CENS
CENTER FOR EXOTIC NUCLEAR STUDIES

Particle Detector Workshop 2026

Silicon Detectors for Low-Energy Rare-Isotope Nuclear Physics

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Center for Exotic Nuclear Studies
Institute for Basic Science
(CENS/IBS)

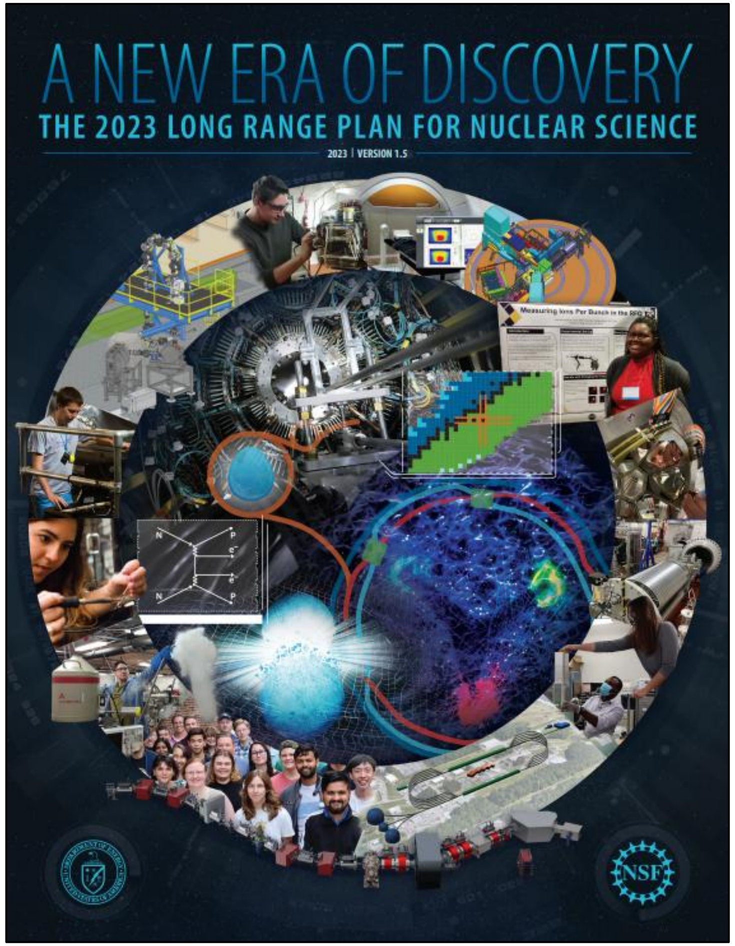
2/6/2026

Front: CENS Nuclear chart with research topics
Background: JWST Deepest Infrared Image of Universe
by NASA, ESA, CSA, and STScI

ibs 기초과학연구원 Institute for Basic Science

Main Scientific Questions in 2023 LRP

- The 2023 Long Range Plan by Nuclear Science Advisory Committee
  (at the request of the DOE Office of Science and the NSF Directorate of Mathematical and Physical Sciences)



THE SCIENCE QUESTIONS

Nuclear science addresses some of the outstanding challenges to modern physics, including the properties and limits of matter, the forces of nature, and the evolution of the universe:

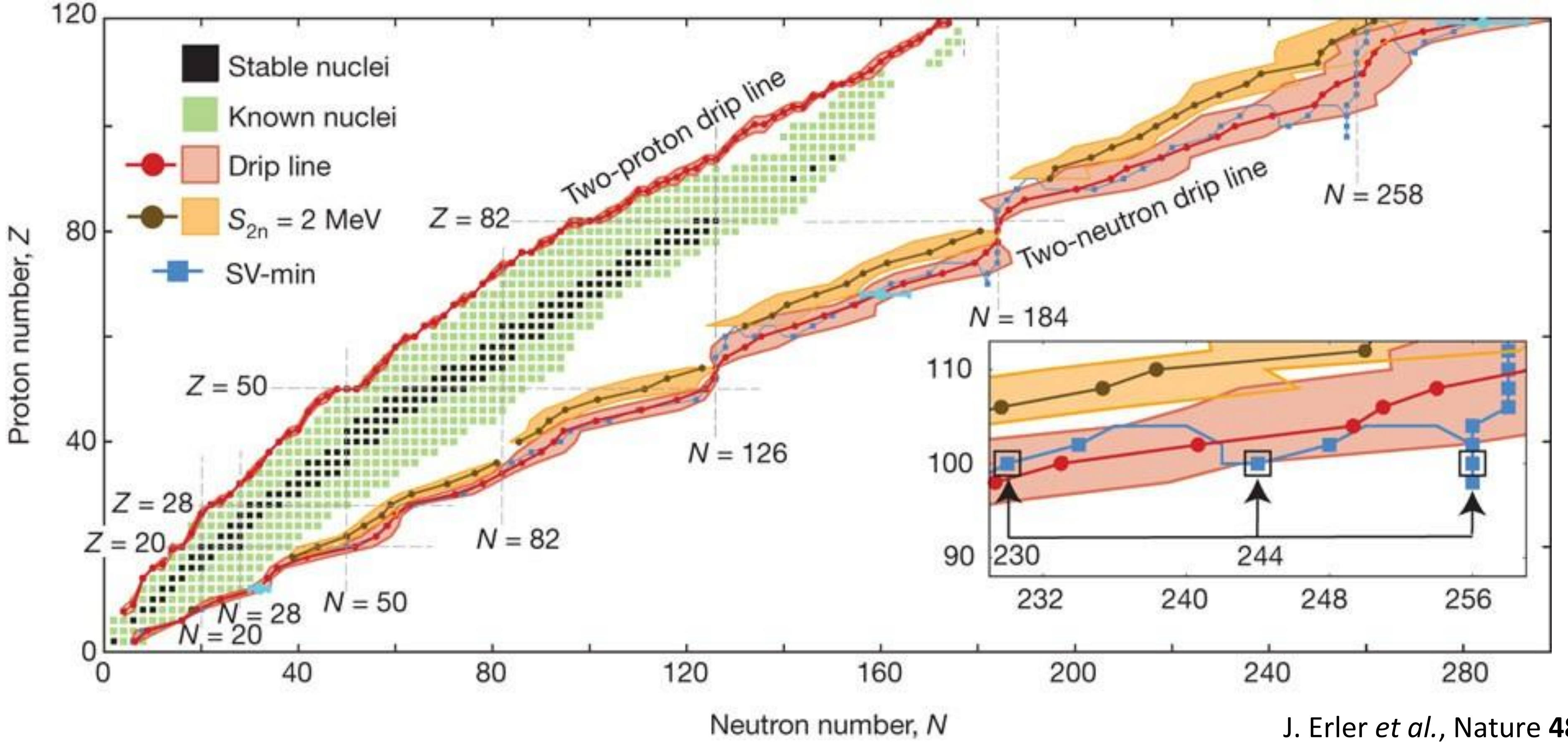
✓ Question 1. How do quarks and gluons make up protons, neutrons, and, ultimately, atomic nuclei?

✓ **Question 2. How do the rich patterns observed in the structure and reactions of nuclei emerge from the interactions between neutrons and protons?**

✓ **Question 3. What are the nuclear processes that drive the birth, life, and death of stars?**

✓ Question 4. How do we use atomic nuclei to uncover physics beyond the Standard Model?

The limits of the nuclear landscape



J. Erler *et al.*, Nature **486**, 509 (2012)

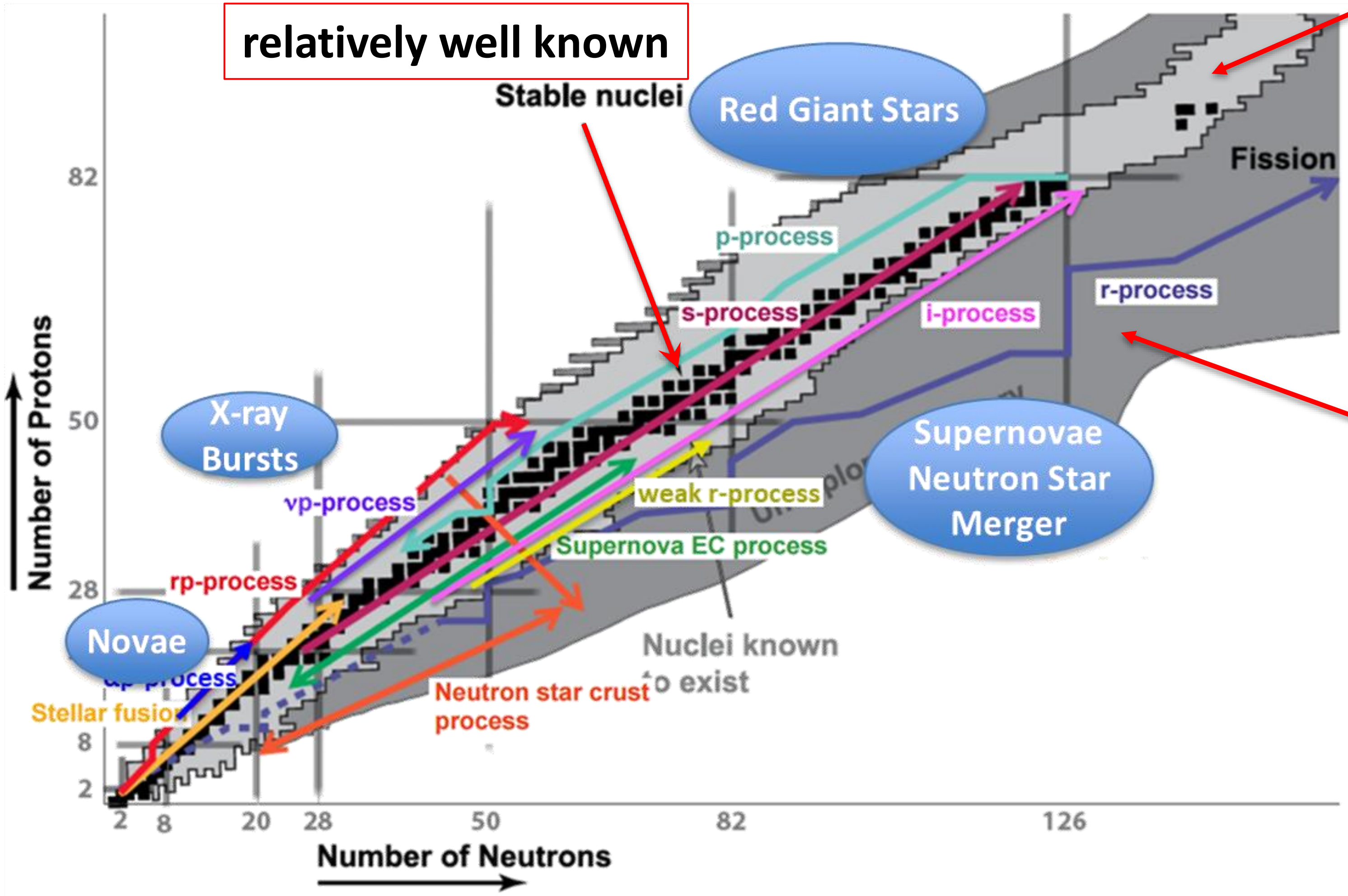
- Only 288 nuclei forms the valley of stability.
- About 3,000 nuclei are known.
- Nuclear theorists estimate about 6,900 nuclei are bound.
- Nuclei away from stability are short lived (down to µsec).

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

relatively well known

a little bit known



Unknown?!

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

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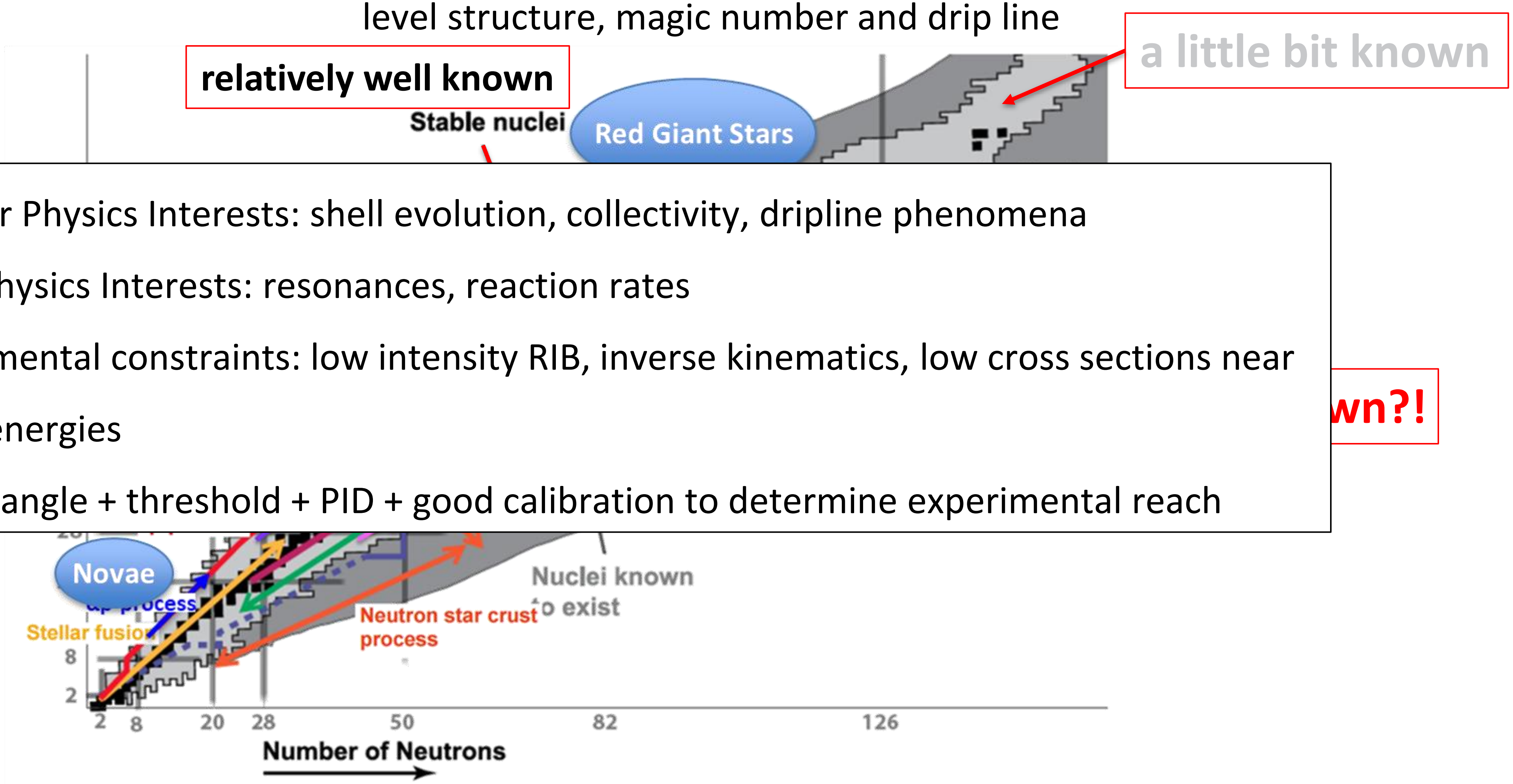


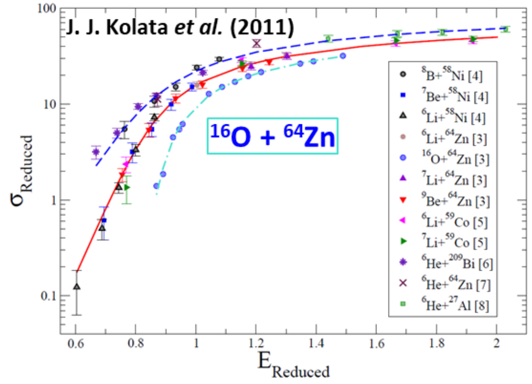
- Nuclear Physics Interests: shell evolution, collectivity, dripline phenomena
- Astrophysics Interests: resonances, reaction rates
- Experimental constraints: low intensity RIB, inverse kinematics, low cross sections near barrier energies

➔ solid angle + threshold + PID + good calibration to determine experimental reach

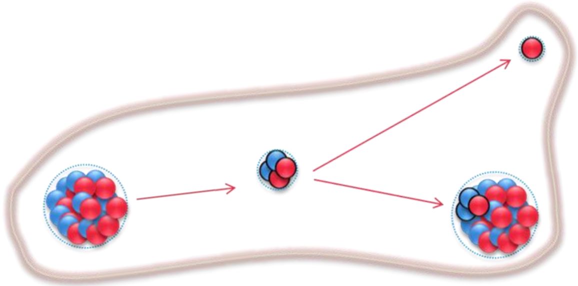
Schematic overview of the nuclear processes on nuclear chart
H. Schatz, *2016*

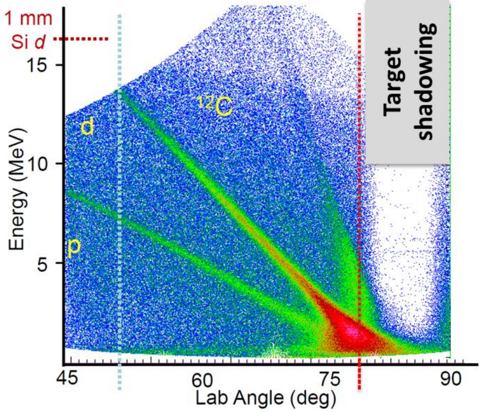
Nuclear Reaction Research Topics in Low-Energy RI

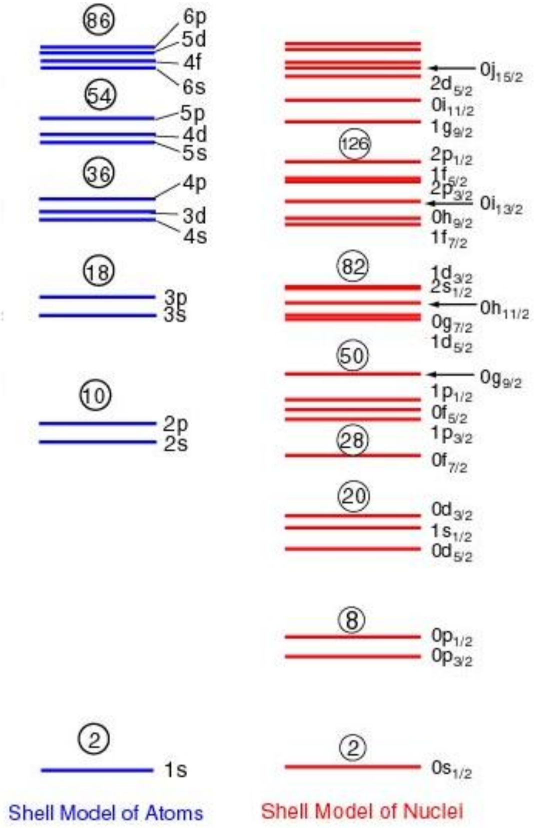
- Structure / shell evolution: (d,p), (p,d), inelastic → single-particle, SF, J^{π}
- Nuclear astrophysics: resonant states, (α,p), (p,γ), (n,γ) → rates
- Near-barrier reaction dynamics: elastic/breakup → OMP, coupling effects
- Needs: angular distributions + E_x or Q-value + PID + coincidences

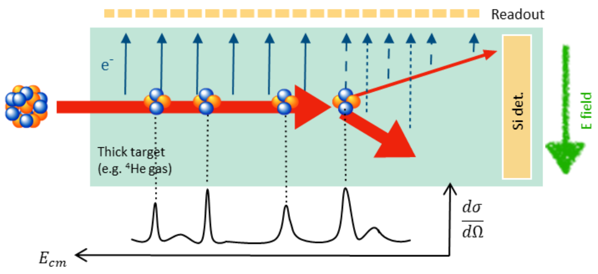


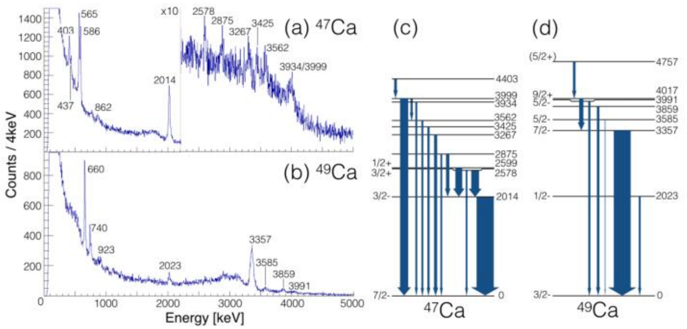
Reduced total reaction cross sections



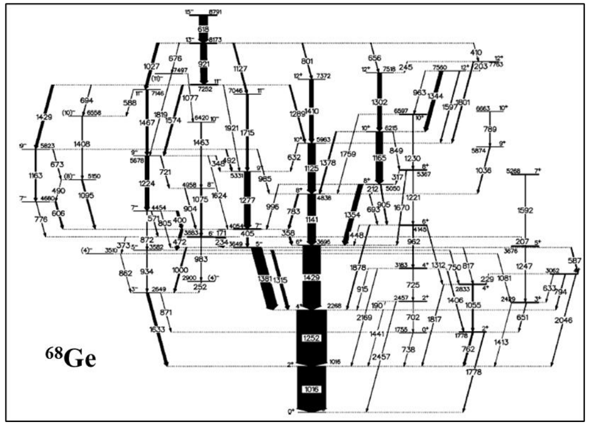








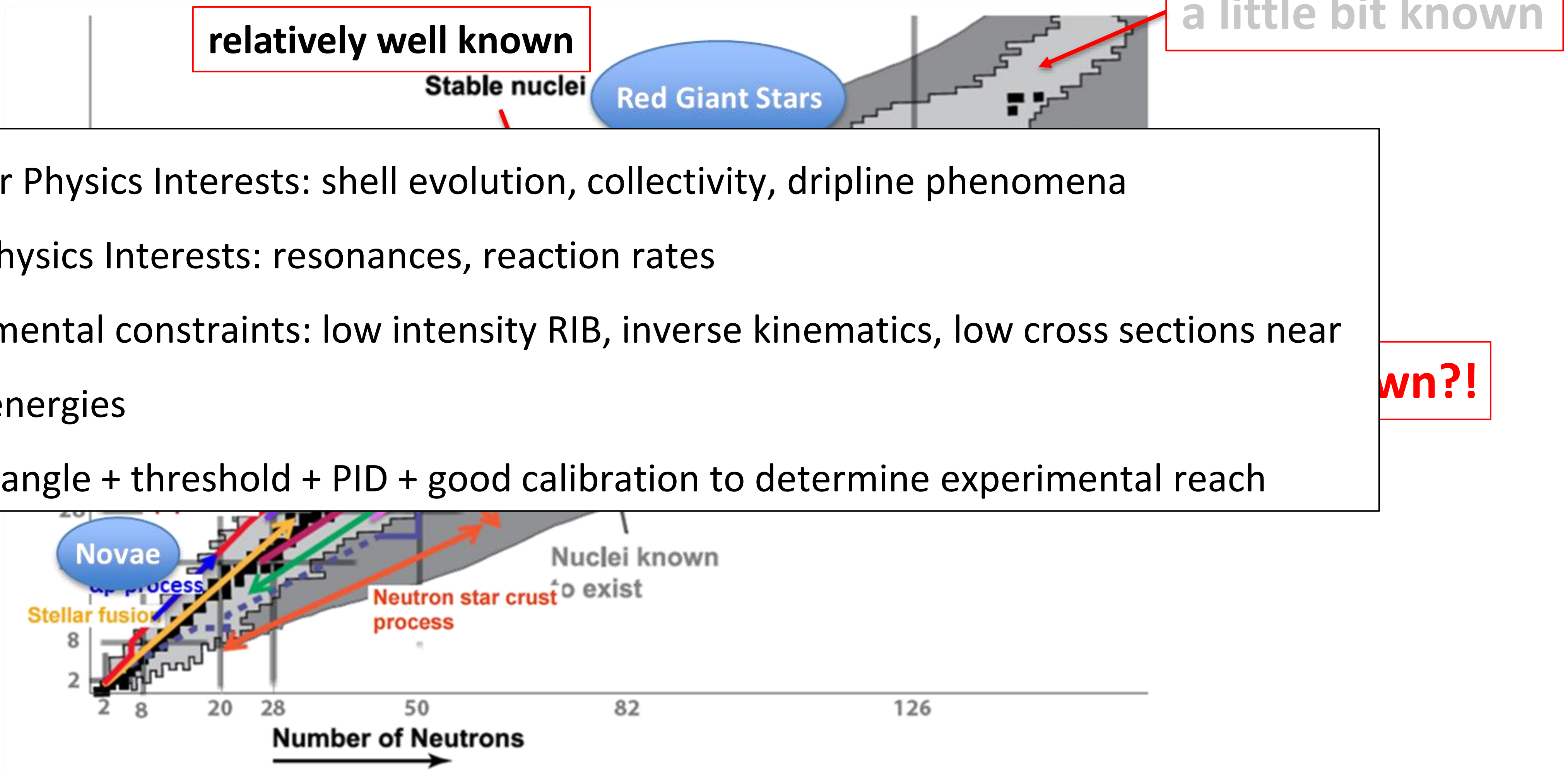
H. L. Crawford *et al.*, 2016



L. Chaturvedi et al., Phys. Rev. C **43**, 2541 (1991).

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



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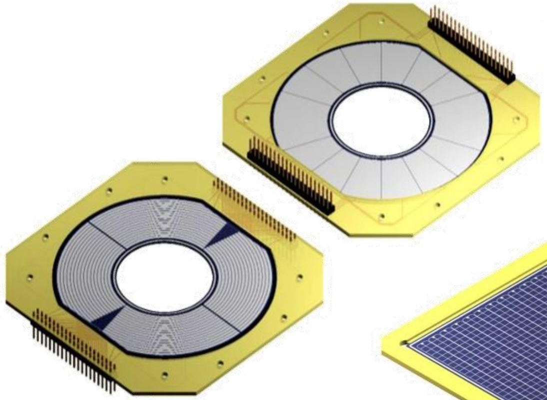
Schematic overview of the nuclear processes on nuclear chart
H. Schatz, *2016*

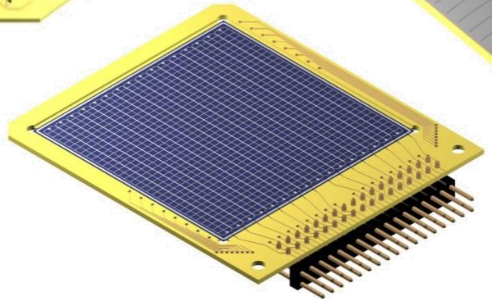
Silicon Detector Property Requirements

- **SSSD vs DSSSD:** energy vs position (θ) granularity
- **Strip pitch / Active area:** Δθ & multiplicity handling
- **Thickness:** ΔE/E design, punch-through control
- **Dead layer & Threshold:** low-energy p/α sensitivity
- **Bias & QC:** IV/CV, leakage(T), microdischarge

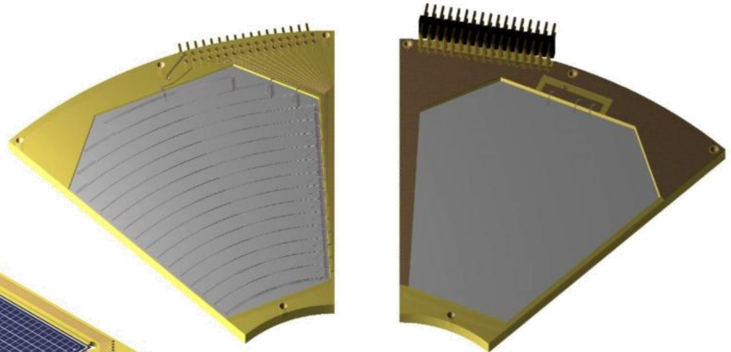
- ΔE–E telescope: **particle ID** for p/d/t/α
- **Punch-through / stopping** boundaries
- Backing detectors (e.g., CsI(Tl)) as option
- Calibration methods: **α sources + elastic kinematics**



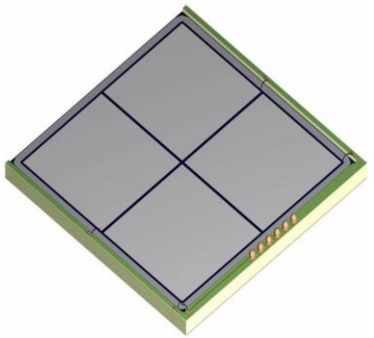
S1 (48 mm ID & 96 mm OD)
64x16 strips



BB15 (50x50 mm^2)
16x16 strips

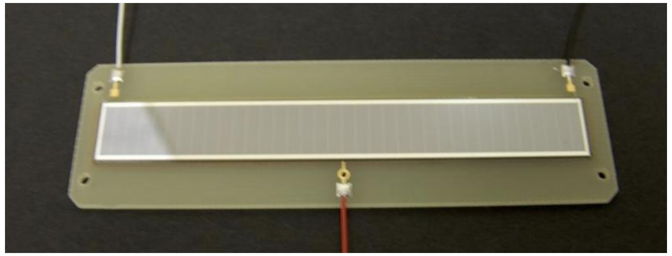


YY1 (55 mm ID & 13 mm OD)
16x1 strips

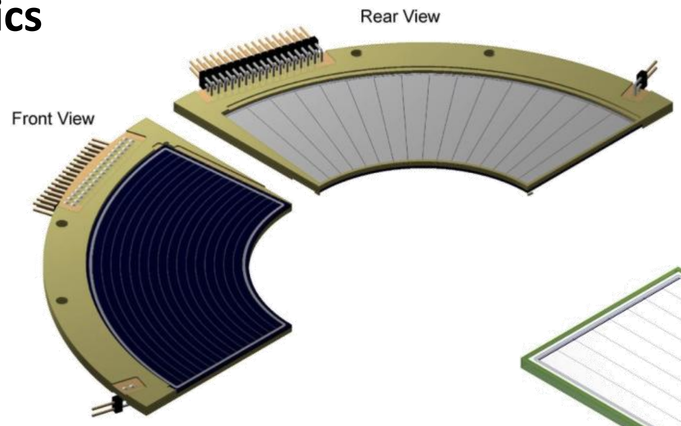


MSQ25-1000
(50x50 mm^2)

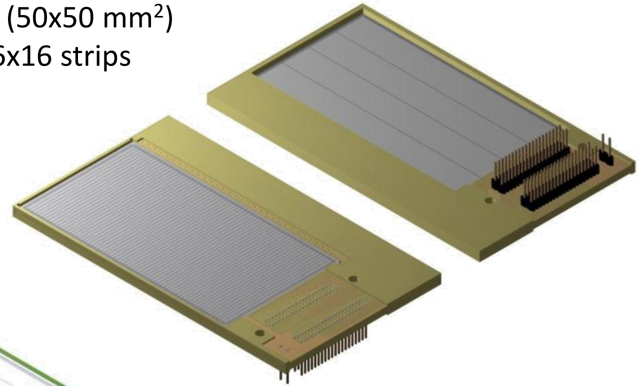
HELIOS PSD (56 x 12 mm^2)



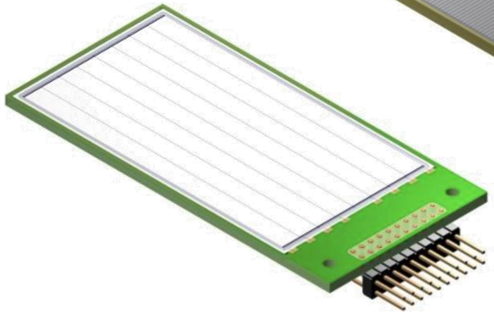
TT-500 PSD (190 x 40 mm^2)



QQQ3 (50.1 mm ID & 99 mm OD)
16x16 strips
QQQ5 (25.3 mm ID & 82 mm OD)
32x4 strips



BB15 (75x40.3 mm^2)
64x4 strips



BB10 (75x40.3 mm^2)
8x1 strips

Electronics and DAQ Systems (Conventional vs ASICs vs Digitizer)

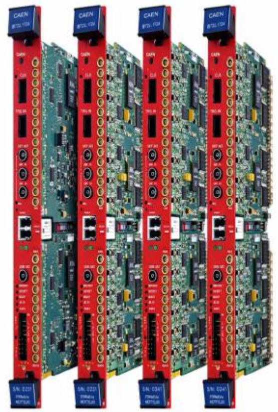
- **Large number of channels** from the detector setup: Conventional Electronics requires space and cost problems, complicated setup, easy signal tracing.
- **ASIC-based:** high channel density, low noise, compact cabling, low cost (~1/10) and small space (~1/5), simple setup.

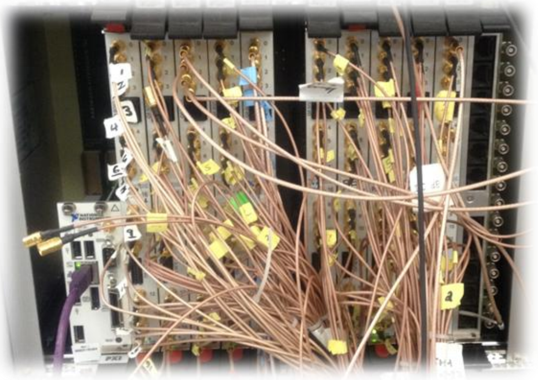
✓ HINP (Heavy Ion Nuclear Physics) Chip: 16 channels per chip, 512 channels per motherboard

✓ GET (Generic Electronics for TPC): 64 channels per chip, 256 channels per AsAd board

- **Digitizer-based:** waveform access, flexible triggering, rapid bring-up
- **Sync:** common clock/timestamps, coincidence window
- **Rate & dead time:** pileup, buffer, throughput
- **Grounding/shielding (low noise):** vacuum feedthrough, cross-talk control

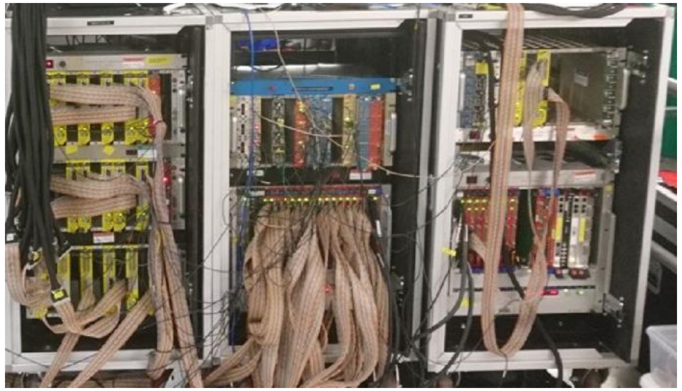
CAEN V-series digitizer (PHA&PSA)



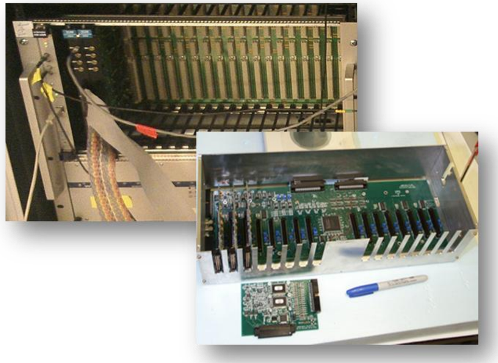


XIA Pixie16 digitizer (PHA)

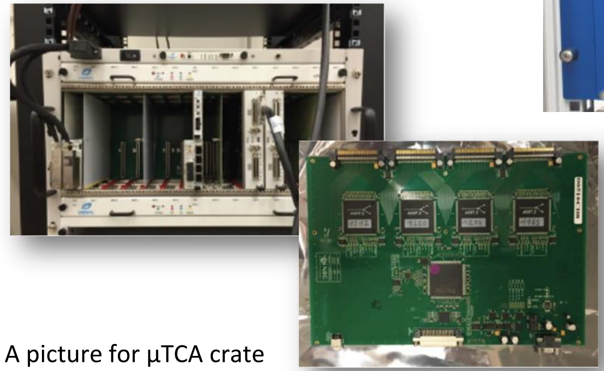
Digitizer for ASGARD and Stark Jr. with domestic company (Notice Korea)



A picture of Conventional Electronics Set-up



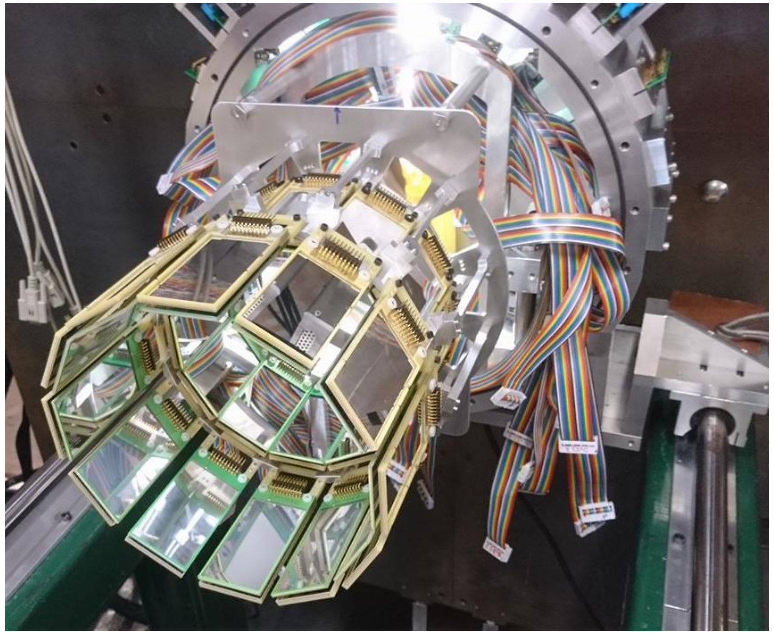
A picture for HINP16C chip and motherboard
G.L. Engel, CAARI Conference (2010)

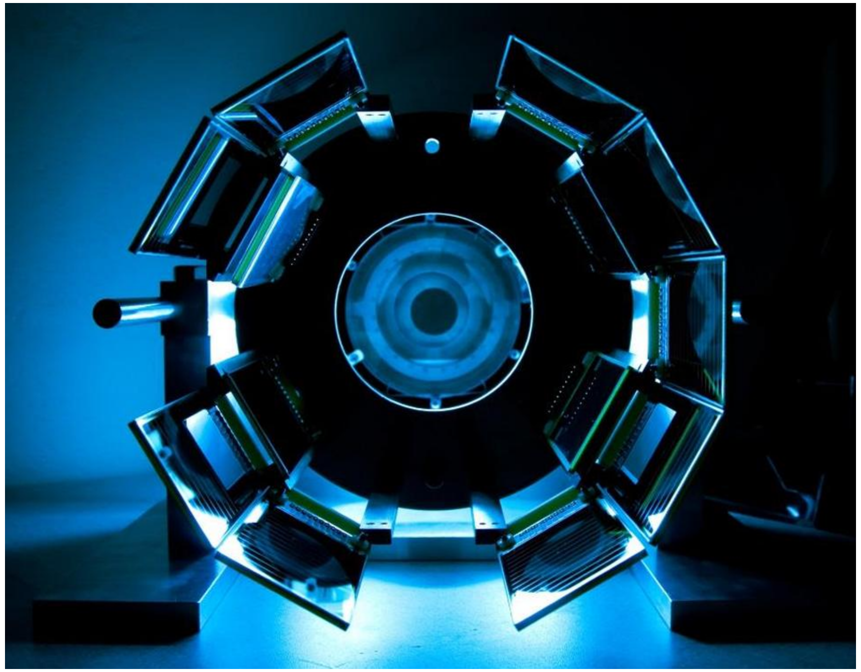


A picture for µTCA crate
and AsAd board (4 AGET chips)
G. Rogechev, GDSs Workshop (2018)

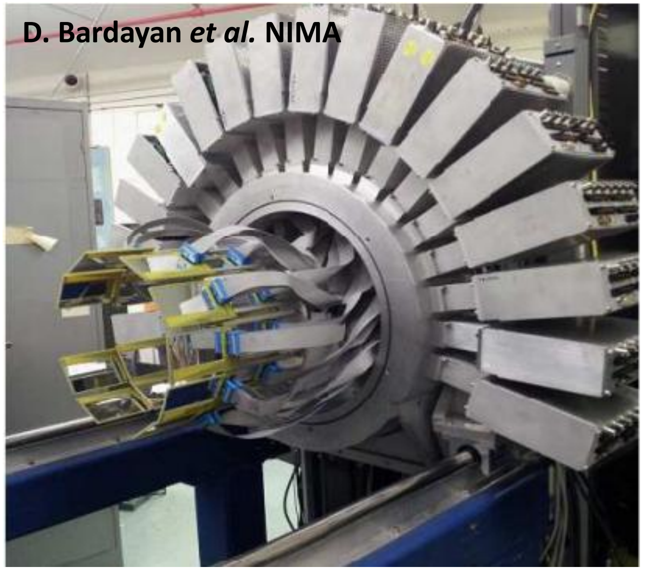
ORRUBA and superORRUBA

- Purpose: **inverse kinematics transfer** with large acceptance
- Layout concept: **barrel + endcap** Si strips, 12 detectors/telescopes per ring
- Key design: **segmentation → Δθ**, high solid angle
- Typical outputs: **angular distributions, Q-value spectra**
- Integration: target chamber geometry & alignment discipline





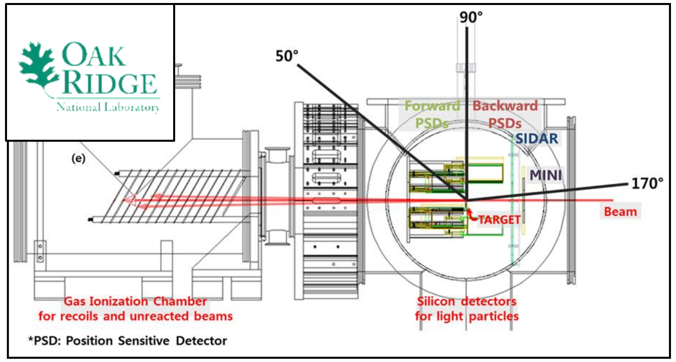
ORRUBA （Oak Ridge Rutgers University Barrel Array）

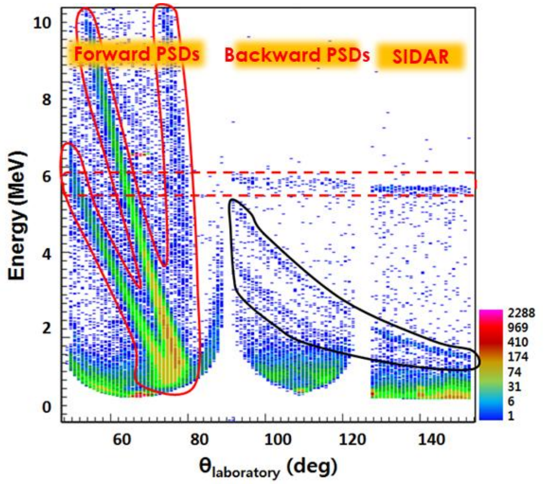


SuperORRUBA

ORRUBA: Research Highlights

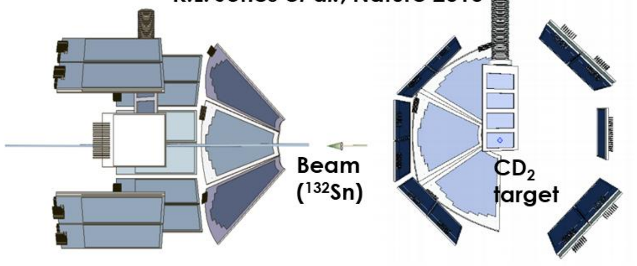
- **Doubly Magic nucleus:** ^{132}Sn(d,p)^{133}Sn single-particle states (inverse kinematics)
  - ✓ Angular dist. provides **ℓ assignment, SF**, state identification.
  - ✓ Doubly magic property is confirmed.
- **Neutron capture reaction rates:** ^{80}Ge(d,p)^{81}Ge neutron transfer
  - ✓ Angular dist. provides **ℓ assignment, SF**, state identification.
  - ✓ The results provides new cross section of ^{80}Ge(n,γ)^{81}Ge reaction.

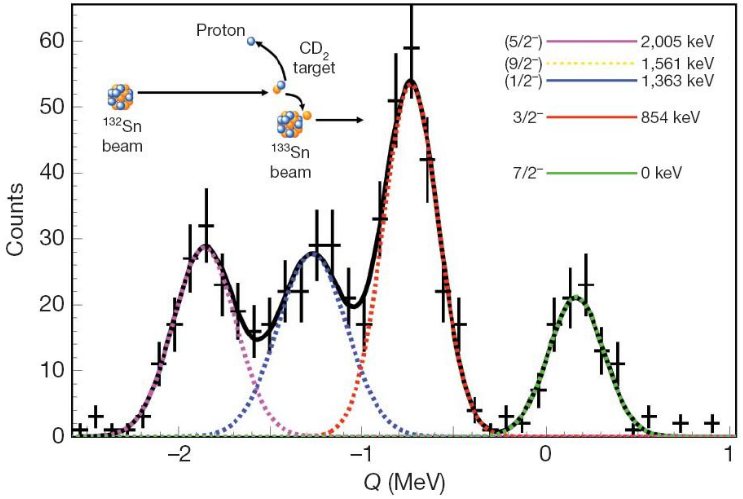




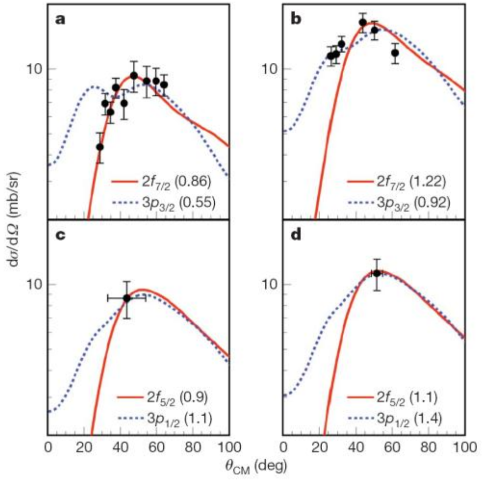
S. Ahn *et al. PRC* 100, 044613 (2019)

K.L. Jones *et al.*, Nature 2010

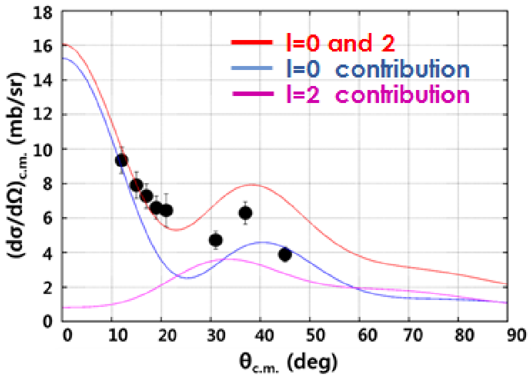




Q-value spectrum



Proton angular distributions



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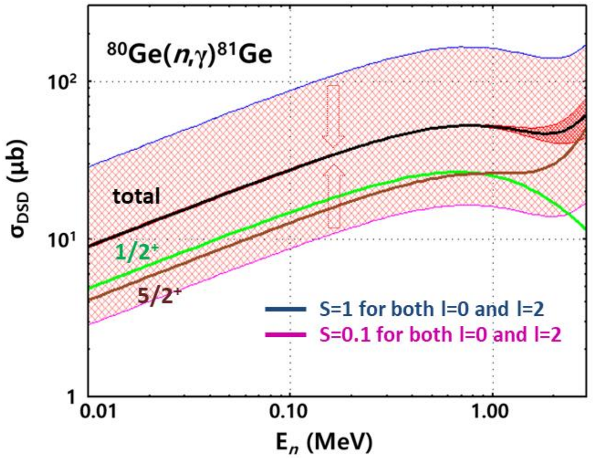
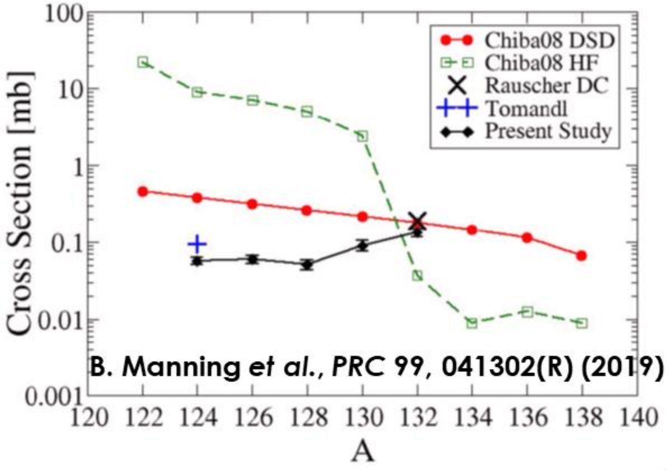


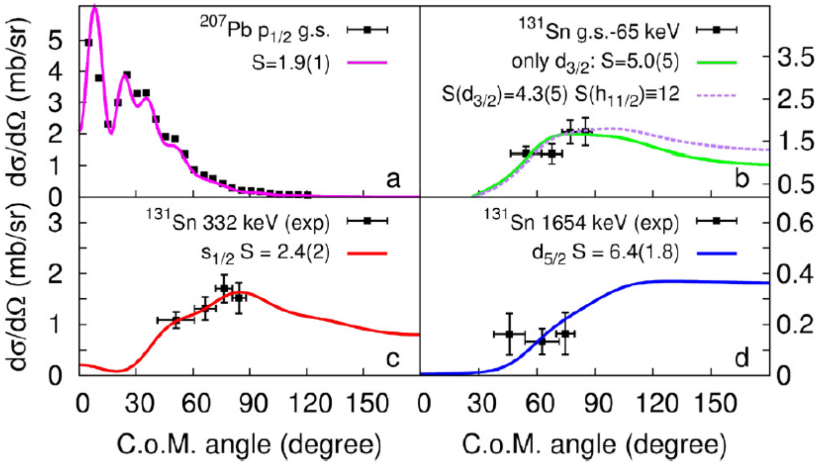
Calculated DSD cross sections for the ^{80}Ge(n,γ)^{81}Ge reaction

ORRUBA: Research Highlights

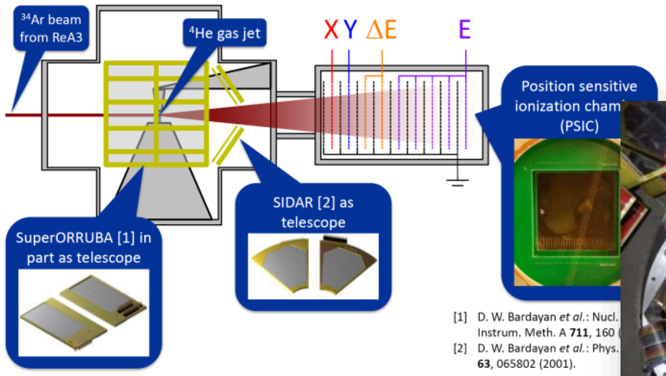


DSD neutron capture cross sections of Sn isotopes

R. Orlandi *et al.*, *PLB* 785, 615 (2018)

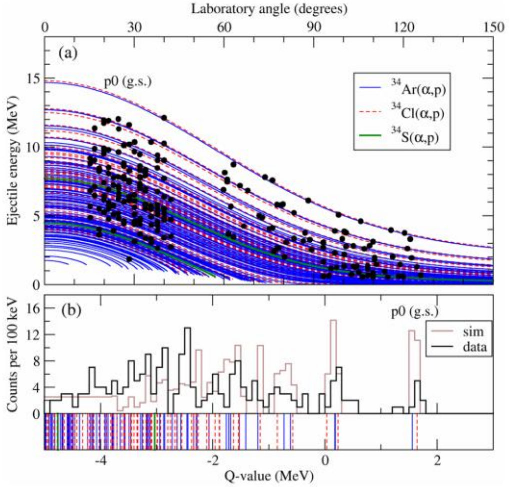


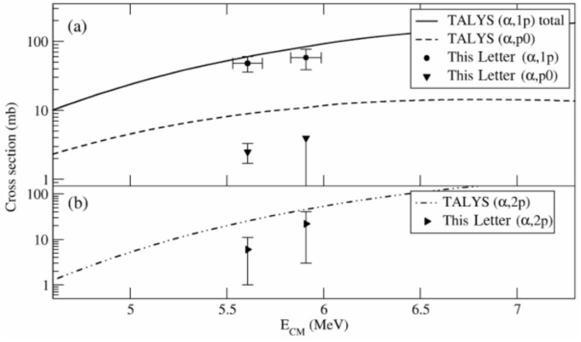
Proton angular distributions



K. Schmidt *et al.*, NPA8 2017

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



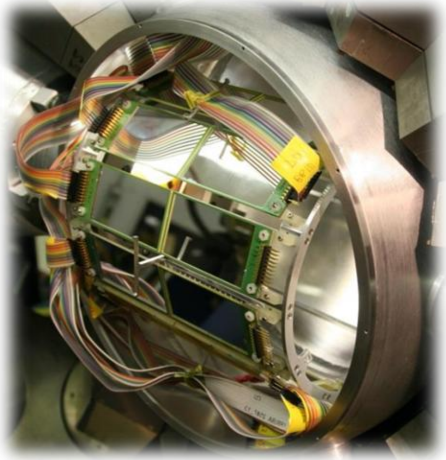


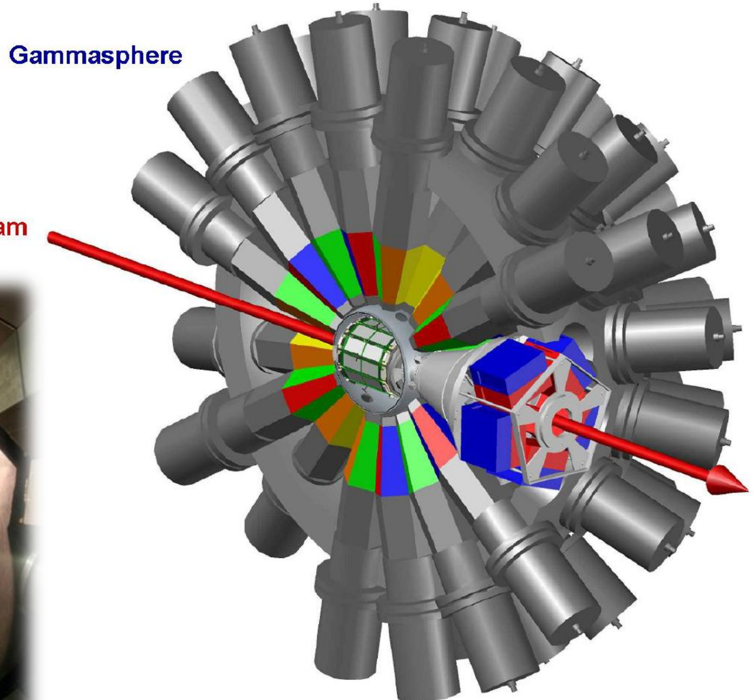
Cross section as a function of E_{cm}

GODDESS: particle–γ coupling (ORRUBA + γ-ray detector array)

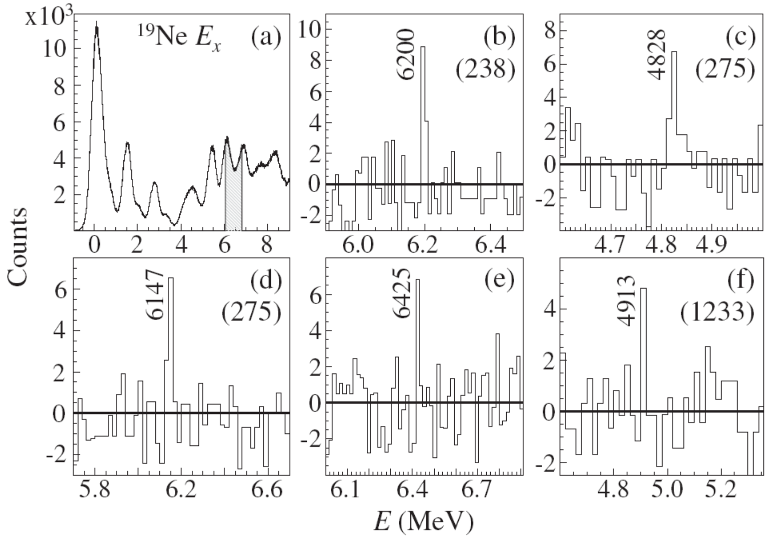
- Concept: **Si identifies reaction channel**, γ tags final state (Jπ/level scheme)
- Requirements: timestamp sync, coincidence logic, event building
- Benefit: background suppression via **particle gating**
- Typical outputs: E_x spectrum with **γ coincidence selection**
- Best for: complex level schemes / weak branches

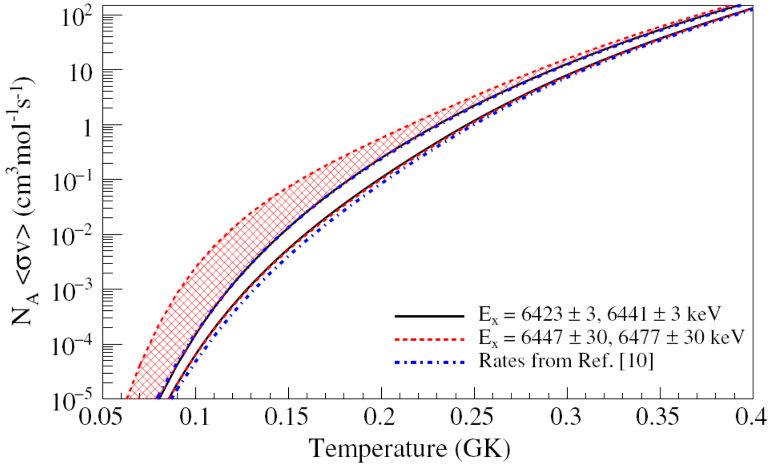
M.R. Hall *et al.*, *PRL* 122, 052701 (2019)


GODDESS Si Det. Barrel Array



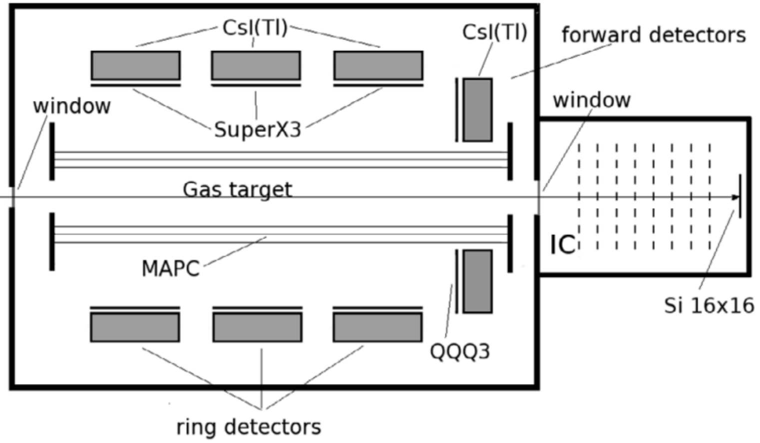
GODDESS design





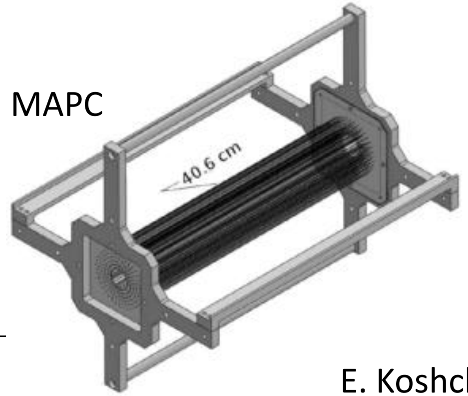
ANASEN: Detector Design & Highlights

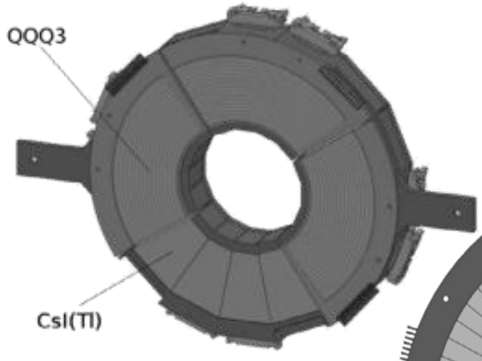
- Method : vertex → dE/dx → reconstructed CM energy → excitation function
- Systematic uncertainty: gas P/T stability, drift calibration, track fit quality
- Si systematics: threshold, dead layer, gain matching
- Rate issues: pileup/trigger, event size (tracking)
- It can provide resonance parameters and reaction rate constraints.

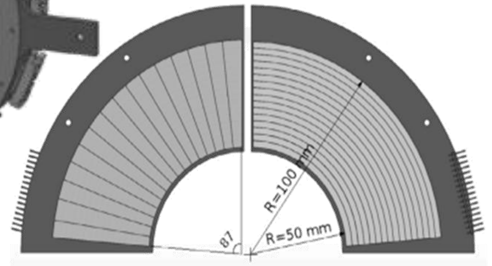


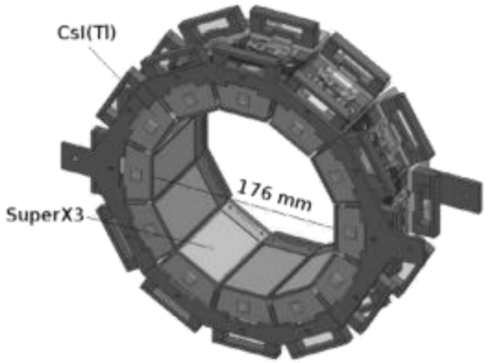
Schematic cross-section view of ANASEN

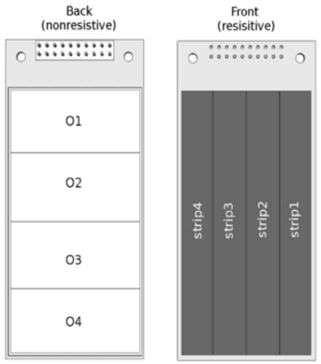
MAPC







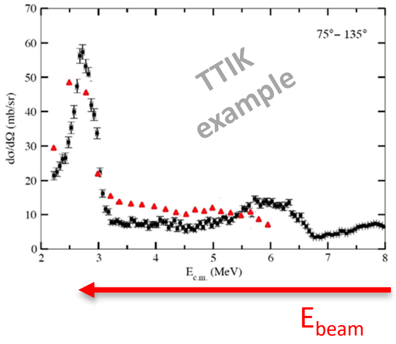




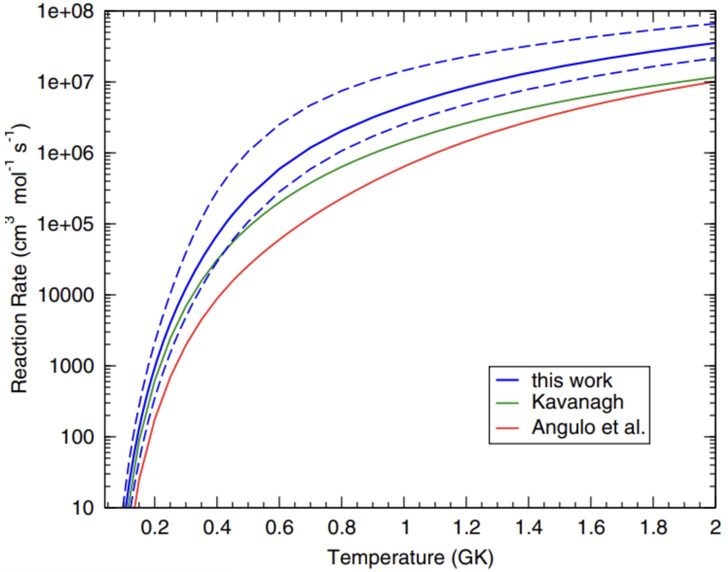
E. Koshchiy *et al.* NIMA 870 (2017) 1–11

SuperX3 (75x40.3 mm^2)
4x4 strips

N. Rijal *et al.* Phys. Rev. Lett. 123, 239902 (2019)

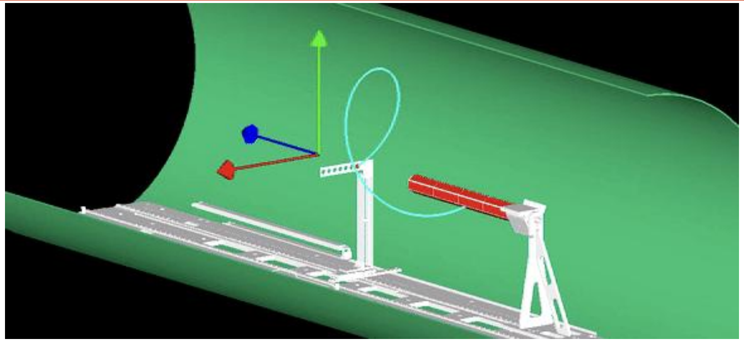


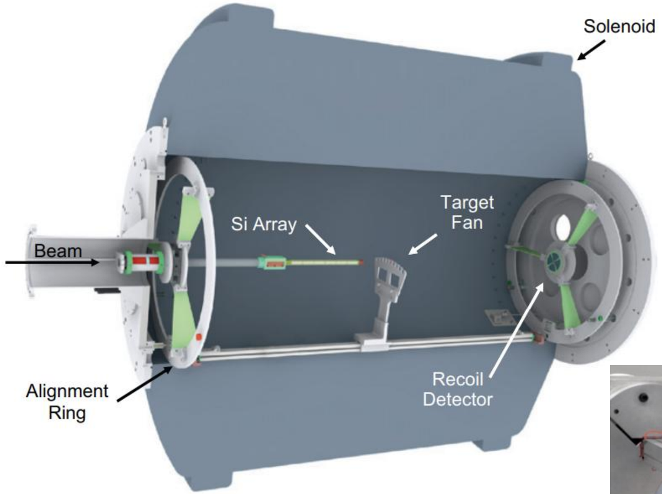
J^π	E_x	$E(d+{}^7\mathrm{Be})_{\mathrm{c.m.}}$	Γ_{p0}	Γ_{p1}	Γ_d	Γ_α
$(5/2^+)$	2.8		545	...	...	5
$(5/2^-)$	14.7		...	650	...	650
$(5/2^+)$	16.849 (5)	0.361 (5)	...	1	3.3	50
$(5/2^+)$	17.198 (9)	0.710 (9)	4	...	143	14
$(3/2^+)$	17.309 (21)	0.821 (21)	...	...	114	127
$(5/2^+)$	17.614 (28)	1.126 (28)	205	112	643	85
$(7/2^-)$	17.670 (11)	1.182 (11)	...	45	183	105
$(5/2^-)$	18.047 (32)	1.559 (32)	48	148	743	...
$(3/2^-)$	18.313 (83)	1.825 (83)	0.02	...	334	349
$(5/2^-)$	18.389 (17)	1.901 (17)	8	42	1600	1470
$(7/2^-)$	18.489 (7)	2.001 (7)	...	...	73	60
$(7/2^+)$	18.602 (88)	2.114 (88)	...	...	680	620

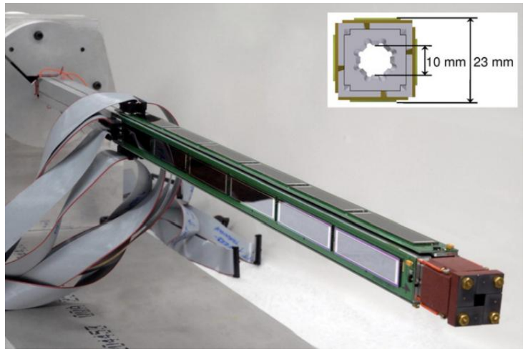


Solenoidal Spectrometer + on-axis DSSSD

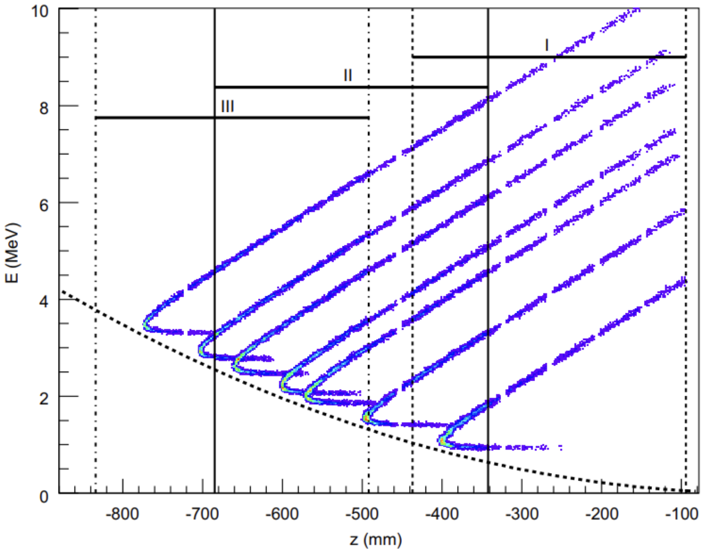
- Approach: solenoid kinematics focusing → improved kinematic reconstruction
- Detector: on-axis DSSSD array (modular), optimized for E_x/Q-value extraction
- Readout: ASICs, dense channels, stable sync
- Best for: transfer/inelastic at low energies (< 10 MeV/u)
- It can provide high-quality Q-value/E_x spectra and angular distribution



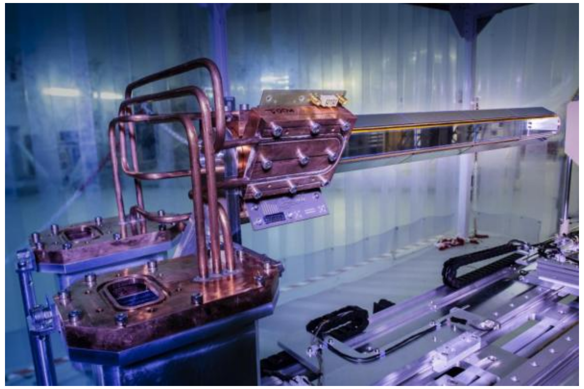




HELical Orbit Spectrometer (HELIOS)

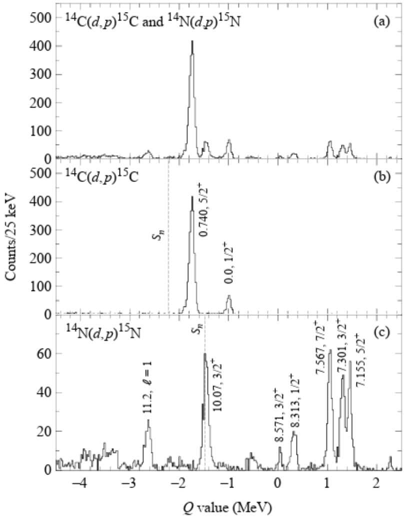


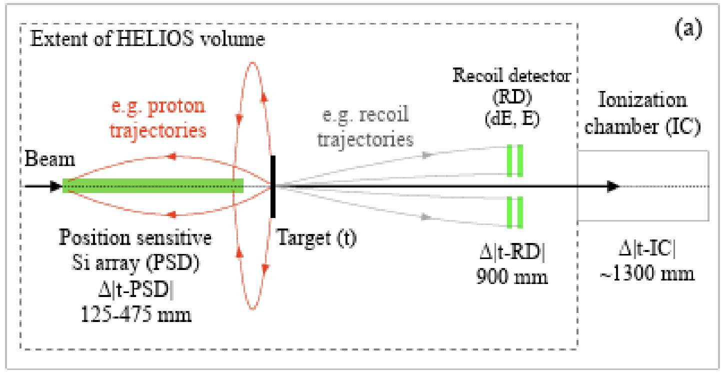
ISOLDE Solenoidal Spectrometer (ISS)



HELIOS & ISS: Q-value Measurements in Experimental Data

- Parameters: **Δθ (strip granularity)**, alignment, B-field uniformity
- Energy-loss correction: target thickness / stopping power tables
- Electronics: noise, gain stability, cross-talk
- Angle reconstruction affects a mapping to E_x/Q → uncertainty propagation.
- ΔQ < 100 keV in total

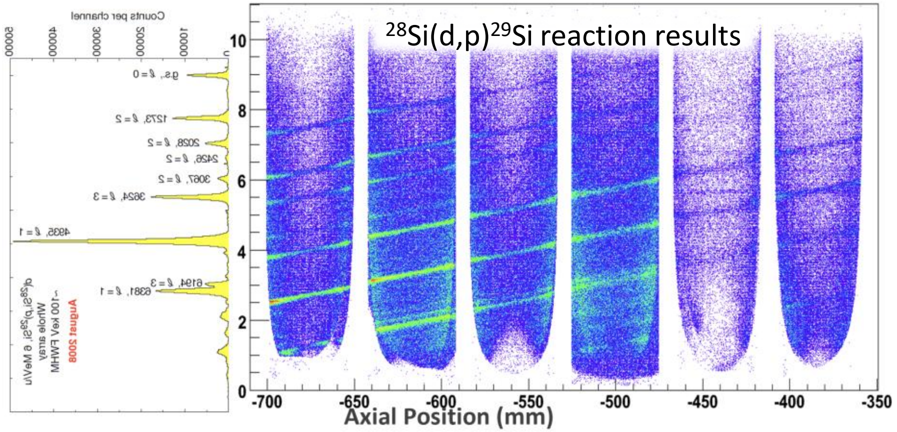




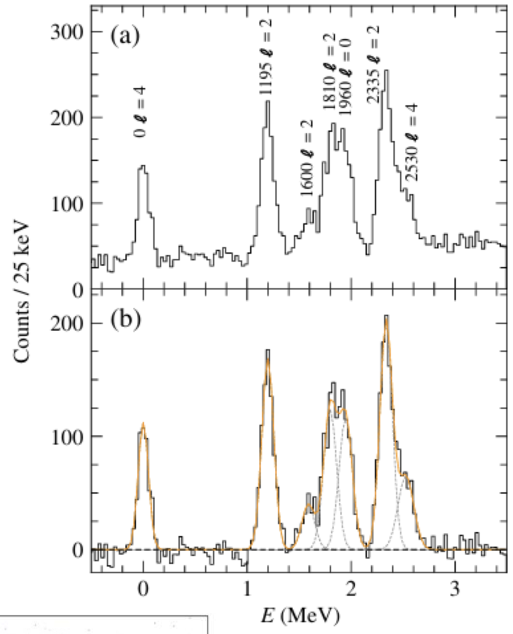
^AX	nlj	ΔS (MeV)	SF	SF_{SM}	R
^{15}C	$1s_{1/2}$	−19.86	0.51(12)	0.80	0.64(15)
	$0d_{5/2}$	−19.12	0.41(7)	0.78	0.53(9)
^{15}N	$1s_{1/2}$	+8.08	0.41(11)	0.80	0.51(14)
	$0d_{5/2}$	+8.29	0.61(12)	0.84	0.73(14)

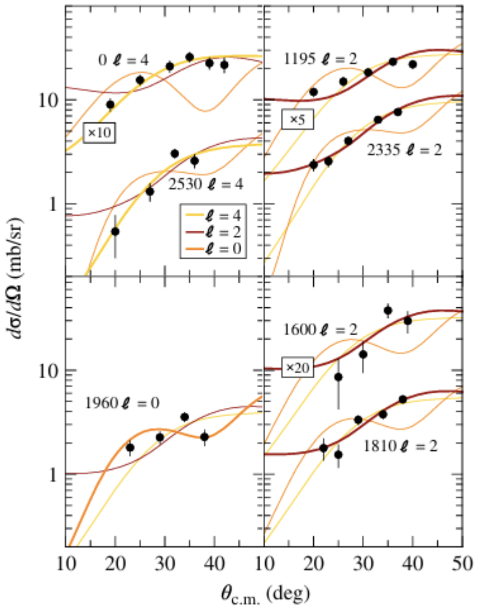
P. T. MacGregor *et al.* PRC 104 L051301 (2021)

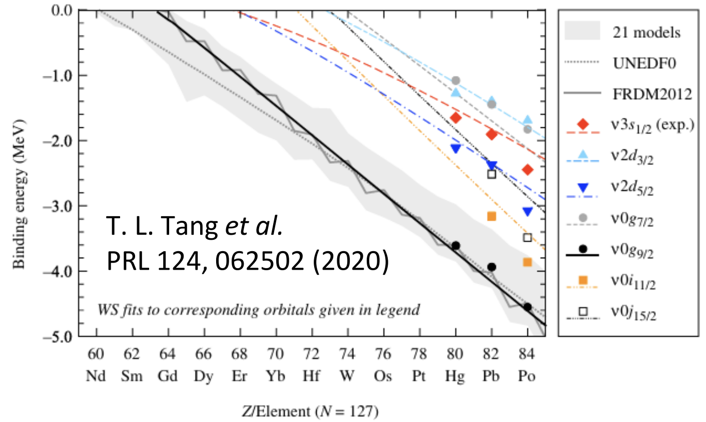
^{28}Si(d,p)^{29}Si reaction results



^{206}Hg(d,p)^{207}Hg reaction results

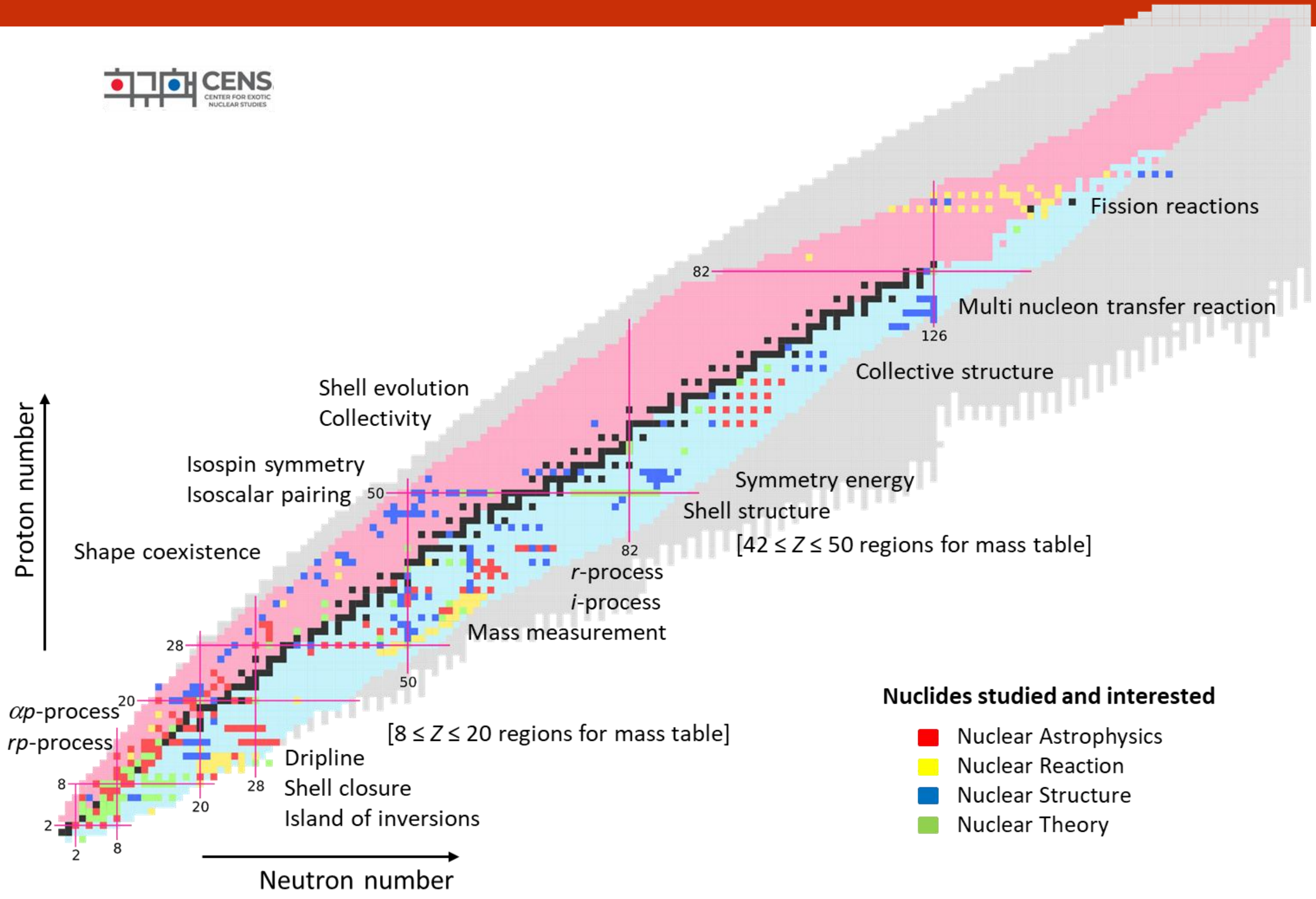




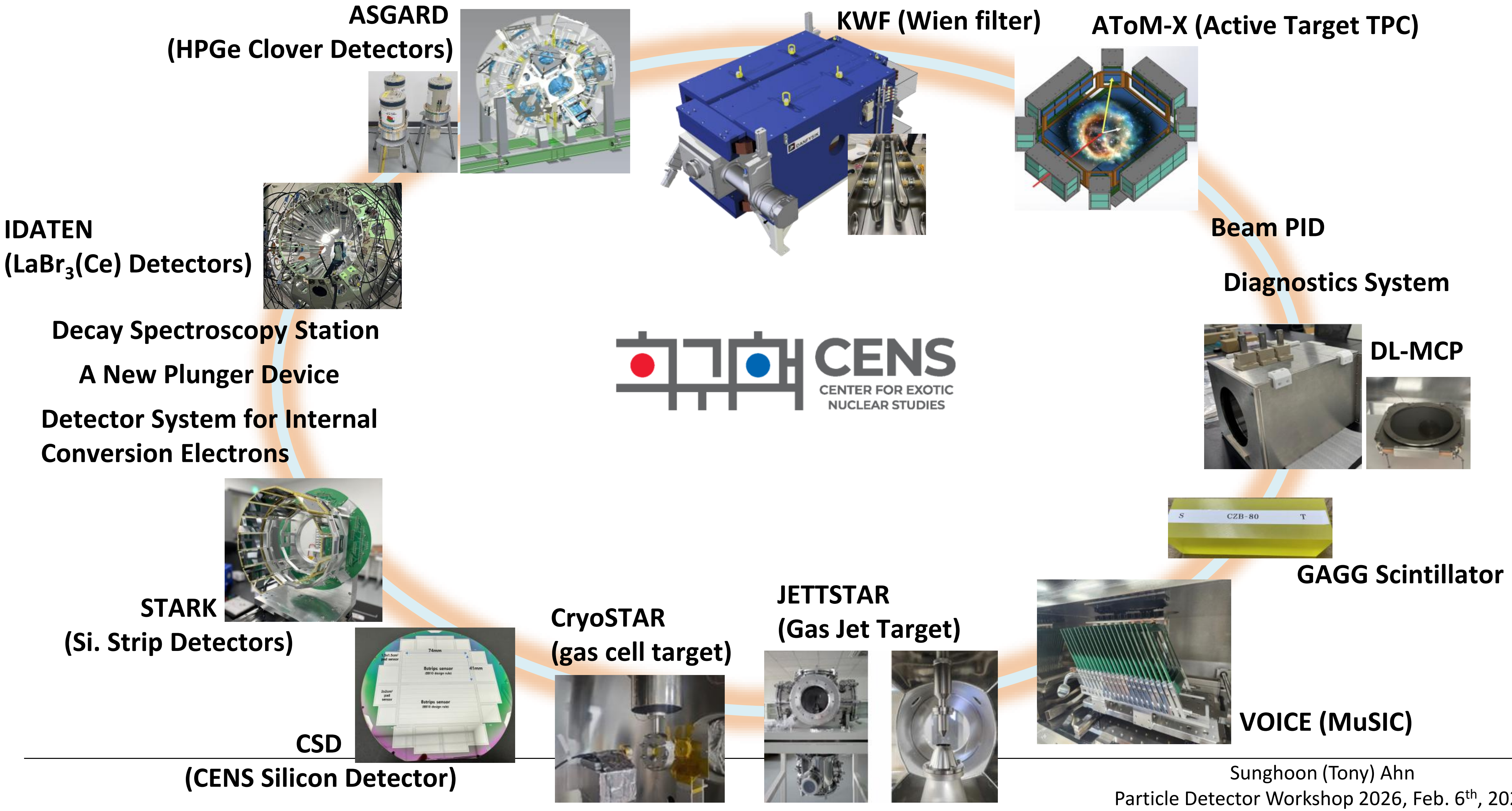


T. L. Tang *et al.*
PRL 124, 062502 (2020)

CENS Nuclear Chart

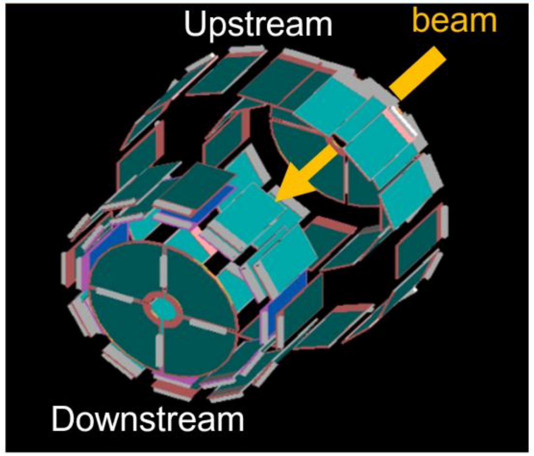


Detectors and Devices Developed at CENS

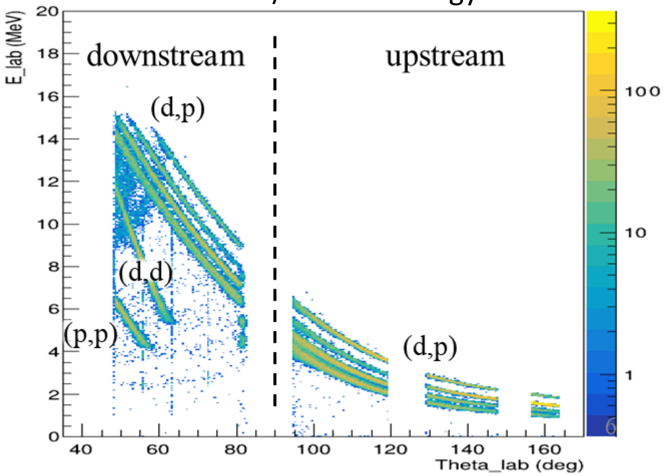


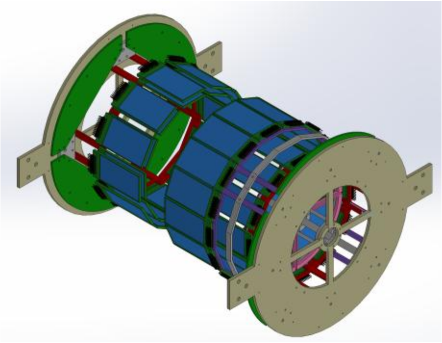
STARK Detector Development at CENS

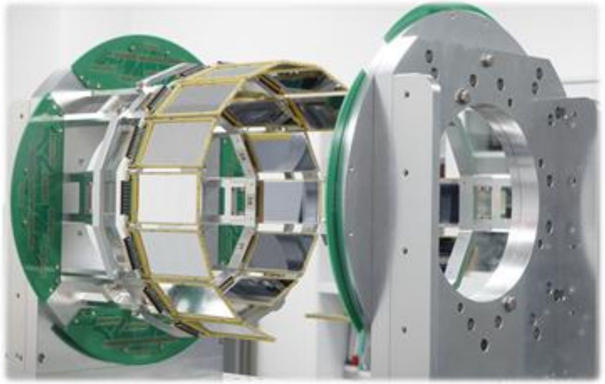
- STARK: Silicon Telescope Array for Reactions in inverse Kinematics
- One of the best tools to probe a broad range of nuclear properties (energy, angular momentum, cross section, spectroscopic factor).
- Powerful experimental method to study direct reaction experiments.
- Providing information into the nuclear structure of exotic nuclei.
- Array consisting of 40 double-sided resistive silicon strip detectors.
- Large Solid angle coverage: 43° - 78° and 105° – 150° in polar angle.



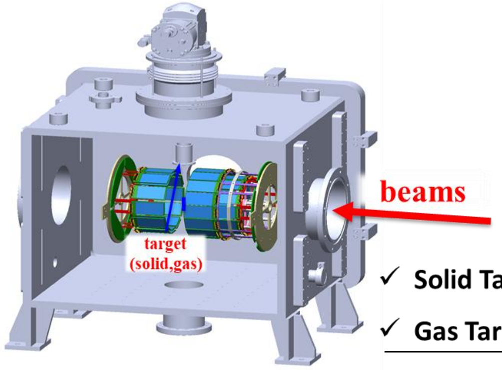
$^{22}Ne(d,p)$ reaction simulation with 5 MeV/u beam energy





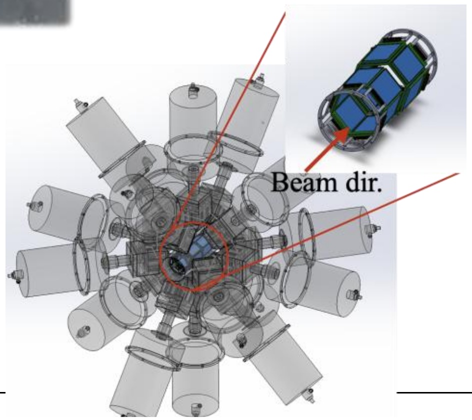


Conceptual Design of STARK

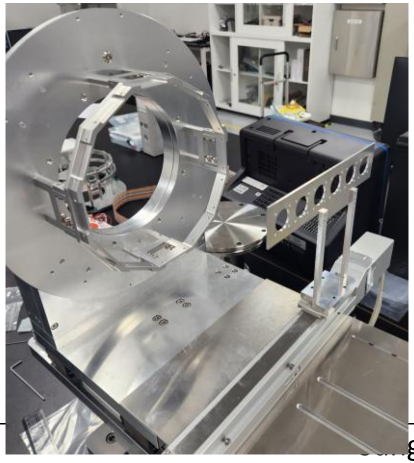


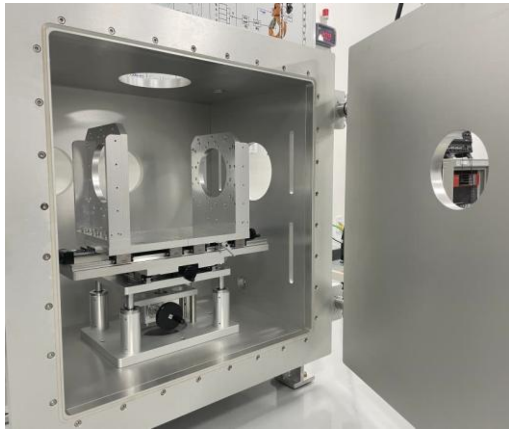
- ✓ Solid Targets: CH_2, CD_2
- ✓ Gas Targets: H_2, D_2, ^{4}He, ^{3}He, N_2

Conceptual Design of STARK chamber



Conceptual Design of STARK Jr.

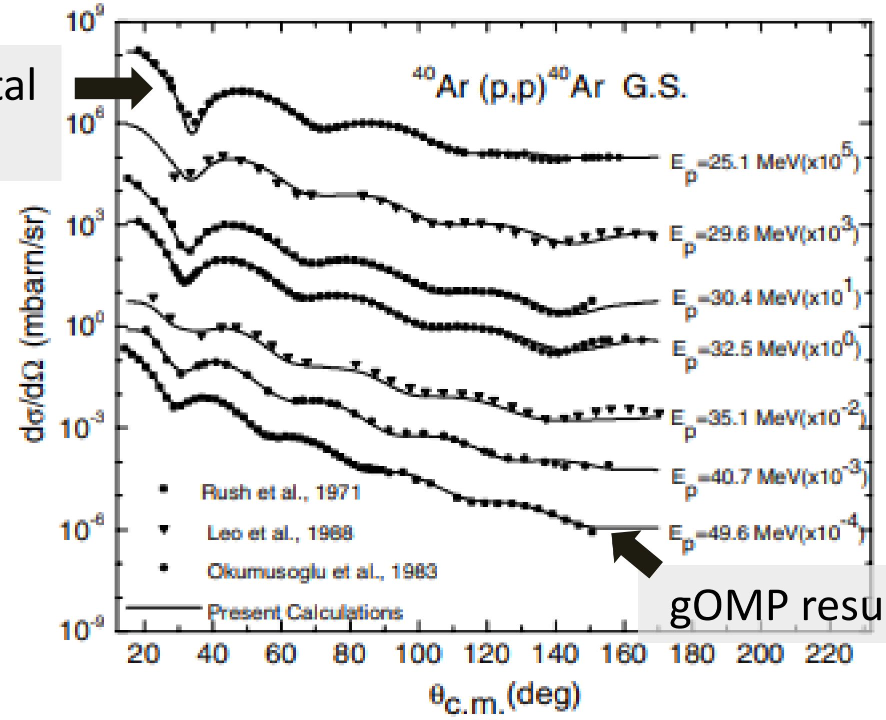




Optical Model Potential Study with ^{40}Ar + p elastic scattering

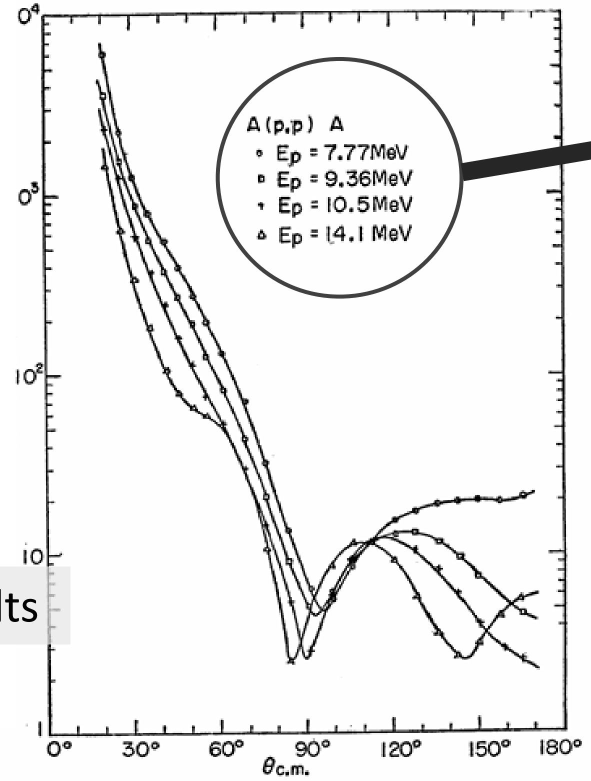
- Optical model potential (OMP) parameters are required to predict cross-section for each energy.
- Lack of optical model parameters at low energies, especially near the Coulomb barrier.

Experimental data



gOMP results

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



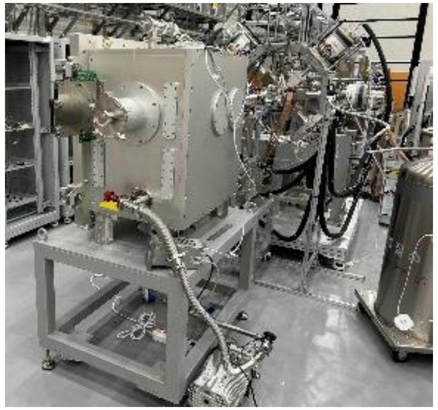
At lower energies,
No gOMP parameters were obtained.
(E_p < 7 MeV)
No data available near the Coulomb barrier.
(V_c = 4.1 MeV)

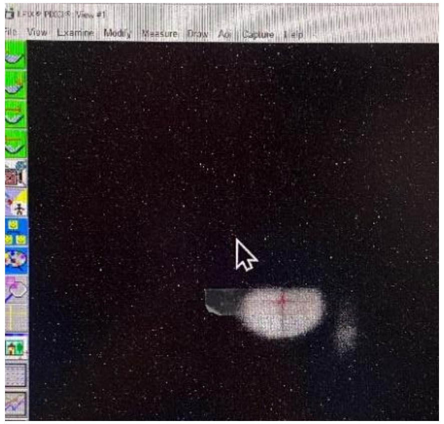
[Main Goal] Measure ^{40}Ar+p elastic scattering cross-sections at low energies including near the Coulomb barrier, and to use them to compare with global OMP predictions and extract parameters.

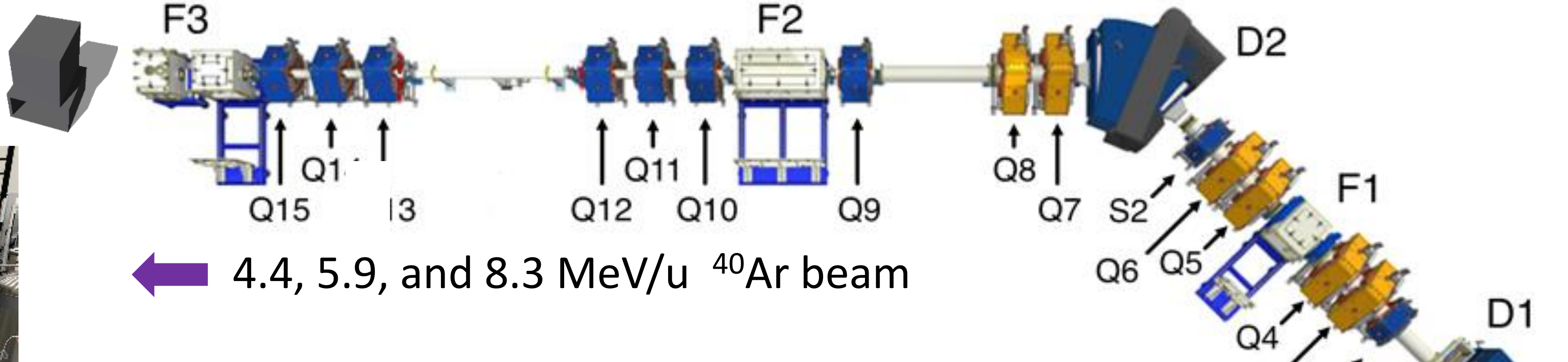
^{40}Ar + *p* elastic scattering at KoBRA, RAON

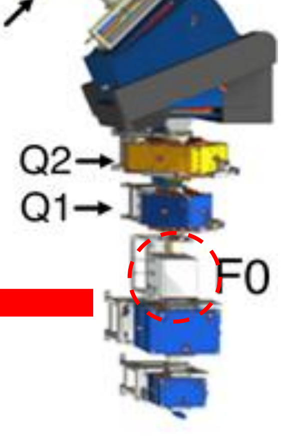
Courtesy of the KoBRA presentation

ELARK Chamber



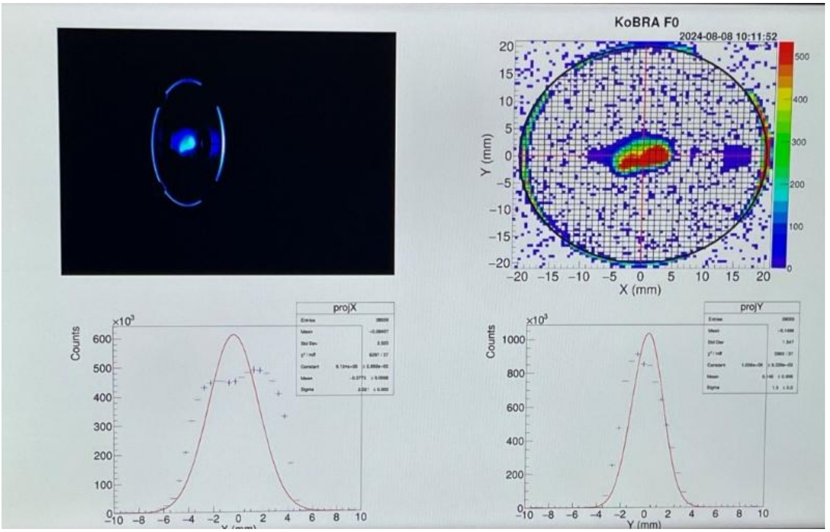




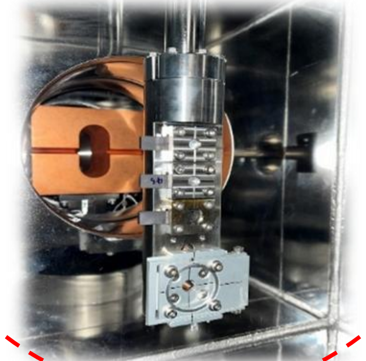


4.4, 5.9, and 8.3 MeV/u ^{40}Ar beam

^{40}Ar beam profile

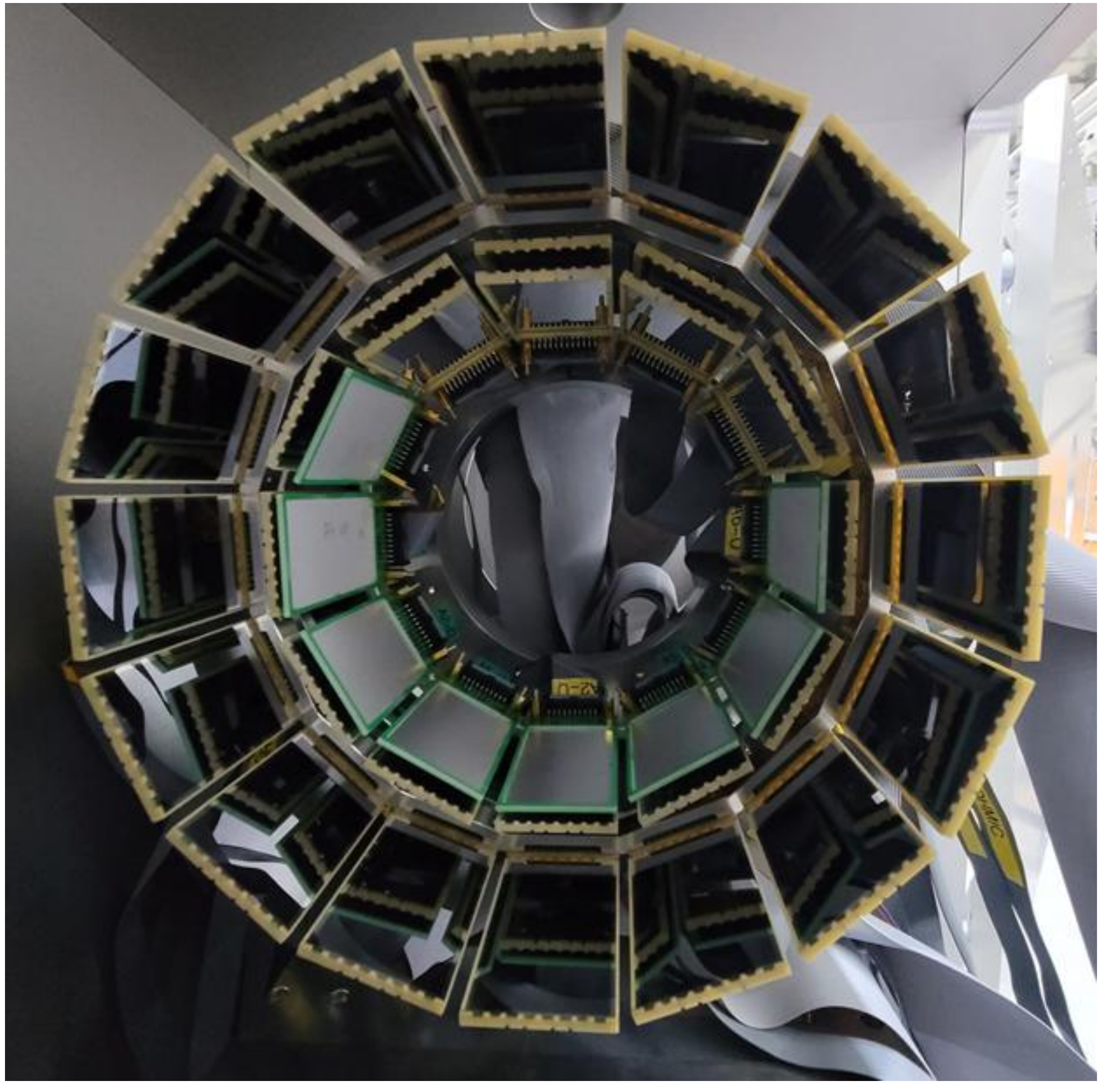


Al 30.2 & 46.3 um degraders at F0



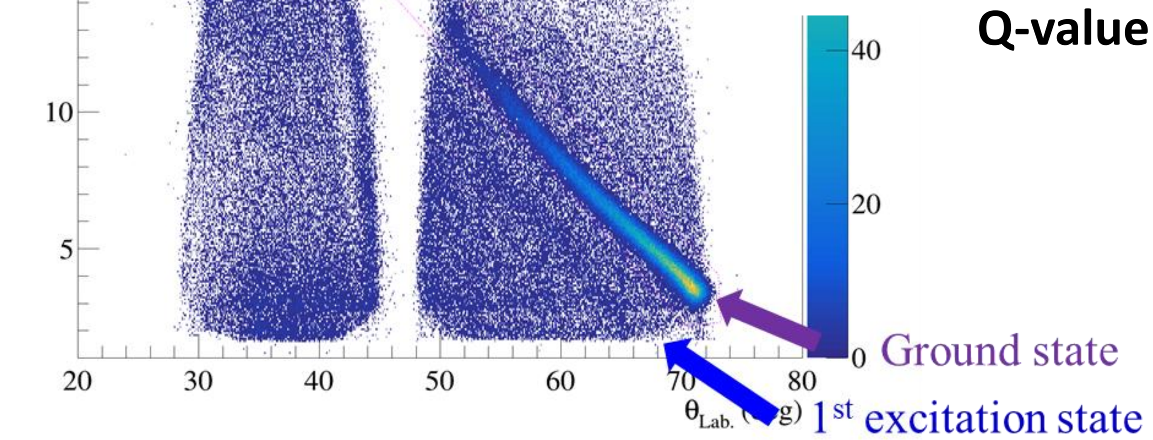
8.3 MeV/u ^{40}Ar beam

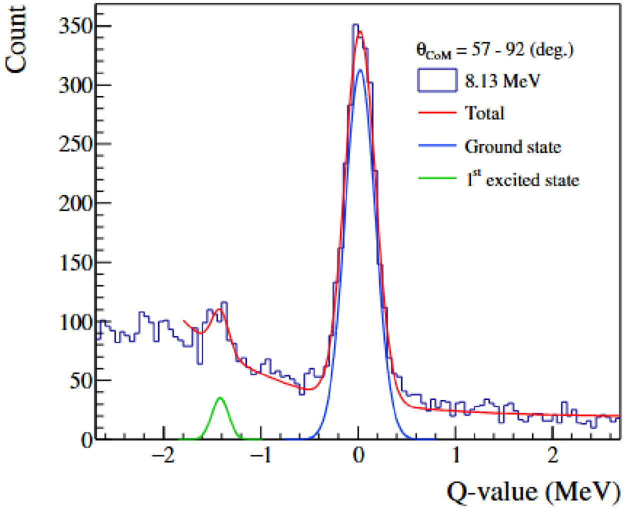
Experimental setup photos



Results of the ^{40}Ar+*p* scattering data analysis

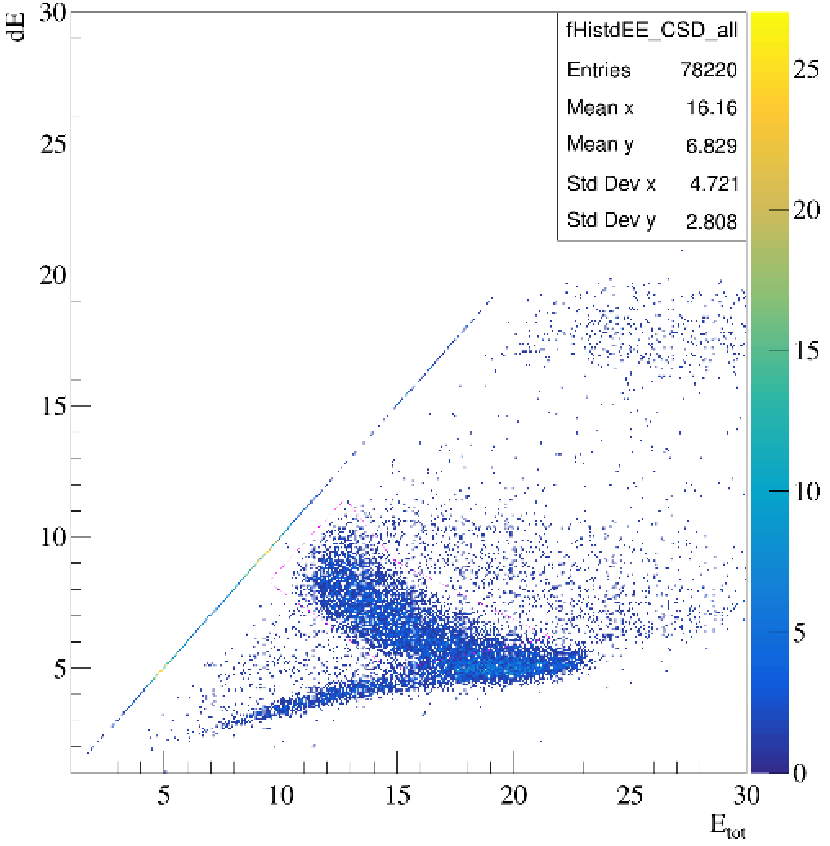
Kinematics plot





Q-value plot

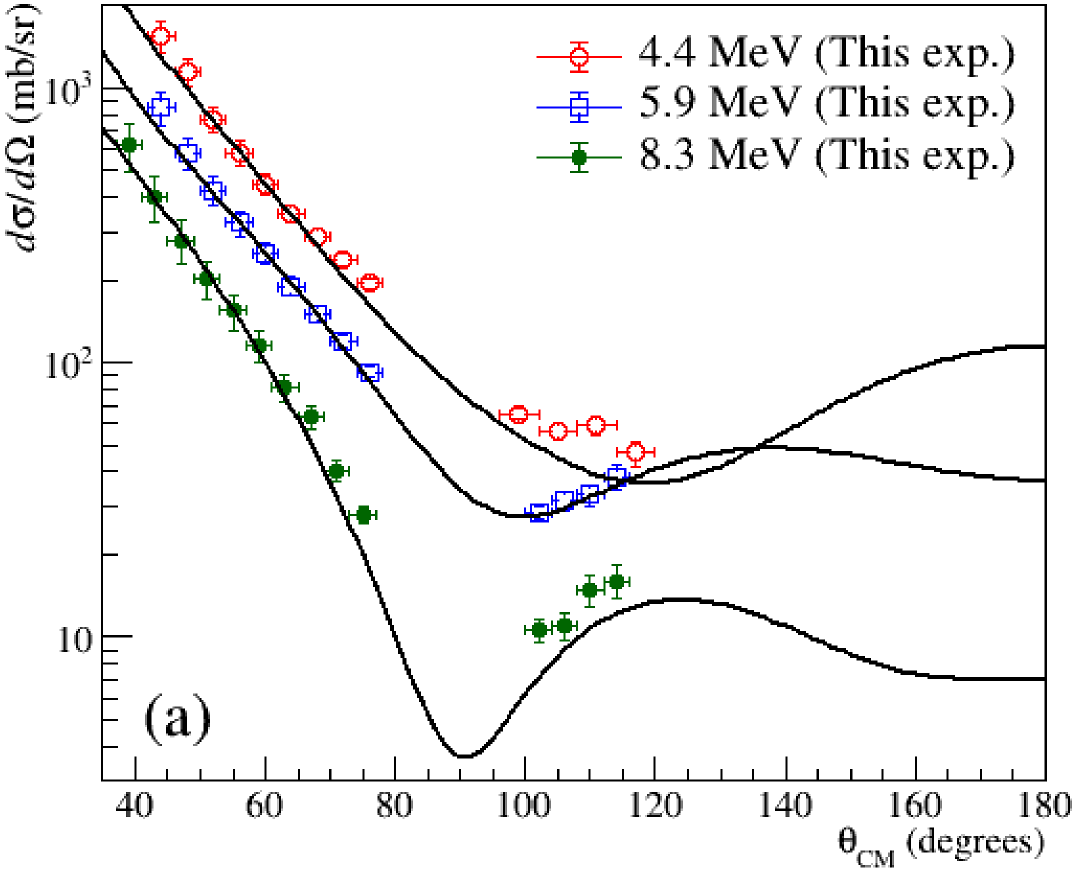
dE-E plot



E_{tot} = Total deposited energy in *dE-E* telescopes

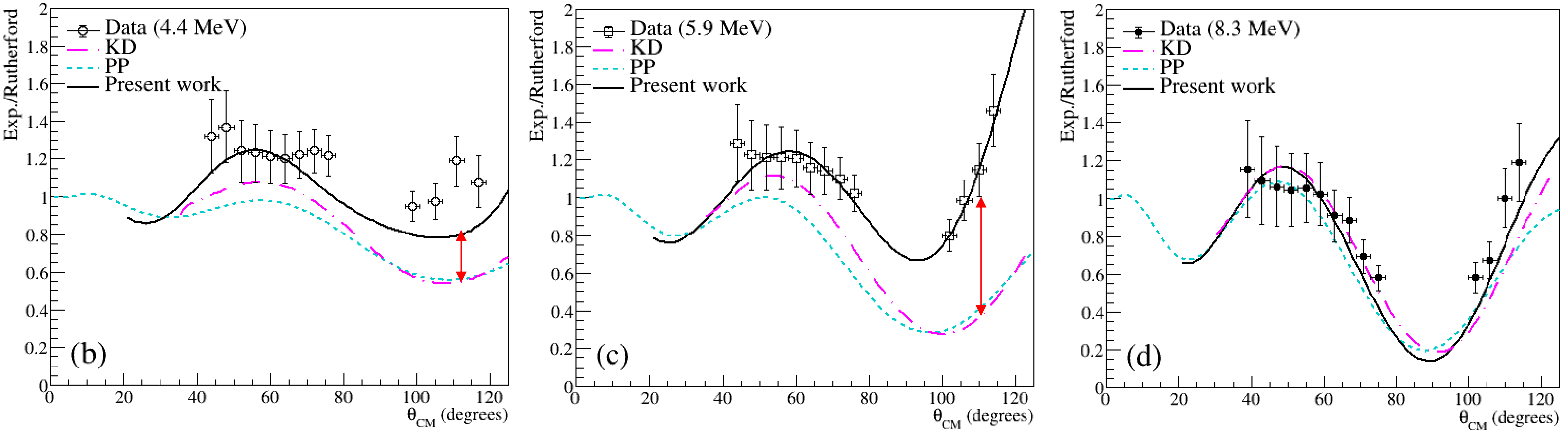
Analyzed by Dr. J. W. Lee (CENS)

Angular distribution



- Differential cross-sections were obtained at 4.4, 5.9, and 8.3 MeV/u.
- SFRESCO fitting results are plotted as a black solid line.

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.

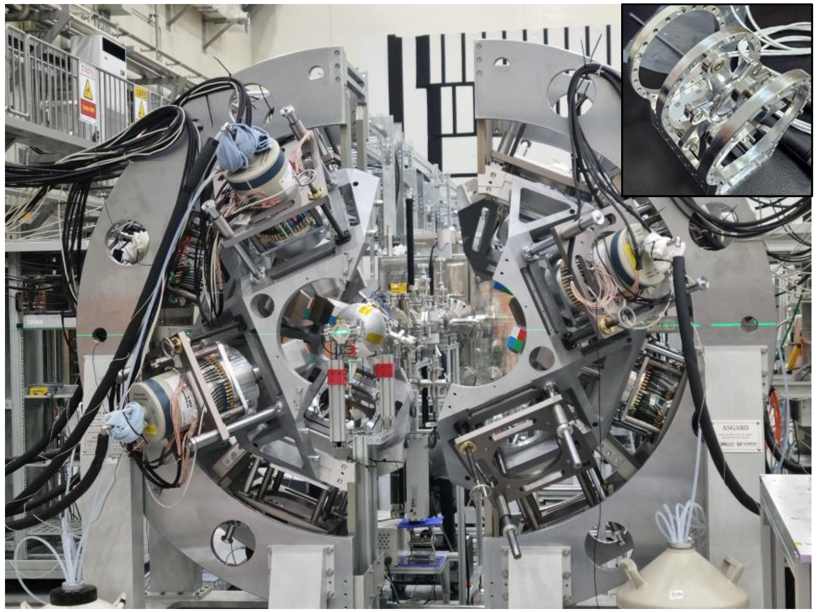
Energy (MeV)	V (MeV)	r_v (fm)	a_v (fm)	W_d (MeV)	r_d (fm)	a_d (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)
4.4	58.1	1.19	0.672	0.050	1.29	0.540	5.75	0.996	0.590
5.9	43.2	1.39	0.430	5.97	1.87	0.368	5.75	0.996	0.590
7.77 [13]	55.8	1.19	0.672	6.35	1.29	0.540	5.75	0.996	0.590
8.3	57.5	1.19	0.672	8.02	1.29	0.540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

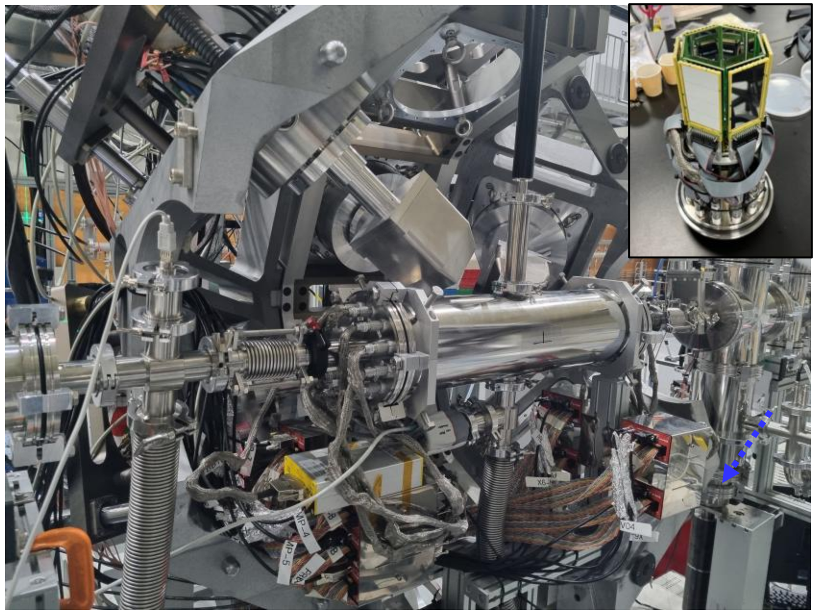
User experiments at KoBRA (2025)

- Four In-beam γ-ray spectroscopy experiments (Oct. 20th ~ Nov. 28th):
  - ✓ Explore Triaxiality and re-measure the lifetime of the excited states in A ~ 80 using fusion evaporation reaction
  - ✓ Probing isospin symmetry and the systematics of single nucleon removal with mirror reactions
  - ✓ High-spin spectroscopy of N~20 nuclei towards the island of inversion by RIB-induced fusion-evaporation reactions
  - ✓ Coulomb excitation of ^{181}Ta and ^{197}Au with ^{40}Ar

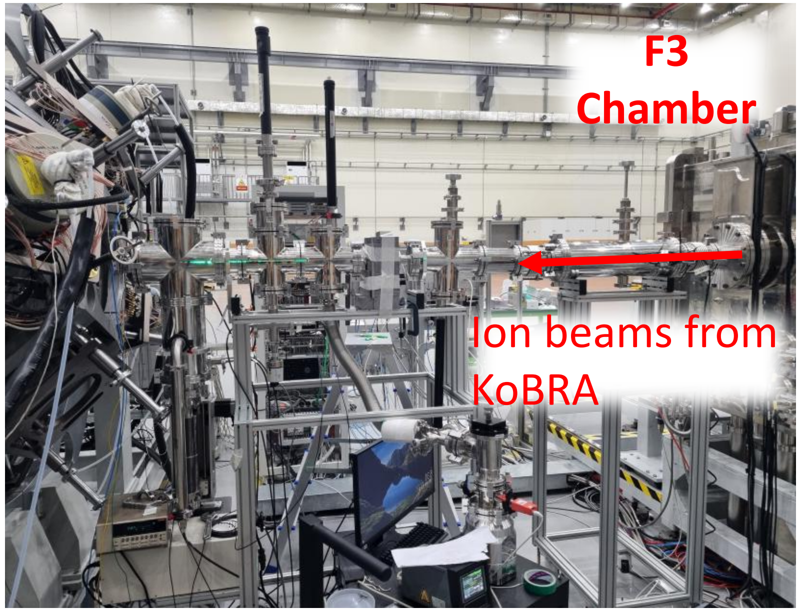
ASGARD + plunger



ASGARD + Stark Jr.



Beamline from F3 chamber to detector



Summary & Outlook

Summary

- In low-energy RI experiments, physics studies is constrained by solid angle, segmentation (Δθ), PID thresholds, and calibration stability (not only beam intensity).
- Silicon Detector Arrays used in RI Nuclear Physics: large-acceptance Si arrays (ORRUBA), particle–γ coupling (GODDESS), active-target hybrids (ANASEN) and solenoidal kinematic focusing (HELIOS/ISS).
- We need to consider ΔE–E thickness pairing, dead-layer/threshold control, alignment & energy-loss corrections, and timestamp synchronization / event building dominate systematic uncertainties.
- In Korea, CENS developed STARK and STARK Jr. to enable key experimental studies using RI beams.
  ➔ ^{40}Ar + p elastic scattering using ELARK detector system was conducted to study global optical model potential (pGOMP).

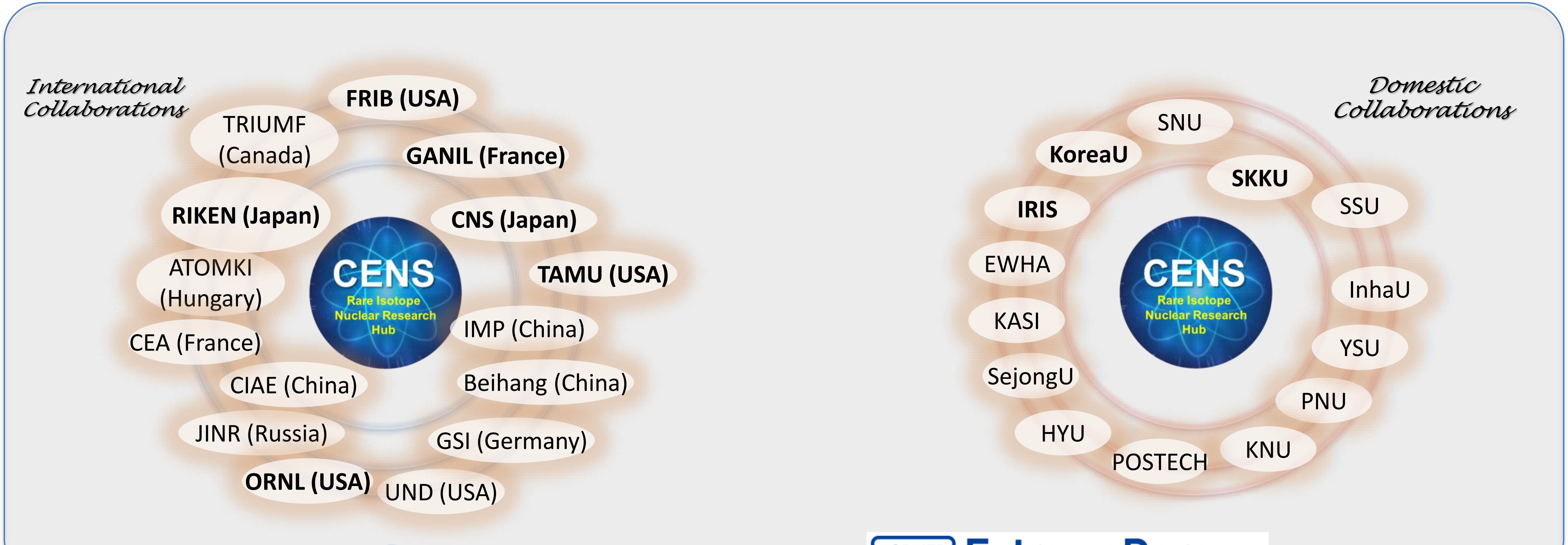
Outlook

- Detector/DAQ improvements:
  - ✓ **In-house silicon detector development is critical.**
  - ✓ more robust common-clock timing/event building and standardized calibrations are necessary.
- **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
  - ✓ 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

We welcome your collaborations!!

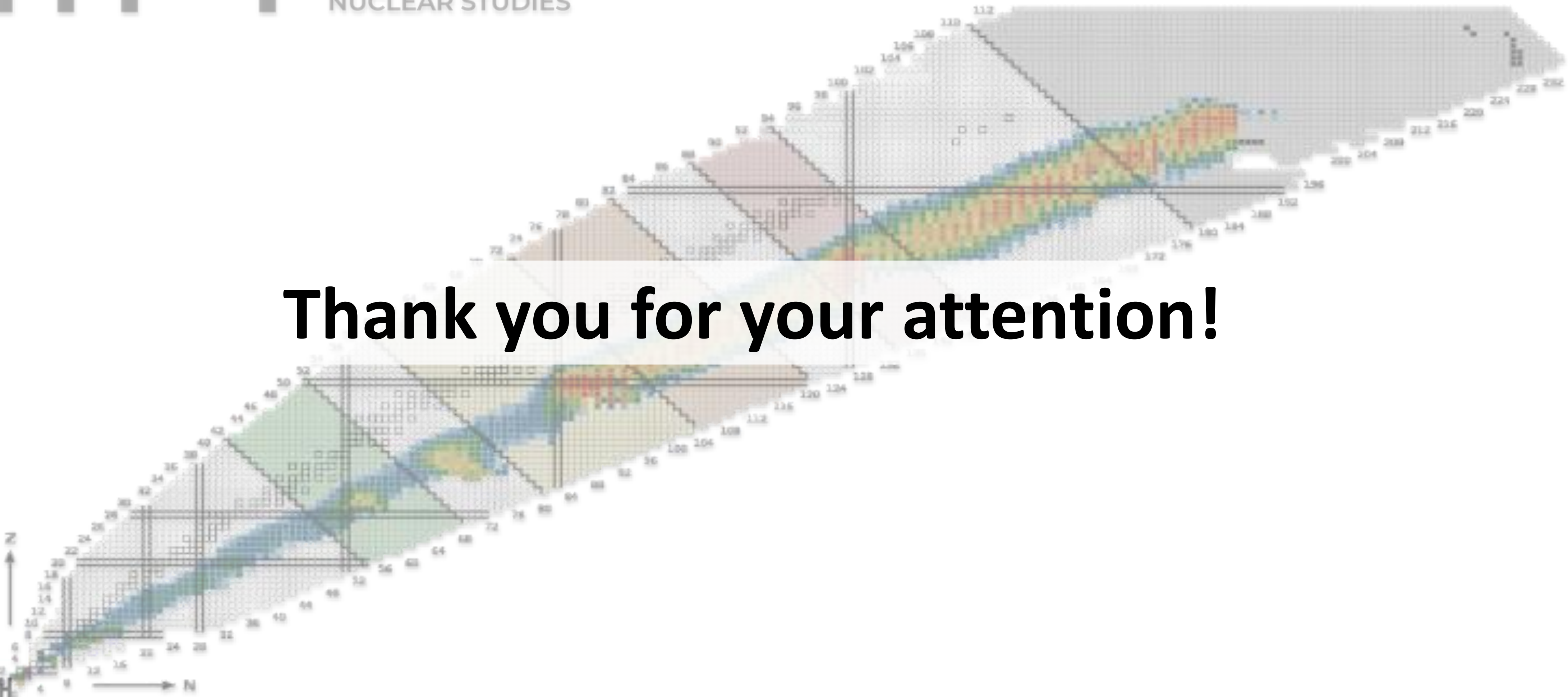
Acknowledgements

All the CENS members &



IRIS Institute for Rare Isotope Science

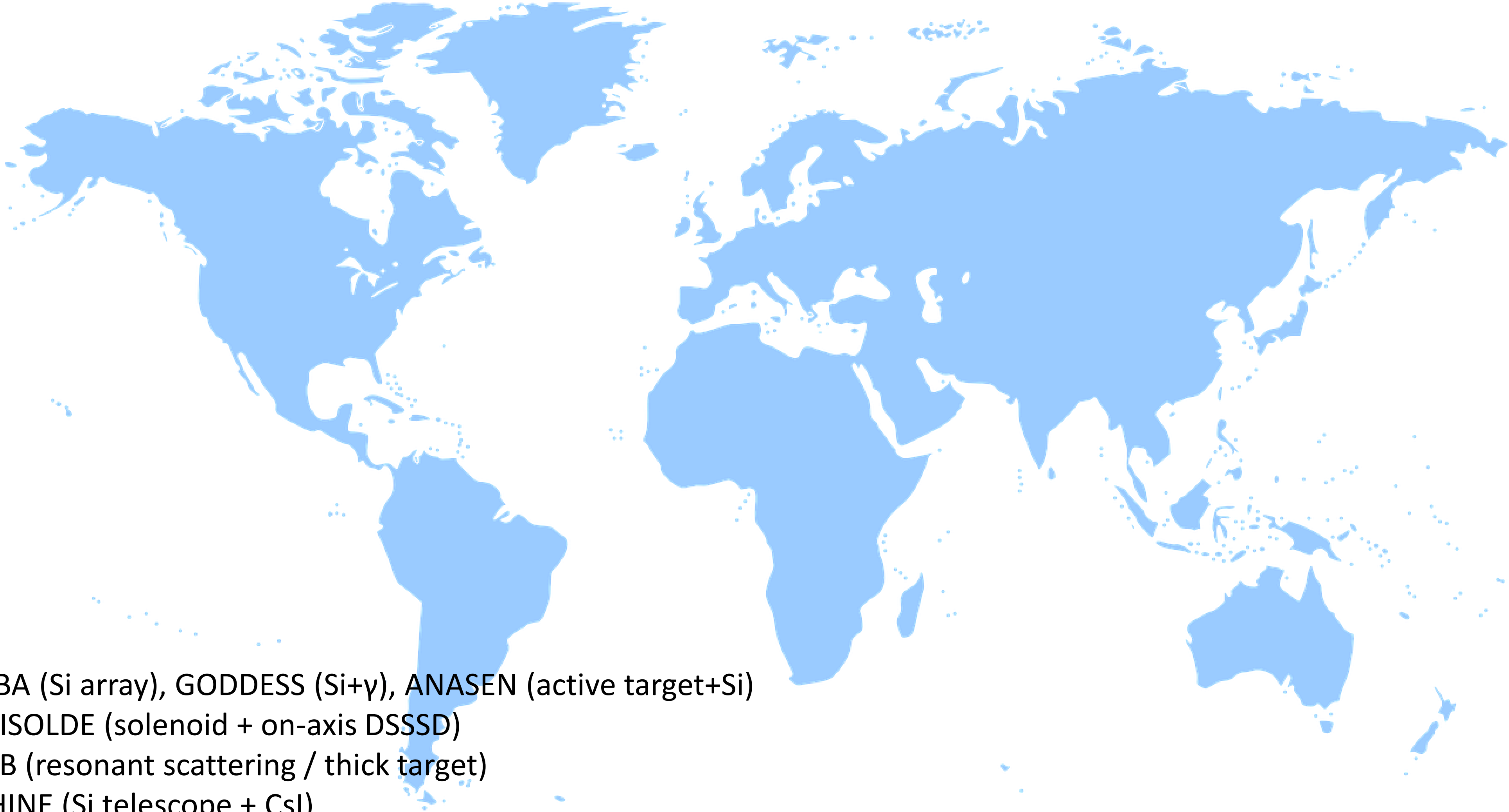
TOPTIER RAON IBF ExtremeRare IsotopeScience



Thank you for your attention!

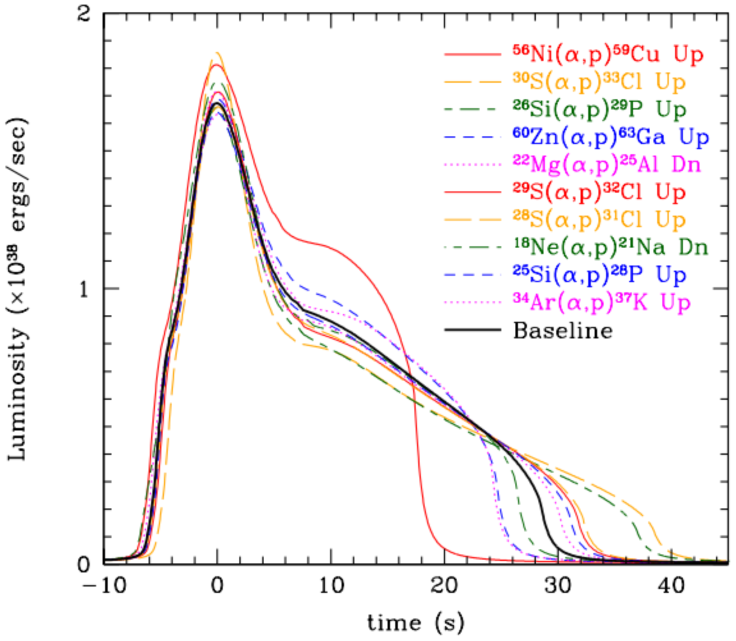
Backup Slides

Global Silicon Detector Landscape



US: ORRUBA (Si array), GODDESS (Si+γ), ANASEN (active target+Si)
EU: ISS @ ISOLDE (solenoid + on-axis DSSSD)
Japan: CRIB (resonant scattering / thick target)
China: CSHINE (Si telescope + CsI)
Korea: STARK (main array) + STARK Jr. (ΔE–E telescope + digitizer DAQ)

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

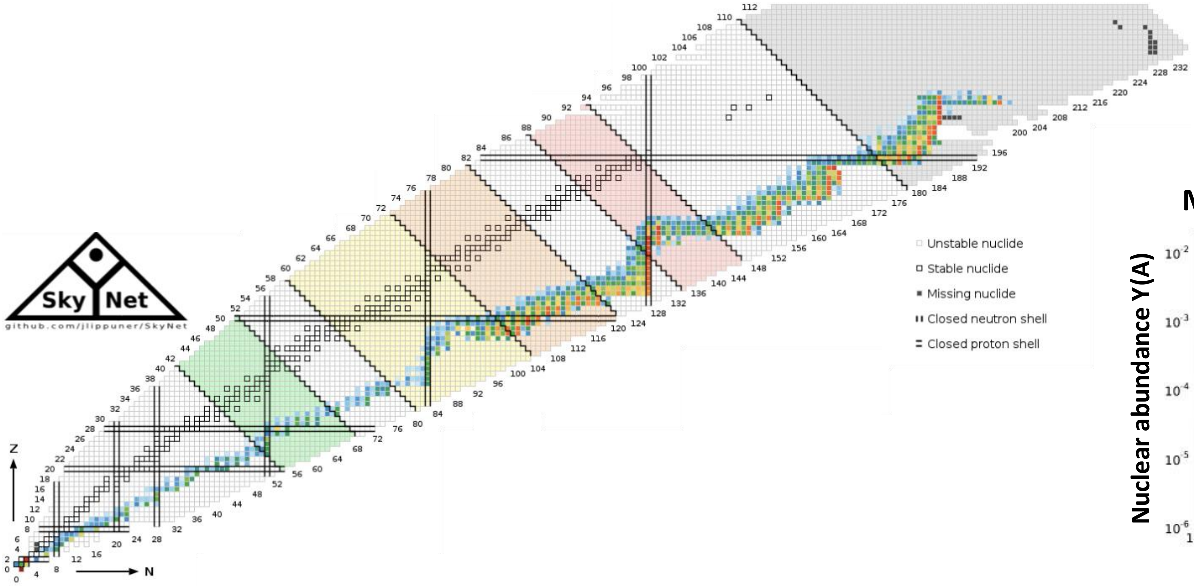
Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	^{15}O(α, γ)^{19}Ne	D	16	1
2	^{56}Ni(α, p)^{59}Cu	U	6.4	1
3	^{59}Cu(p, γ)^{60}Zn	D	5.1	1
4	^{61}Ga(p, γ)^{62}Ge	D	3.7	1
5	^{22}Mg(α, p)^{25}Al	D	2.3	1
6	^{14}O(α, p)^{17}F	D	5.8	1
7	^{23}Al(p, γ)^{24}Si	D	4.6	1
8	^{18}Ne(α, p)^{21}Na	U	1.8	1
9	^{63}Ga(p, 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)

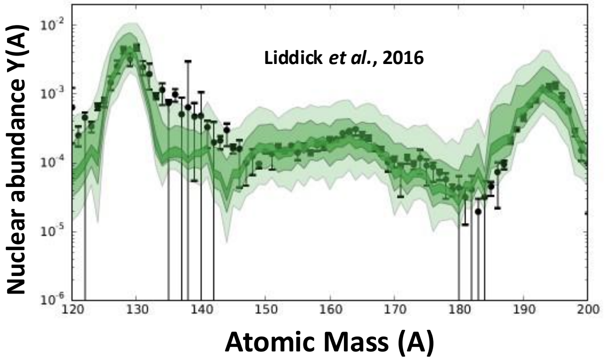
- **Key Research Question:**
  1. direct measurements of key (*α,p*) reaction cross sections which important for *αp*-process *and p*-process.

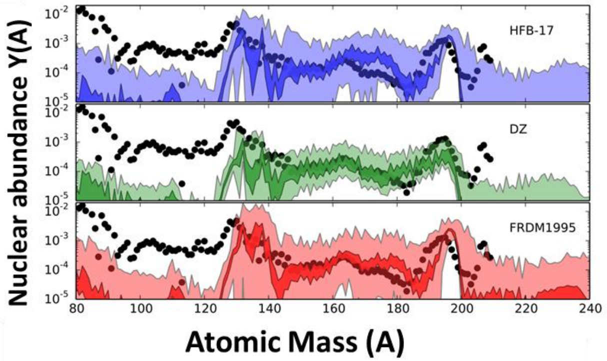
- **Methods:**
  1. Thick Target in Inverse Kinematics (TTIK) using TexAT_v2, AToM-X or VOICE
  2. (*α,p*) Reaction in Inverse Kinematics using JENSA, CryoSTAR or JETTSTAR with STARK

CENS *n**-explorer Project



Monte-Carlo variations of (*n*,*γ*) rates





Monte-Carlo variations of nuclear mass
Mumpower *et al.*, 2015

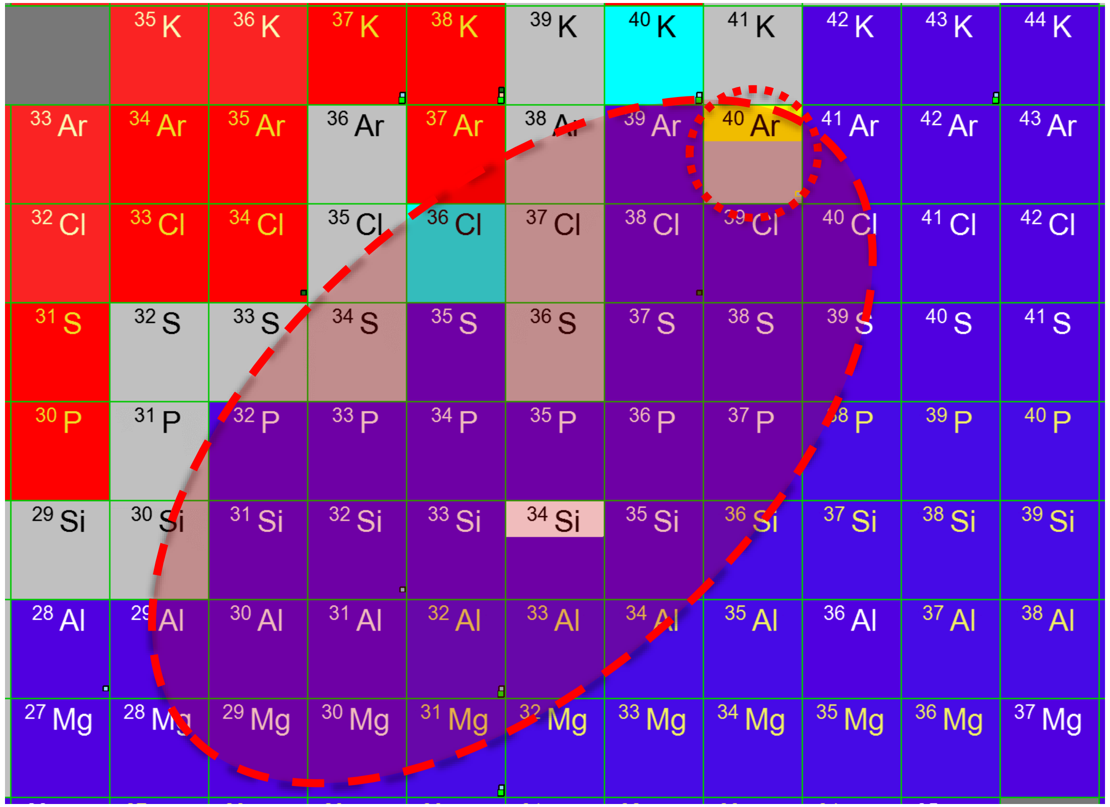
- **Key Research Questions:**
  1. Indirect measurements of **neutron reaction** cross sections which are important for *i*-process and *r*-process.
  2. **Mass measurement** which are important for r-process.
  3. Direct measurements of **(α,n) reaction cross sections** which are important for weak r-process.

- **Methods:**
  1. (d,p) reaction in inverse kinematics using gas/solid target with STARK.
  2. Lifetime measurements of excited states using IDATEN.
  3. New mass measurements using Bρ Time-of-Flight or MR-ToF method.
  4. (α,n) Thick Target in Inverse Kinematics (TTIK) using MUSIC, VOICE, neutron detector, SECAR or AToM-X.

List of Key Unknowns from Sensitivity Studies

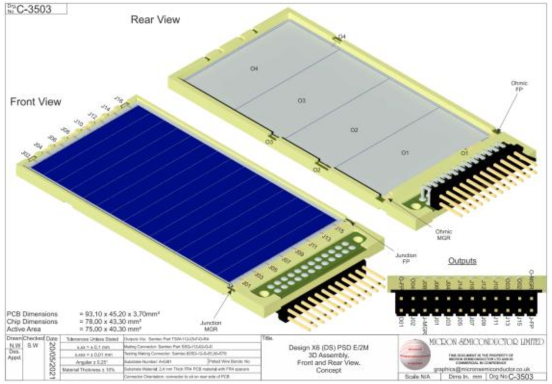
- Sensitivity Study #1. AIP Advances 4, 041008 (2014) by R. Surman *et al.* and no studies for light particles (Z=30~40) yet.
  - ✓ (*d,p*) or (*d,pγ*) reactions for (*n,γ*) reactions with stable beams near the interest region.
  - ✓ **(*d,d*) reactions: *d*-OMP from excitation func.**
  - ✓ **(*p,p*) reactions: *p*-OMP from excitation func.**

- Sensitivity Study #2. "*i*-process reaction flow", PhD. Thesis (2015) by Hampel *et al.*
  - ✓ (*d,p*) or (*d,pγ*) reactions for (*n,γ*) reactions: **^{31}Si, ^{32}Si , ^{34}S**, ^{45}Ca and ^{47}Ca
  - ✓ **(*d,d*) reactions: *d*-OMP from excitation func.**
  - ✓ **(*p,p*) reactions: *p*-OMP from excitation func.**

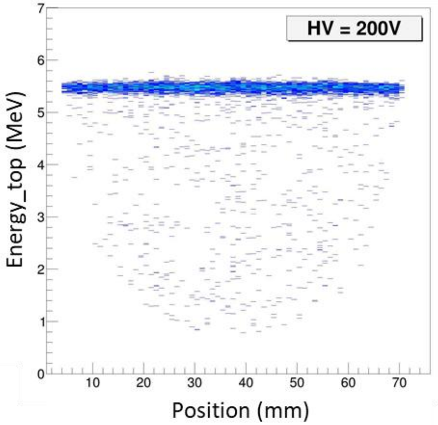


ΔE–E telescope and DAQ systems in STARK

- **ΔE–E telescope**: PID + threshold optimization, quick diagnostics
- **Digitizer DAQ (Jr.-dedicated):** waveform access, flexible trigger, rapid bring-up
- Primary roles: beam tuning, alignment, calibration rehearsal, risk reduction
- Deliverables: stable calibration constants, verified noise/threshold, validated timing
- Interface: scale results/conditions to STARK main runs



X6 PSD (75x40.3 mm^2)
8x4 strips



E.C. Pollacco *et al.* NIMA 887, 2018, 81-93