Nuclear reaction measurements using solenoid

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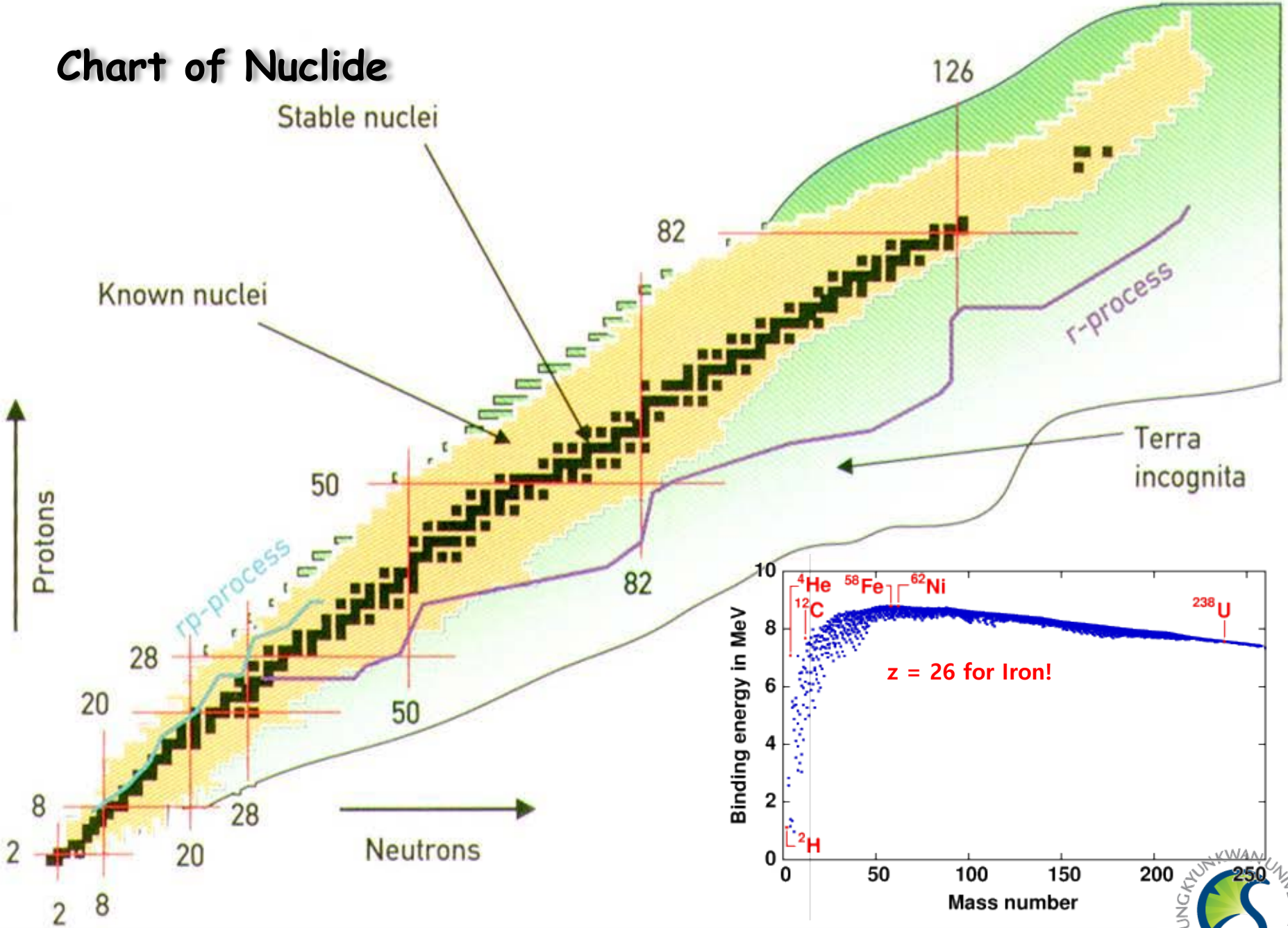
http://nucastro.skku.edu

Chart of Nuclide

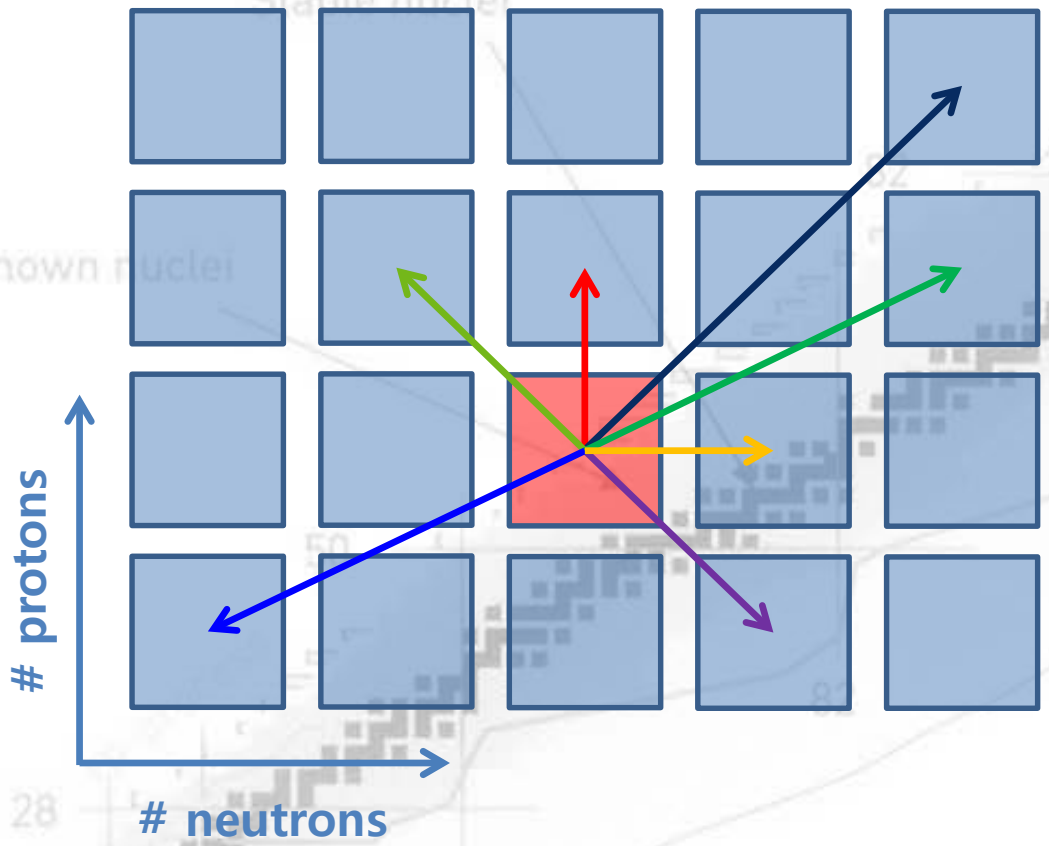


The question driving the nuclear astrophysics

11 greatest unanswered questions of Physics
(National Academy of Science Report, 2002)

1. What is dark matter?
2. What is dark energy?
3. **How were the heavy elements from iron to uranium made?**
4. Do neutrinos have mass?
5. Where do ultrahigh-energy particles come from?
6. Is a new theory of light and matter needed to explain what happens at very high energies and temperatures?
7. Are there new states of matter at ultrahigh temperatures and densities?
8. Are protons unstable?
9. What is gravity?
10. Are there additional dimensions?
11. How did the universe begin?

Stellar Nuclear Reactions

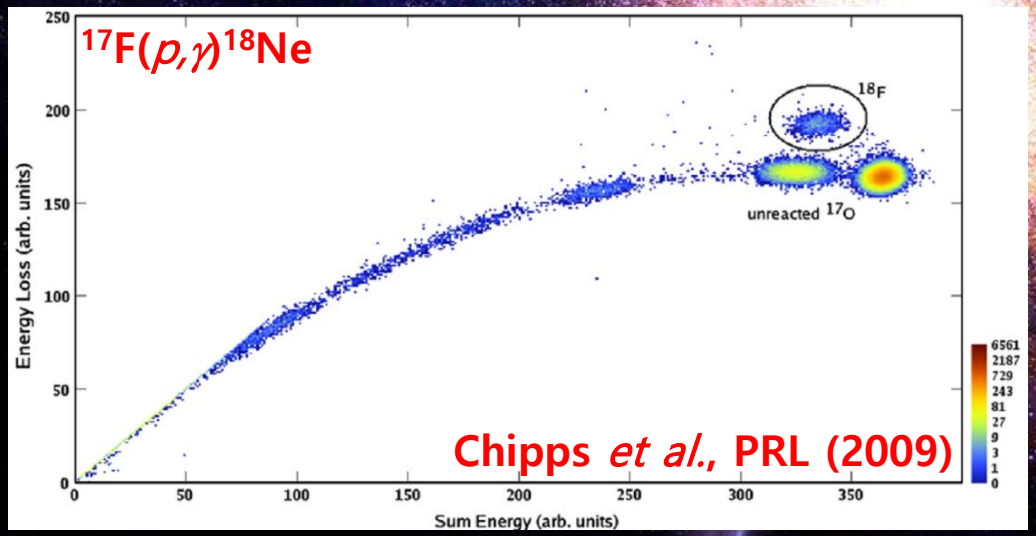


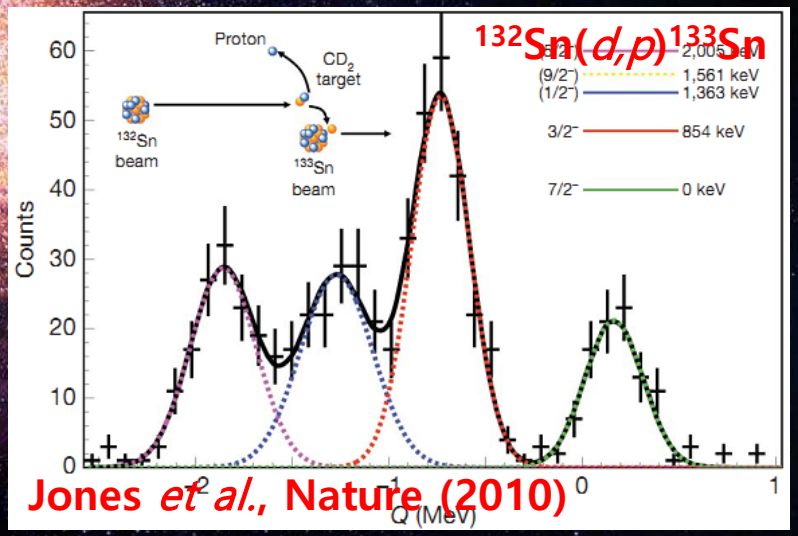
- (p,γ) reaction
- (α,γ) reaction
- (p,α) reaction
- (α,p) reaction
- (n,γ) reaction
- β^- decay
- β^+ decay

- light particle induced
- use of radioactive isotopes as the beam
- **Radioactive Ion Beam Facility is needed!**

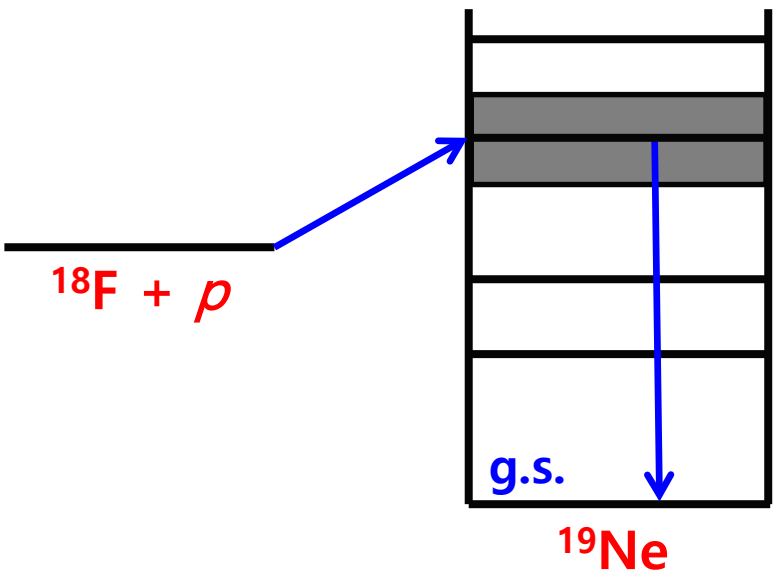
Needs in experimental nuclear astrophysics & structure

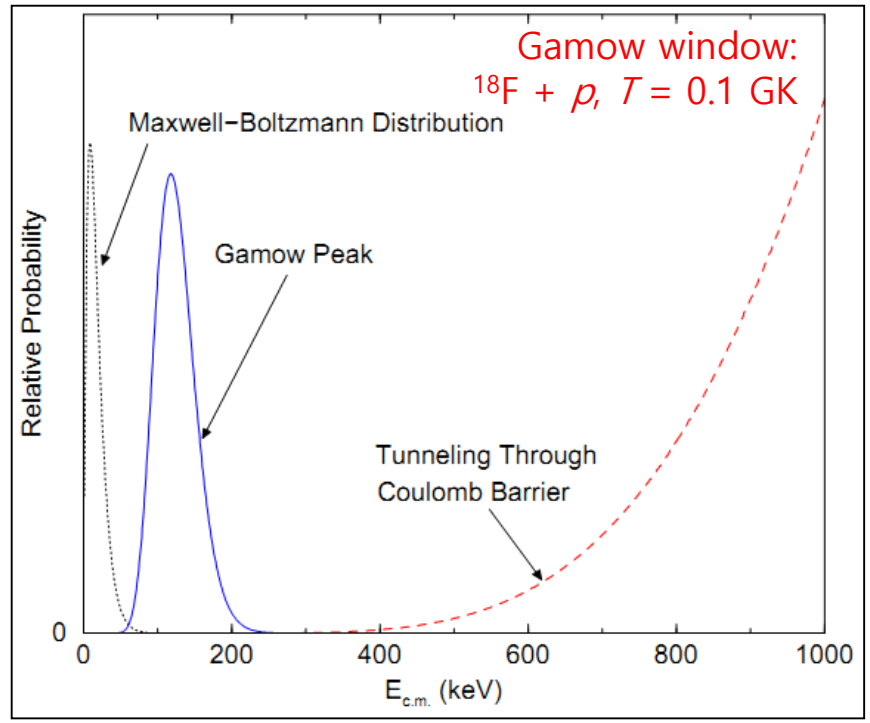
- Radiative capture reactions, (p,γ) & (α,γ), require high beam intensities: $< 10^8$ particles per second or so
- Transfer reaction measurements can give spectroscopic information: (d,p), $(^3He,d)$, etc.





Gamow window





- eg. the ^{18}F(p,γ)^{19}Ne reaction

- reaction rate ∝ exp(-E/kT)·exp(-b/E$^{1/2}$)
→ strongly localized in energy

$$< \sigma v >= \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) \exp\left[-\frac{E}{kT} - \frac{b}{E^{1/2}}\right] dE$$

- Nova temperature: 0.3-0.6 GK
→ ^{18}F beam energies of ~ 4-8 MeV are required.

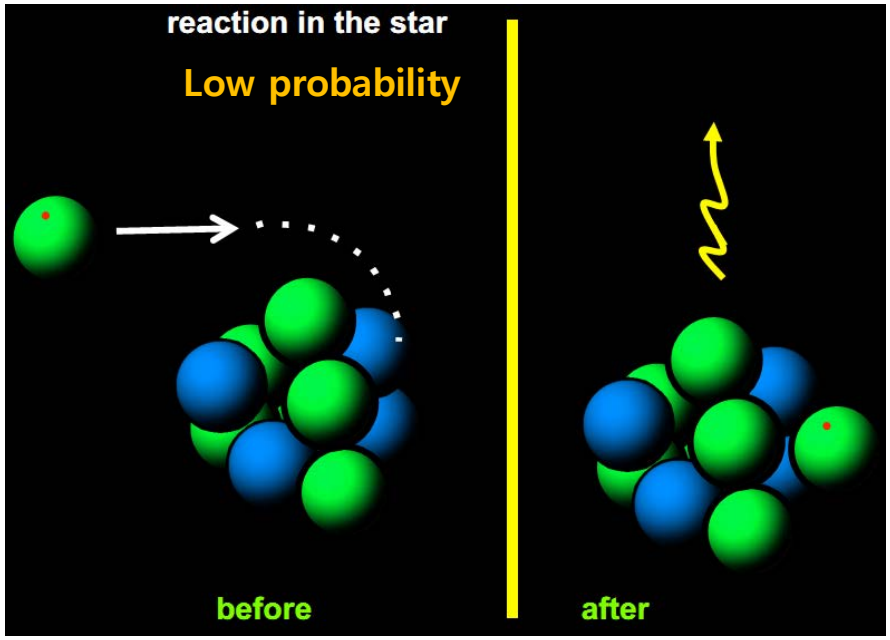
Transfer reactions

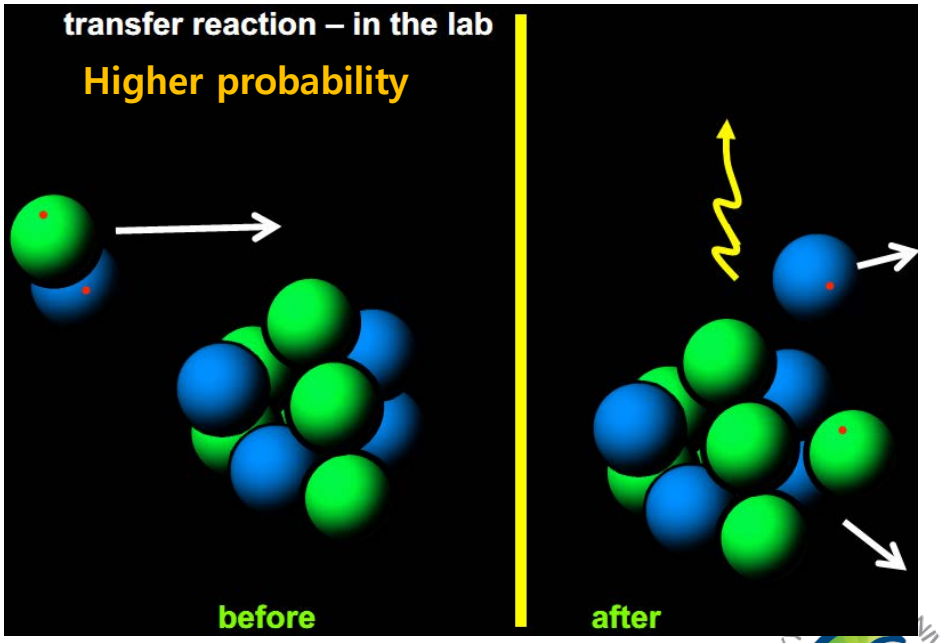
- Transfer reaction involving single nucleon transfer

- The state shows a structure that can be expressed as the core + transferred nucleon orbiting around it ("single particle" states)
- The energies of shell model orbitals can be well probed

- (*d*,*p*) deuteron 'stripping' reaction by Butler *et al.* (1967)

- angular dist. of *p* → unique determination of *l*-value for the transferred neutron

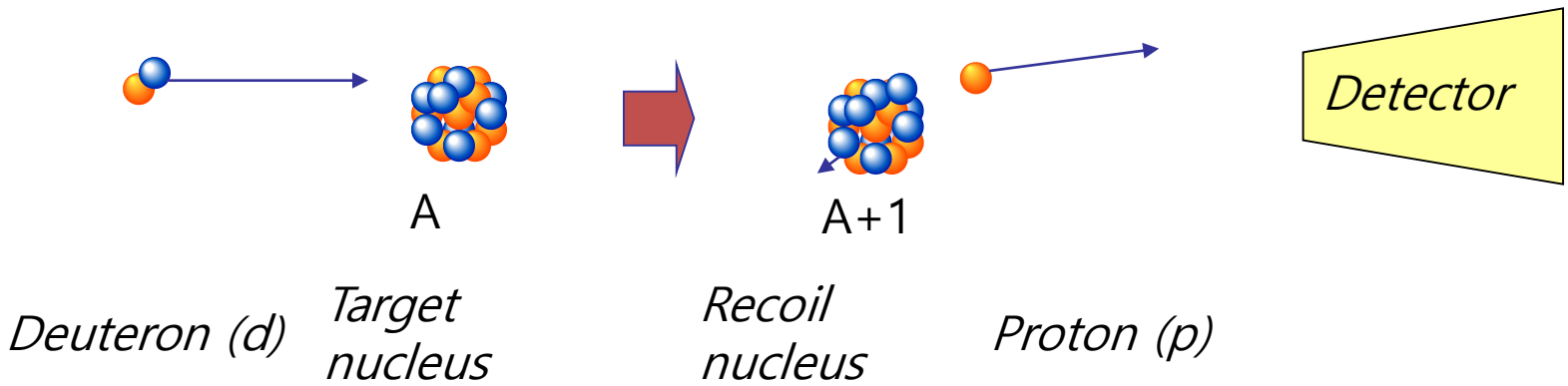




https://www.phy.ornl.gov/groups/astro/measurements/transfer.html

(d,p) reactions

- To study single-neutron states
  (energies, angular momentum, spectroscopic information)
- Traditionally, deuteron beams on a target (normal kinematics)



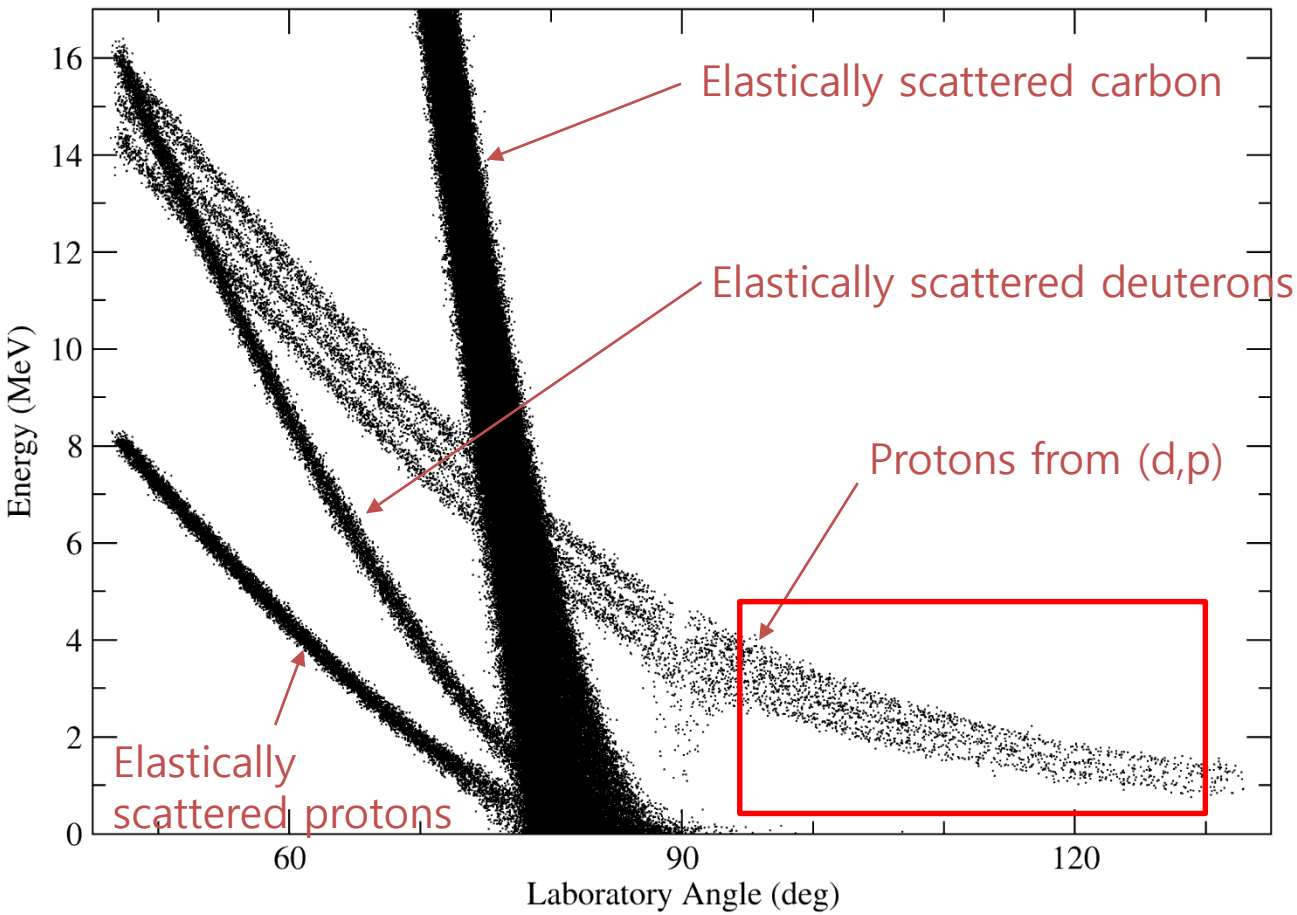
- A neutron is transferred from the deuteron to the target nucleus, forming a recoil nucleus.
- The proton is ejected from the system, in a **forward direction.**
  Its energy and angle carries information on the nuclear state populated.

e.g. $^{12}C(d,p)^{13}C$, $^{16}O(d,p)^{17}O$, $^{124}Sn(d,p)^{125}Sn$, $^{208}Pb(d,p)^{209}Pb$

(d,p) measurements in inverse kinematics

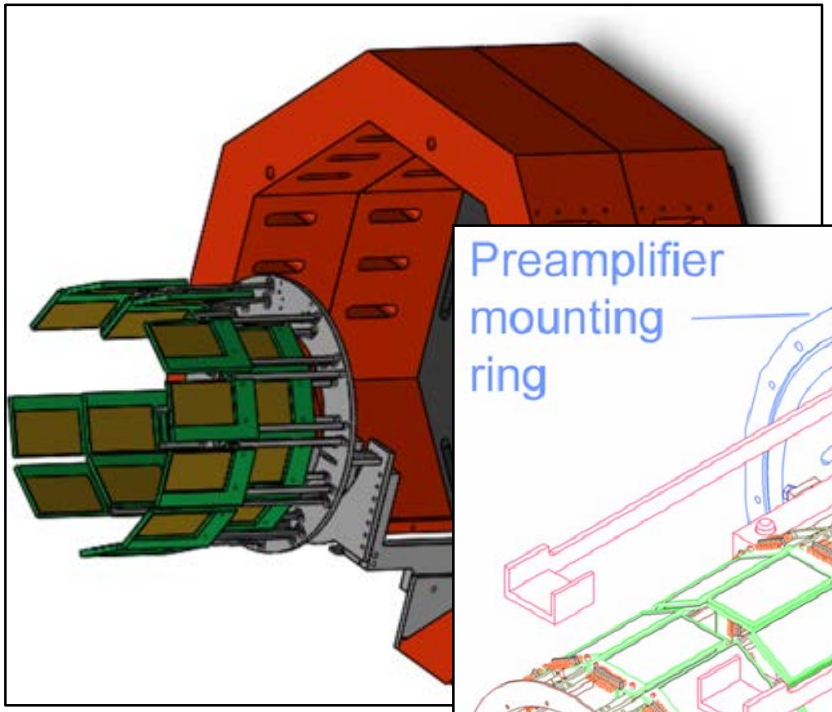
^{132}Sn(*d,p*)^{133}Sn in inverse kinematics

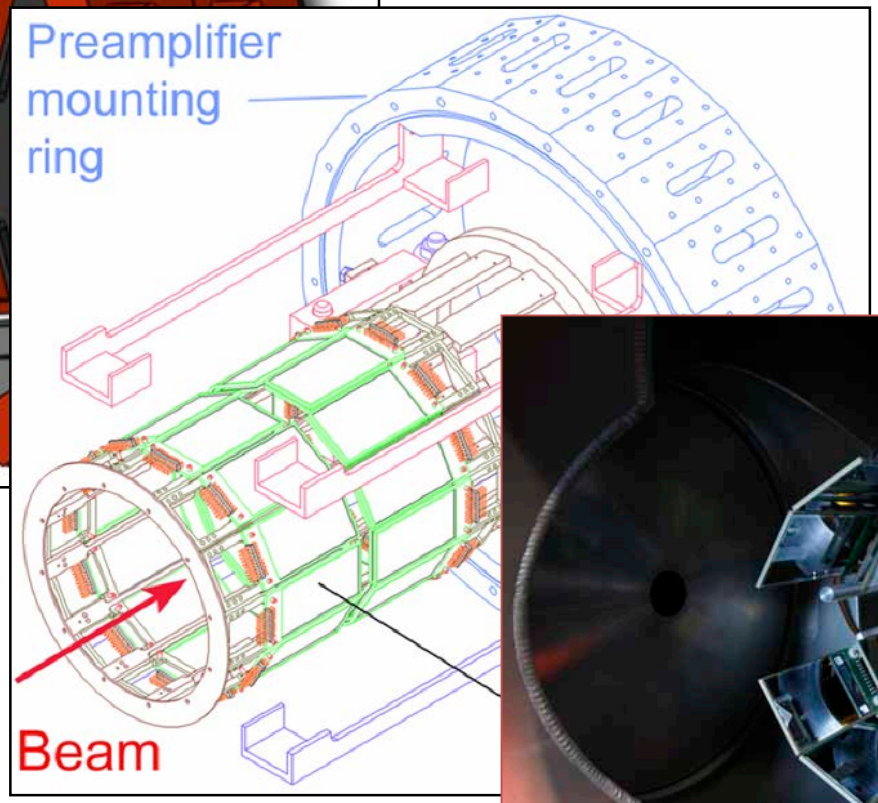
^{132}Sn beam + **CD_2** solid target, E_x = 0, 1, and 1 MeV in ^{133}Sn

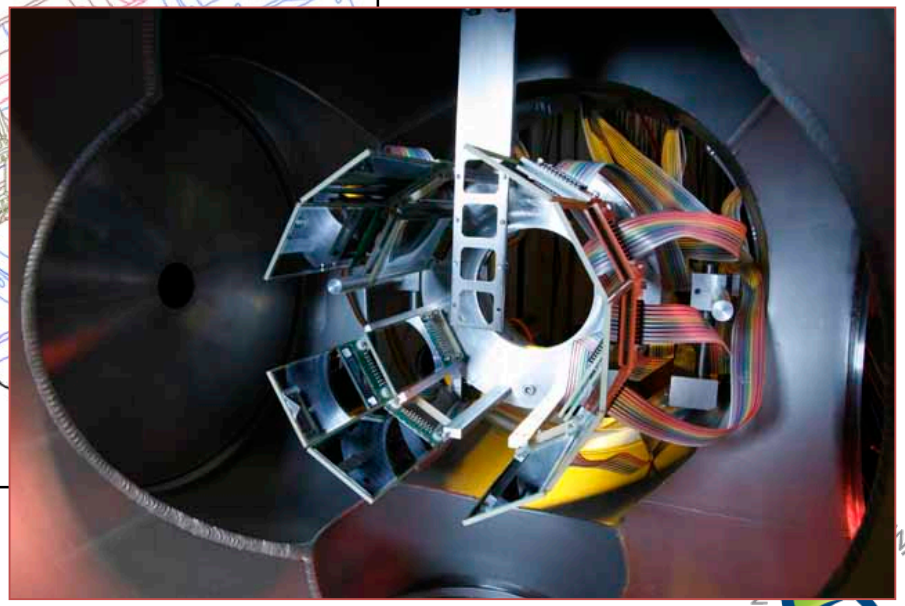


- forward $\theta_{C.M.}$ = backward θ_{lab}
- at backward angle, cross section and E_p become very small
- at forward angle, E_p rises quickly with angle ($dE/d\theta$ is large)
- High solid angle coverage
- good resolutions (angle & energy)
- large dynamic range
- barrel-type silicon detector array: ORRUBA

ORRUBA





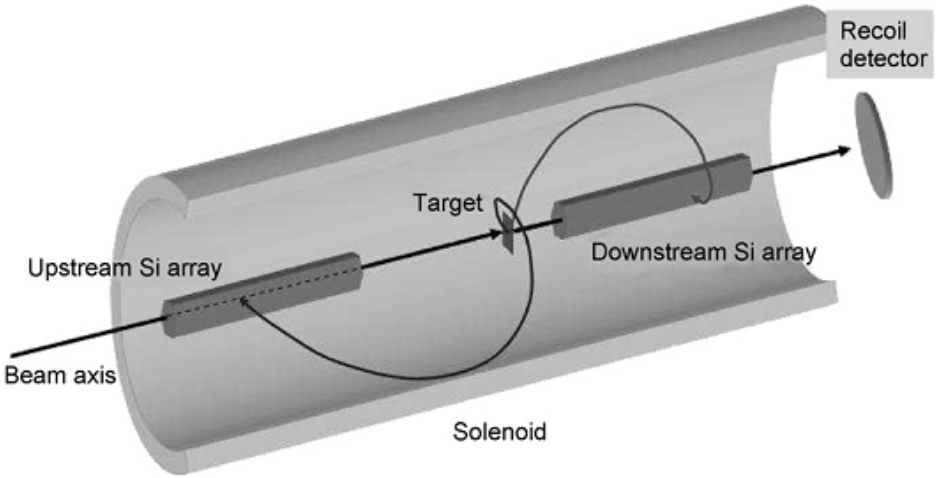


previous works

- ^{132}Sn(d,p)^{133}Sn – double magicity (K.L. Jones, **Nature**)
- ^{10}Be(d,p)^{11}Be – systematic study (K.T. Schmitt, **Phys. Rev. Lett**.)
- ^{130}Sn(d,p)^{131}Sn – single particle levels (R.L. Kozub, **Phys. Rev. Lett**.)
- ^{26}Al(d,p)^{27}Al – mirror states for astrophysics (S.D. Pain, **Phys. Rev. Lett.**)
- ^{126,128}Sn(d,p)^{127,129}Sn – tracking the single-neutron levels (B. Manning, **Phys. Rev. C**)
- ^{80}Ge(d,p)^{81}Ge – light fission fragment (S. Ahn)
- ^{134}Te(d,p)^{135}Te – away from double shell closures (S.D. Pain)
- …

Wonderful jobs! But, we think we can do **better**.

Solenoid-based charged particle detector system

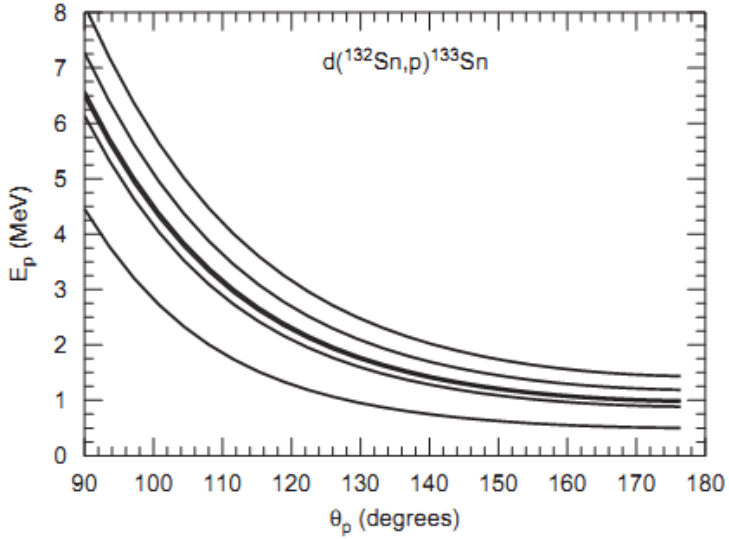


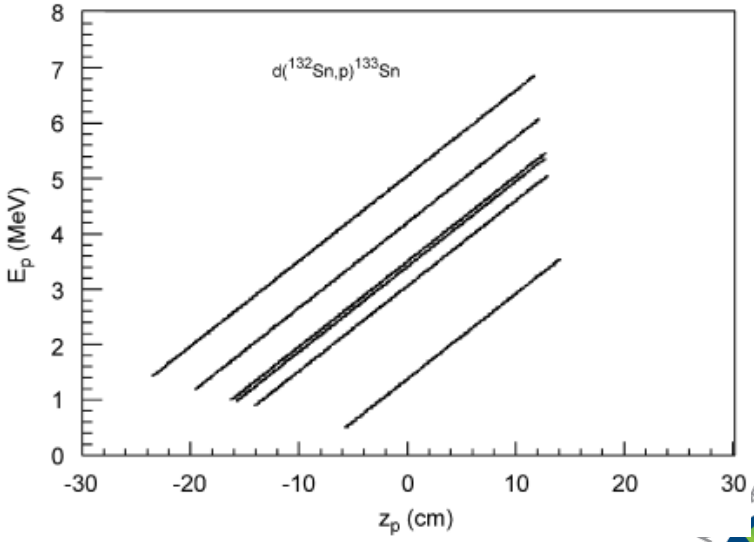
Helical Orbit Spectrometer, HELIOS

- designed for transfer reaction measurements in inverse kinematics with RIBs
- large-bore, uniform-field magnetic solenoid with B ~ 3 Tesla

→ better Q-value resolution, large solid angle, easy particle ID

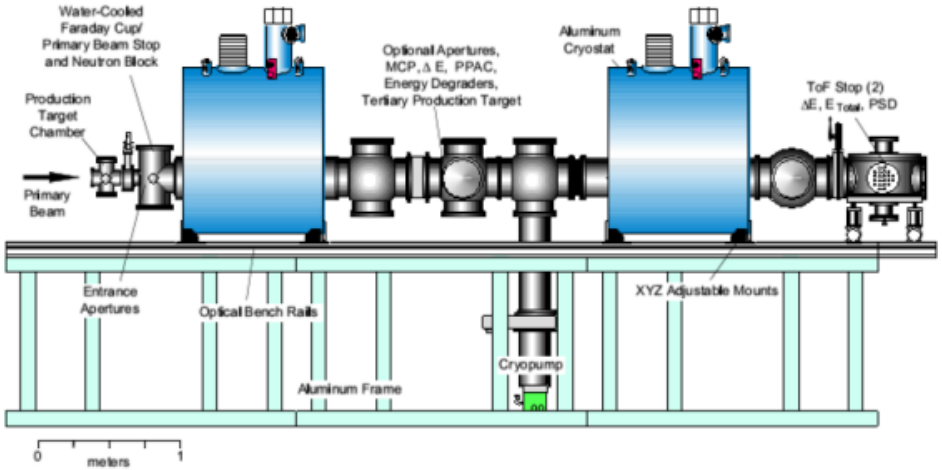
- used with RIBs from ATLAS ^{17}O(d,p), ^{19}O(d,p), ^{86}Kr(d,p), …

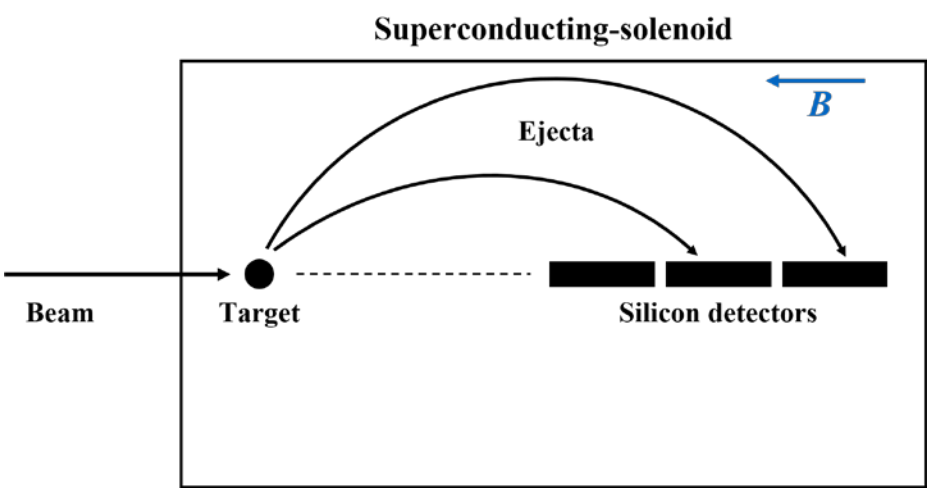




Figures taken from Wuosmaa *et al.*, NIMA 580, 1290 (2007)

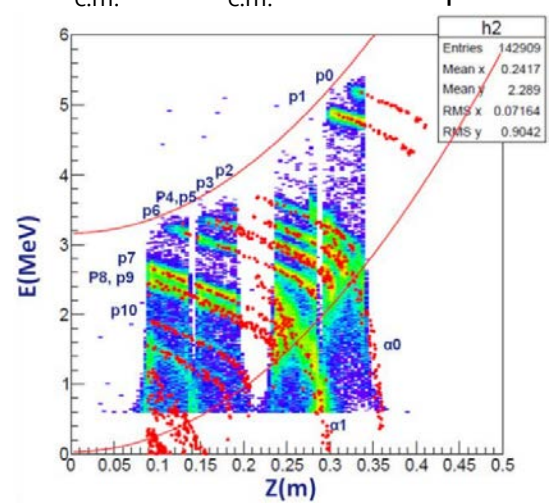
Solenoid Spectrometer for Nuclear Astrophysics (SSNAP)



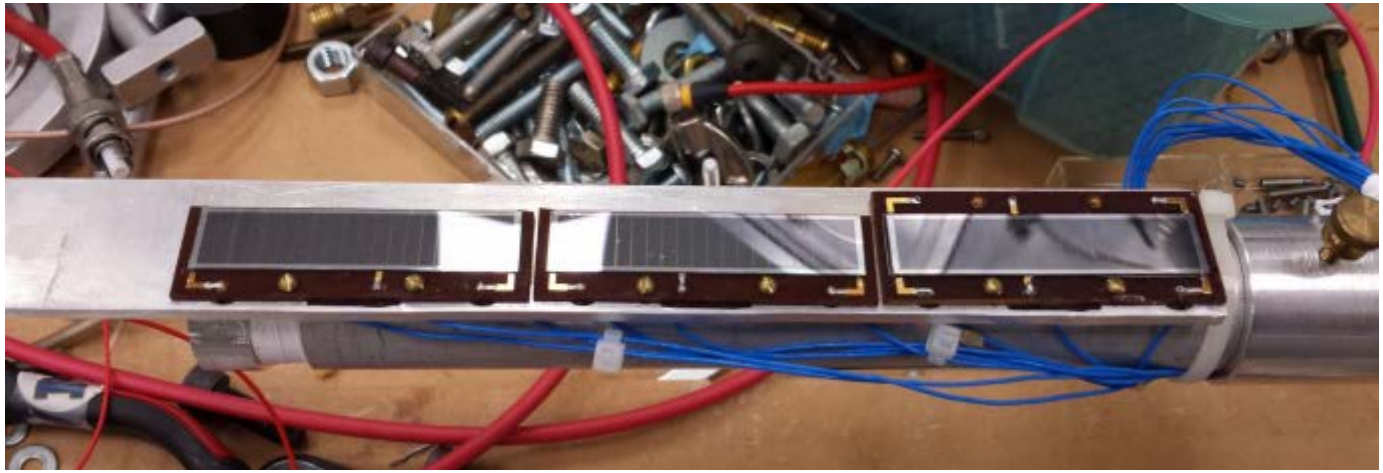


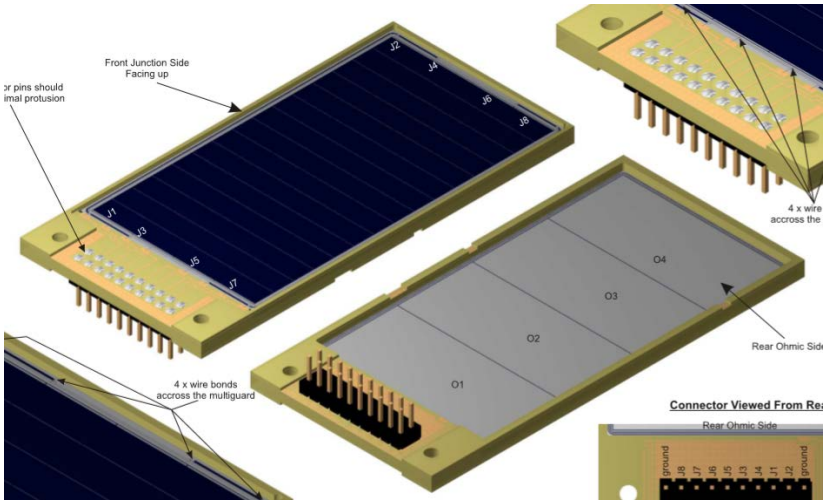
- TwinSol: a pair of superconducting solenoids for RIB production (^{7}Be, ^{17}F, ^{25}Al,… light particles)
- SSNAP: Solenoid Spectrometer for Nuclear Astrophysics, similar to HELIOS
- used to detect light charged ejectiles from reactions important for astrophysics
- path: determined by charge-to-mass ratio, energy, ejected angle
- time-of-flight, energy, position of ejectile can be measured

→ $E_{c.m.}$ and $\theta_{c.m.}$ can be reproduced!



New SSNAP with Super X3

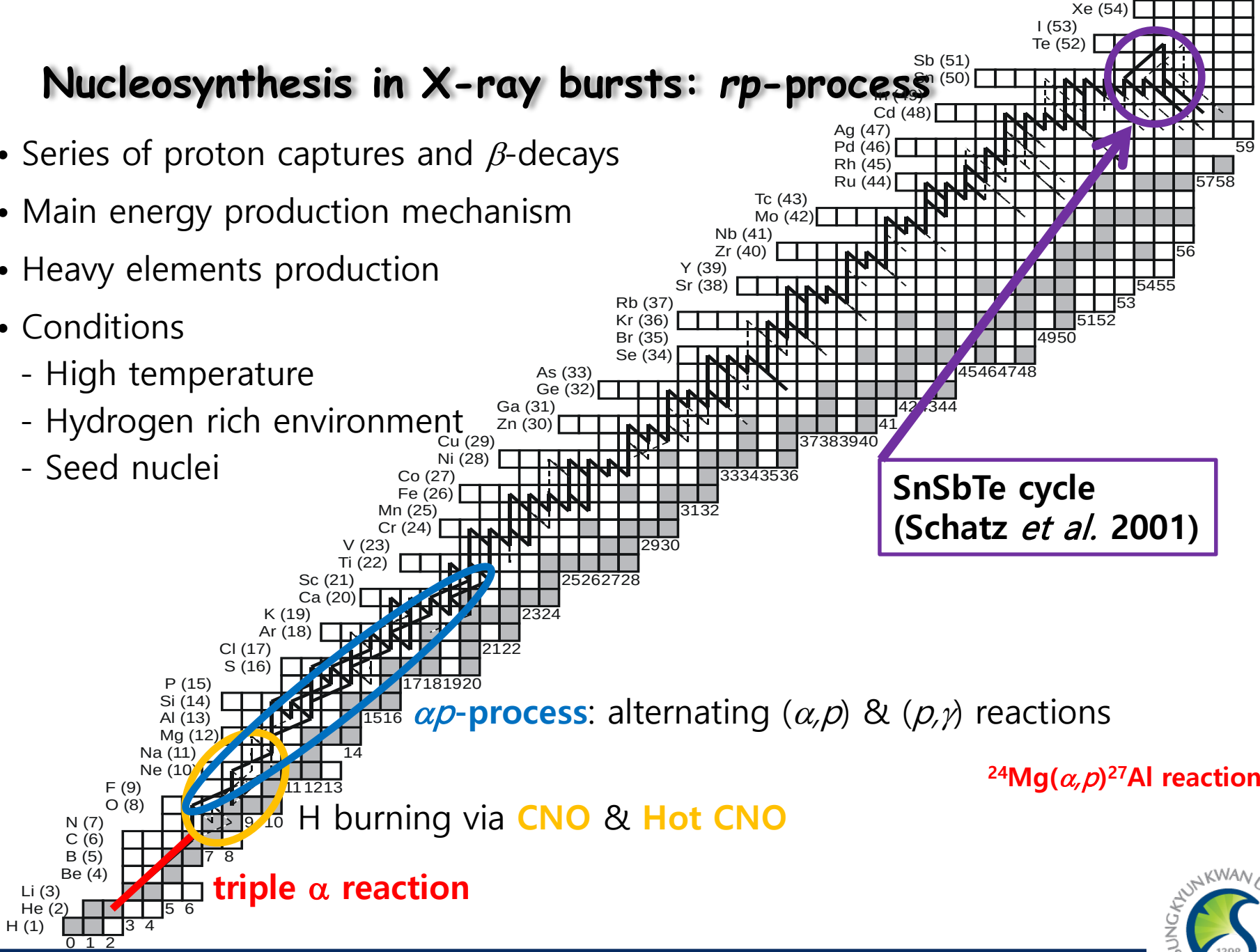




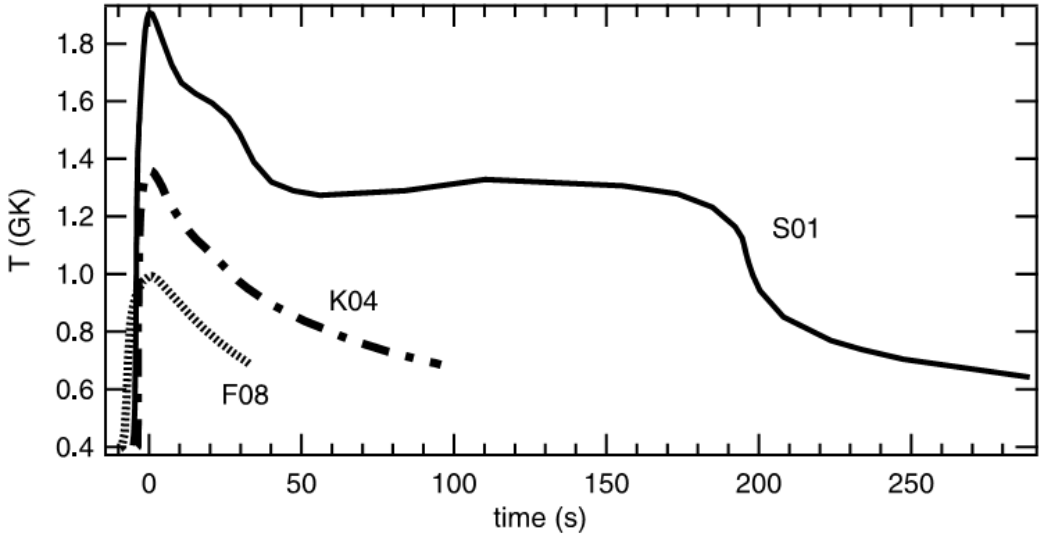
- Super X3 detectors
  - 4 resistive front strips, 4 back segments
  - energy resolution: ~ 55 keV (back), ~ 75 keV (front)
  - position resolution: ~ 1.2 mm
  - 7.5 cm long active area
- updated frame for better data
- versatile array: (d,p), (p,t), (^{3}He,t)…
- ^{12}C(d,p)^{13}C measurement for commissioning
- astrophysical **^{24}Mg(α,p)^{21}Na** reaction?

Nucleosynthesis in X-ray bursts: *rp*-process

- Series of proton captures and β-decays
- Main energy production mechanism
- Heavy elements production
- Conditions
  - High temperature
  - Hydrogen rich environment
  - Seed nuclei



Sensitivity study



- A. Parikh *et al.*, ApJS **178** 110 (2008)
"The effects of variations in nuclear processes on type I x-ray burst nucleosynthesis"

- Koike *et al.* 2004 (K04) model:
- a spherically symmetric, multizone model of accretion onto a 1.3 $M_\odot$ neutron star
- peak temperature of 1.36 GK
- densities ranging from 0.54-1.44 g/cm^3
- burst duration of ~ 100 seconds

- investigates the effect of reaction rate variations in final abundance ratios by a factor of 10 (up and down)

^{24}Mg(α,p)^{27}Al reaction affects on the final abundances of **^{34}S** and **^{30}Si**, and the **total nuclear energy** of burst

TABLE 20

NUCLEAR PROCESSES AFFECTING THE TOTAL ENERGY OUTPUT BY MORE THAN 5% AND AT LEAST ONE ISOTOPE

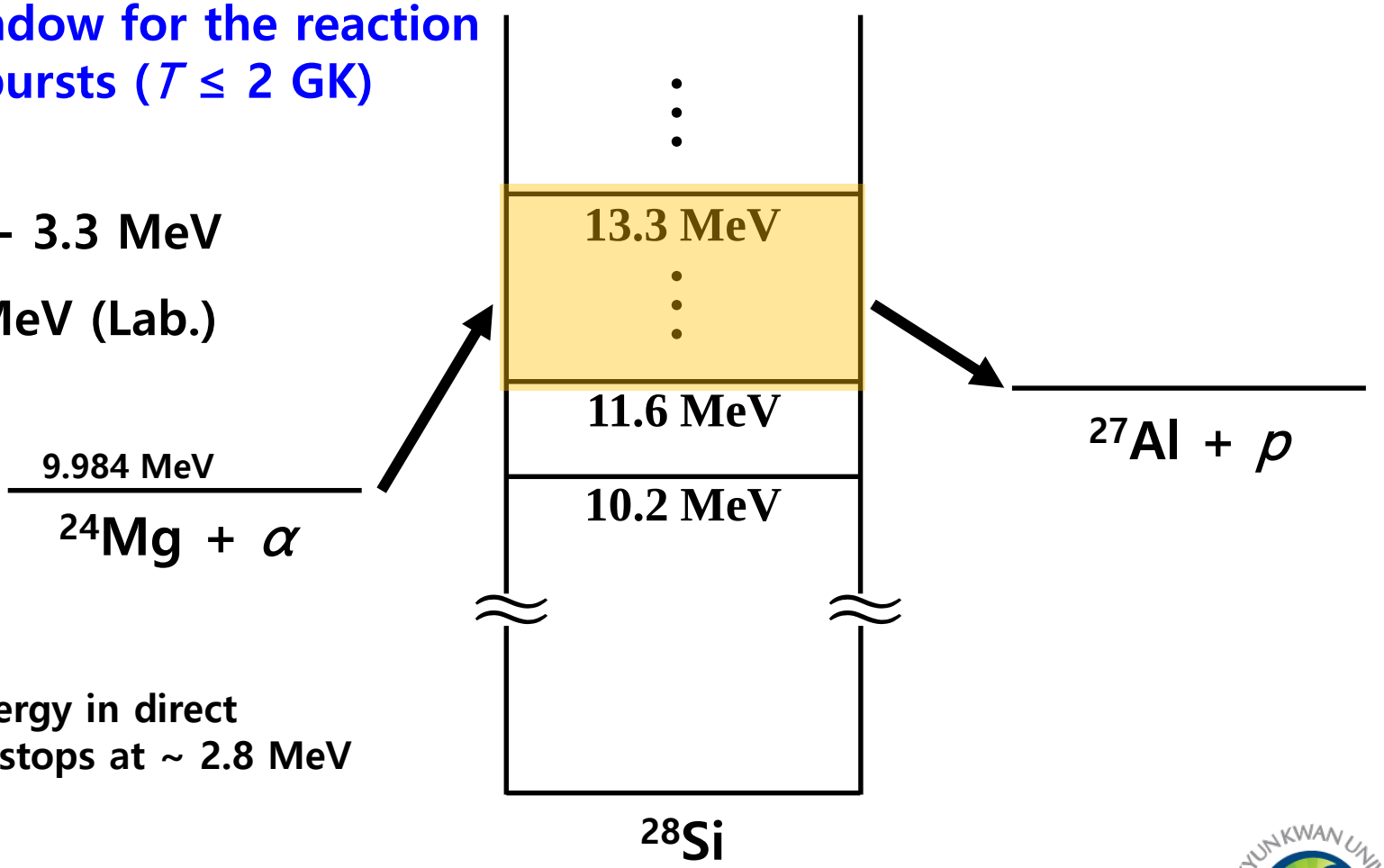
Reaction	Models Affected
^{15}O(α, γ)^{19}Ne^a	K04, K04-B1, K04-B6
^{18}Ne(α, p)^{21}Na^a	K04-B1, K04-B6
^{22}Mg(α, p)^{25}Al	F08
^{23}Al(p, γ)^{24}Si	K04-B1
^{24}Mg(α, p)^{27}Al^a	K04-B2
^{26g}Al(p, γ)^{27}Si^a	F08
^{28}Si(α, p)^{31}P^a	K04-B4
^{30}S(α, p)^{33}Cl	K04-B4, K04-B5
^{31}Cl(p, γ)^{32}Ar	K04-B3
^{32}S(α, p)^{35}Cl	K04-B2
^{35}Cl(p, γ)^{36}Ar^a	K04-B2
^{56}Ni(α, p)^{59}Cu	S01
^{59}Cu(p, γ)^{60}Zn	S01
^{65}As(p, γ)^{66}Se	K04, K04-B2, K04-B3
^{69}Br(p, γ)^{70}Kr	S01
^{71}Br(p, γ)^{72}Kr	K04-B7
^{103}Sn(α, p)^{106}Sb	S01

The $^{24}Mg(\alpha,p)^{27}Al$ reaction

Gamow window for the reaction x-ray bursts ($T \leq 2$ GK)

$E_{c.m.}$ = 1.5 - 3.3 MeV

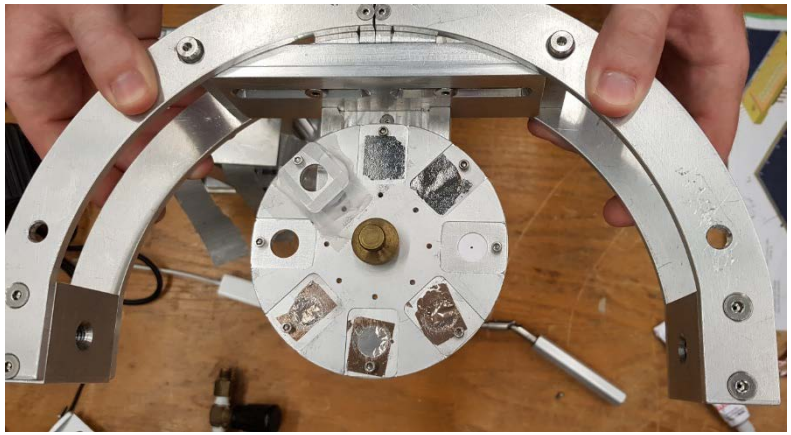
$E_p \leq$ ~ 2 MeV (Lab.)



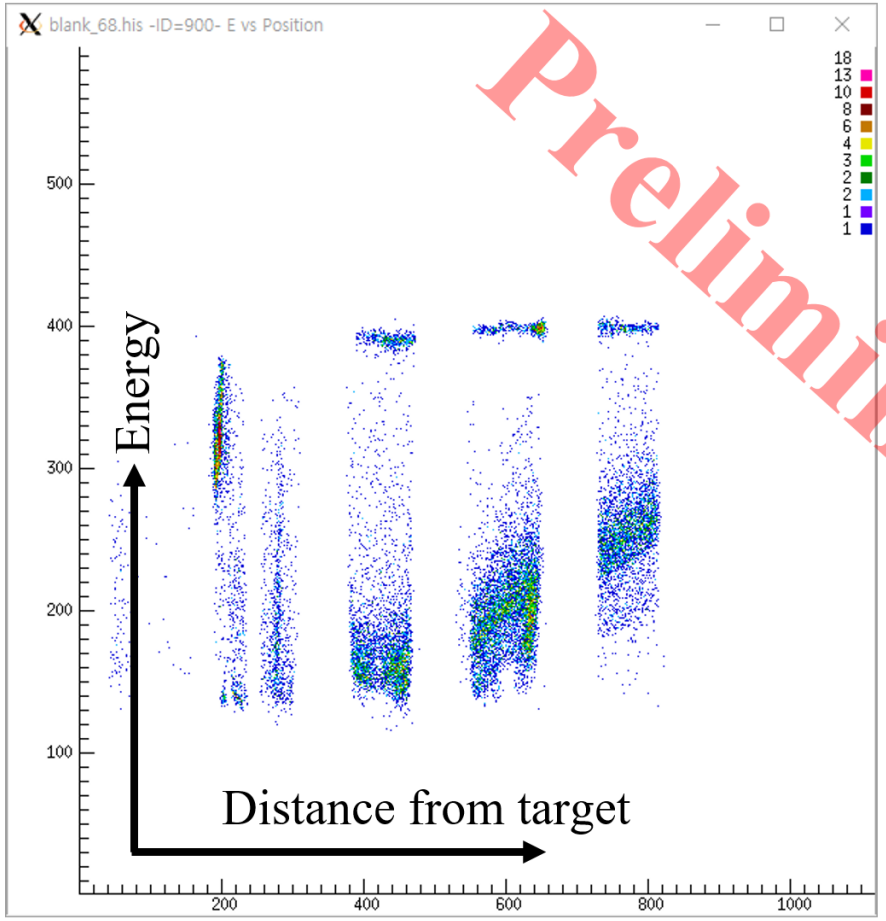
The lowest energy in direct measurement stops at ~ 2.8 MeV

$^{24}Mg(\alpha,p)^{27}Al$ measurement at U. of Notre Dame

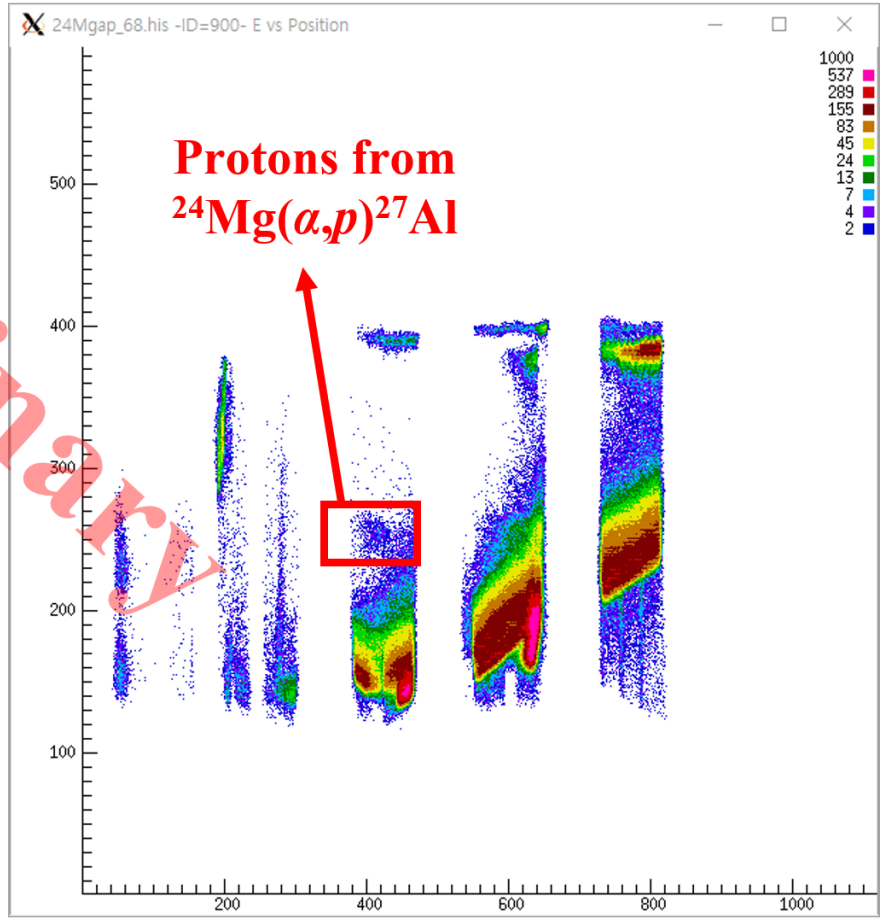
- α beams (I ~ 2 nA) from 10 MV FN tandem accelerator
- E_{beam} = 3 - 5 MeV ($E_{c.m.}$ = 2.6 – 4.3 MeV)
- evaporated ^{24}Mg solid targets (~ 50 μg/cm^2 thick) on thin ^{12}C backing material (~ 5 μg/cm^2 thick)
- ΔE_{beam} ~ 30-40 keV, about 40 beam energies
- ~ few hours per beam energy



Preliminary results



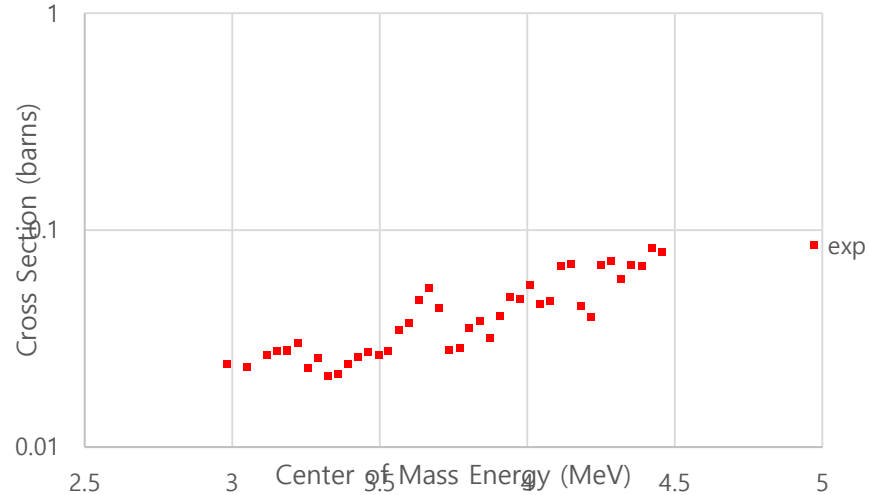
Blank frame



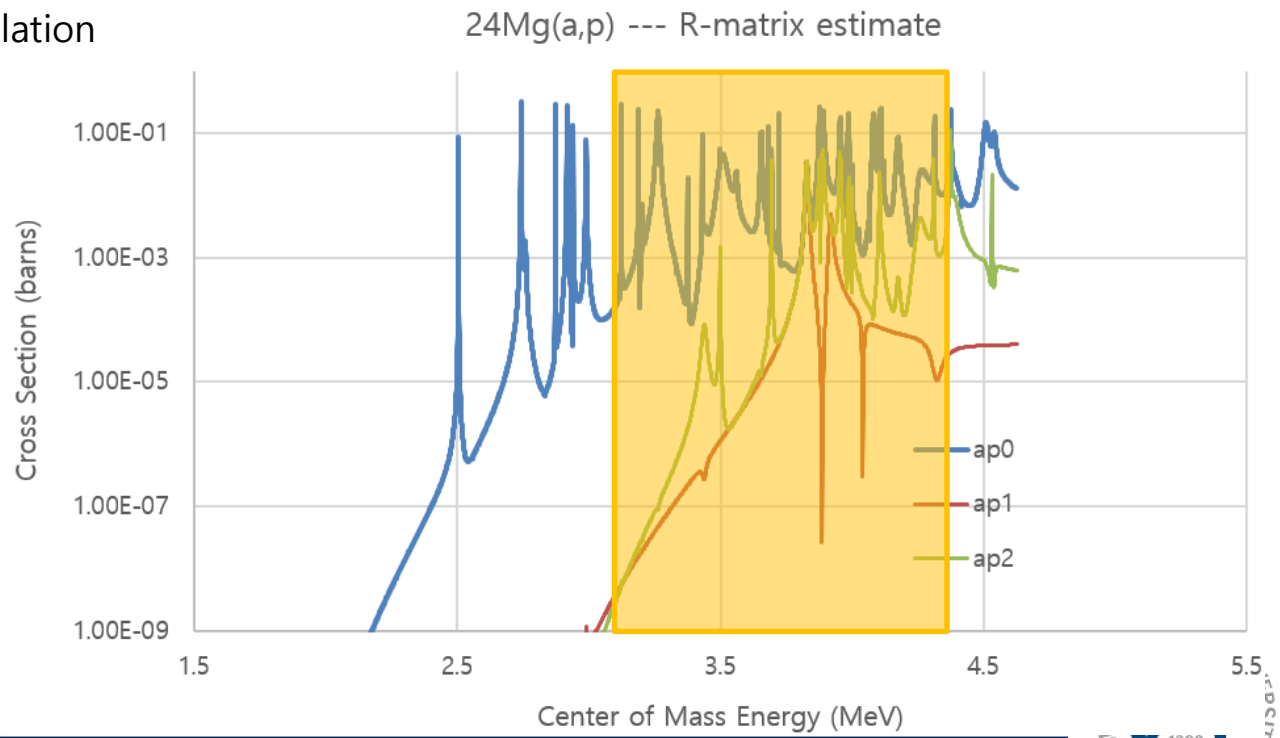
^{24}Mg target

Future Plan

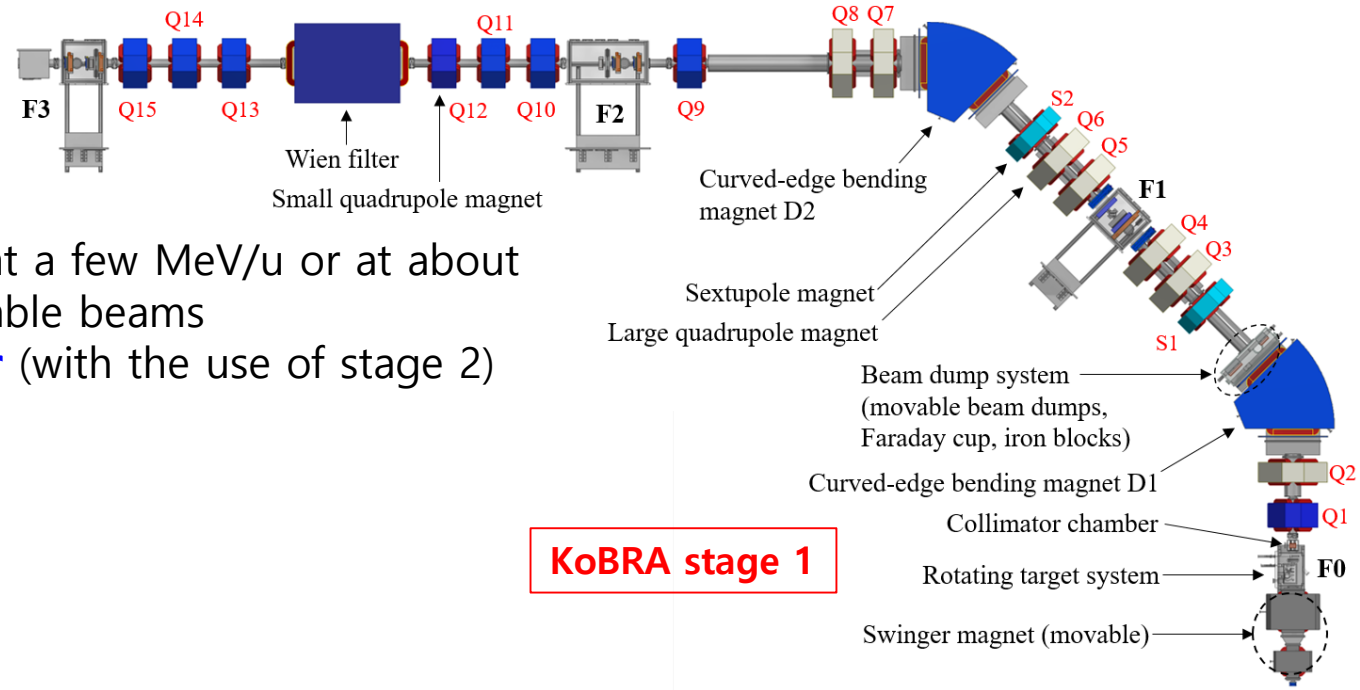
- develop simulation code for SSNAP
- extract differential cross section values at $E_{c.m.}$ = 2.6 – 4.3 MeV
- identify populated resonances in ^{24}Mg+α (^{26}Si) system
- *R*-matrix fitting for resonance parameters
- ^{24}Mg(α,p)^{27}Al reaction rate calculation
- nucleosynthesis calculation



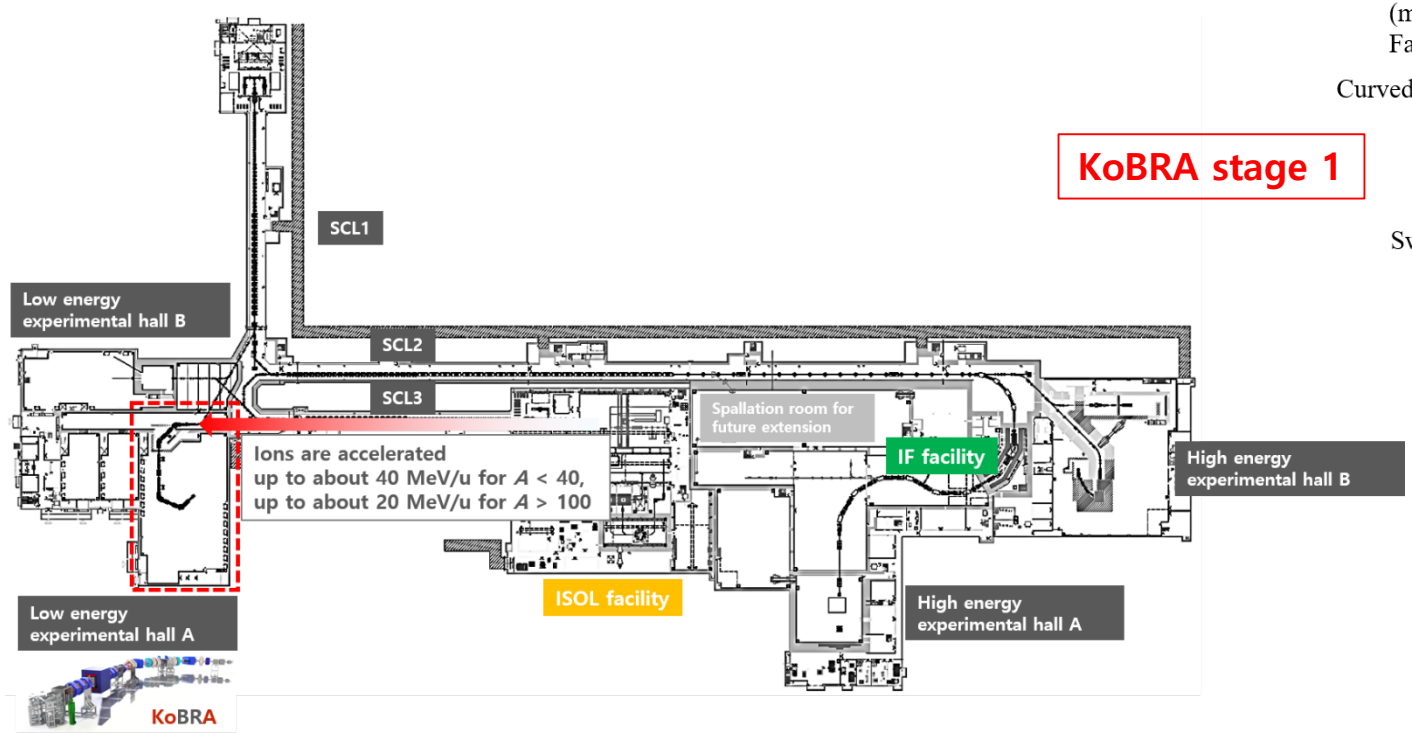
^{27}Al+p [Nelson *et al.* PRC **29,** 1656 (1984)] and ^{24}Mg(α,α) [Nucl. Phys. A **385**, 43 (1982)]



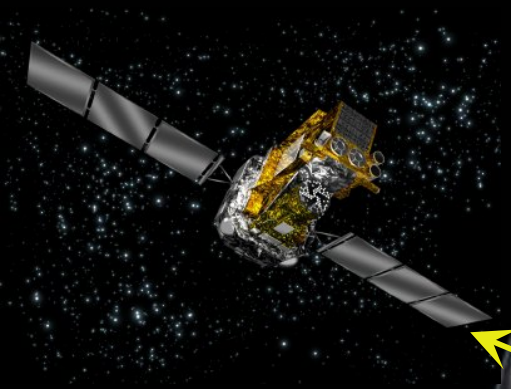
Korea Broad acceptance Recoil spectrometer and Apparatus



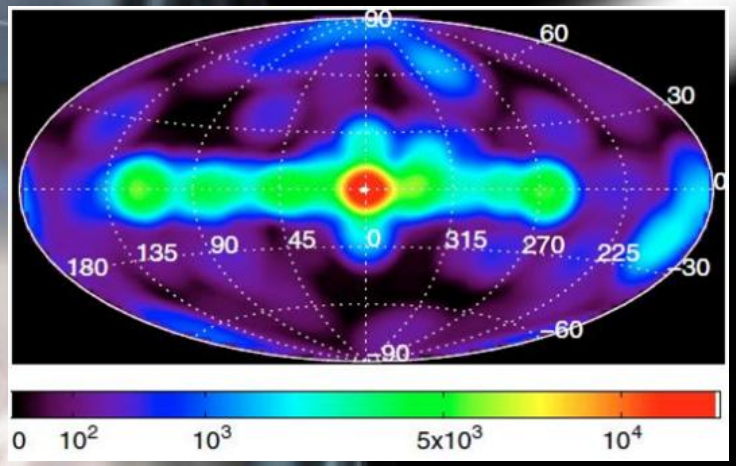
- **RI beam production** at a few MeV/u or at about 20-40 MeV/u using stable beams
- **Recoil mass separator** (with the use of stage 2)



Radioisotopes produced in novae



INTEGRAL
(ESA, 2002)



All sky map of 1.809 MeV γ-rays

Isotope	Lifetime	Decay process	γ-ray produced	Nova type
^{13}N	0.24h	β^+-decay	511 keV + cont.	CO & ONeMg
^{18}F	2h	β^+-decay	511 keV + cont.	CO & ONeMg
^{7}Be	77d	e^--capture	478 keV line	CO
^{22}Na	3.75y	β^+-decay	1275 keV + 511 keV	ONeMg
^{26}Al	10^6y	β^+-decay	1809 keV + 511 keV	ONeMg

Radionuclide ^{18}F

$^{17}O(p,\gamma)$ } ^{18}F { $(p,\alpha)^{15}O$

$^{17}F(p,\gamma)^{18}Ne(e^{+}\nu_e)$ } ^{18}F { $(p,\gamma)^{19}Ne$

^{18}F

- τ ~ 2 hrs, β^{+}-decay (^{18}O)
- large production rate

→ **important positron annihilation source!**

$^{18}F(p,\alpha)^{15}O$

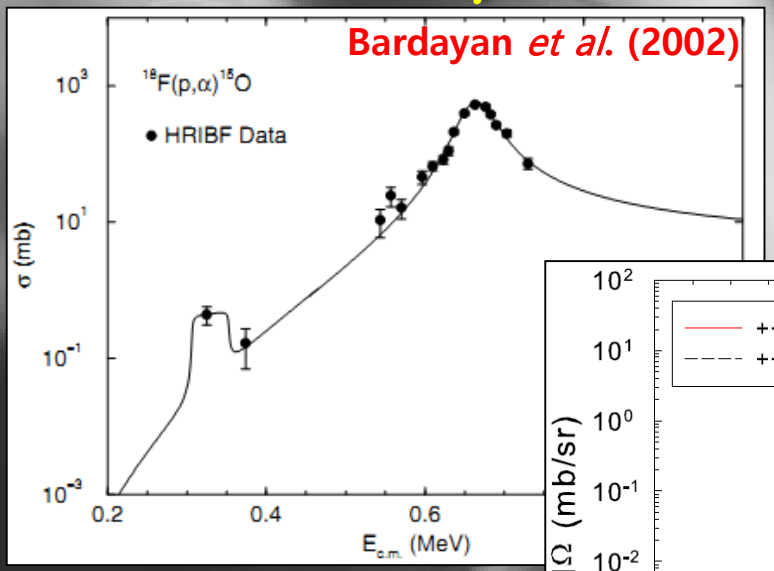
- direct measurements:

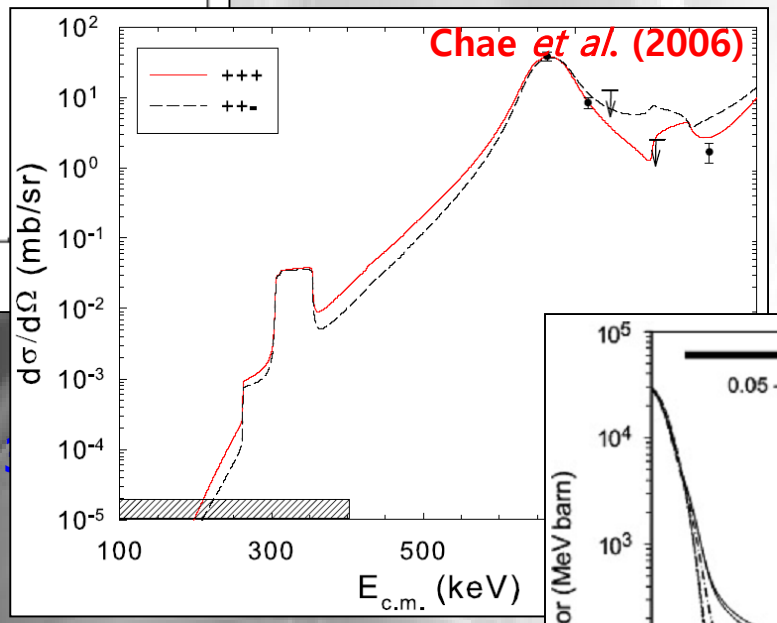
  Bardayan (2002), Chae (2006), Sereville (2009), Beer (2011)

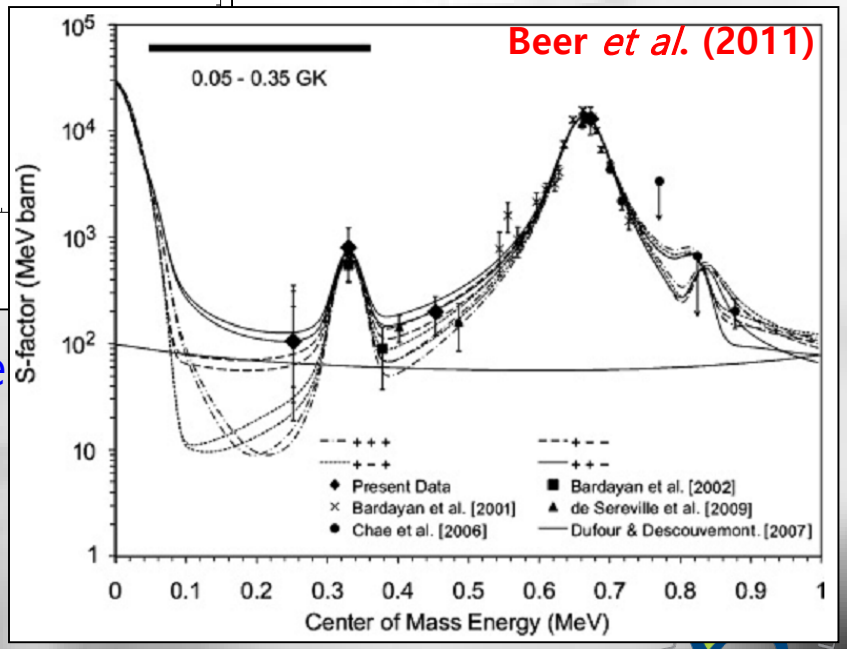
- many indirect measurements

$^{18}F(p,\gamma)^{19}Ne$: measured only one time by Akers (2013)

Previous $^{18}F(p,\alpha)^{15}O$ measurements







- precise measurement
- first measurement of
- first study on the inte

^{18}F Beams

- beam intensities:
  - For **^{18}F(p,α)^{15}O:** ~ 10^6 pps (for the 330 keV resonance)
  - For **^{18}F(p,γ)^{19}Ne:** ~ $10^{7\text{-}8}$ pps
- beam production:
  - high intensity α beam from the cyclotron and HfO_2 ISOL target
  - Radionuclide ^{18}F will be produced through the ^{16}O(α,pn)^{18}F reaction

- beam size: ~ few mm^2 at the target position
- high beam purity
- beam time of ~ 10 days
- very wide range of beam energy is required

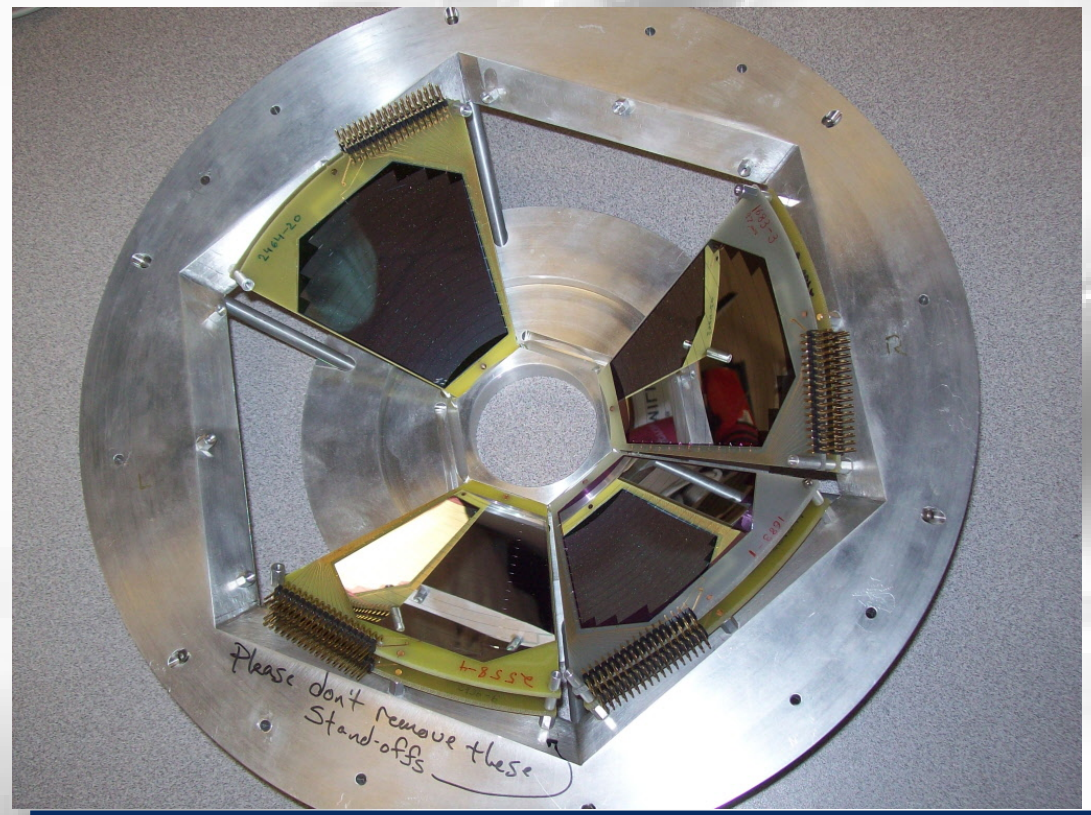
Silicon detector system

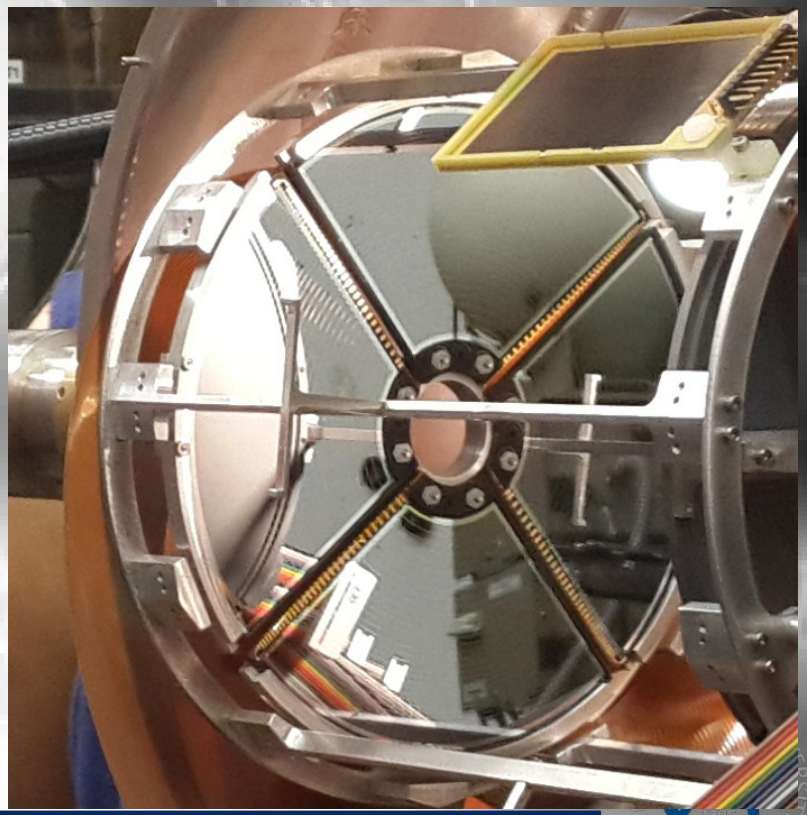
YY-1 type

- 16 radial strips
- α's from the (p,α) reaction
- covers forward angles

QQQ type

- newly developed QQQ5
- 36 channels per wedge
- covers very forward angles
- α's from the (p,α) reaction, **heavy recoils**





Summary

- Solenoid-based detector system SSNAP was originally developed for transfer reaction studies

- SSNAP was used to measure astrophysical $^{24}Mg(\alpha,p)^{21}Na$ reaction

- Excitation function for the reaction was obtained at Ec.m. = 2.6-4.3 MeV by using a beams at various beam energies from FN tandem accelerator

- Data analysis is on going

Thank you very much!