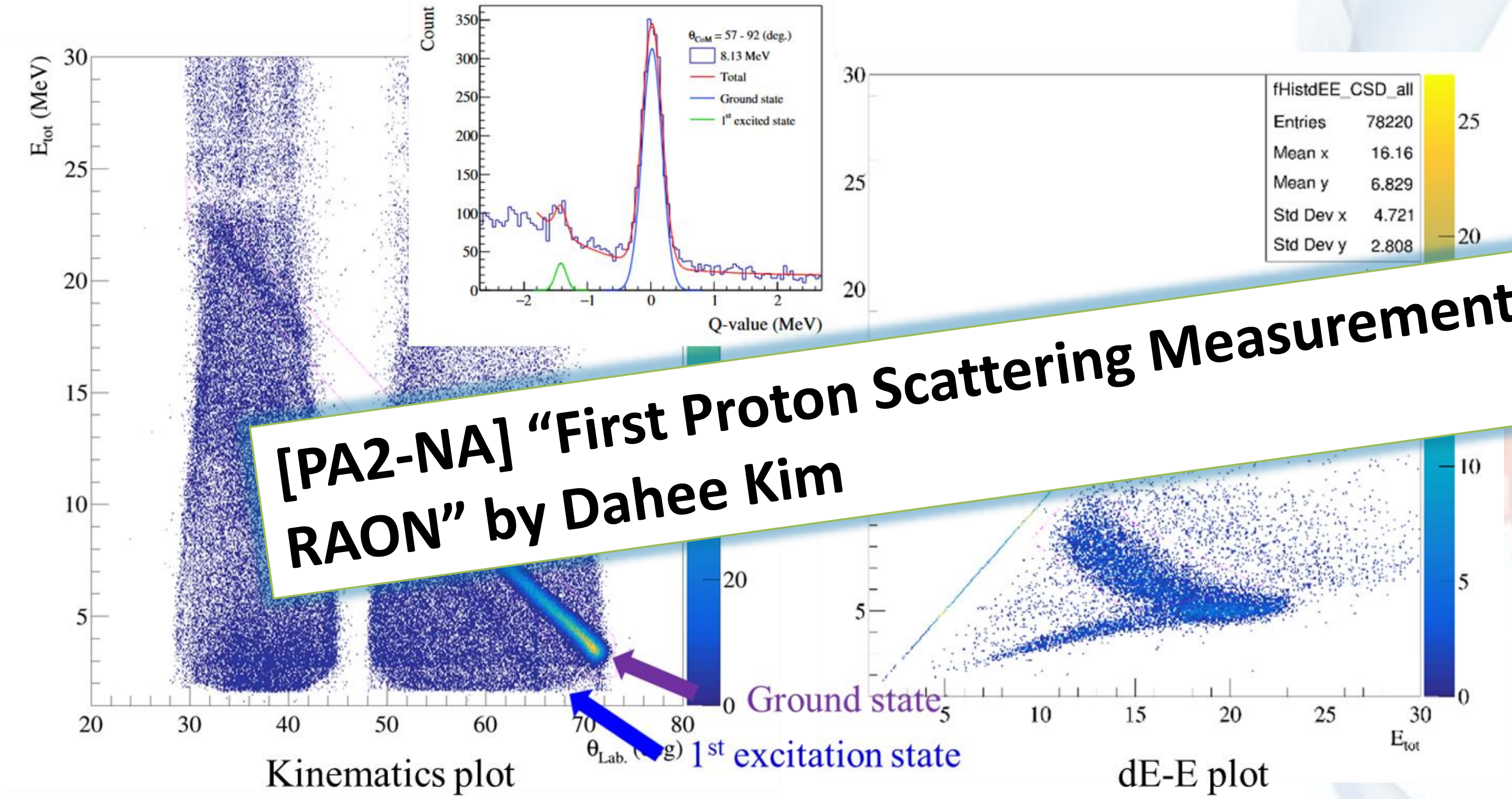
- E_{beam} = 4.4, 5.9, and 8.3 MeV/u ^{40}Ar stable beam at F3 focal plane

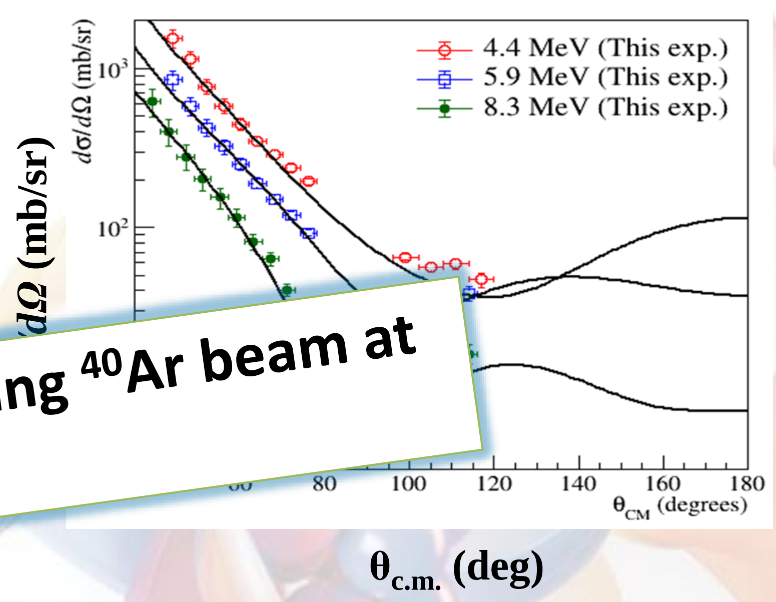






Analysis results of the ^{40}Ar+p scattering data





[PA2-NA] "First Proton Scattering Measurement using ^{40}Ar beam at RAON" by Dahee Kim

Energy (MeV)	V (MeV)	r_v (fm)	a_v (fm)	W_d (MeV)	r_d (fm)	a_d (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)
4.4	58.1	1.19	0.672	0.050	1.29	0.540	5.75	0.996	0.590
5.9	43.2	1.39	0.430	5.97	1.87	0.368	5.75	0.996	0.590
7.77 [13]	55.8	1.19	0.672	6.35	1.29	0.540	5.75	0.996	0.590
8.3	57.5	1.19	0.672	8.02	1.29	0.540	5.75	0.996	0.590
9.36 [13]	55.1	1.19	0.672	8.21	1.29	0.540	5.75	0.996	0.590
10.5 [13]	56.0	1.19	0.672	8.63	1.29	0.540	5.75	0.996	0.590
14.1 [13]	52.0	1.19	0.672	8.96	1.29	0.540	5.75	0.996	0.590

Extracted new optical model parameters using SFRESCO.

D. Kim, S. Ahn *et al.*, submitted to PRC

Summary

- The origin of elements is an important question to answer, and properties of exotic nuclei play a very important role. However, there are large uncertainties on the nuclear properties from theoretical models triggering experimental study to confirm and provide accurate information.

➔ **Experimental measurements are very critical to reduce them.**

- **We recently focus on nuclear spectroscopic studies such as nuclear reactions occurred in a special astrophysical conditions.**
  - ✓ Direct cross section measurements of **$^{14}O(\alpha,p)^{17}F$ and $^{34}Ar(\alpha,p)^{37}K$** reactions using TexAT_v2 and AToM-X at CRIB/CNS.
  - ✓ **$^{12}C(p,p')$ proton upscattering measurement** of Hoyle state at JAEA.
  - ✓ Optical Model Potential study of **$^{40}Ar+p$ elastic scattering** at low energy region.

- New major horses for nuclear astrophysics studies: **AToM-X, CryoSTAR, JETTSTAR, IDATEN, Bρ-ToF, KoBRA Wien Filter, STARK, CENS Silicon Sensors and ASGARD**.

- **More key experimental studies can be performed using RI beams at world-leading facilities (RIKEN, FRIB, IMP, HIAF and RAON).**
  - ✓ Optical Model Potentials for Exotic Nuclei such as ^{25}Na + p elastic scattering measurements
  - ✓ (α,p) cross section studies related to *ap*-process: (α,p) reaction with ^{22}Mg, ^{18}Ne, ^{21}Na, ^{17}F beams; (p,α) reaction with ^{10}Be beam (CRIB)
  - ✓ Nuclear structures related to *i*-process: (d,p) or (d,pγ) with ^{32}Si, ^{34}Si and ^{32}Mg beams
  - ✓ Neutron transfer reactions and ToF mass measurements related to *r*-process
  - ✓ (α,n) cross section studies related to weak *r*-process: (α,n) with ^{8}Li, ^{20}Ne, ^{27}Al, ^{63}Co, ^{87}Kr, ^{84}Se, ^{94}Sr, ^{82}Ge beams

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All the CENS members
&

International Collaborations

CENS Rare Isotope Nuclear Research Hub

- **FRIB (USA)**
- **GANIL (France)**
- **CNS (Japan)**
- **TAMU (USA)**
- IMP (China)
- Beihang (China)
- GSI (Germany)
- UND (USA)
- **ORNL (USA)**
- JINR (Russia)
- CIAE (China)
- CEA (France)
- ATOMKI (Hungary)
- **RIKEN (Japan)**
- TRIUMF (Canada)

Domestic Collaborations

CENS Rare Isotope Nuclear Research Hub

- SNU
- **SKKU**
- SSU
- InhaU
- YSU
- PNU
- KNU
- POSTECH
- HYU
- SejongU
- EWHA
- **IRIS**
- **KoreaU**

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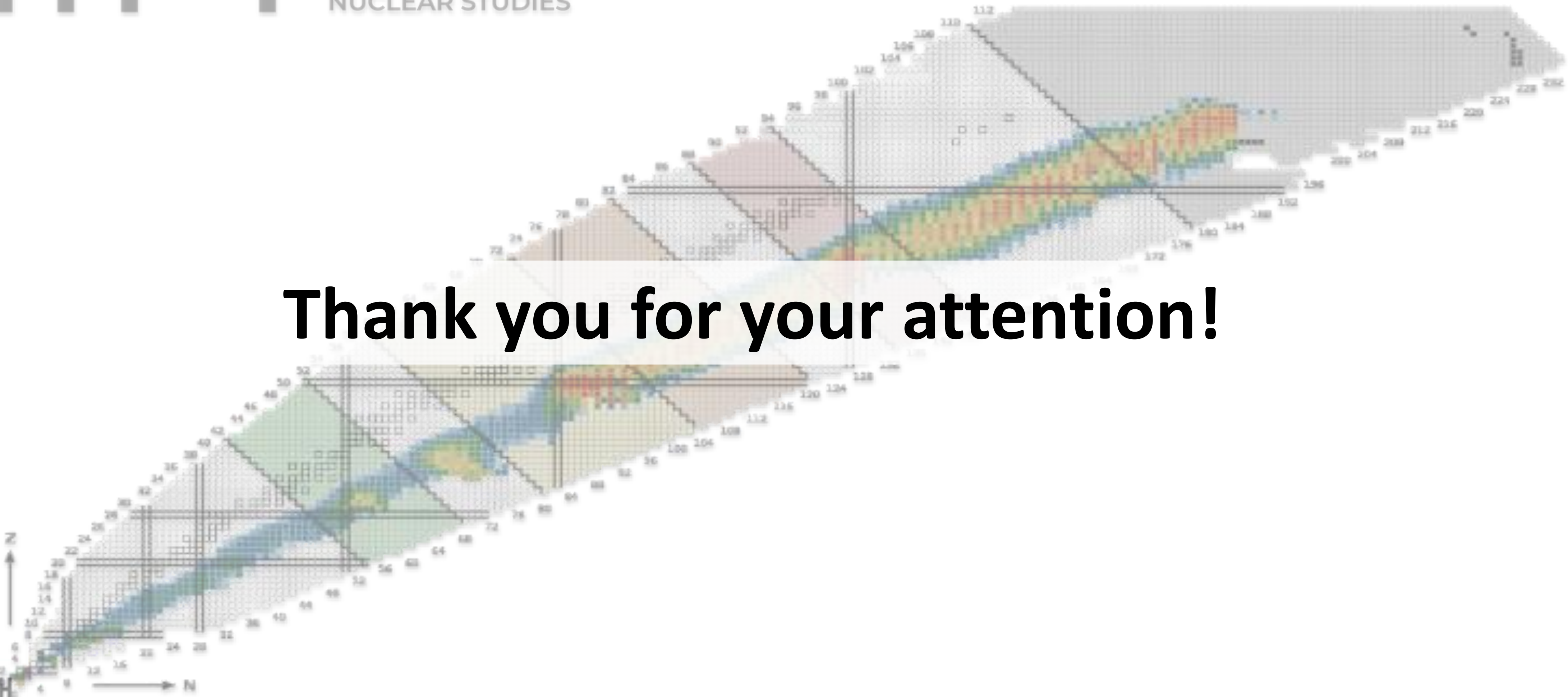

Thank you for your attention!