Measuring compound nucleus reaction using solenoid-based detector system

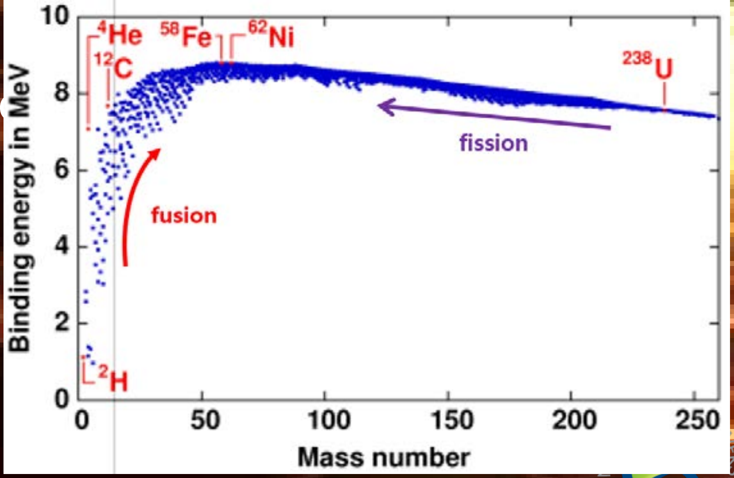
Kyungyuk Chae (kchae@skku.edu)

http://nucastro.skku.edu

The question driving the nuclear astrophysics

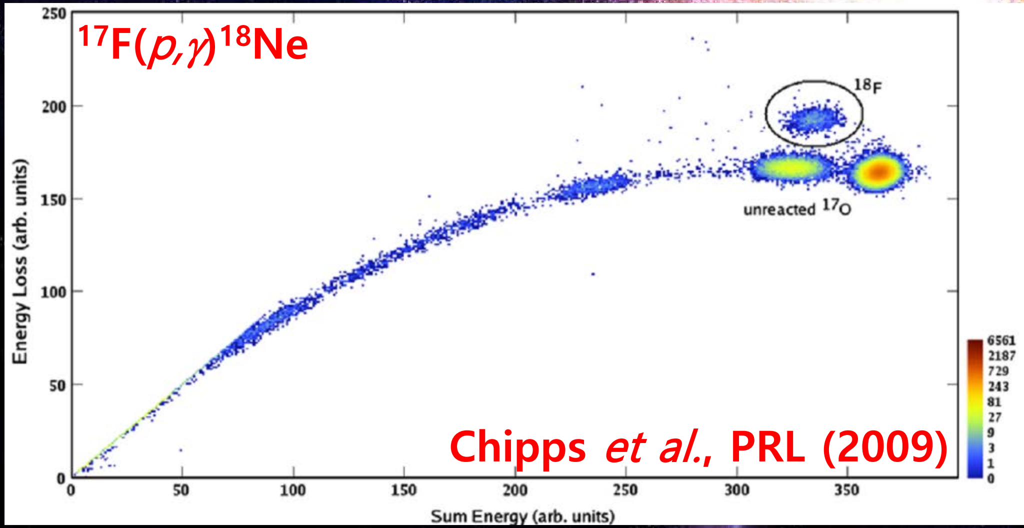
11 greatest unanswered questions of Physics
(National Academy of Science Report, 2002)

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 tempe
8. Are protons unstable?
9. What is gravity?
10. Are there additional dimensions?
11. How did the universe begin?



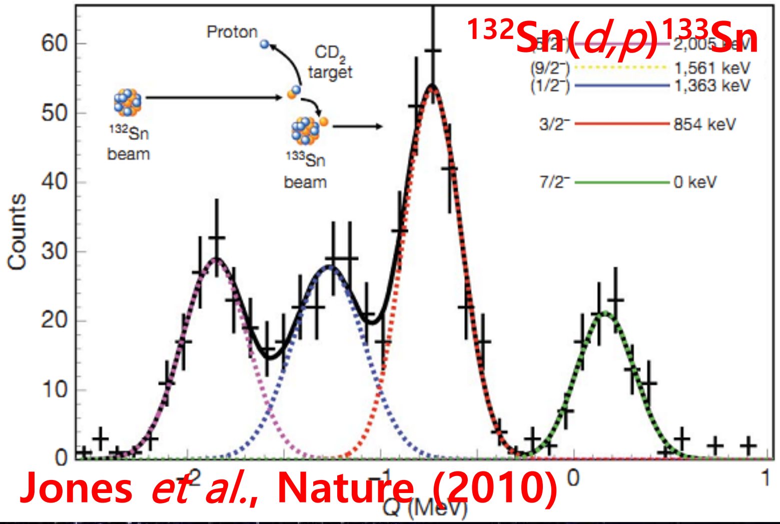
Needs in experimental nuclear astrophysics & structure

- Radiative capture reactions, (*p,γ*) & (*α,γ*), require high beam intensities
  - (direct measurements)
- Transfer reaction measurements can give spectroscopic information: (*d,p*), (^{3}He,*d*), etc. – (indirect measurements)



^{17}F(*p,γ*)^{18}Ne

Chipps *et al.*, PRL (2009)

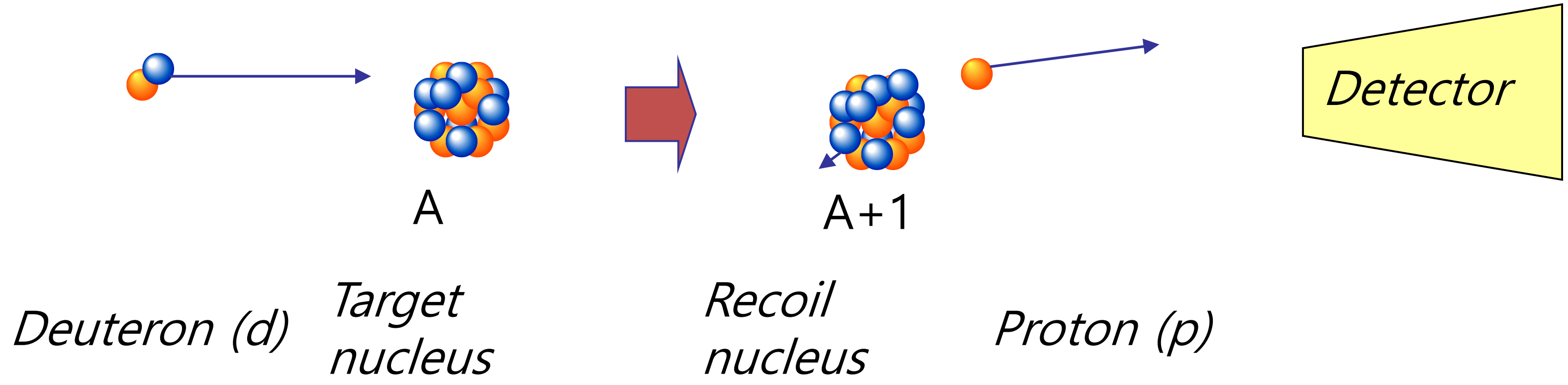


^{132}Sn(*d,p*)^{133}Sn

Jones *et al.*, Nature (2010)

transfer reactions in normal kinematics

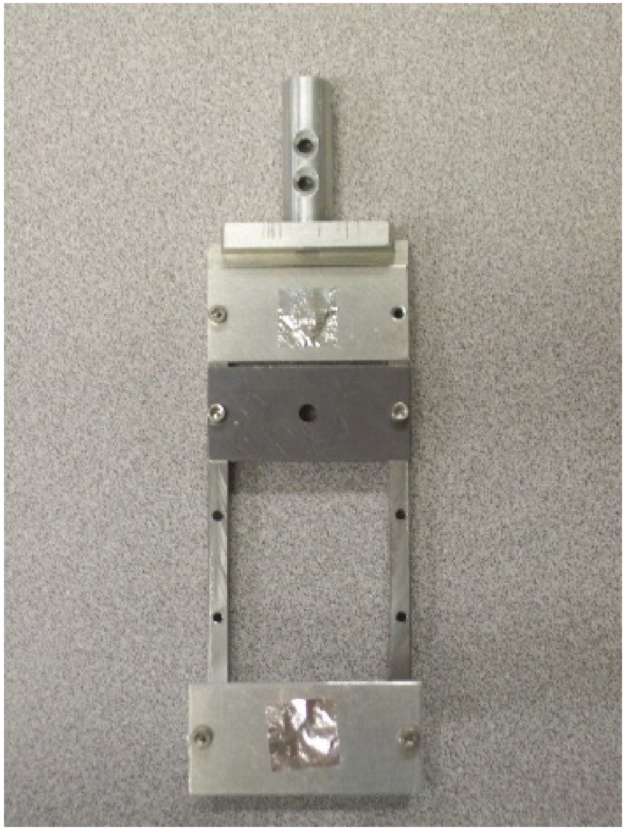
- To study single-particle (single-hole) states
  (energies, angular momentum, spectroscopic information)
- Traditionally, light beams on heavy targets (normal kinematics)



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

Probably, the most efficient target ever

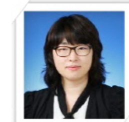


- Isotopically-enriched **^{24}Mg**
- ~ $500 for 3 targets (2007)

Constraint on the astrophysical ^{18}Ne(a,p)^{21}Na reaction rate through a ^{24}Mg(p,t)^{22}Mg measurement
Phys. Rev. C **79**, 055804 (2009)

Spin assignments to excited states in ^{22}Na through a ^{24}Mg(p,^{3}He)^{22}Na reaction measurement
Phys. Rev. C **82**, 047302 (2010)

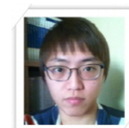
^{24}Mg(p,a)^{21}Na reaction study for spectroscopy of ^{21}Na
J. Korean Phys. Soc. **67**, 1435 (2015)



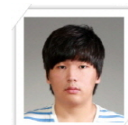
Spectroscopic study of the radionuclide ^{21}Na for the astrophysical ^{17}F(a,p)^{20}Ne reaction rate
Phys. Rev. C **96**, 025810 (2017)

Measuring one nucleon transfer reaction ^{24}Mg(p,d)^{23}Mg for astrophysical reaction rates
J. Korean Phys. Soc. **67**, 1435 (2017)

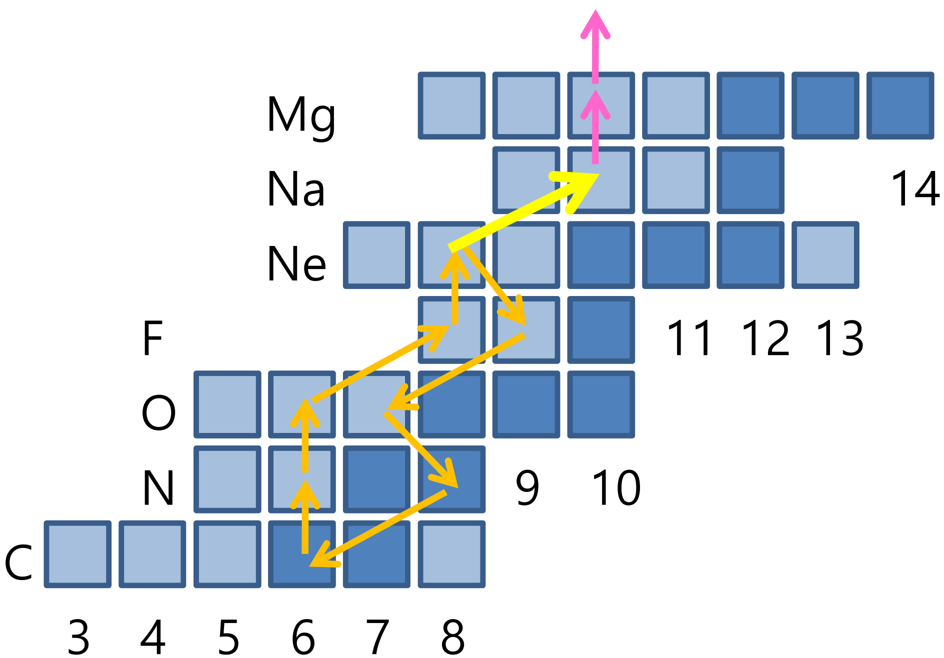
Spin assignments for ^{23}Mg levels
Submitted to Eur. Phys. J A (2019)



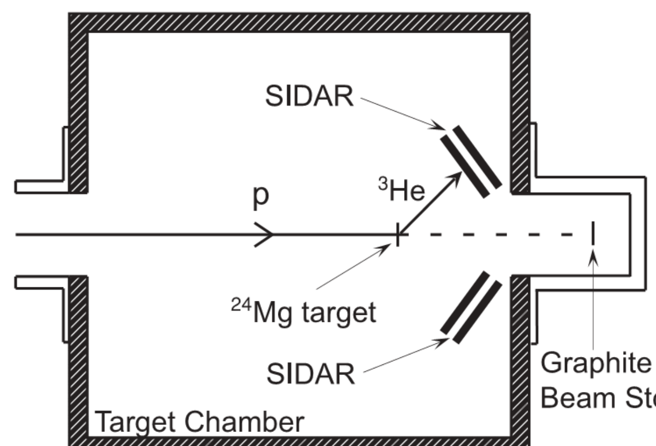
Proton decay of ^{21}Na for ^{20}Ne energy levels
will be submitted to J. Korean Phys. Soc. (2019)



Example: ^{24}Mg(p,t)^{22}Mg for ^{18}Ne(α,p)^{21}Na



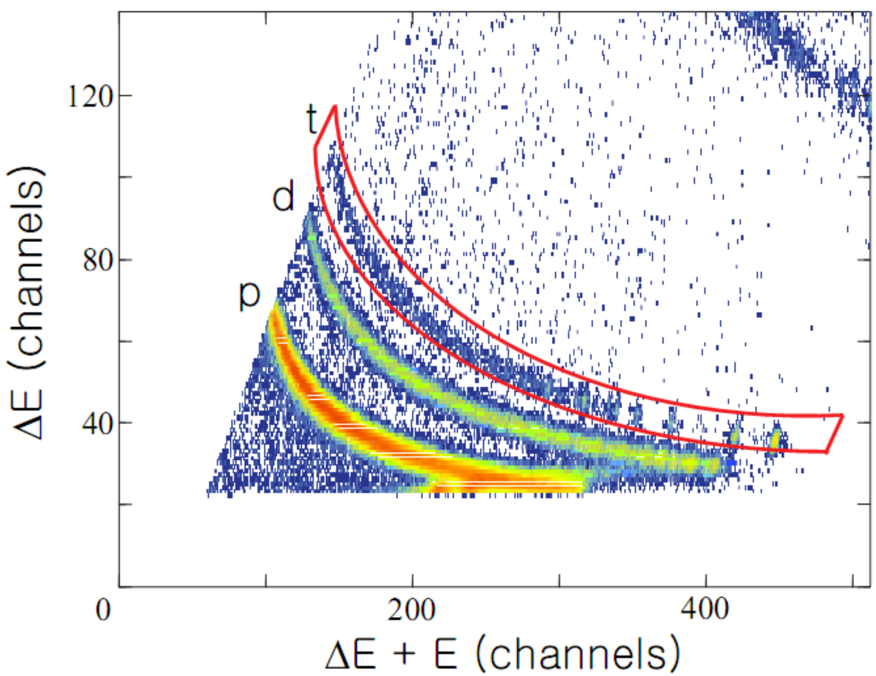
- 16 radial strips (5-13 cm)
  → angular distributions
- 100 μm - 1000 μm
  → "telescope mode" for particle ID
  ($\Delta E \cdot E \propto MZ^2$)
- proton beams from tandem accelerator
  (E_{beam} = 41 & 41.5 MeV)
- 500 μg/cm^2 pure ^{24}Mg targets



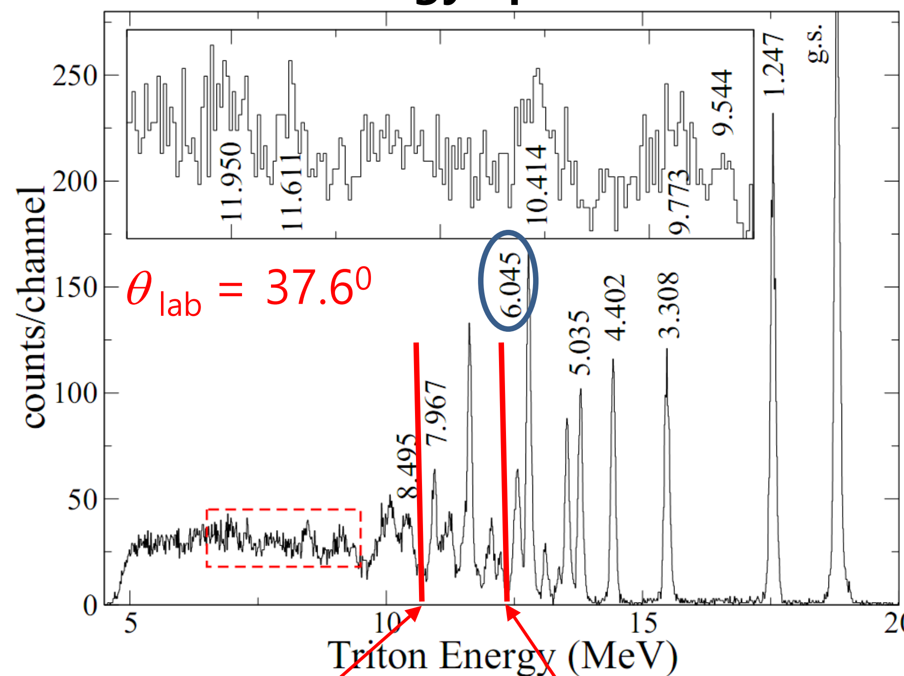
- astrophysical ^{18}Ne(α,p)^{21}Na reaction rate
- A.A. Chen *et. al.* (2001)
  - ^{12}C(^{16}O,^{6}He)^{22}Mg reaction
  - Found 18 new levels over wide range
- Spins & Parities assignments are still required

Results

Particle Identification



Energy spectrum



"telescope mode"
$(\Delta E \cdot E \propto MZ^2)$

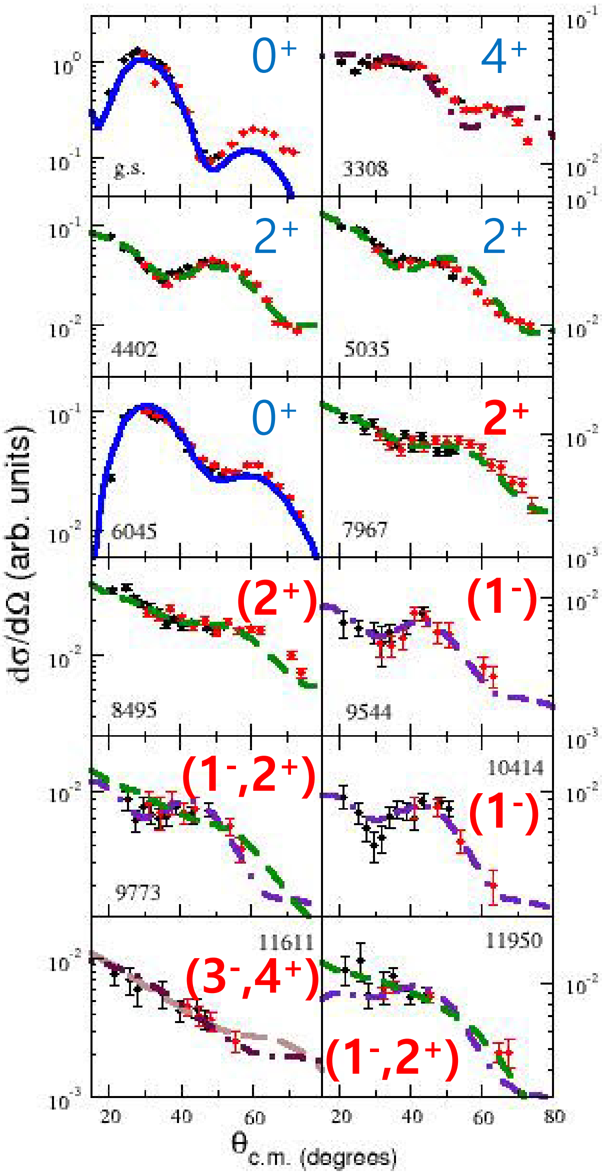
$^{18}Ne+\alpha$ at 8.142 MeV

$^{21}Na+p$ at 5.504 MeV

Differential cross section: $$\left(\frac{d\sigma}{d\Omega}\right)_{r,\theta} = \frac{Y_{r,\theta}}{I\,N\,\Delta\Omega_\theta}$$

yield ($Y_{r,\theta}$), solid angle ($\Delta\Omega_\theta$), # beam particles (I), # target atoms (N)

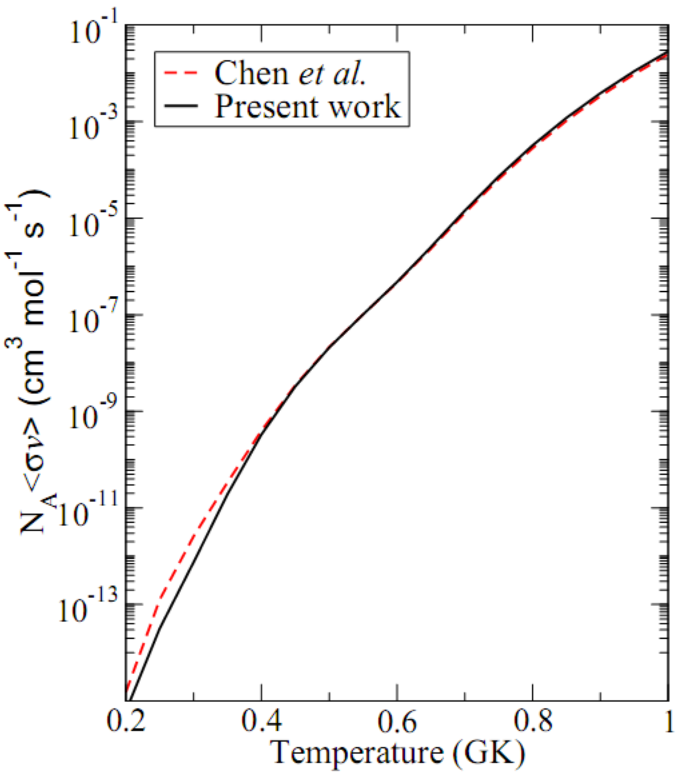
Angular distributions



E_x	0^+	1^-	2^+	3^-	4^+
3308	61.93	9.38	37.60	28.12	4.11
4402	87.85	35.05	5.09	57.35	40.43
5035	54.51	11.88	5.87	31.71	12.58
6045	7.65	55.19	70.18	25.00	20.80
7967	21.50	9.29	2.35	16.24	11.45
8495	19.06	13.31	3.35	14.12	10.38
9544	26.89	3.61	12.93	27.78	22.80
9773	8.49	2.54	4.60	11.15	9.14
10414	12.19	1.21	6.16	16.55	14.00
11611	3.32	3.67	2.46	1.34	1.20
11950	4.30	1.99	0.95	6.04	10.09

- **DWBA calculations** using DWUCK5
- Optical parameters taken from Fleming *et al.* Nucl. Phys. A **162** 225 (1971): $^{16}O(p,t)^{14}O$
- Hauser-Feshbach calculations of $^{24}Mg(p,t)^{22}Mg$ angular distribution → 0.01-5%, nearly flat

$^{18}Ne(\alpha,p)^{21}Na$ reaction rate

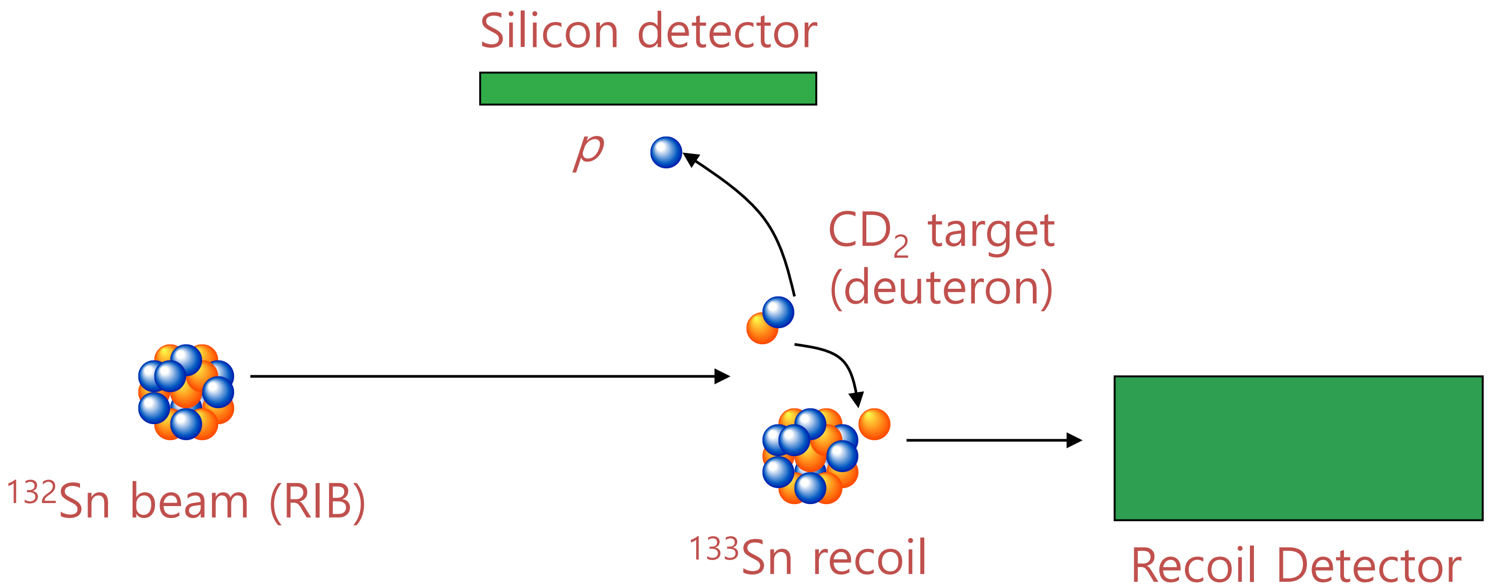


- Resonance parameters from A.A. Chen *et al.* PRC **63**, 065807 (2001)
- 7 levels between 8.495 and 9.827 MeV
- J^π values of 8.945- and 9.773-MeV levels were taken from present work (2^+ and 1^-)
- Resonance strengths have been corrected
- Reaction rate is valid at T = 0.2-1.0 GK
- Can be considered as a lower limit

- Reaction rate is a factor of 4 smaller than the one from Chen *et al.*

Chae *et al.*, Phys. Rev. C 79, 055804 (2009)

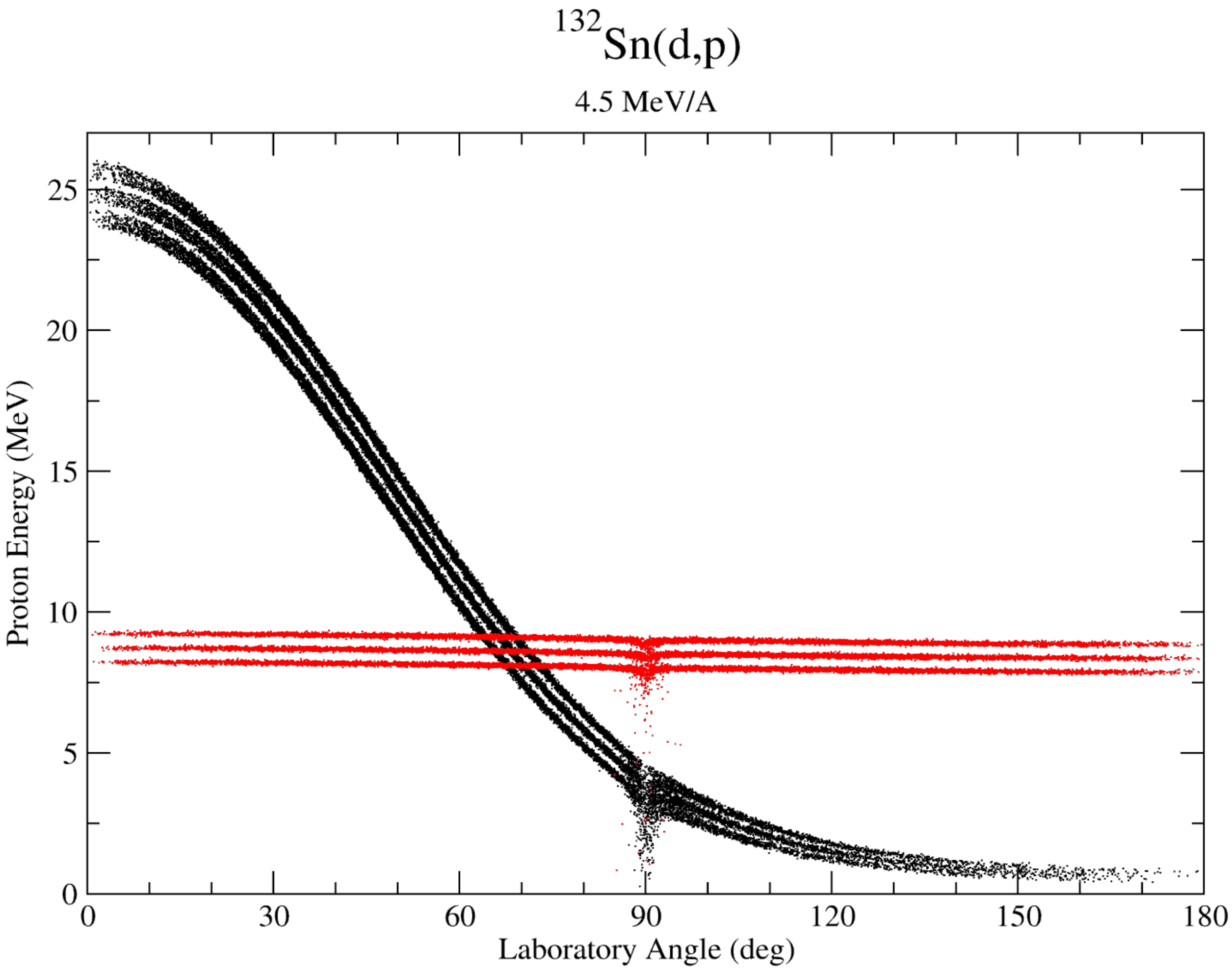
Transfer reaction measurements in inverse kinematics



- short-lived radioactive nuclei beams – various (d,p) reactions are possible
- The proton is ejected over a wide range of angles.

  → large solid angle, good energy resolution are required

(*d,p*) measurements in inverse kinematics



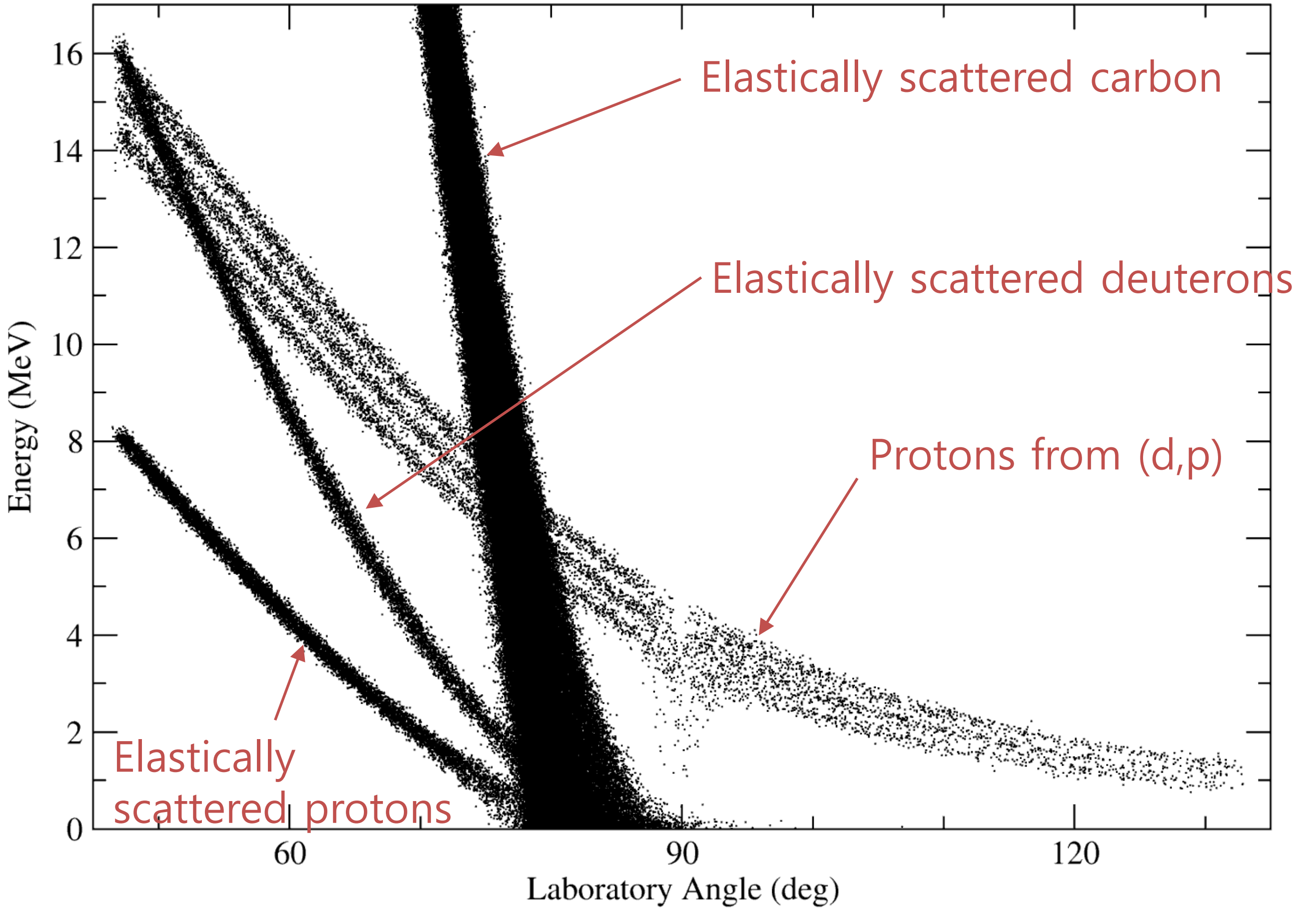
- ^{132}Sn(*d,p*)^{133}Sn reaction: 0-, 1-, and 2-MeV levels
- forward $\theta_{C.M.}$ = backward θ_{lab}
- at backward angle, cross section and E_p become very small
- at forward angle, E_p rises quickly with angle ($dE/d\theta$ is large)

- unfavorable kinematics → Reduced Q-value Resolution

(*d*,*p*) measurements in inverse kinematics

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

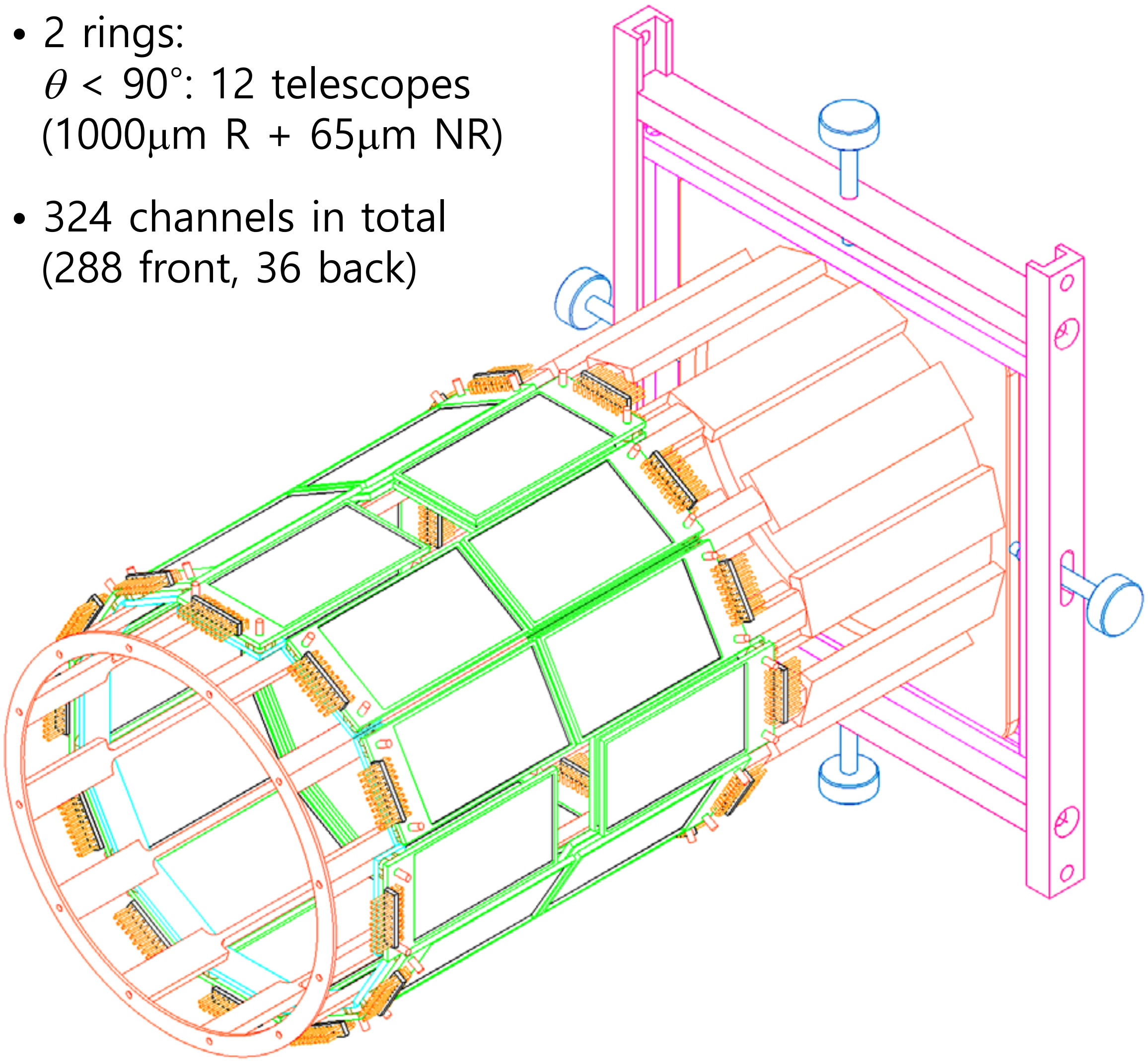
^{132}Sn beam + **CD_2** solid target, E_x = 0, 1, and 1 MeV in ^{133}Sn



- 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/dθ is large)
- High solid angle coverage
- good resolutions (angle & energy)
- large dynamic range
- barrel-type silicon detector array: ORRUBA

Oak Ridge Rutgers University Barrel Array

- 2 rings:
  $\theta < 90°$: 12 telescopes
  (1000μm R + 65μm NR)
- 324 channels in total
  (288 front, 36 back)

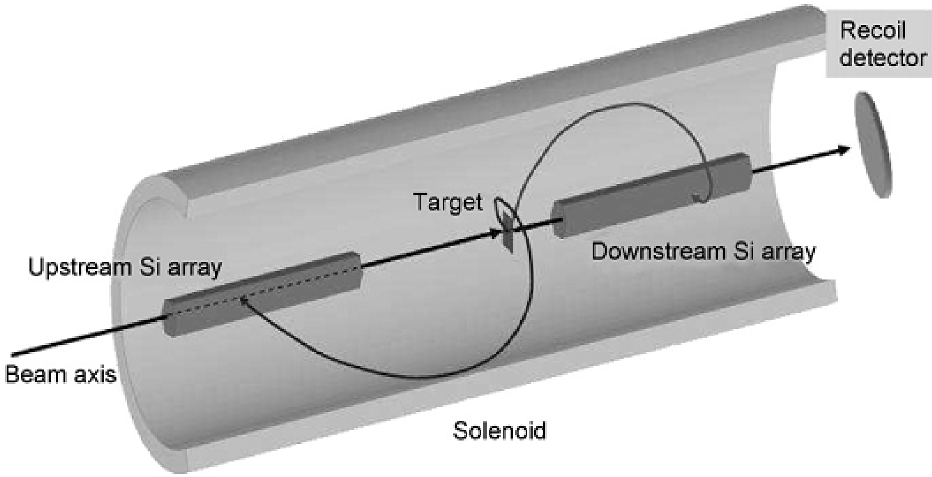


S. D. Pain
ORNL

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.**)
- ^{80}Ge(d,p)^{81}Ge – light fission fragment (S. Ahn, **Phys. Rev. C**)
- ^{126,128}Sn(d,p)^{127,129}Sn – tracking the single-neutron levels (B. Manning, **Phys. Rev. C**)
- ^{134}Te(d,p)^{135}Te – away from double shell closures (S.D. Pain)
- …

Solenoid-based charged particle detector system

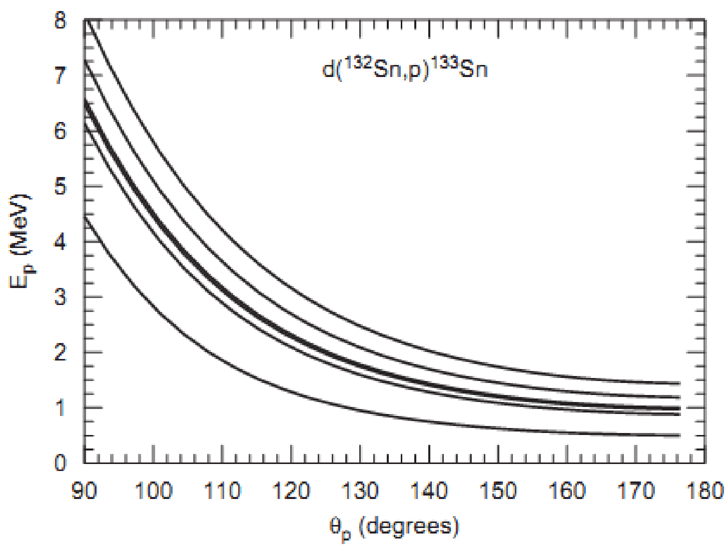


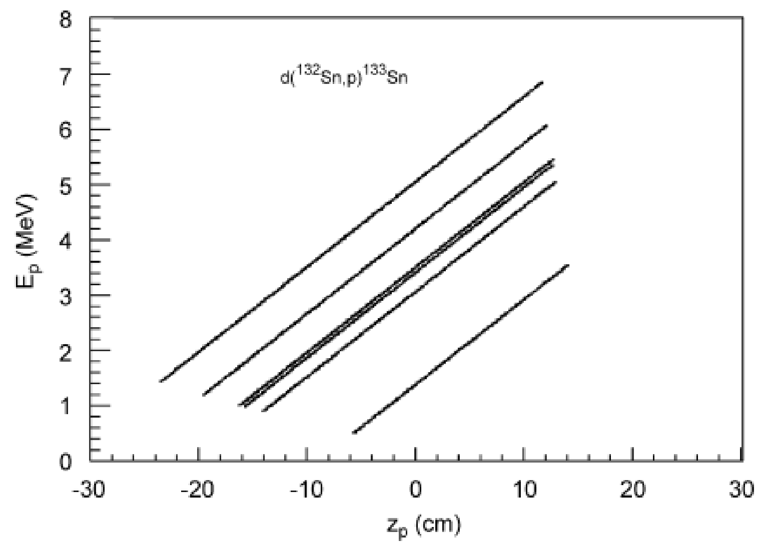
Helical Orbit Spectrometer, HELIOS

- 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

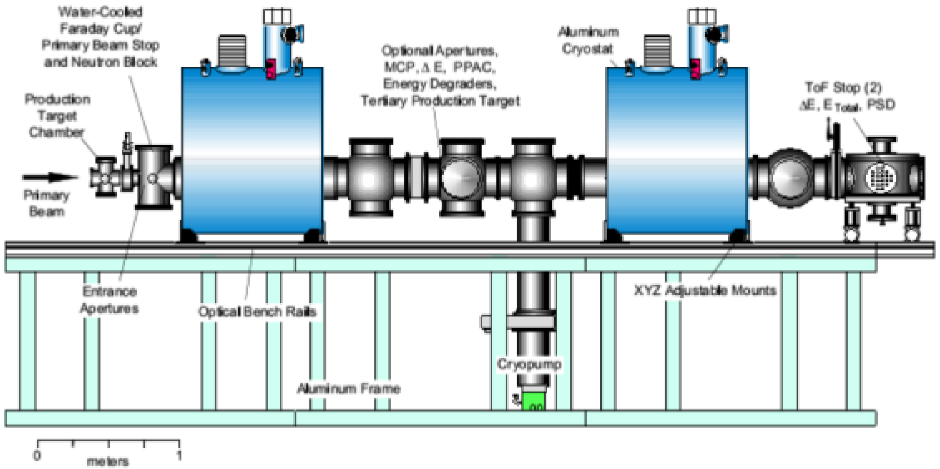
- used with RIBs from ATLAS ^{17}O(d,p), ^{19}O(d,p), ^{86}Kr(d,p), …

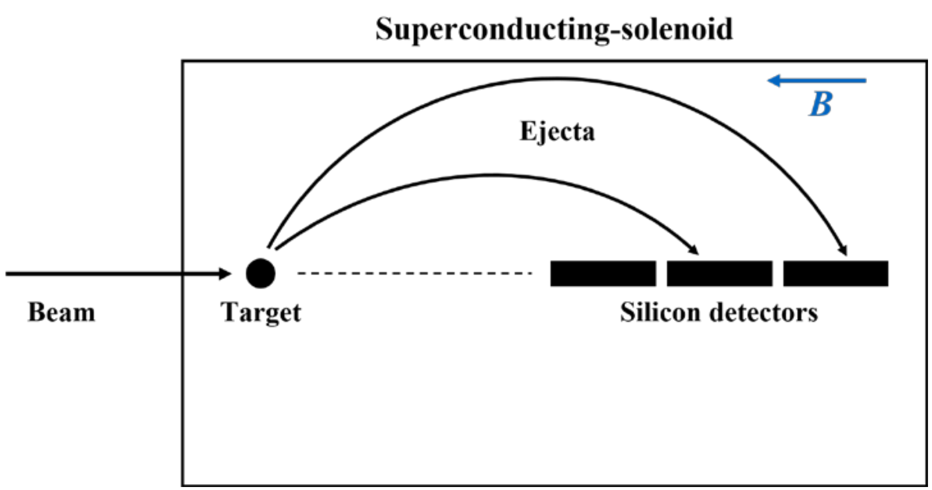




Figures taken from Wuosmaa *et al.*, NIMA 580, 1290 (2007)

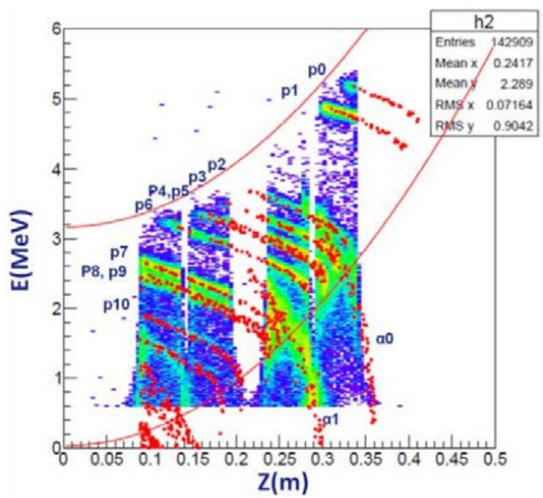
Solenoid Spectrometer for Nuclear Astrophysics (SSNAP)





- 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

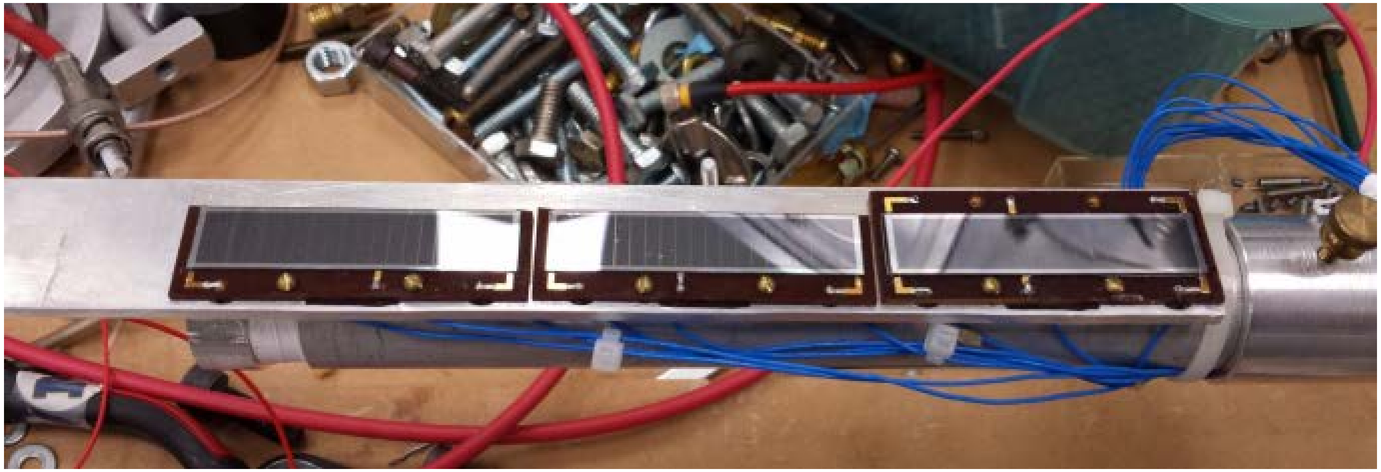
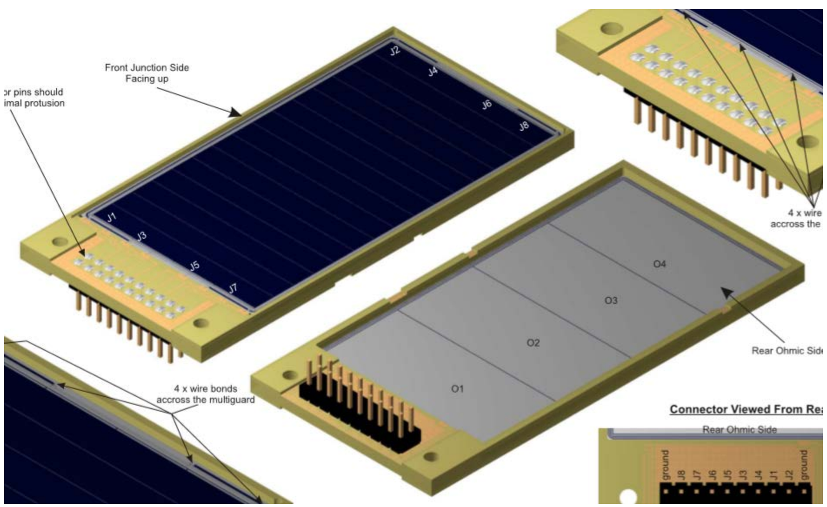


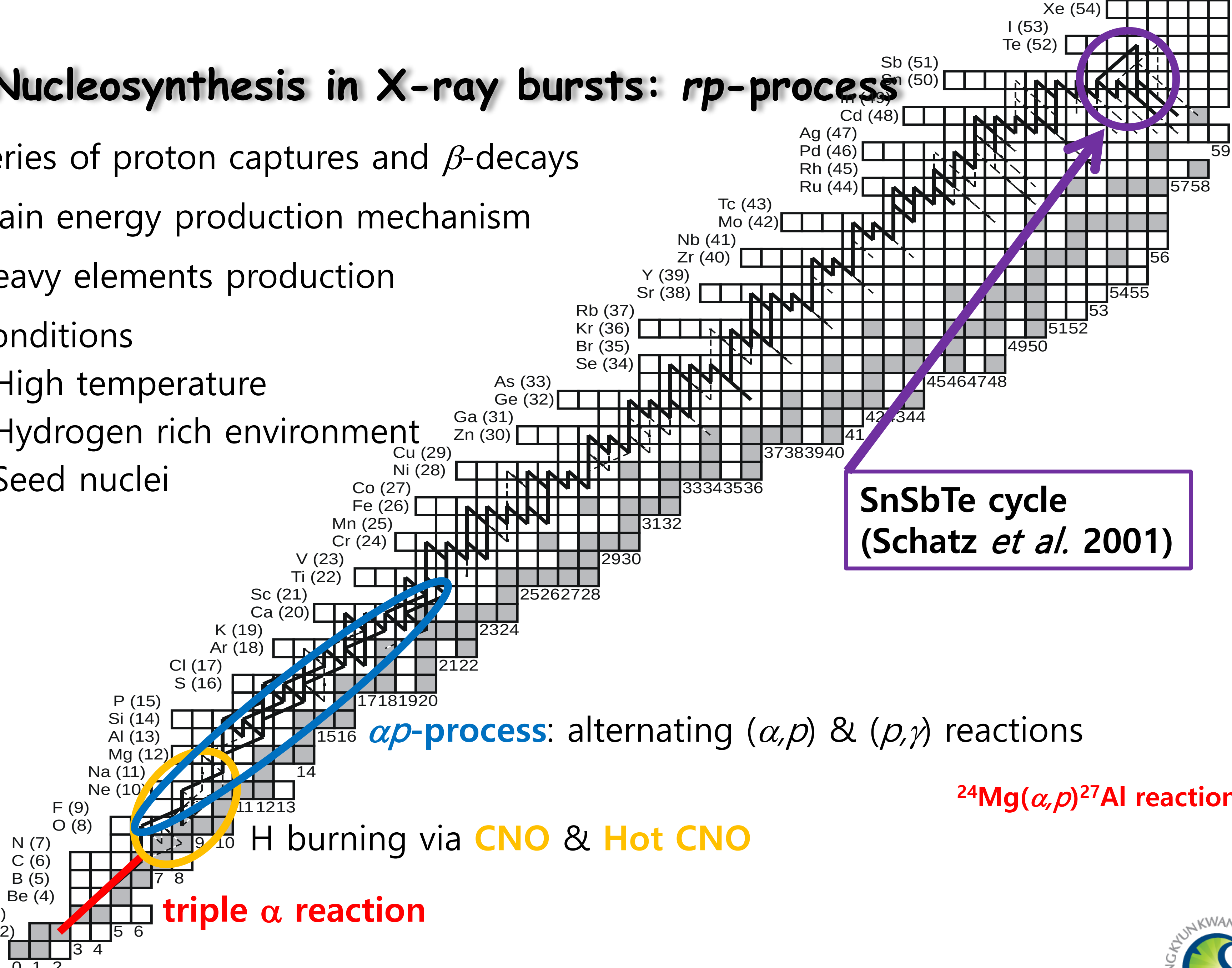
Figure taken from O'Malley



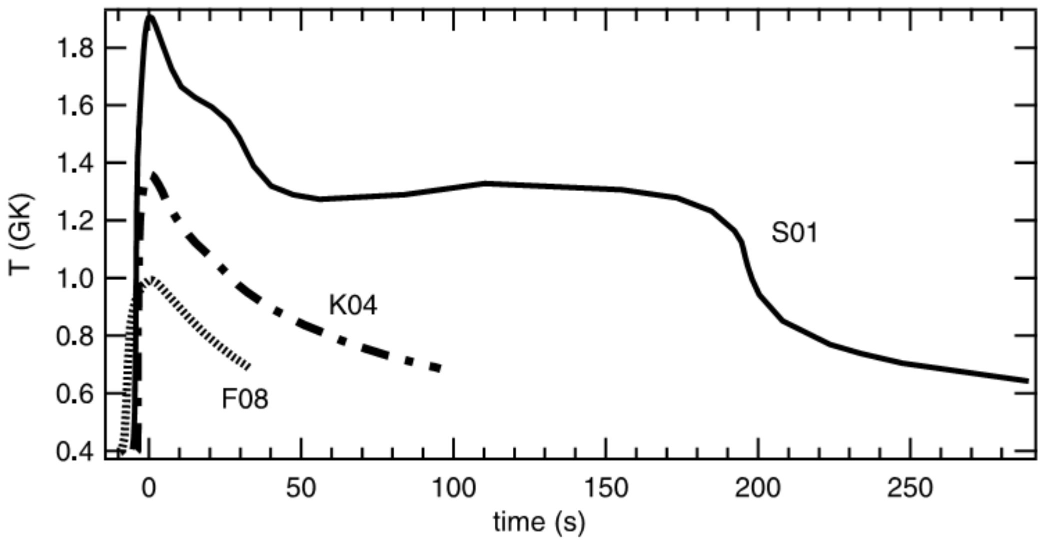
- Super X3 detectors
  - 4 resistive front strips, 4 back segments
  - energy resolution: ~ 55 keV (back), ~ 75 keV (front)
  - position resolution: ~ 1.2 mm
  - 7.5 cm long active area
- updated frame for better data
- versatile array: (*d,p*), (*p,t*), (^{3}He,*t*)…
- ^{12}C(*d,p*)^{13}C measurement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

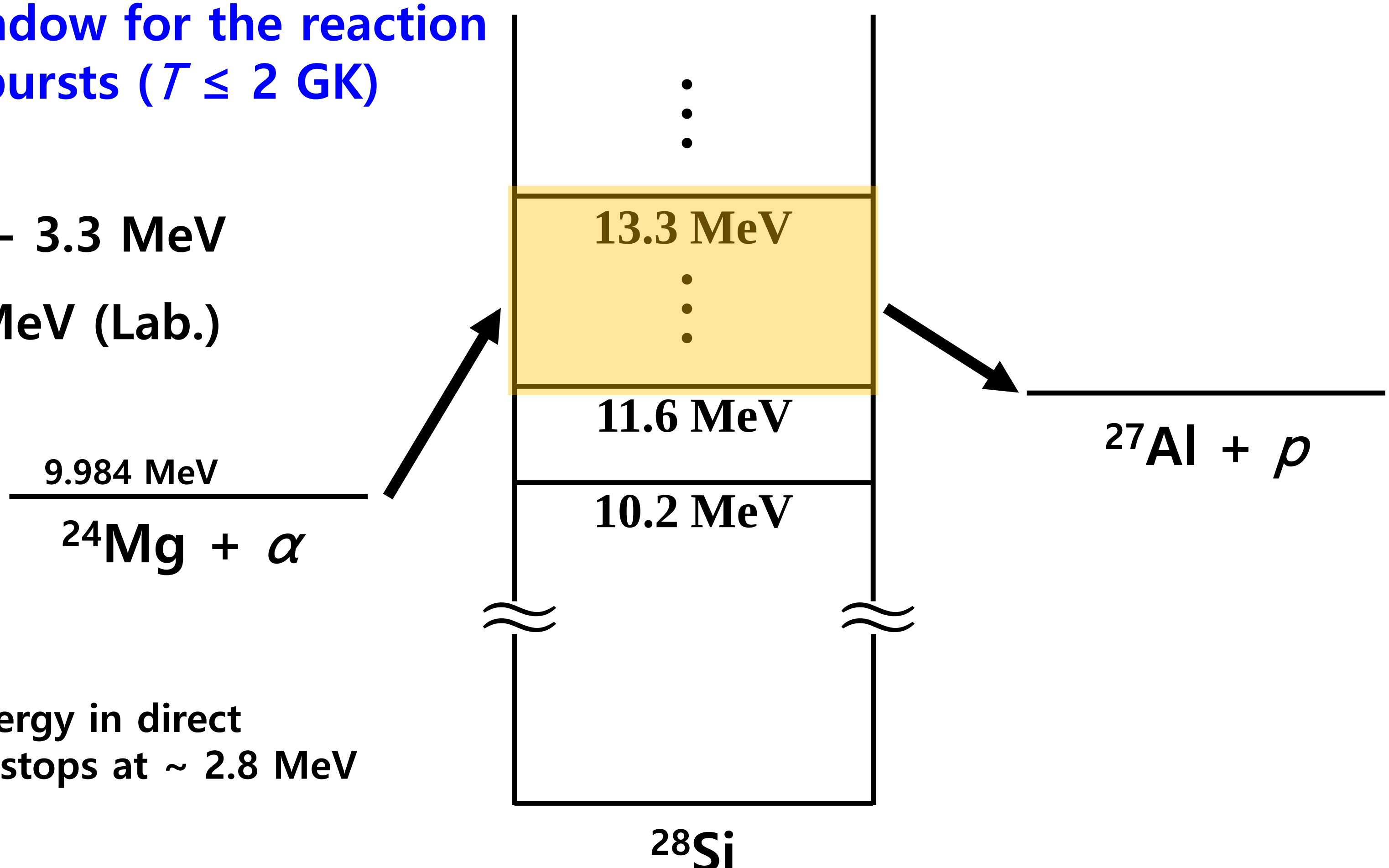
Reaction	Models Affected
^{15}O(α, γ)^{19}Ne^{a}	K04, K04-B1, K04-B6
^{18}Ne(α, p)^{21}Na^{a}	K04-B1, K04-B6
^{22}Mg(α, p)^{25}Al	F08
^{23}Al(p, γ)^{24}Si..................	K04-B1
^{24}Mg(α, p)^{27}Al^{a}	K04-B2
^{26g}Al(p, γ)^{27}Si^{a}...............	F08
^{28}Si(α, p)^{31}P^{a}	K04-B4
^{30}S(α, p)^{33}Cl....................	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(α,p)^{27}Al reaction

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

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

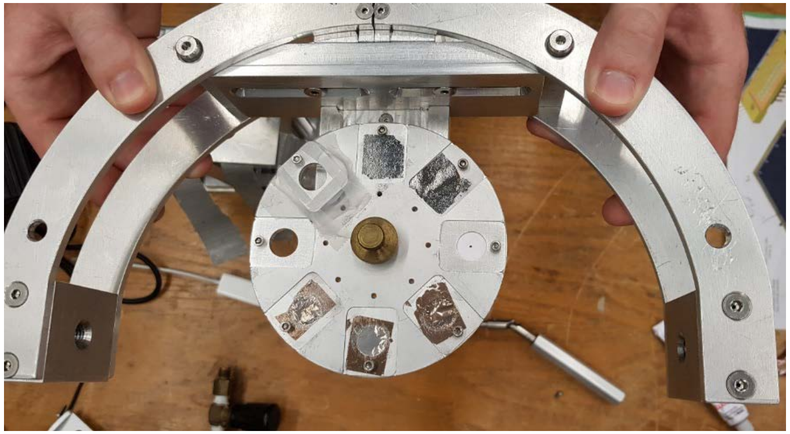
$E_p \leq$ ~ 2 MeV (Lab.)



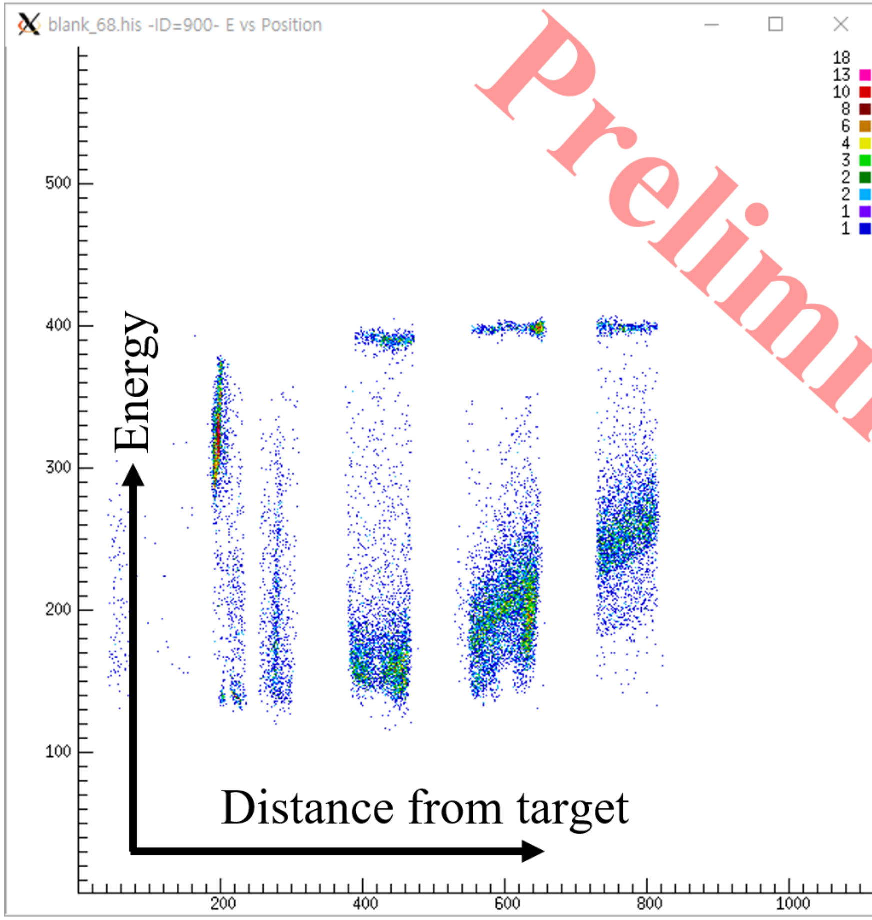
The lowest energy in direct measurement stops at ~ 2.8 MeV

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

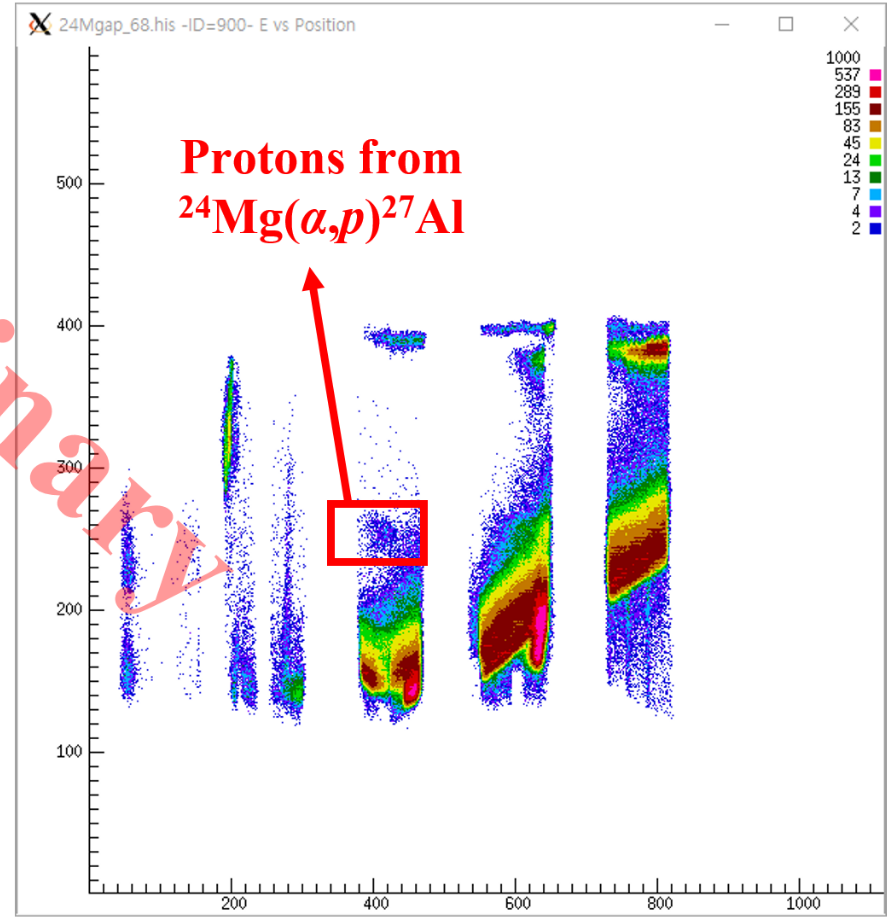
- α beams (I ~ 2 nA) from 10 MV FN tandem accelerator
- E_{beam} = 3 - 5 MeV ($E_{c.m.}$ = 2.6 – 4.3 MeV)
- evaporated ^{24}Mg solid targets (~ 50 μg/cm^2 thick) on thin ^{12}C backing material (~ 5 μg/cm^2 thick)
- ΔE_{beam} ~ 30-40 keV, about 40 beam energies
- ~ few hours per beam energy



Preliminary results



Blank frame

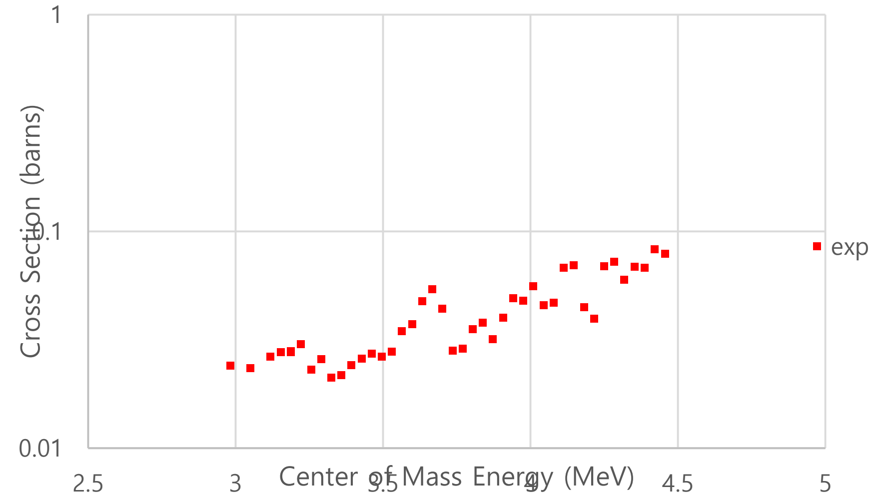


^{24}Mg target

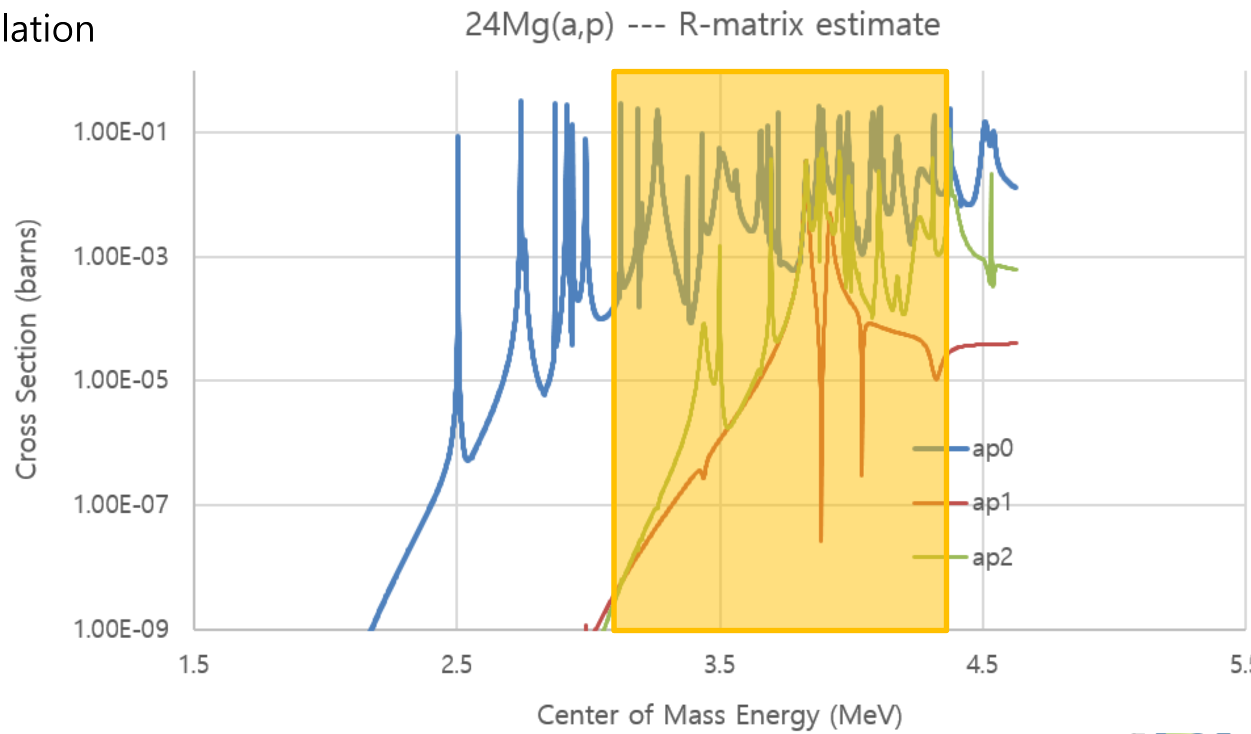
Future Plan

- develop simulation code for SSNAP
- extract differential cross section values at $E_{\mathrm{c.m.}}$ = 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

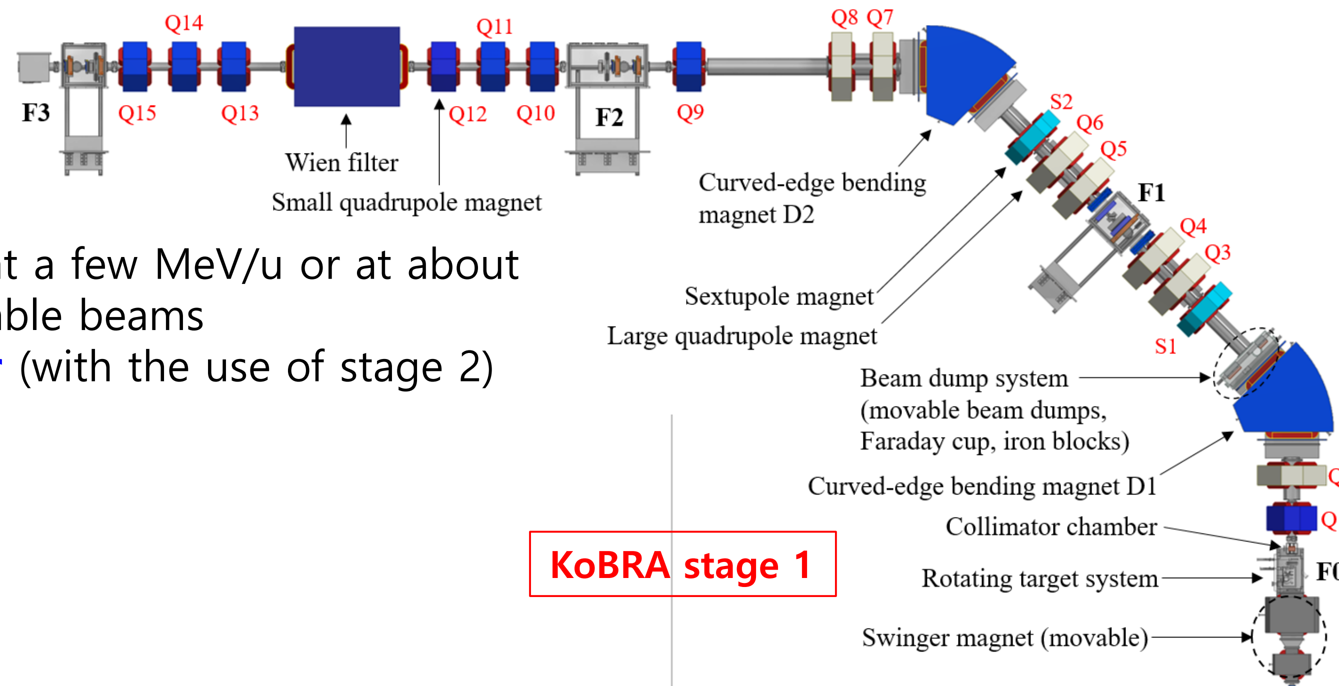
Gyoungmo Gu
SKKU



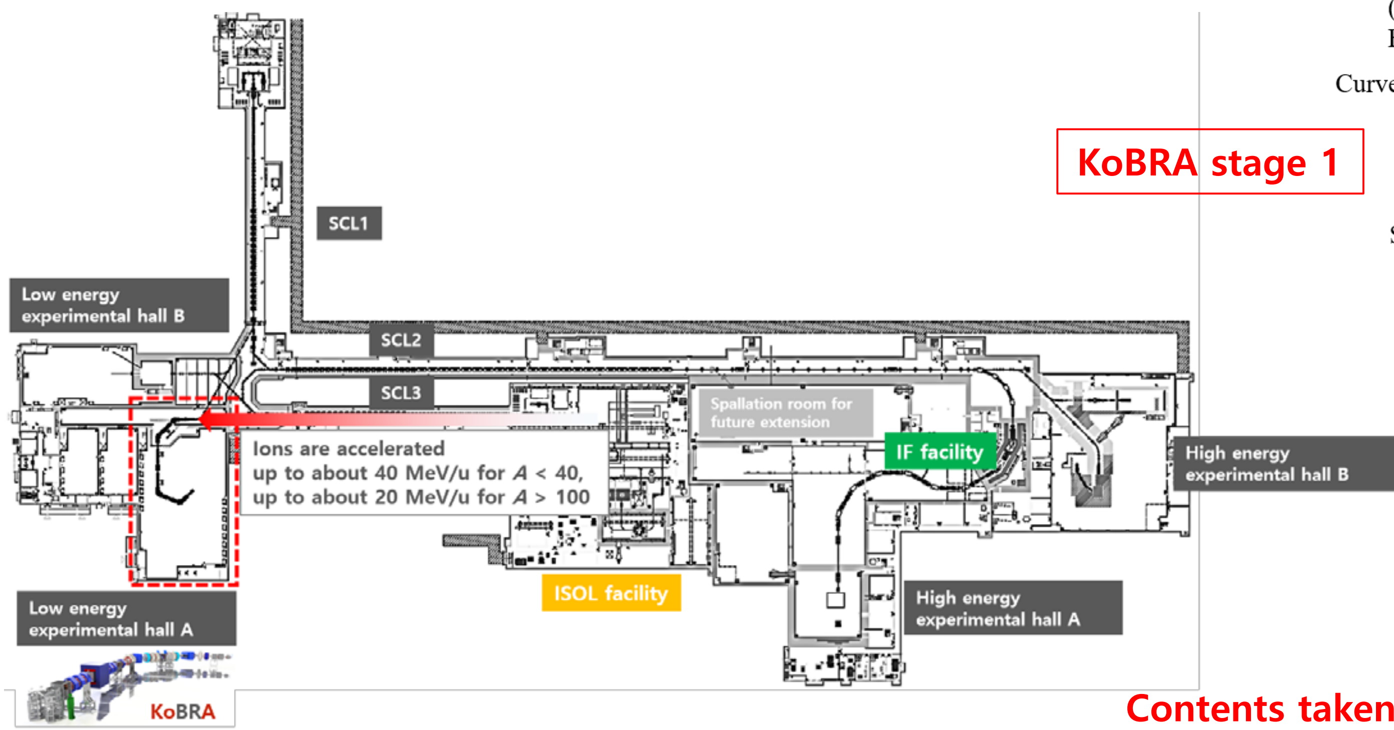
^{27}Al+p [Nelson *et al.* PRC **29**, 1656 (1984)] and ^{24}Mg(α,α) [Nucl. Phys. A **385**, 43 (1982)]



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)



Contents taken from Dr. Tshoo

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!