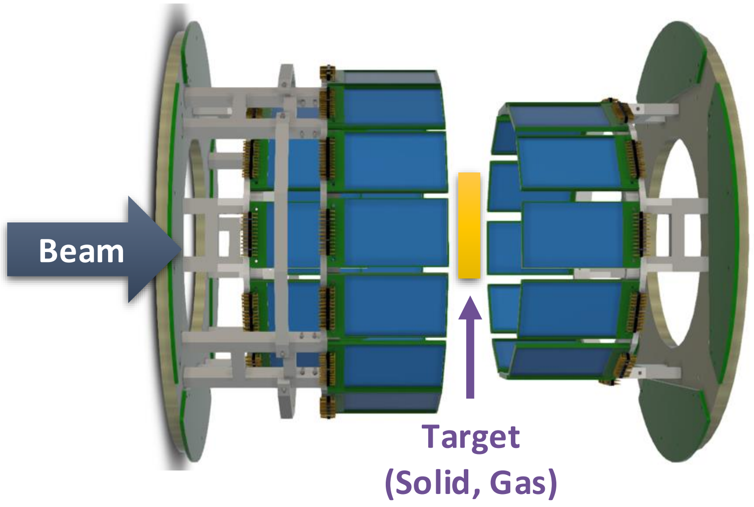
실리콘 검출기 어레이를 활용한 핵천체물리 연구

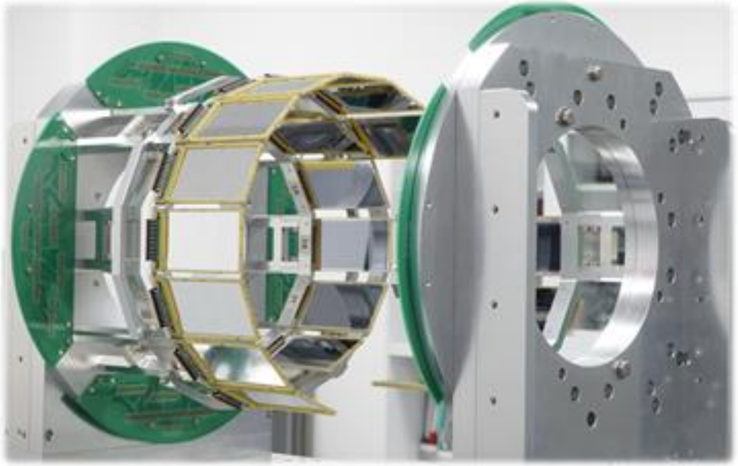
이화여자대학교
김다히

STARK_v1

Silicon **T**elescope **A**rray for **R**eaction studies in inverse **K**inematics

- Charged particle detection from collision ($E, \vec{p}$)
- Barrel type array, 12(12) + 16 + 12 side ring
- Φ = 92.5, 118.8, 107 mm, 28.4 mm gap from a target
- **$\Delta\theta_{lab} < 1^{\circ}$ expected with wide coverage**
  ($43^{\circ} \sim 78^{\circ}$, $105^{\circ} \sim 150^{\circ}$)
  => Comparable than state-of-the-art detectors
- Newly designed resistive silicon strip detector, **X6**
- Useful for many rare isotope facilities (ex. RIKEN, IMP, FRIB, and RAON)





[Related-project]

1. STARK Jr. with using ASGARD
2. CENS Si detector development

Introduction

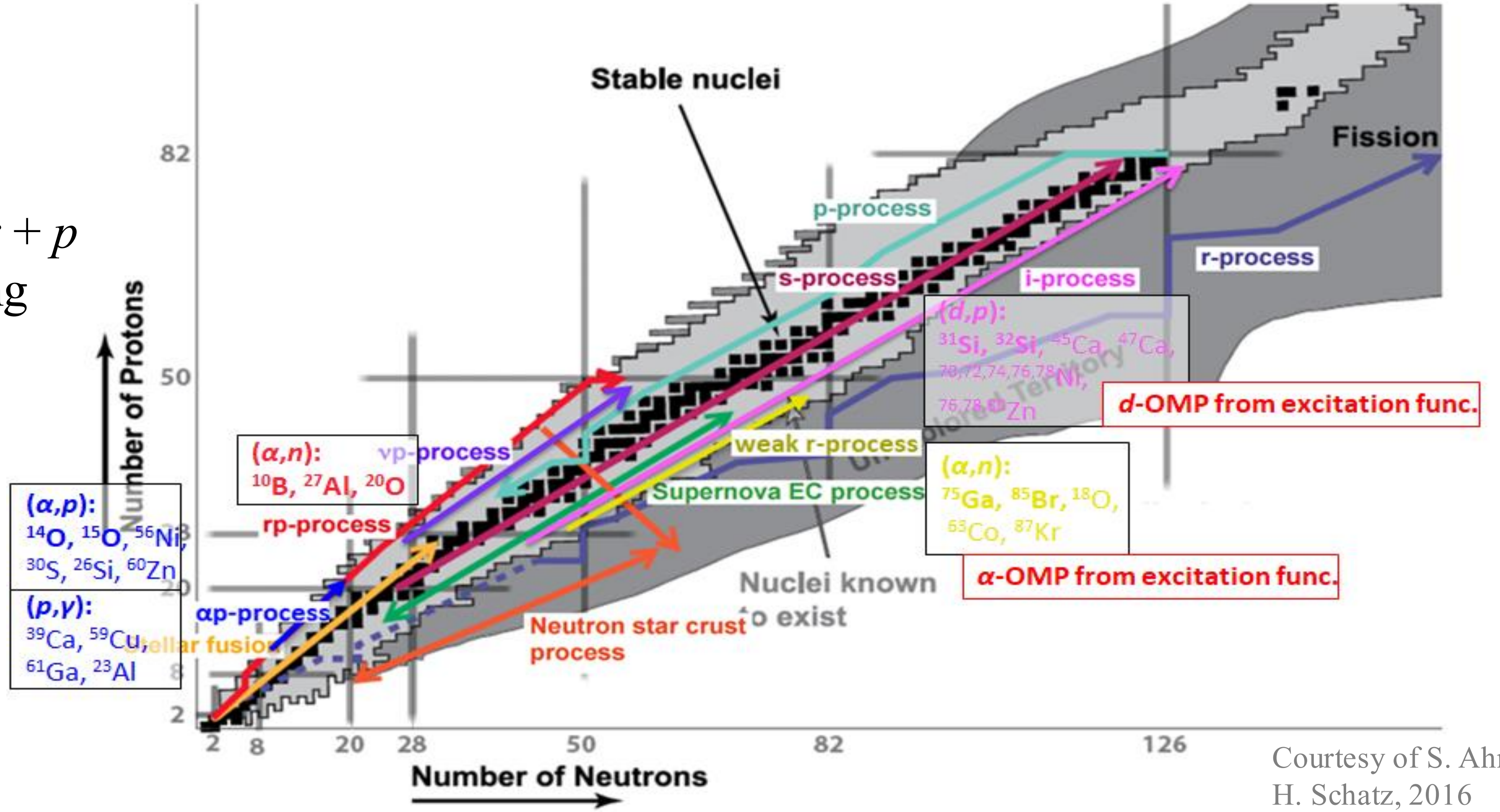
Optical potentials are essential in the nuclear reaction calculations

In case of ^{40}Ar,

^{40}Ar(p, n)^{40}K

^{38}Ar(α, $p\gamma$)^{40}Ar

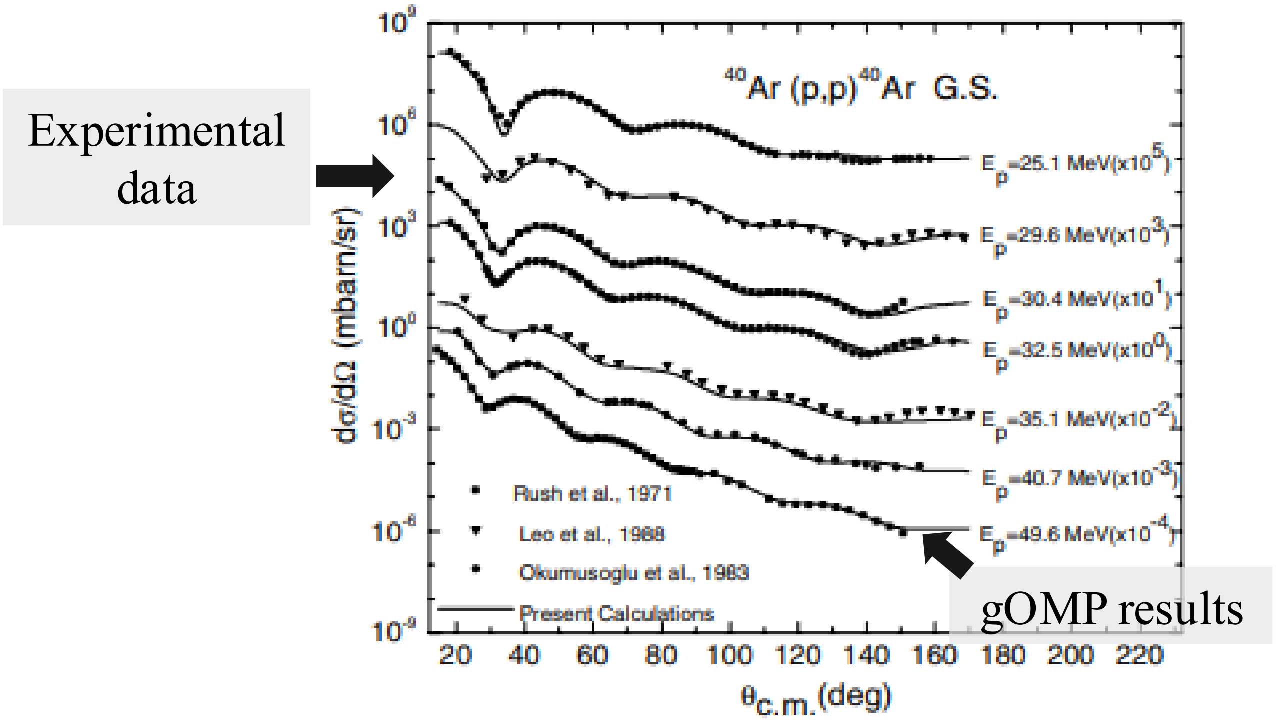
p-OMP from ^{40}Ar + p elastic scattering experiment



Courtesy of S. Ahn presentation
H. Schatz, 2016

Optical model potential for ^{40}Ar + p

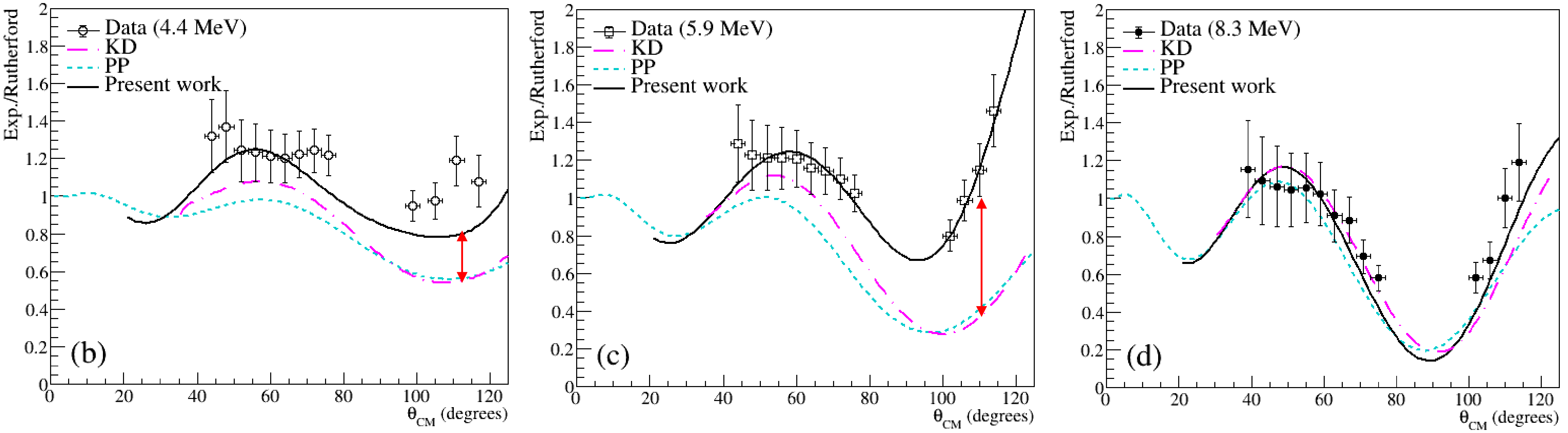
- Optical model potential (OMP) parameters can not be extracted if the data is not existed.
- Global optical model potential (gOMP), Perey-Perey(PP) and Koning-Delaroche(KD), was developed to account for various nuclei and energy range at once where data do not exist.



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

- Extrapolated optical potentials at energies are not always be reliable.
- Especially, near the Coulomb barrier, due to the drastic changes in the potentials known as threshold anomaly, extrapolation of optical potentials often would not work.

Results - OMP parameters



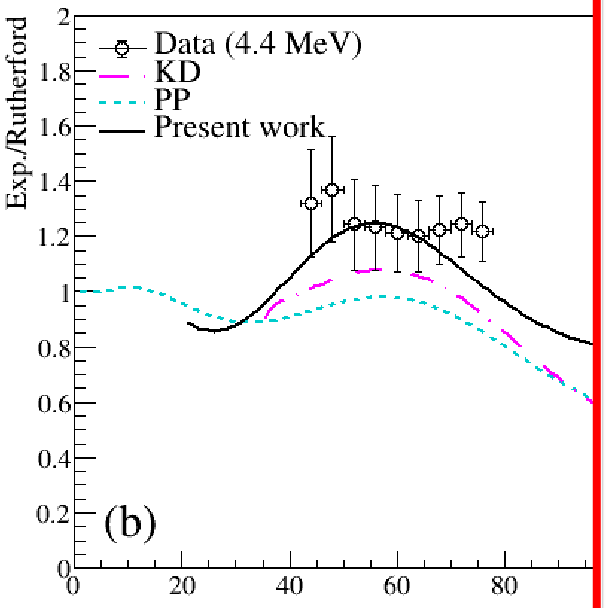
Cross-section to the Rutherford cross-sections for each beam energy

- Perey-Perey(PP) and Koning-Delaroche(KD) gOMPs work at 8.3 MeV.
- But underestimate data at lower energies.

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. Searching reliable OMP parameters

Results - OMP pa



^{40}Ar+p Elastic Scattering Measurement at Energies near the Coulomb Barrier for Optical Potential Study

D. Kim[a,b], S. Ahn[a,*], J. W. Lee[a], H. Y. Lee[a], G. M. Gu[a,c], Y. H. Song[d], S. W. Hong[c,d], D. S. Ahn[a], C. Akers[d], S. M. Cha[a], K. Y. Chae[c], Y. Cho[e], S. Choi[a], S. Do[f,a], K. I. Hahn[a,b], J. W. Hwang[a], Y. Jang[a,f], M. S. Kwag[d], C. H. Kim[c], D. G. Kim[d], E. Kim[d], J. C. Kim[d], M. J. Kim[a], M. J. Kim[d], S. H. Kim[c], Y. Kim[a], Y. H. Kim[a], C. S. Lee[d], J. Lee[a,f], K. B. Lee[d], S. Lee[d], C. Y. Lim[d], G. H. Oh[d], M. Park[a,b], S. J. Park[d], X. Pereira-Lopez[a], S. J. Pyeon[d], T. Shin[d], C. W. Son[d], K. Tshoo[d], J. Won[a]

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Abstract

Nuclear optical potentials are essential for calculating nuclear cross-sections and for probing nuclear structures and dynamics. The phenomenological global optical model potentials (pGOMPs), such as Koning-Delaroche (KD) and Perey-Perey (PP) potentials, have been extensively tested and are generally accepted. However, optical potentials extrapolated at low energies where data do not exist are not always reliable. This study aims to measure new ^{40}Ar+p elastic scattering data at low energies near the Coulomb barrier to extract optical model potential parameters. The elastic scattering of ^{40}Ar+p in inverse kinematics was performed at energies of 4.4, 5.9, and 8.3 MeV/u using KoBRA at the RAON facility. The ELARK barrel-type silicon detector array was employed to detect scattered protons. The angular distributions of the elastic scattering cross-sections were analyzed and compared with those calculated using the GOMPs. Our measured angular distributions could not be reproduced by pGOMPs at low energies. The experimental angular distributions were analyzed to extract optical potential parameters via χ^2 minimization, which were subsequently shown to satisfy the dispersion relation. The results show the limitations of the pGOMPs at lower energies near the Coulomb barrier and indicate the need for further studies of optical potentials with more experimental data to improve the reliability of pGOMPs in reproducing experimental observations.

Keywords:
Elastic scattering, Nucleon-nucleus optical potentials, Global optical model potentials, RAON, KoBRA, ELARK, Cross-section measurements

1. Introduction

The nuclear optical model is a fundamental framework in nuclear physics, providing a key input for the calculation of angular distributions of elastic and inelastic cross-sections, as well as various reaction cross-sections. For example, it plays a crucial role in analyzing transfer reactions through the use of the distorted wave Born approximation, where absorption and refraction phenomena of wavefunctions in the entrance and exit channels can be properly addressed by the distorted waves calculated from the optical model. Therefore, establishing reliable optical potentials is essential for studying nuclear structure and reaction dynamics.

In principle, optical potentials can be deduced by analyzing individual elastic scattering data for various combinations of projectiles, targets, and incident energies. The optical model potentials obtained in this way have successfully described numerous elastic and inelastic scattering phenomena of stable nuclei using complex effective potentials. However, the challenges in measuring the elastic cross-sections for all possible combinations of nuclear systems and the limited experimental data far from the valley of stability have hindered the progress. To overcome these challenges, systematic analysis of extensive scattering data has been performed, revealing systematic trends in potential parameters as a function of the target nucleus's mass, charge, and the incident energy. Such efforts led to the development of so-called phenomenological global optical model potentials (pGOMPs) [1–4].

The pGOMP is parameterized as smooth functions of the target's mass number (A) and atomic number (Z), the projectile type (proton or neutron), and the incident beam energy (E). This approach provides a useful description of the scattering data across a wide range of variables. Several models have been introduced to describe proton elastic scattering, including the Becchetti-Greenlees model [1], the spherical CH89 model [2],

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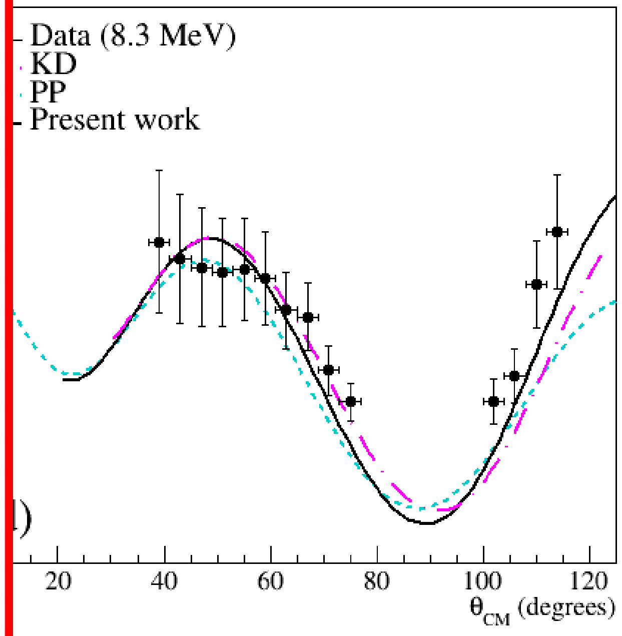


Cros … energy

- Perey-Perey(PP) and Koning-Delaroche(KD) gOMPs work at 8.3 MeV.
- But underestimate data at lower energies.

a_d (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)
0.540	5.75	0.996	0.590
0.368	5.75	0.996	0.590
0.540	5.75	0.996	0.590
0.540	5.75	0.996	0.590
0.540	5.75	0.996	0.590
0.540	5.75	0.996	0.590
0.540	5.75	0.996	0.590

…s using SFRESCO. Searching reliable OMP parameters

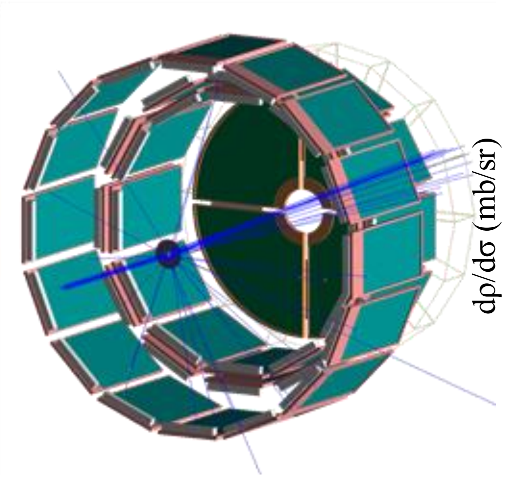
Future plan

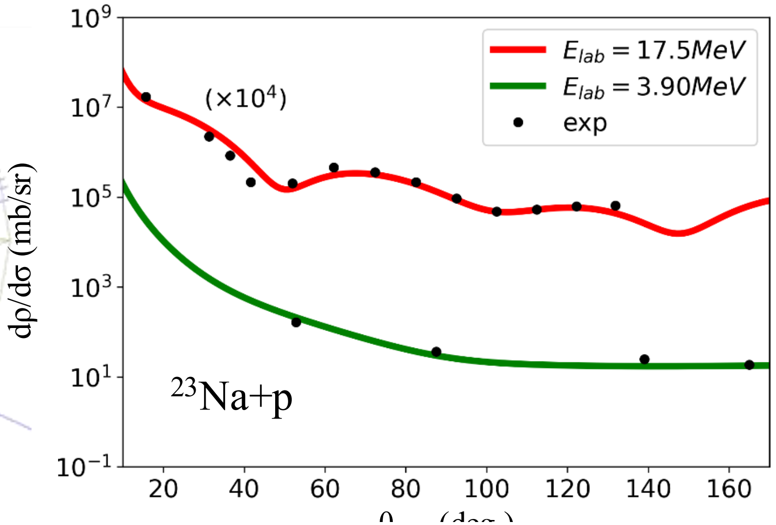
Future experiment –^{21,25}Na + p

**DRHBc: Deformed Relativistic Hartree-Bogoliubov theory in continuum*
***RCHB: Relativistic Continuum Hartree-Bogoliubov theory*

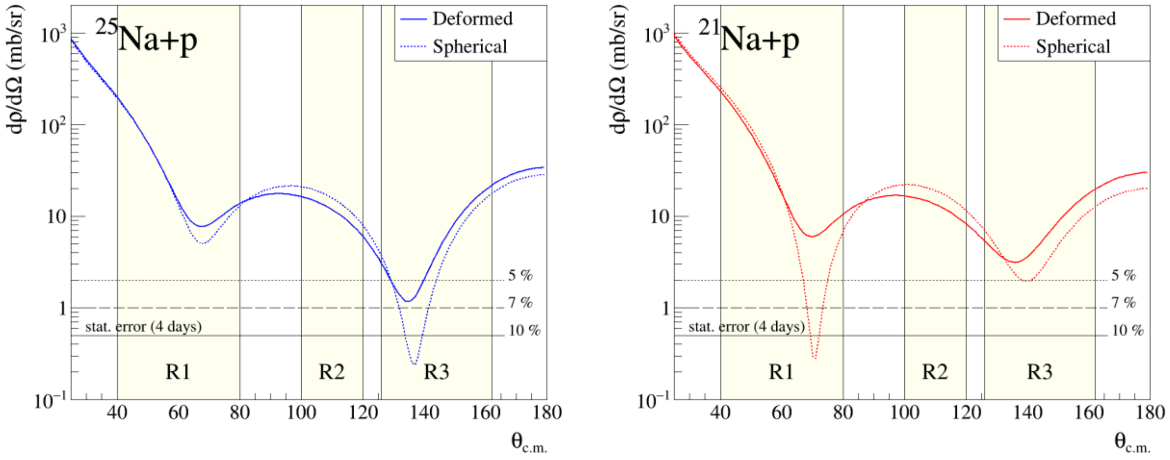
Presentation courtesy of Dr. J. W. Lee

- For the reference, differential scattering cross-sections were calculated with deformed (DRHBc*) and spherical (RCHB**) nucleus theory for ^{21,23,24,25}Na+p elastic scattering at 8 MeV.
- Experimental elastic scattering data for ^{23}Na+p was verified with this method (DRHBc*) for studying the sensitivity of nuclear deformation.
- The ^{21,25}Na+p elastic scattering experiment at KoBRA will be performed in August 2026 for 9 days.
- The results will provide new proton elastic scattering cross section data for ^{21,25}Na isotopes and provide data to verify and improve optical model potential.





Dr. J. W. Lee



Myunghee Park et al., Int. J. Mod. Phys. E 34:05 (2025)

Direct measurement

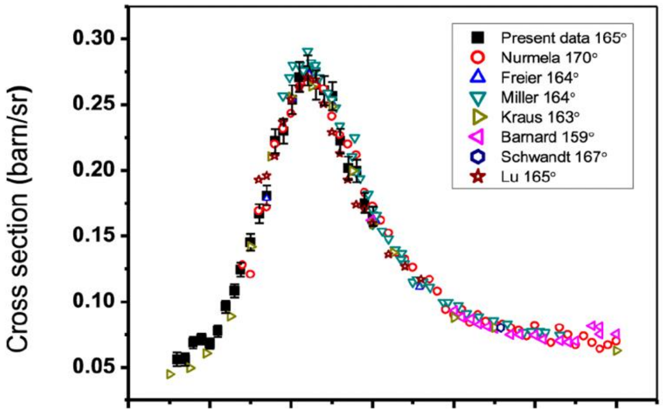
Direct (a,p) reaction study

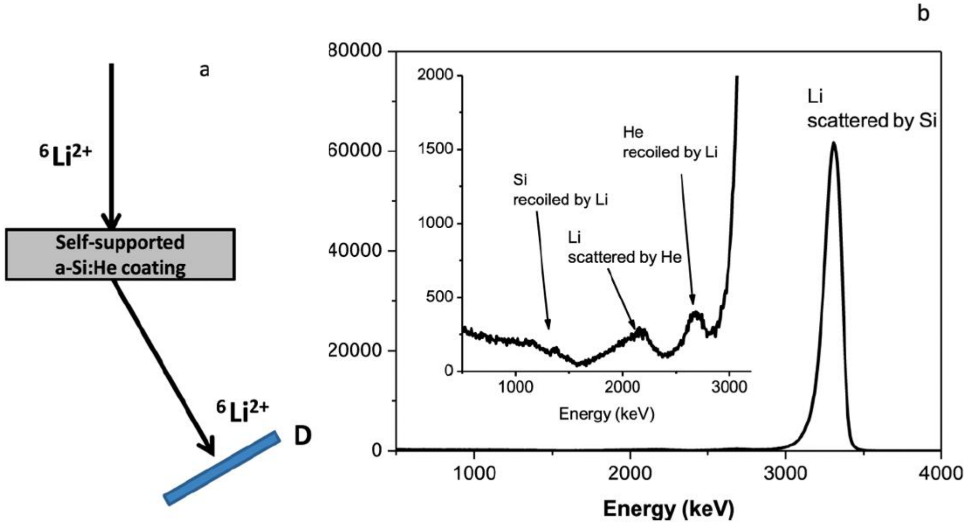
<table>
<tr><th>Reaction</th><th>Physics</th><th>Energy range</th><th>Method / facility</th><th>Researcher</th></tr>
<tr><td>^{14}O(α, p)^{17}F</td><td rowspan="2">Breakout reaction from HCNO to rp-process</td><td rowspan="2">1.2-5.5</td><td>Thick target / CRIB
TexAT_v2 / CRIB</td><td>A. Kim, K. I. Hahn, S. Ahn, D. Kim, C. Park et al.</td></tr>
<tr><td>^{18}Ne(α, p)^{21}Na</td><td>ANASEN / FSU</td><td>Anastasious et al.</td></tr>
<tr><td>^{17}F(α, p)^{20}Ne</td><td>Impacts the ^{44}Ti abundance and light curve in X-ray bursts</td><td>0-4.5</td><td>AToM-X / CRIB</td><td>S. M. Cha
S. Ahn et al.</td></tr>
<tr><td>^{22}Mg(α, p)^{25}Al</td><td rowspan="3">Affects to the final abundance and light curve in X-ray bursts (^{26}Si and ^{34}Ar are waiting points)
$^{18}\mathrm{Ne}(\alpha,p)^{21}\mathrm{Na}(p,\gamma)^{22}\mathrm{Mg}(\alpha,p)^{25}\mathrm{Al}(p,\gamma)^{26}\mathrm{Si}(\alpha,p)^{29}\mathrm{P}(p,\gamma)^{30}\mathrm{S}(\alpha,p)^{33}\mathrm{Cl}(p,\gamma)^{34}\mathrm{Ar}(\alpha,p)^{37}\mathrm{K}$</td><td rowspan="3">3.0-7.5</td><td>AT-TPC / NSCL</td><td>J. S. Randhawa et al.,</td></tr>
<tr><td>^{26}Si(α, p)^{29}P</td><td>Thick target / CRIB</td><td>S. Hayakawa, M. J. Kim et al.</td></tr>
<tr><td>^{34}Ar(α, p)^{37}K</td><td>JENSA / NSCL
AToM-X / CRIB</td><td>J. Brown
A. Kim</td></tr>
</table>

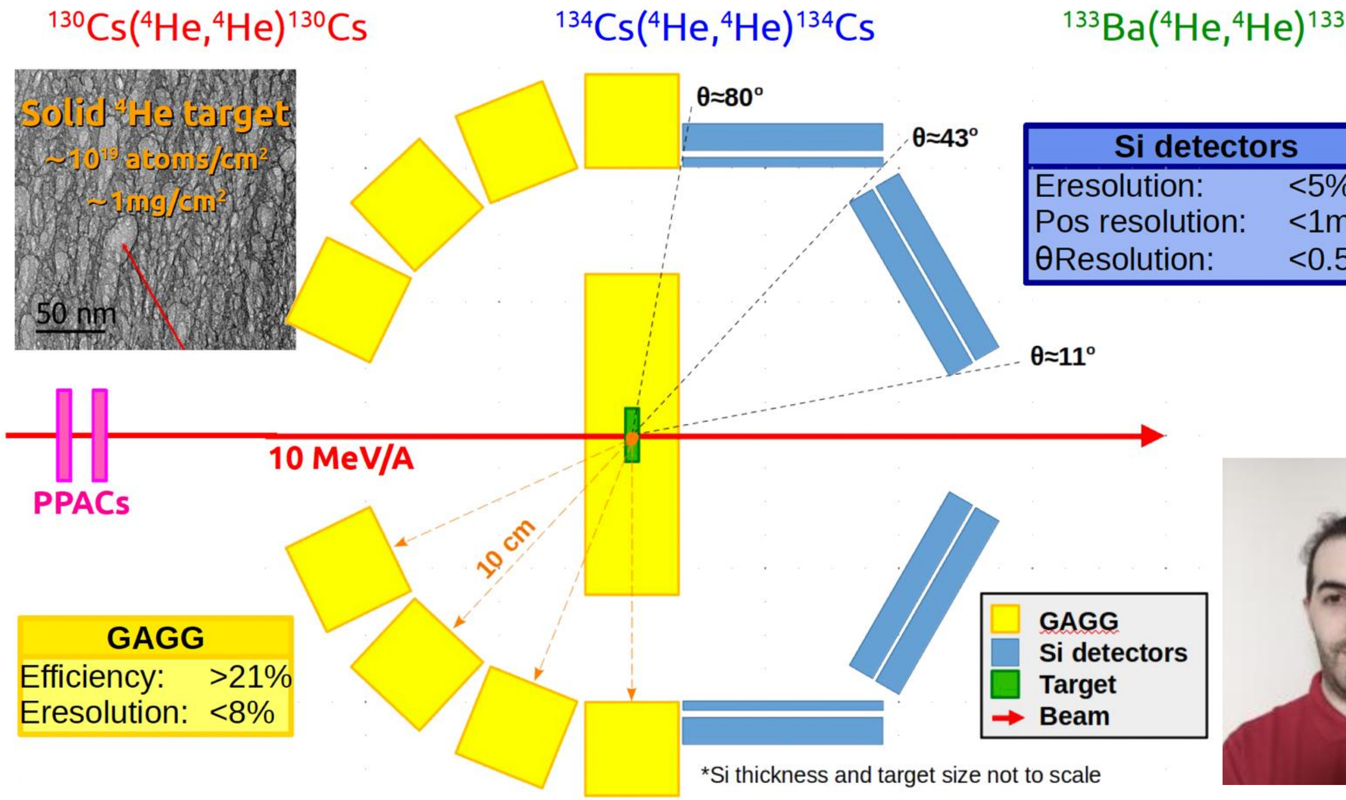
Solid alpha target

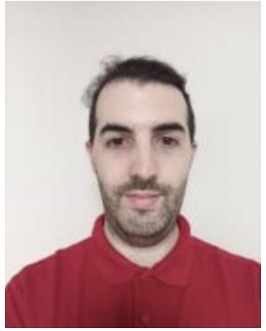
Constraining the αOMP via α-elastic scattering of ^{130,134}Cs, ^{133}Ba on solid He target

- α-Si:He (amorphous-Silicon) / He(p,p)He at scattering angle of 165°





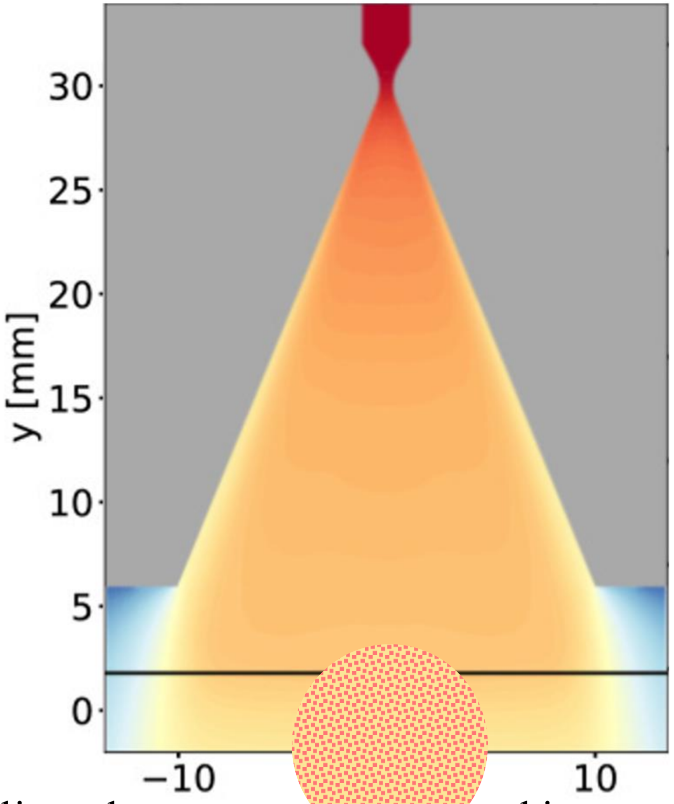




Dr. X. PEREIRA-LOPEZ

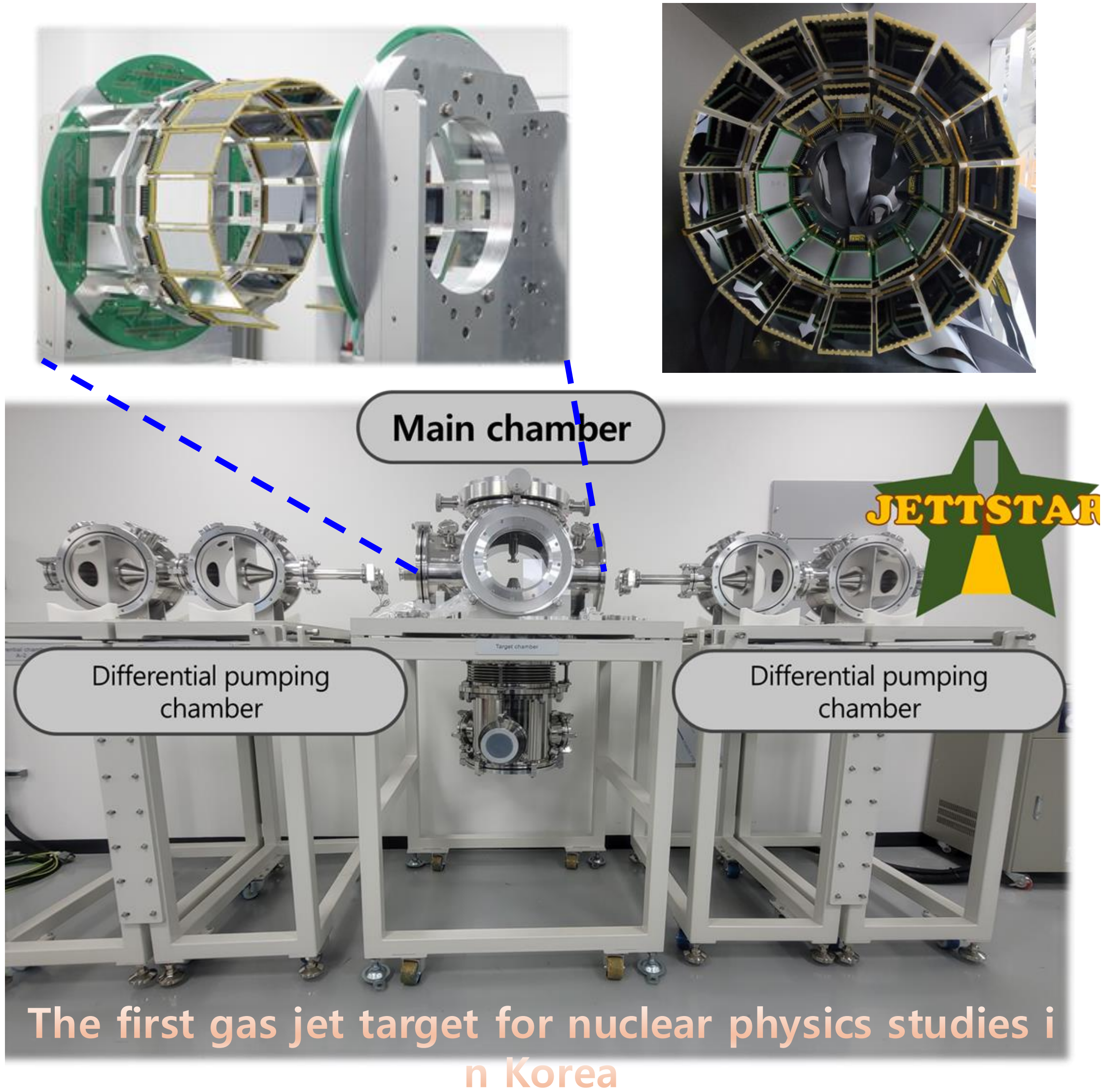
Gas Jet Target and Detector System

Presentation courtesy of Dr. S. Ahn



Using a gas jet target and a silicon detector array, [illegible] achieve

1) no background contamination from the window,
2) localized vertex,
3) high target density
4) enhanced energy/position resolution detectors.



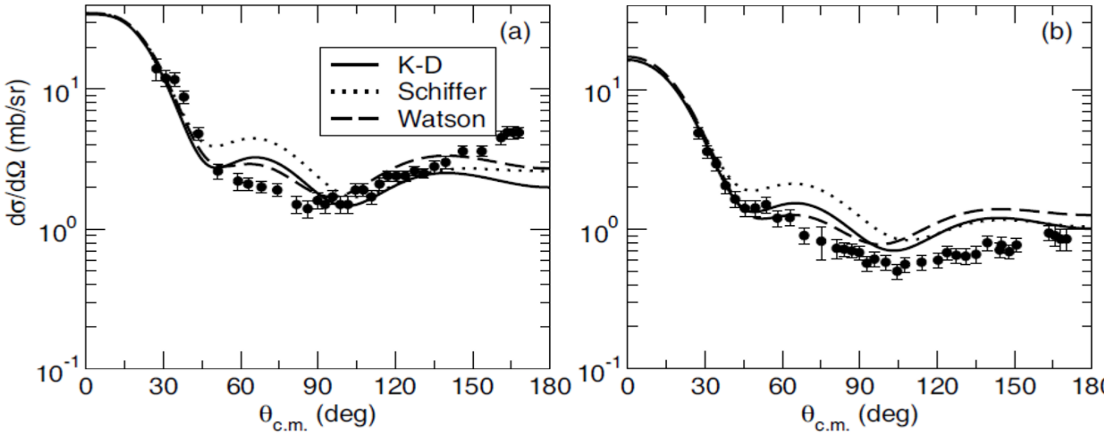
Indirect measurement

^{7}Li(d,p)^{8}Li

JAEA experiment

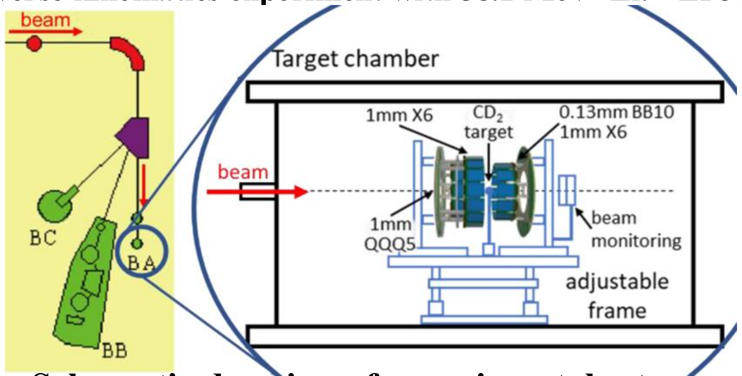
- Study mirror nucleus; ^{7}Be(p, γ)^{8}B which involves the hydrogen burning sequence.
- ^{7}Li(n, γ)^{8}Li which is the possible pathway of the breakout from pp-chain region or of the early stage of r-process in type II supernovae.
- Well studied cross-section for ground and 1st excited states
- Well known energy levels in ^{8}Li:
  - ground state
  - 0.98-MeV 1st excited state
  - 2.255-MeV 2nd excited state (unbound)
- Possible new information for 2nd excited state
  - Spectroscopic factor
- Commissioning at JAEA Tandem beamline
  - ^{7}Li, **40** MeV (~5.7 MeV/u), 10^6 pps
  - Target : ~ 0.2 mg/cm^2 CD_2, Graphite
  - **Total 7 days beam time**

Dr. S. H. Bae

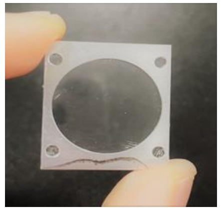


^{7}Li(d,p)^{8}Li reaction cross-section of (a) for ground state and (b) for 1st excited state from an inverse kinematics experiment with 38.1 MeV ^{7}Li. ***EPJ A 53, 167 (2017)***

JAEA Tandem facility

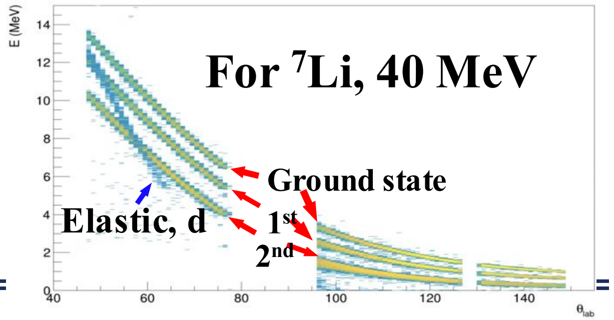


Schematic drawing of experimental setup



CD_2 target

GET electronics DAQ system

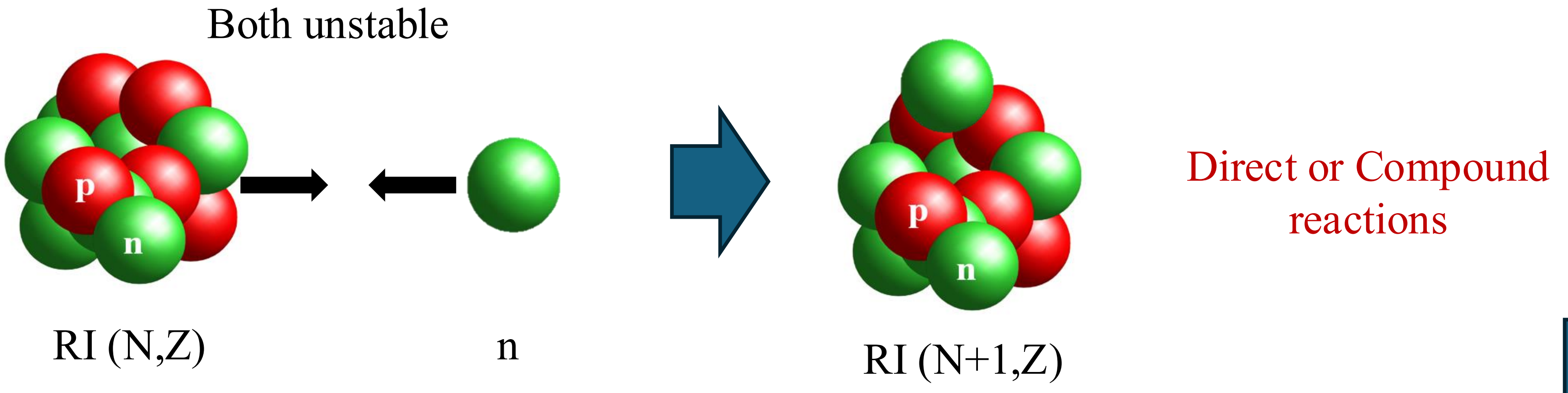


^{7}Li(d,p)^{8}Li Simulation results

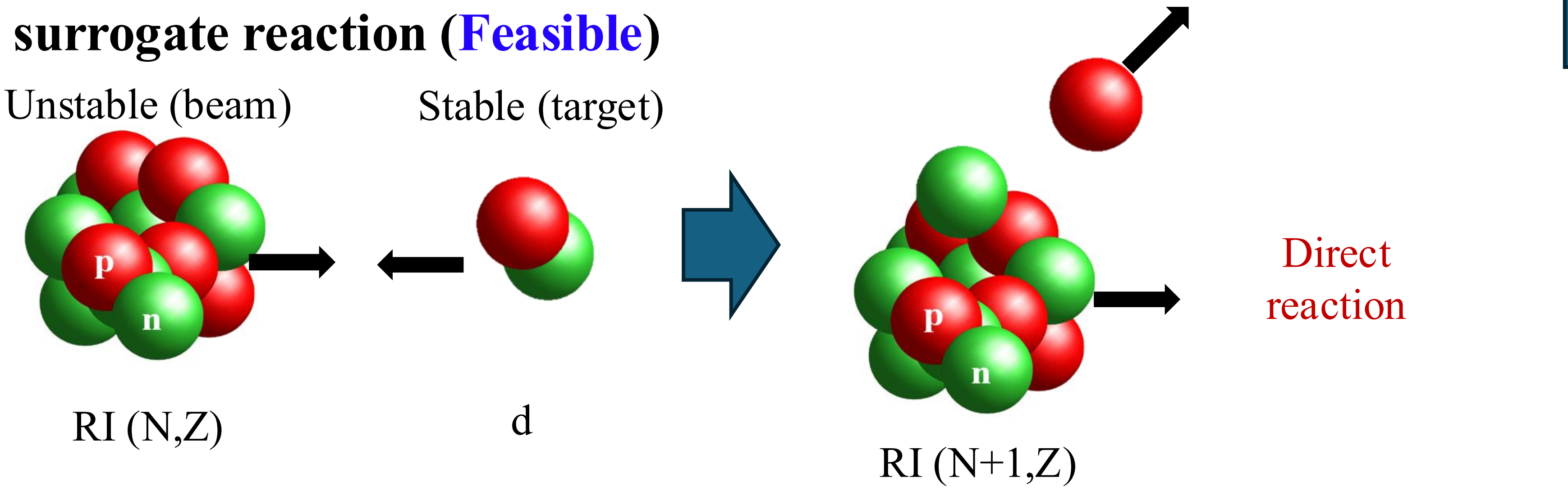
Presentation courtesy of Dr. S. H. Bae

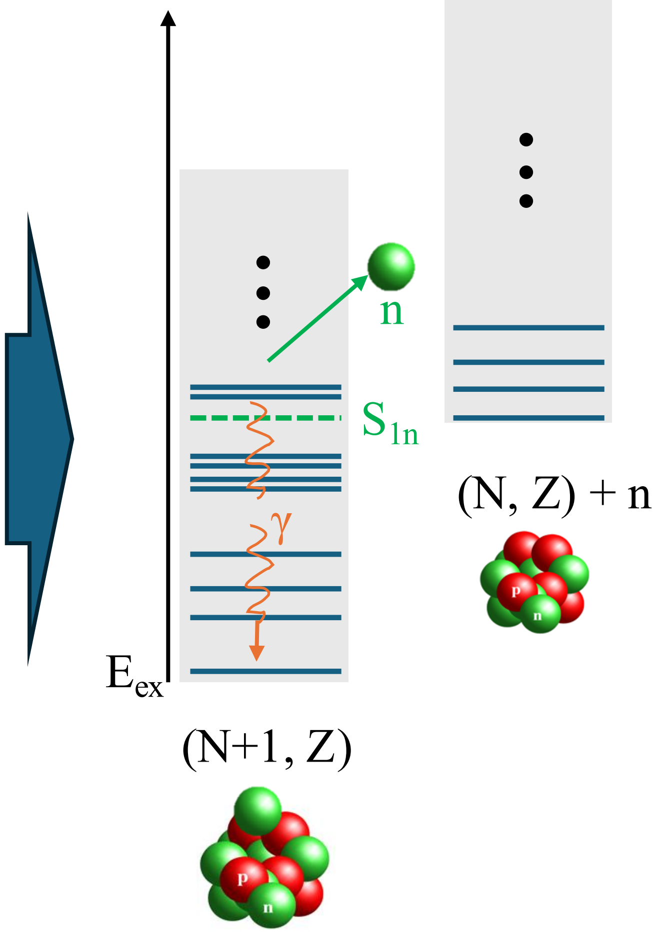
Surrogate method

Neutron capture (Impractical)



(d,p) surrogate reaction (Feasible)





Presentation courtesy of Dr. S. H. Bae

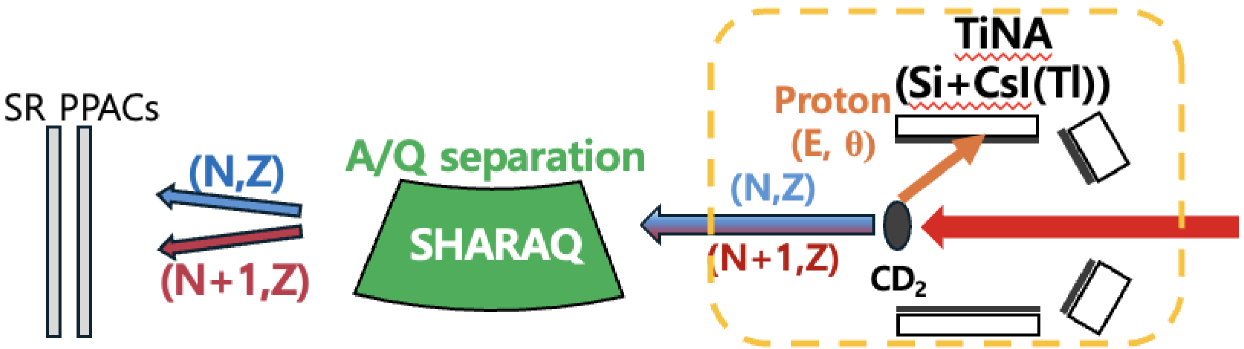
Surrogate method

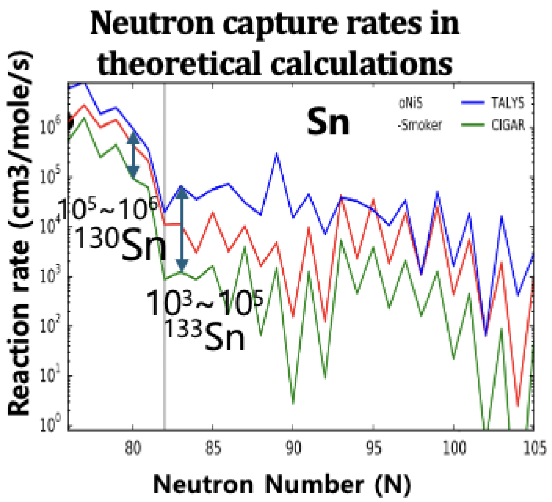
1) $^{130, 133}$Sn

Presentation courtesy of Dr. S. H. Bae

- N = 82 waiting point in r process
  - Second peak of r-process elemental abundances
  - Bottle-neck toward the third abundance peak
- Large impact but lack of experimental input for compound neutron capture rates
- **SHARAQ18 (2022 Apr.)** (*Proposed by N. Imai (CNS), analysis by S. Bae)* **within SAKURA collaboration**
  - **^{130}Sn(d,p) measurement @ CNS OEDO-SHARAQ in RIBF**

Dr. S. H. Bae



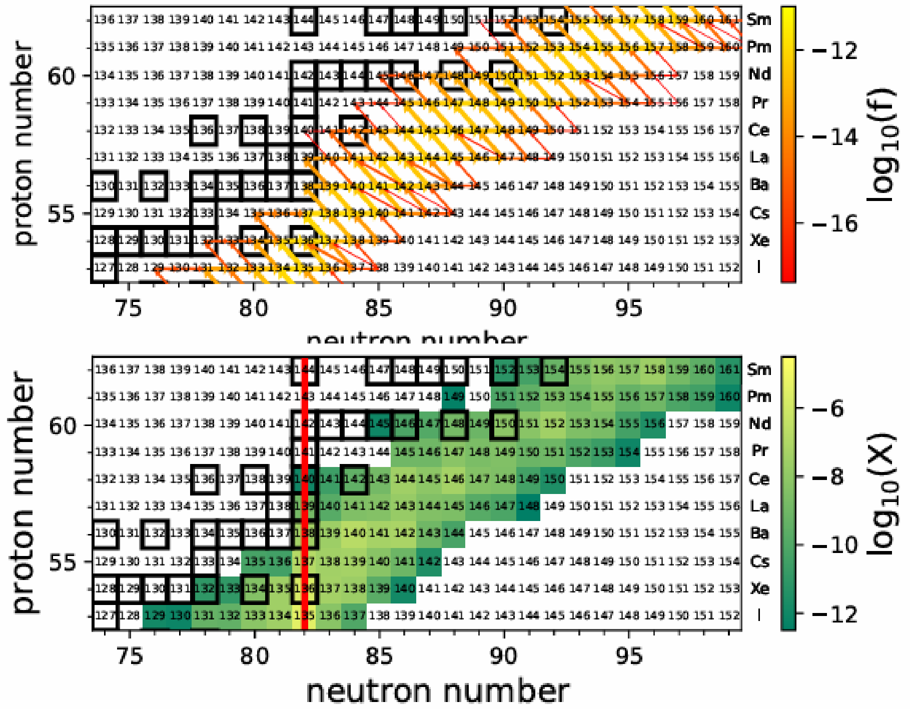


Prog. Part. Nucl. Phys. 86, 86-126 (2016)

Surrogate method

2) $^{134\text{-}137}$Cs *H. Watanabe, D. Kim, S. Ahn (CENS))*

- $^{134,\,135}$Cs : One of the branching point (BP) of s-process
  => n-capture rate, β-decay half-life influence ^{134,136}Ba ratio
- Cs isotopes involves i-process as well with high priority in ^{137}Cs n-capture rate which influences Ba and Pr abundances.



3) ^{20}Ne(n,γ) *D. Kim, S. Ahn (CENS))*

- One of the major neutron poison of weak s-process in C/He burning in massive AGB stars ($4M_{\odot} \leq M \leq 7M_{\odot}$).
- Recently, overestimation of ^{20}Ne(n,γ) ^{21}Ne cross-section was reported.
  => The revised Maxwellian-averaged cross section (MACS) could lead to a 20-30% reduction in the overall s-process abundance.

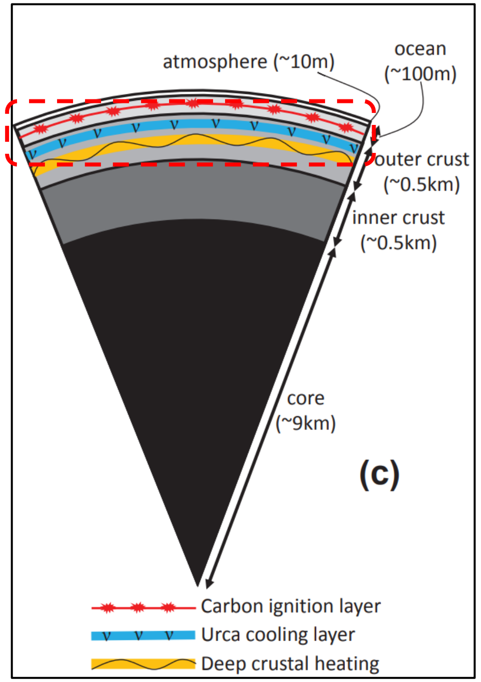
Impact	Reaction
477.89	$^{56}Fe+n \rightarrow {}^{57}Fe+\gamma$
365.37	$^{25}Mg+n \rightarrow {}^{26}Mg+\gamma$
307.50	$^{24}Mg+n \rightarrow {}^{25}Mg+\gamma$
305.04	$^{20}Ne+n \rightarrow {}^{21}Ne+\gamma$
275.19	$^{62}Ni+n \rightarrow {}^{63}N+\gamma$
240.40	$^{68}Ni+n \rightarrow {}^{69}N+\gamma$

Fusion reaction

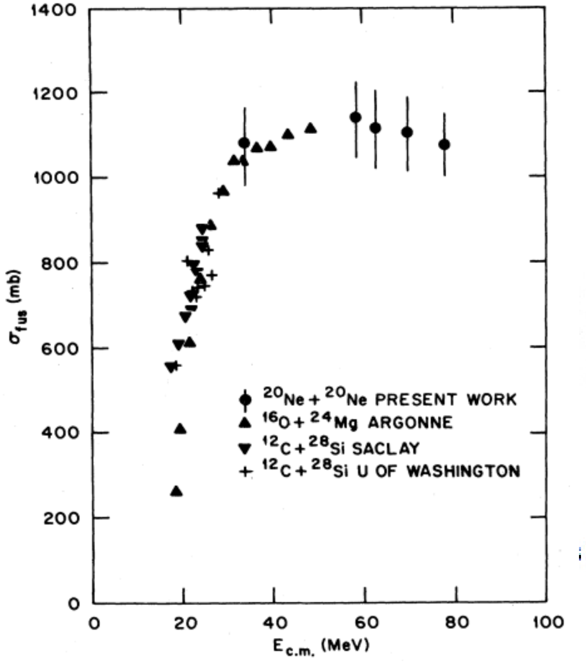
Astrophysical S-factors for Fusion Reactions

Presentation courtesy of Dr. S. Ahn

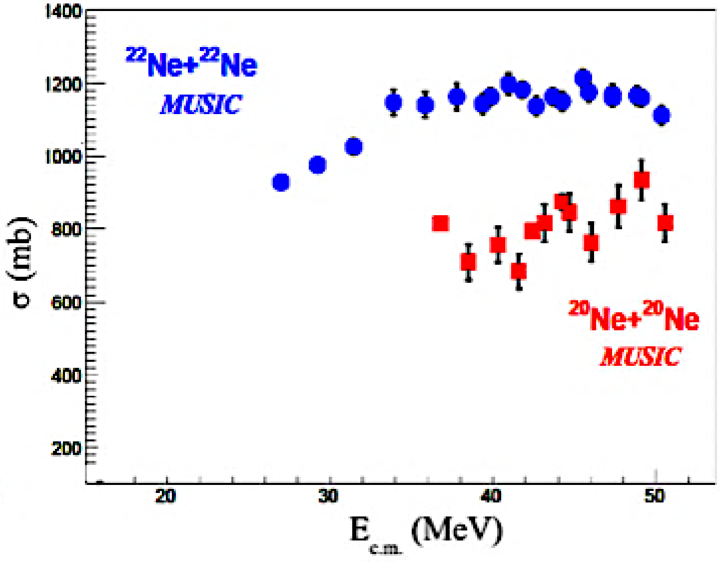
$^{12}C+^{12}C$, $^{24}C+^{24}C$, $^{28}Ne+^{28}Ne$ and so on…

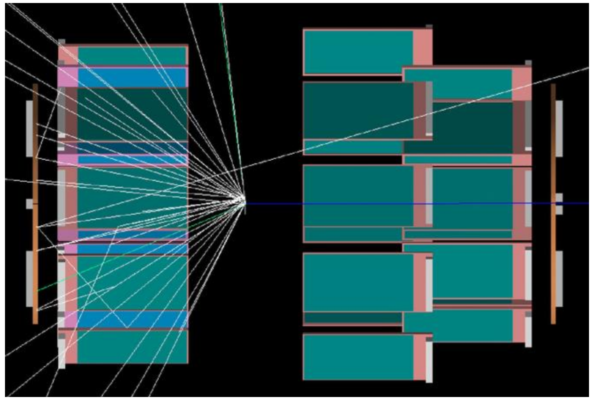


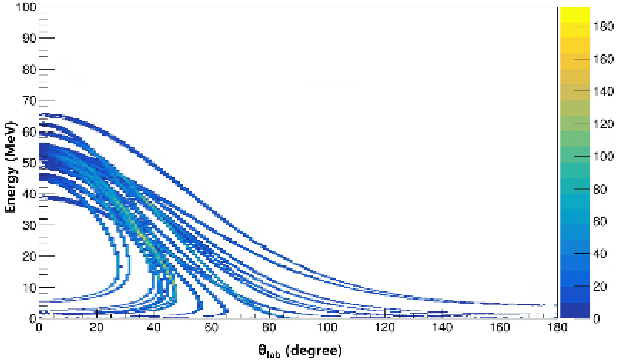
$^{20}Ne+^{20}Ne$ fusion cross section
D. Shapira et al., PRC 28 (1983)



Ne+Ne fusion cross sections with MUSIC
M. L. Avila et al., EPJ 117 08009 (2016)







- Nuclear fusion burning drives nuclear explosions in the surface layers.

→ It is necessary to calculate the astrophysical S-factor for the reactions of interest!

- The angle range was only from 0 to 30 degrees. An ionization counter was used resulting in a large energy and angle resolution.

Summary

1. Foundation: High-Resolution STARK System
   - Barrel-type Array: Advanced configuration (12+16+12) with X6 resistive strip detectors.
   - Performance: World-class angular resolution (<1°) and wide coverage (43° – 150°).
   - Validation: Proven reliability through elastic scattering and transfer reactions (STARK Jr.).
2. Current Strategic Research: Multi-channel Reactions
   - Optical Potential (OMP): Establishing p-OMPs via ^{40}Ar + p for p-process studies.
3. Future Frontier: The Next Decade
   - p-OMP study with radioactive Na beams
   - Surrogate Method: Investigating ^{130,133}Sn(d, p), $^{134\text{-}137}$Cs(d, p), and ^{20}Ne(d, p) for s-process (n, γ).
   - Alpha solid target, Gas jet target for (α, p) reactions via direct measurement
   - The Fusion reaction: Resolving carbon-burning mysteries (^{20}Ne + ^{20}Ne) with a windowless Gas Jet Target.
   - Vision: Building a comprehensive experimental database for global stellar evolution models.