Recent transfer reaction measurements using 30.5 MeV proton beams at JAEA tandem accelerator

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http://nucastro.skku.edu

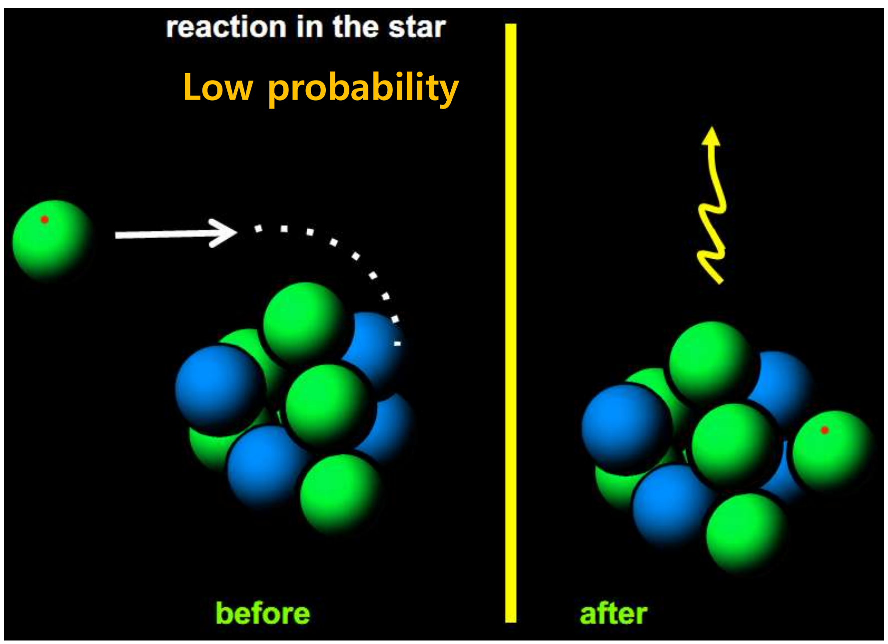
Transfer reactions

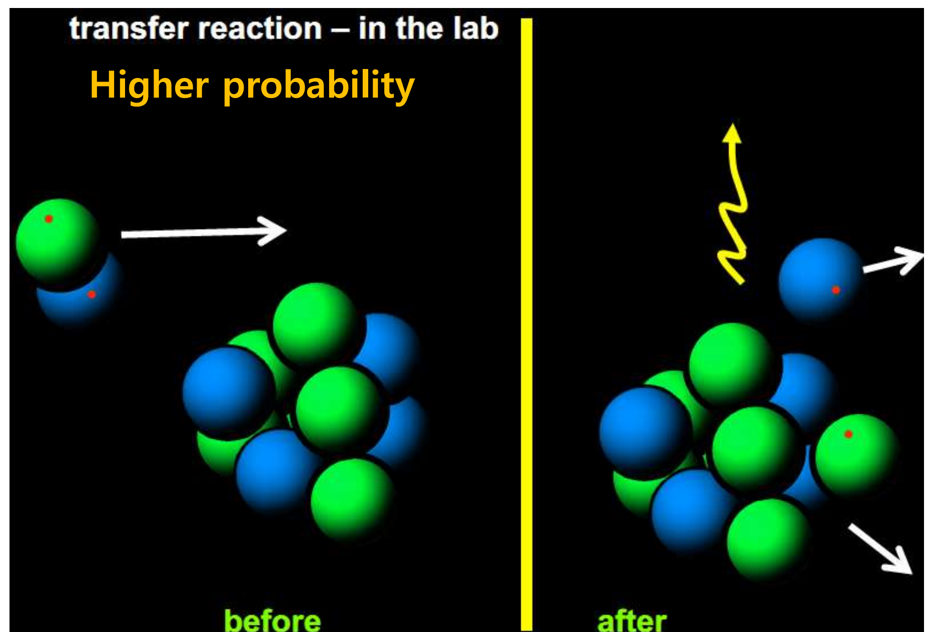
- (*d,p*) deuteron 'stripping' reaction by Butler *et al.* (1967)

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

- 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



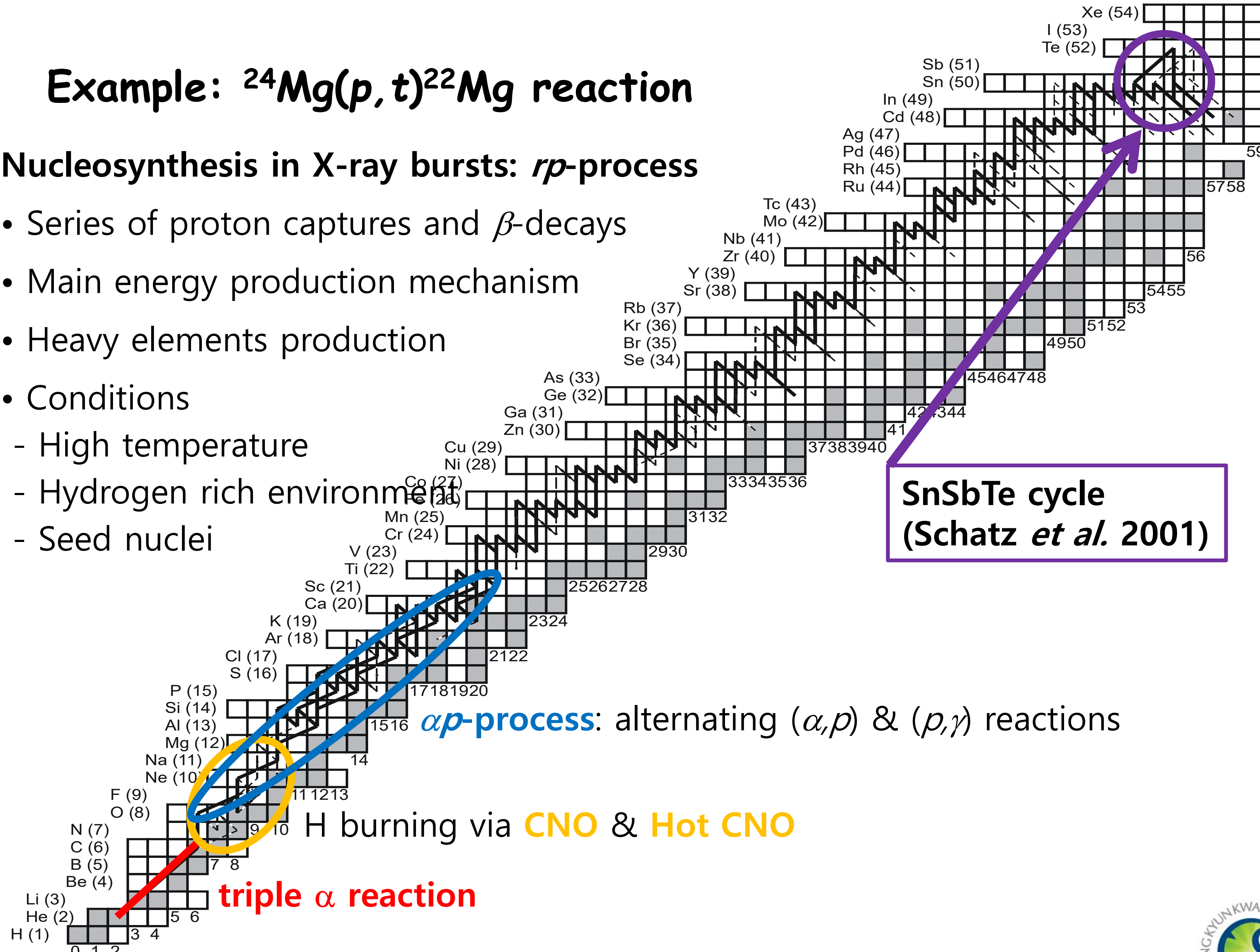


https://www.phy.ornl.gov/groups/astro/measurements/transfer.html

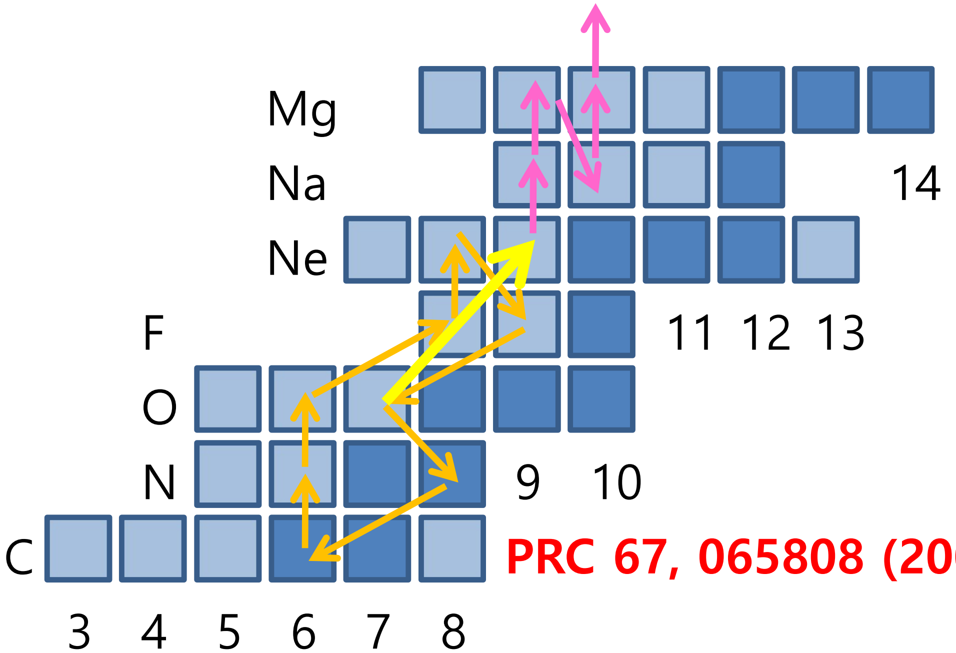
Example: ^{24}Mg(p,t)^{22}Mg reaction

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

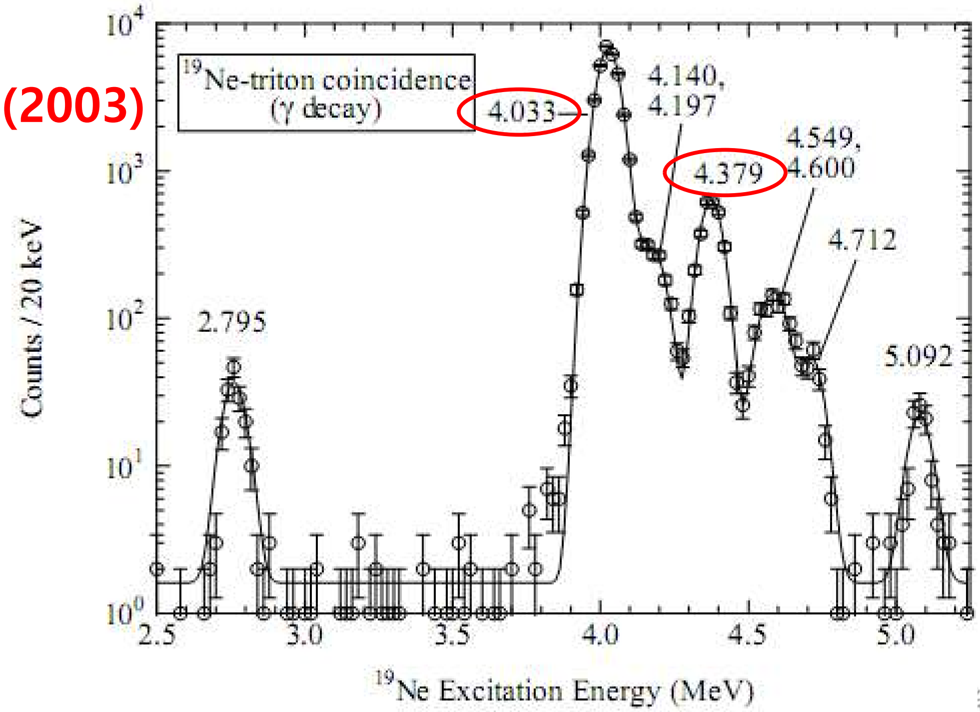


Previous studies on the breakouts: $^{15}O(\alpha,\gamma)^{19}Ne$



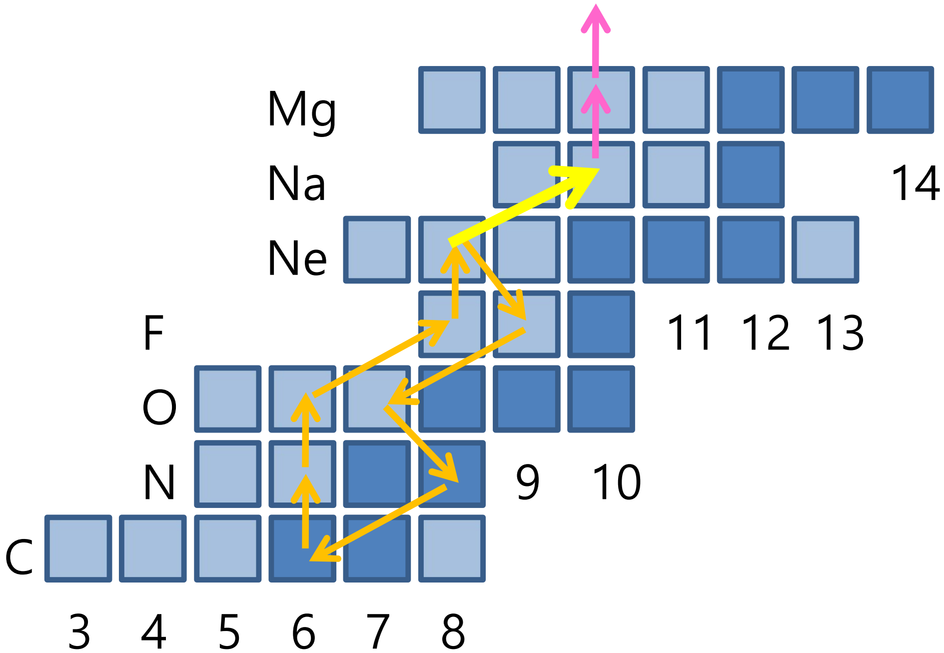
PRC 67, 065808 (2003)

- B. Davids *et. al.* (2003)
  - $^{21}Ne(p,t)^{19}Ne$ reaction
- Measured near α threshold (**3.529 MeV**) levels in ^{19}Ne
- Measured branching ratios
- Determined decay widths



- $^{15}O(\alpha,\gamma)^{19}Ne$ reaction rate
- Hydrodynamic calculations of nova outbursts
- No significant breakout from the Hot CNO cycle to *rp*-process

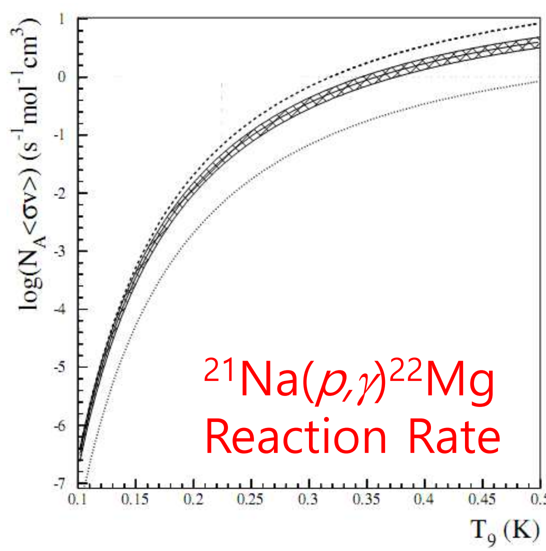
Previous studies on the breakouts: ^{18}Ne(α,p)^{21}Na



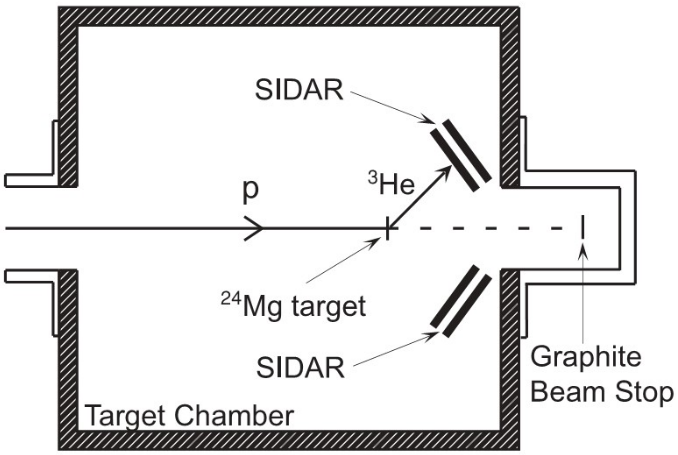
- α threshold in ^{22}Mg (8.142 MeV)
- W. Bradfield-Smith *et. al.* (1999)
  - ^{18}Ne(α,p)^{21}Na reaction
  - 6 levels in ^{22}Mg between 10.5 & 11.3 MeV
  - J^{π}'s were assigned for 3 levels
- A.A. Chen *et. al.* (2001)
  - ^{12}C(^{16}O,^{6}He)^{22}Mg reaction study
  - Found 18 new levels over wide range

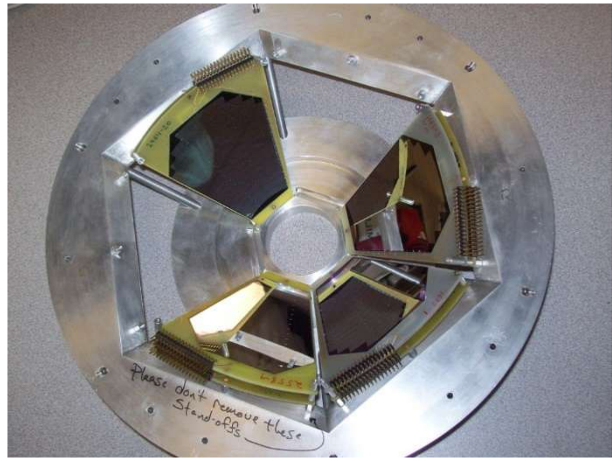
- ^{18}Ne(α,p)^{21}Na reaction rate calculations
- Uncertainty in the reaction rate
- Spins & Parities assignments are still required

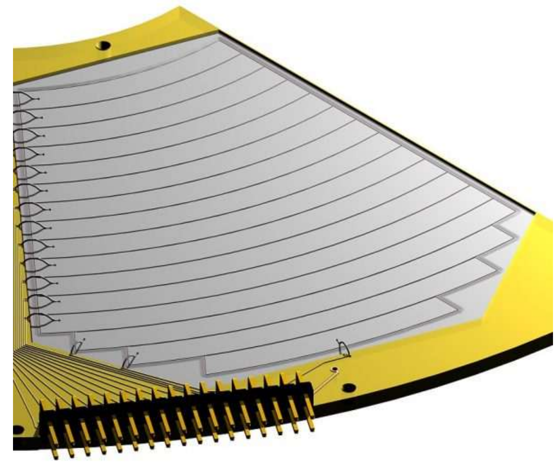
S. Bishop *et. al.*
PRL **90**, 162501 (2003)



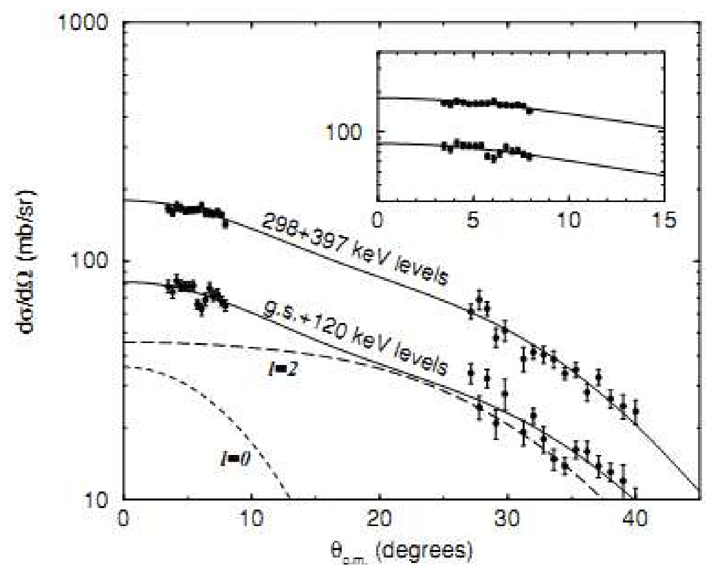
^{24}Mg(p,t)^{22}Mg reaction study (for ^{18}Ne(α,p)^{21}Na)



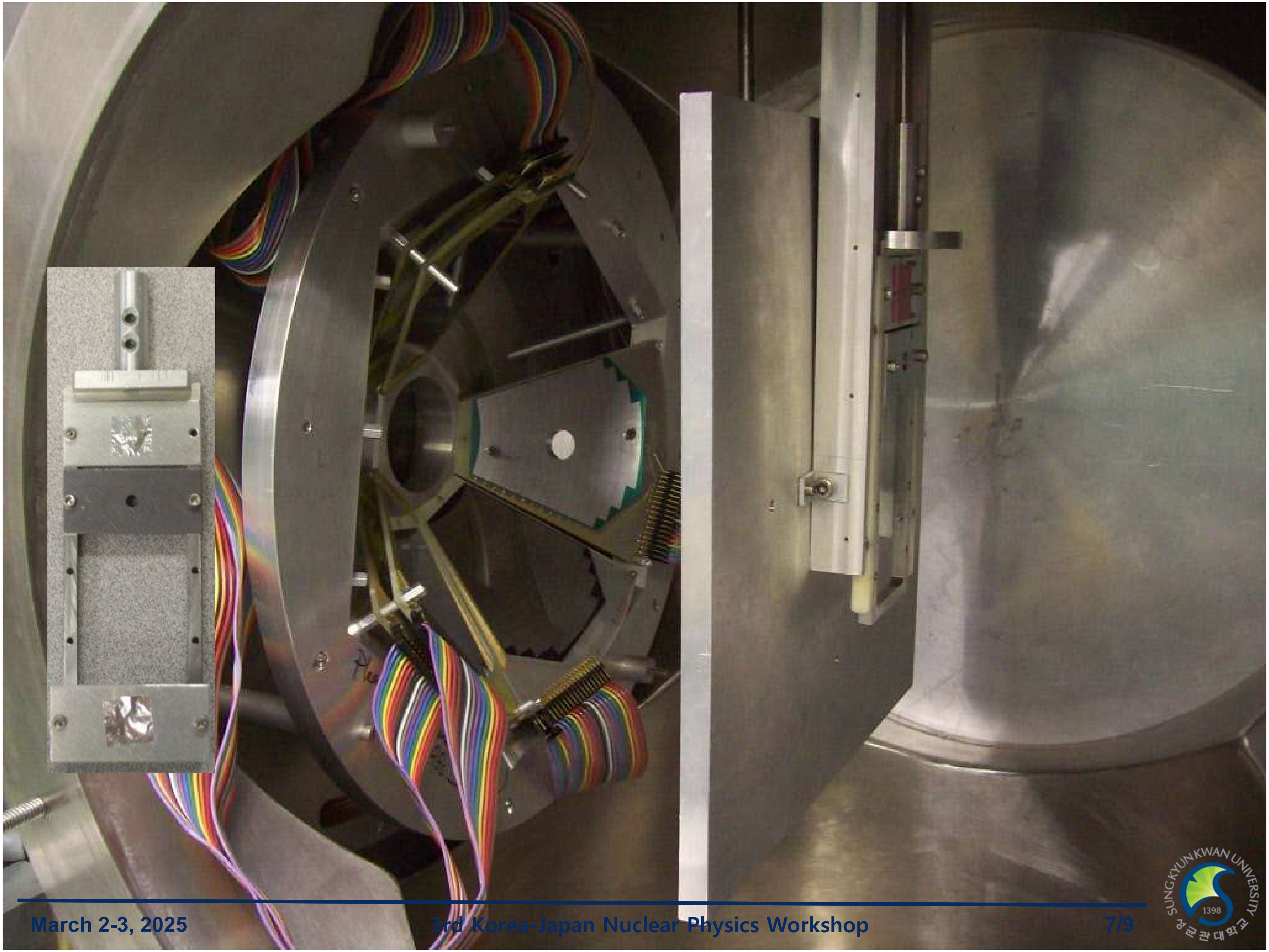




- 16 radial strips (5-13 cm)
  → angular distributions
- 100 μm - 1000 μm
  → "telescope mode" for particle ID
  ($\Delta E \cdot E \propto MZ^2$)
- proton beams from tandem accelerator
  (E_{beam} = 41 & 41.5 MeV)
- 500 μg/cm^2 pure ^{24}Mg targets
- lab angles: 18-48˚, 27-69˚
- BCI for normalization

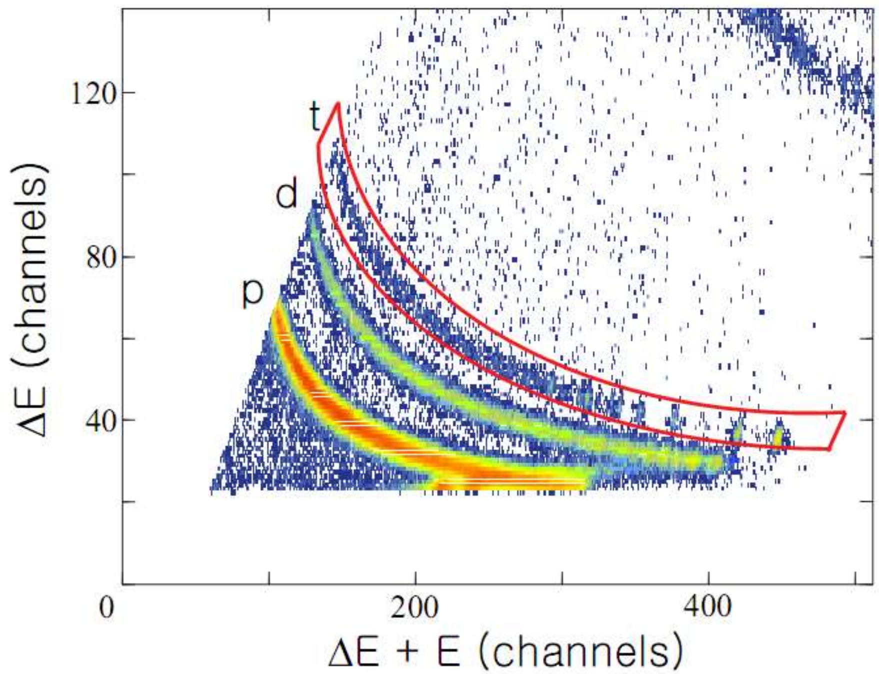


Bardayan *et al.*, Phys. Rev. C **78**, 052801(R) (2008)



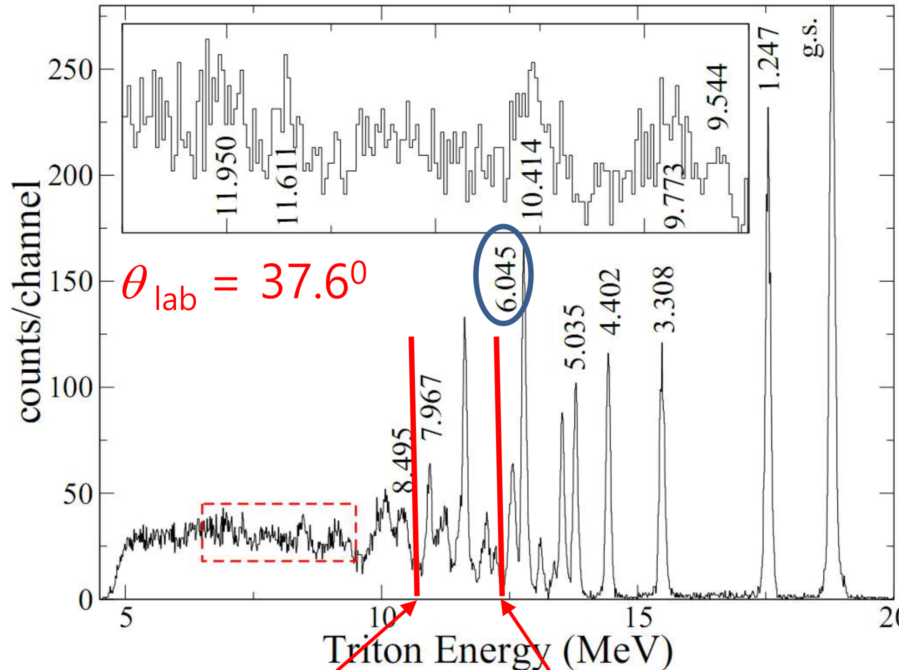
Results

Particle Identification



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

Energy spectrum



^{18}Ne+α at 8.142 MeV

^{21}Na+p at 5.504 MeV

Differential cross section:

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

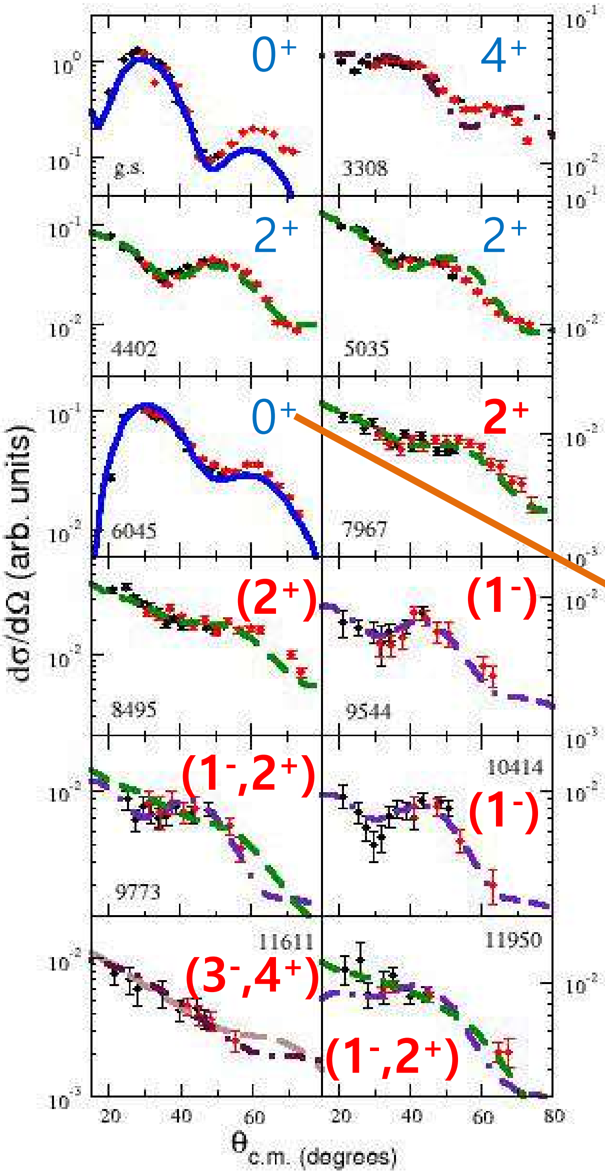
yield

solid angle

beam particles

target atoms

Angular distributions



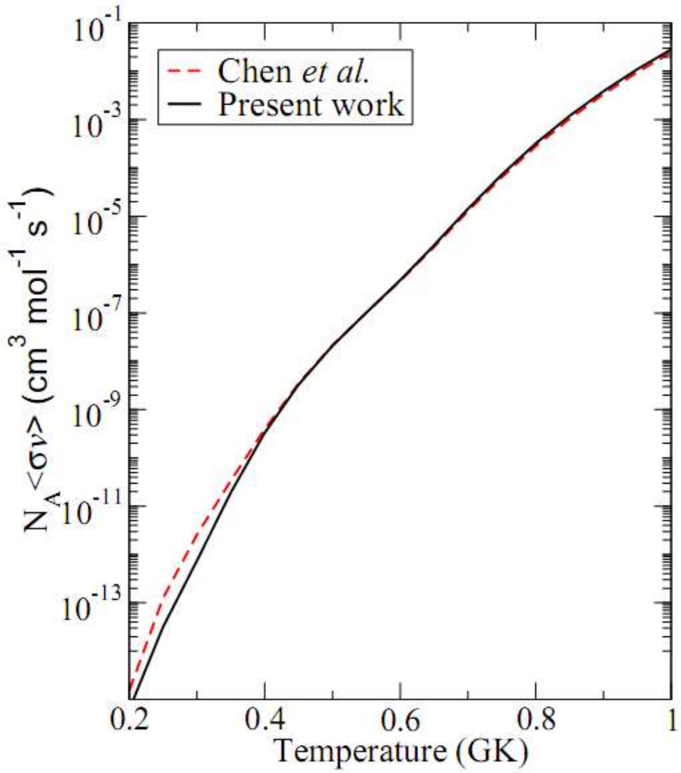
E_x	0^+	1^-	2^+	3^-	4^+
3308	61.93	9.38	37.60	28.12	4.11
4402	87.85	35.05	5.09	57.35	40.43
5035	54.51	11.88	5.87	31.71	12.58
6045	7.65	55.19	70.18	25.00	20.80
7967	21.50	9.29	2.35	16.24	11.45
8495	19.06	13.31	3.35	14.12	10.38
9544	26.89	3.61	12.93	27.78	22.80
9773	8.49	2.54	4.60	11.15	9.14
10414	12.19	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

6237 keV in ^{22}Ne (0^+)

5910 keV in ^{22}Ne (3^-)

- **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

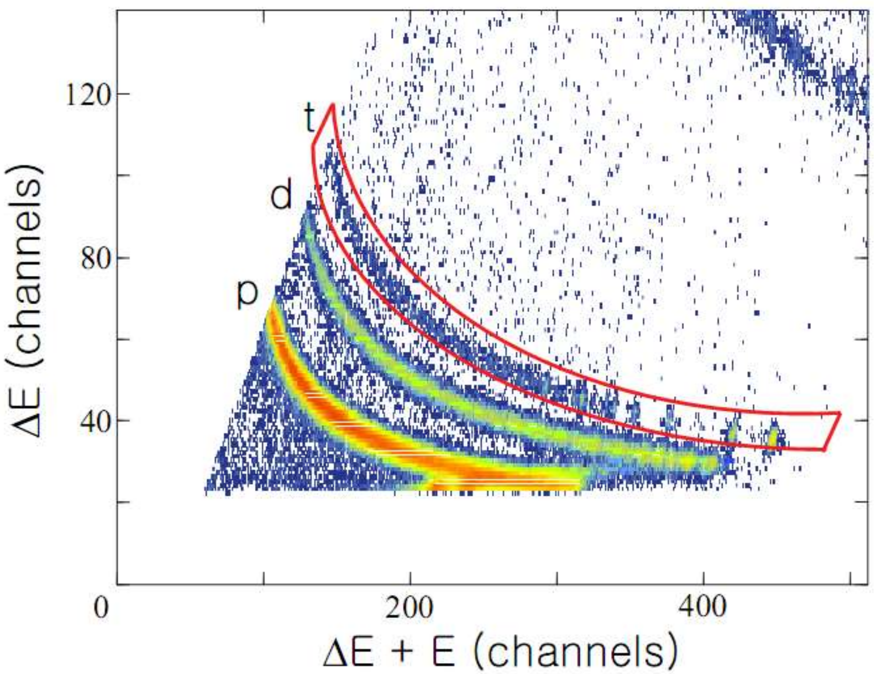


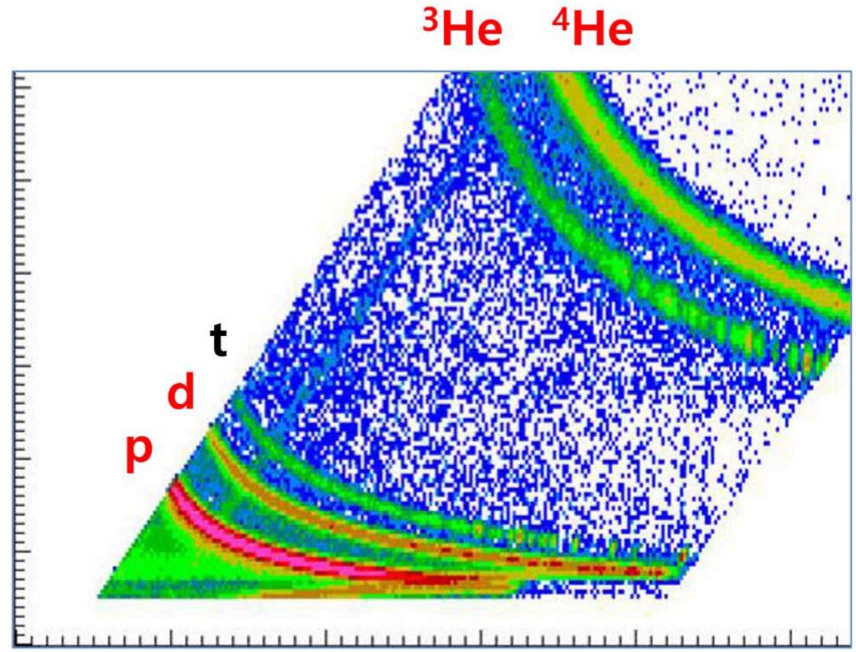
- Resonance parameters from A.A. Chen *et al.* PRC **63**, 065807 (2001)
- 7 levels between 8.495 and 9.827 MeV
- J^{π} values of 8.945- and 9.773-MeV levels were taken from present work (2^+ and 1^-)
- Resonance strengths have been corrected
- Reaction rate is valid at T = 0.2-1.0 GK
- Can be considered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

Wait a minute… (p,^{3}He)?

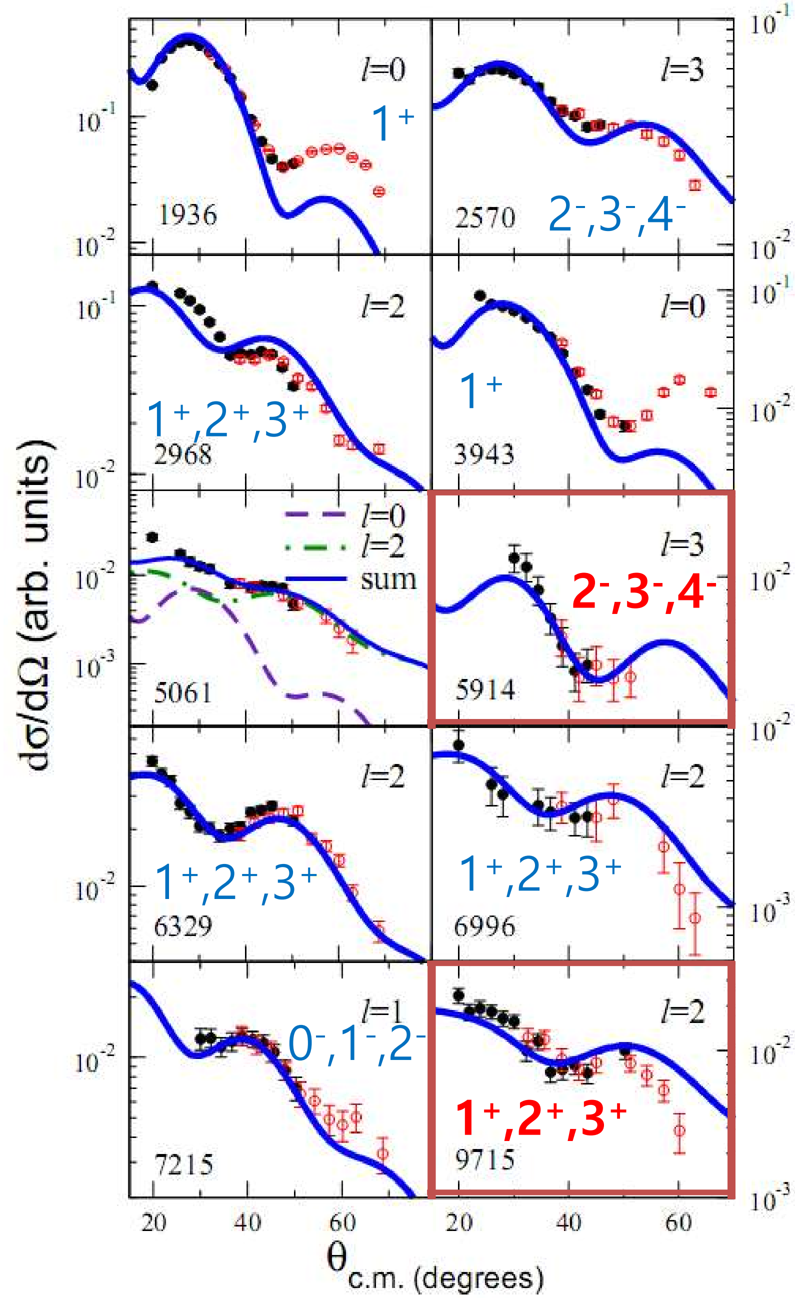




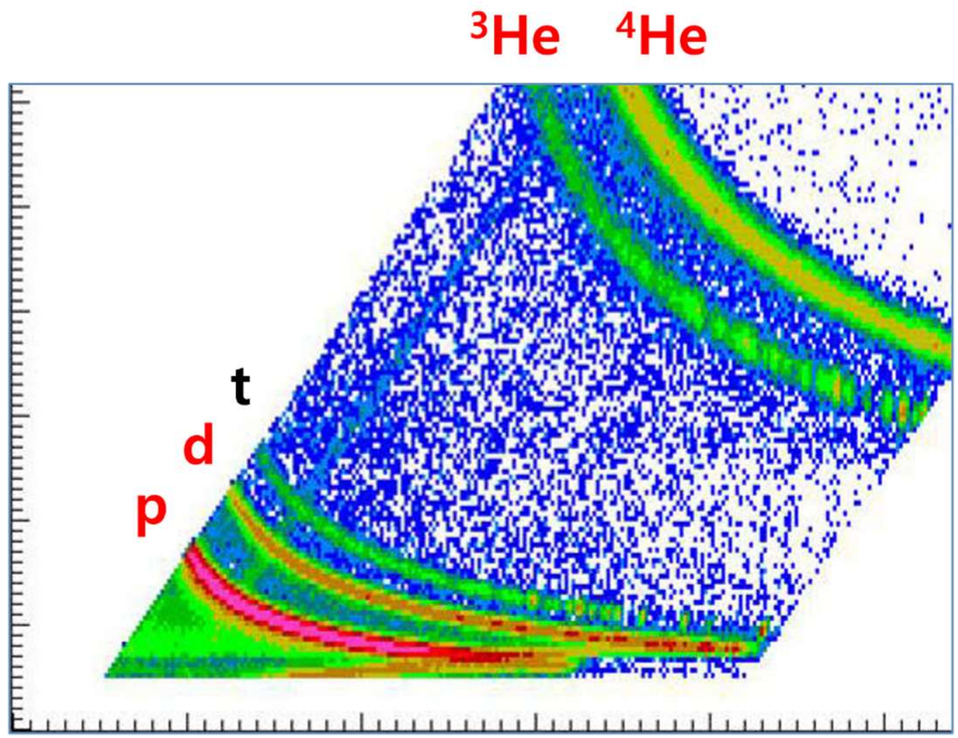
$^{24}Mg(p,^{3}He)^{22}Na$

- Angular distributions for 10 levels
- zero-range DWBA calculations using DWUCK4
- Optical model parameters were taken from Nucl. Phys. **A162**, 225 (1991) – $^{16}O(p,t)$, $(p,^{3}He)$
- J^{π} for 5914 and 9715 keV levels are constrained for the first time
- 5061 keV: *l*=0 (71%) + *l*=2 (29%)
- 6996 keV: 1^+, 2^+, 3^+ (previously: 1^+, 2, 3^+)

Chae *et al.*, Phys. Rev. C 82, 047302 (2010)



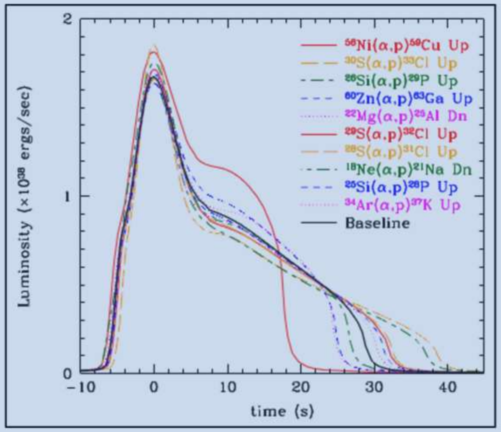
still more channels

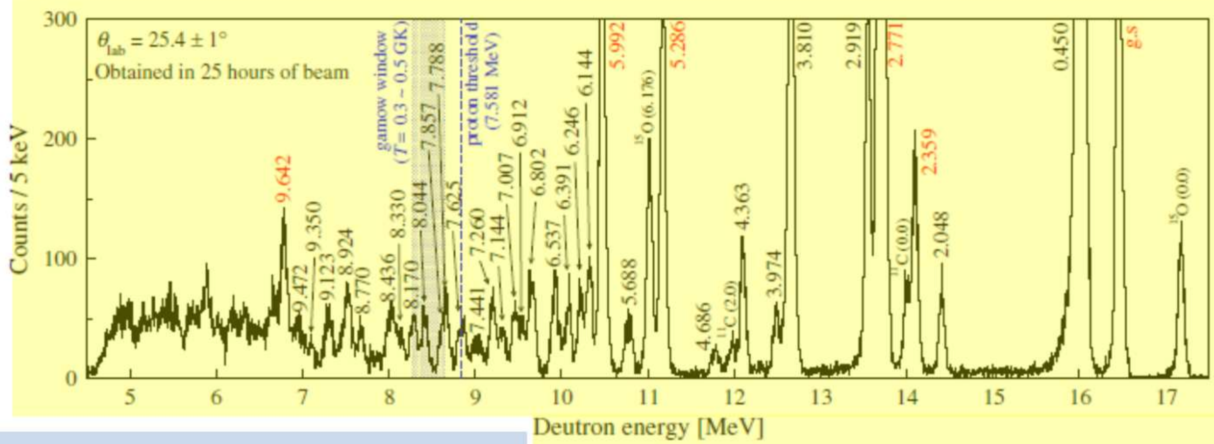


More results!

^{22}Na(p,γ)^{23}Mg reaction rate:

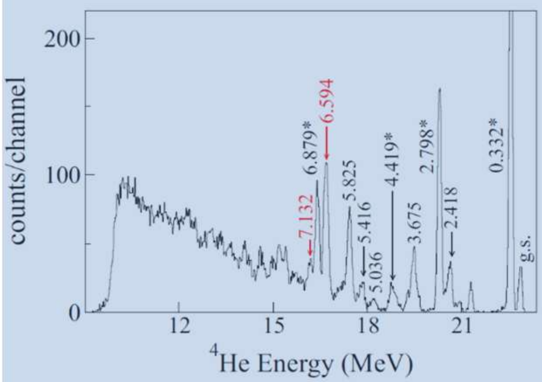
1.275 MeV γ-rays from decay of ^{22}Na for nova explosion

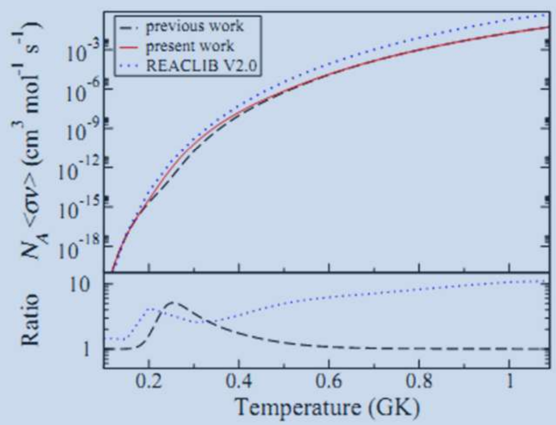


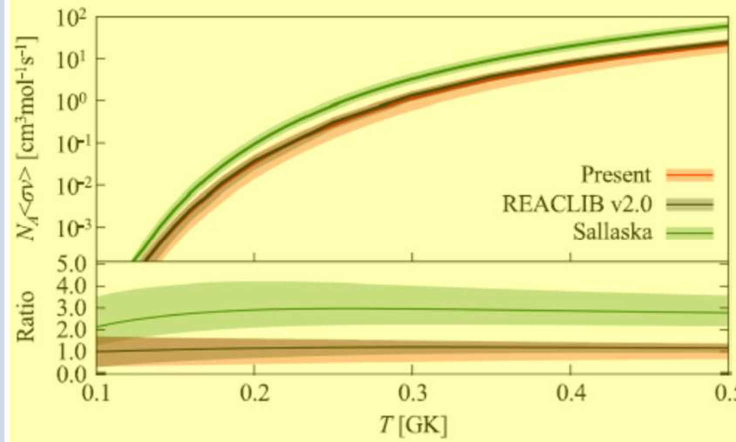


Astrophysical ^{17}F(α,p)^{20}Ne reaction rate:

Light curve of X-ray bursts





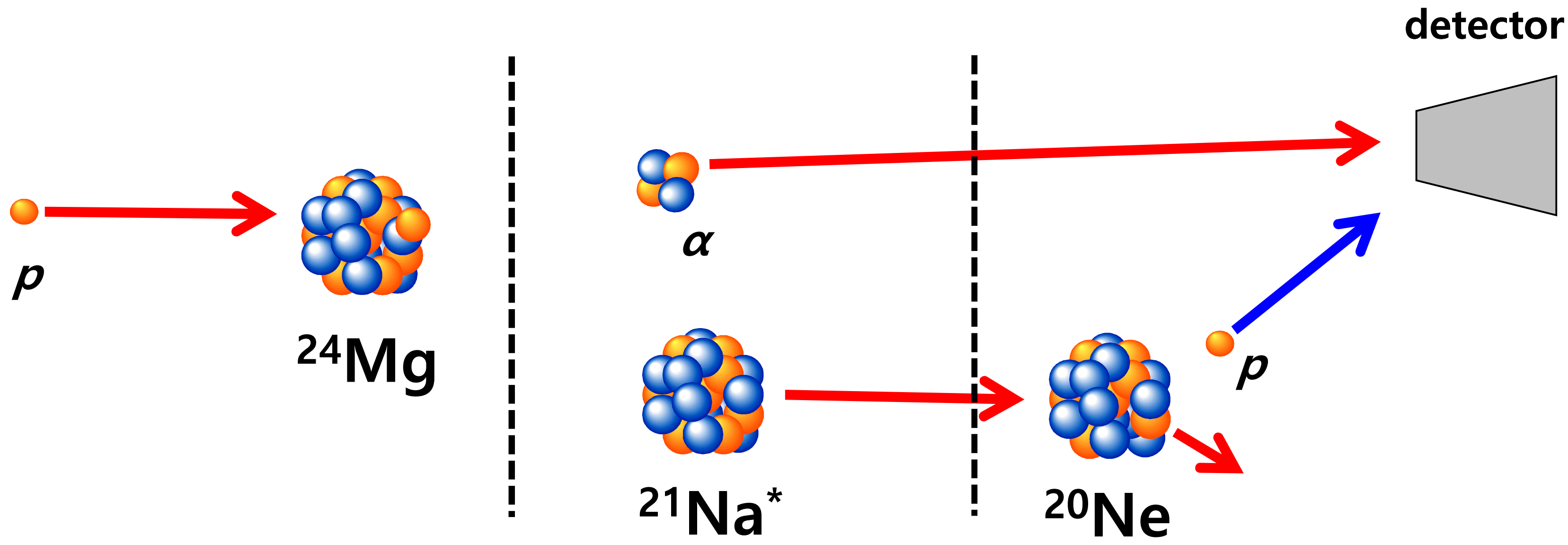


M.S. Kwag *et al.*,

Eur. Phys. J. A56, 108 (2020)

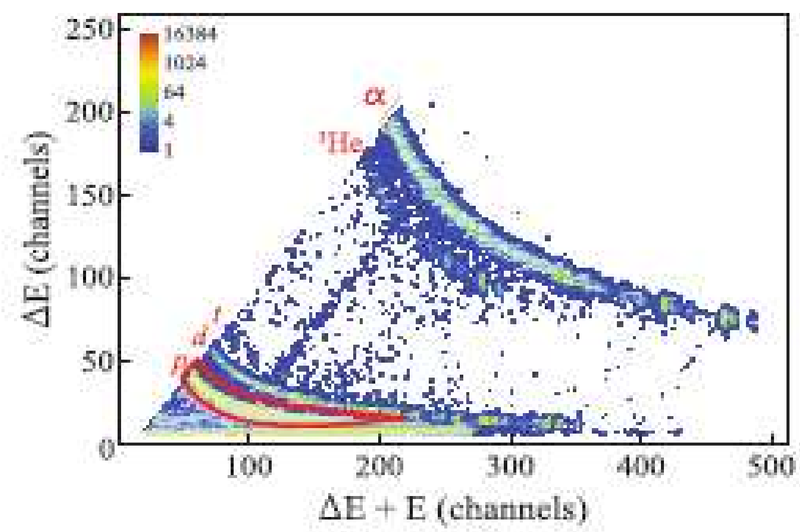
S.M. Cha *et al.*, Phys. Rev. C 96, 025810 (2017)

What happens to the radionuclides?

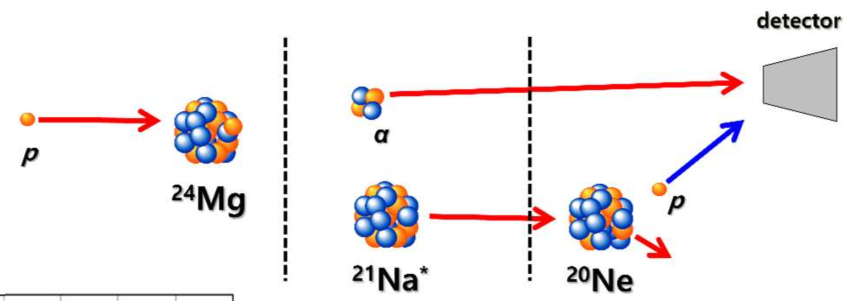


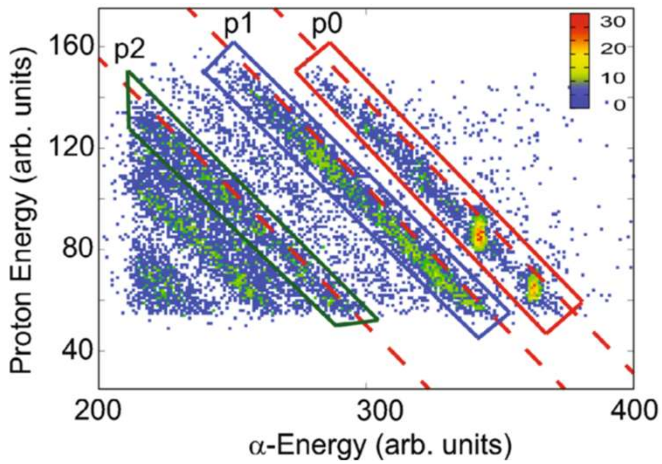
Coincidence between

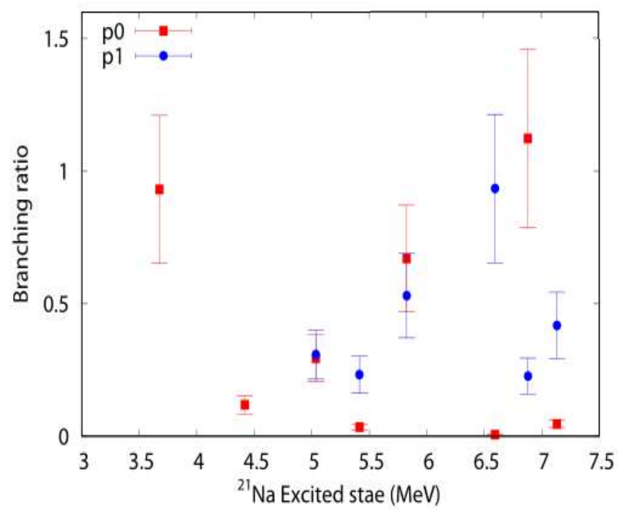
the reaction α particle and decay proton!

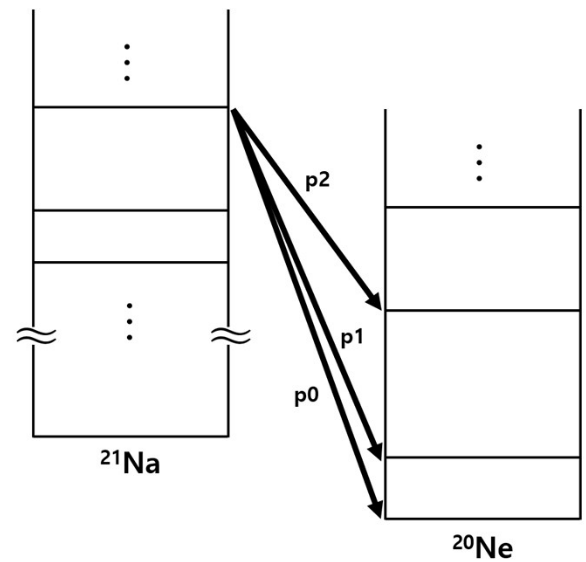


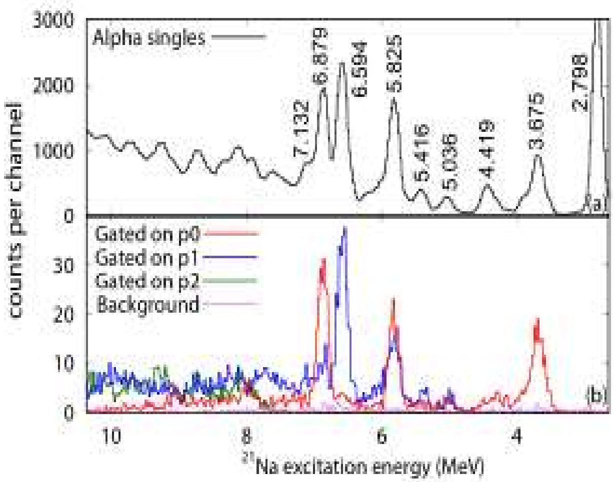
Coincident events

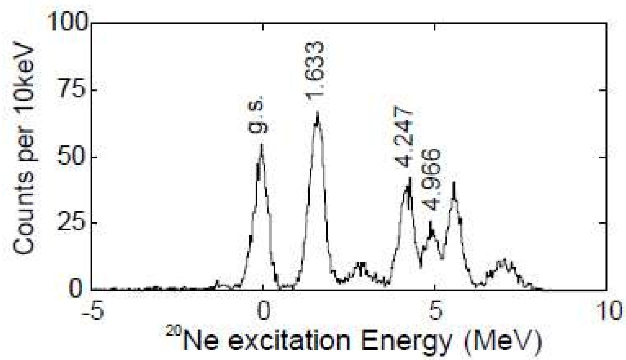








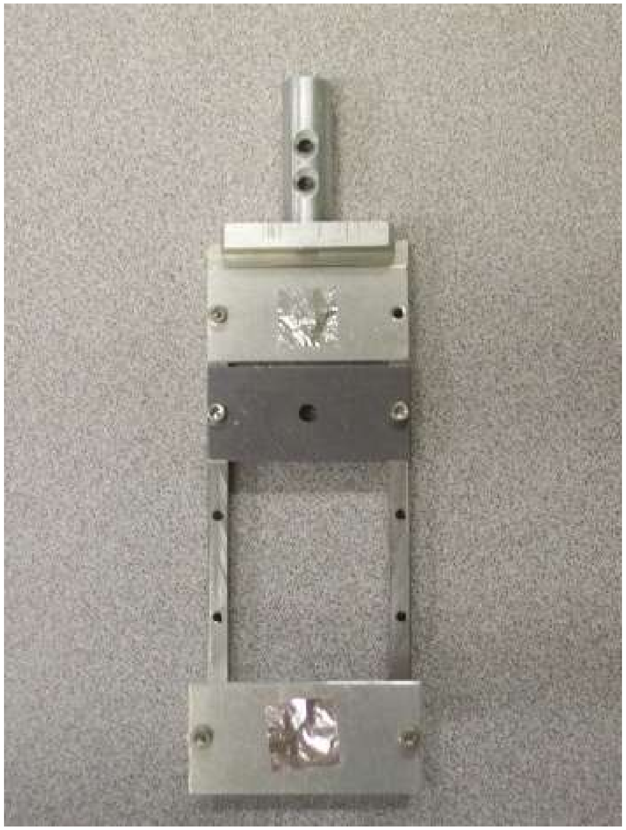




E(level) (keV)	XREF	Jπ(level)	$T_{1/2}$(level)
0.0	ABCD FGHI	0+	STABLE
1633.674 15	ABCD FGHI	2+	0.73 ps 4
4247.7 11	ABCD FGH	4+	64 fs 6
4966.51 20	ABC FG I	2-	3.3 ps 4

M.J. Kim *et al.*, Phys. Rev. C 104, 014323 (2021)

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)

Spin assignments for ^{23}Mg levels and the astrophysical ^{22}Na(p,g)^{23}Mg reaction
Eur. Phys. J A **56**, 108 (2020)

Proton decay of ^{21}Na for ^{20}Ne energy levels
J. Korean Phys. Soc. **77**, 383 (2020)

First measurement of proton decay from a transfer reaction to ^{21}Na
Phys. Rev. C 104, 014323 (2021)

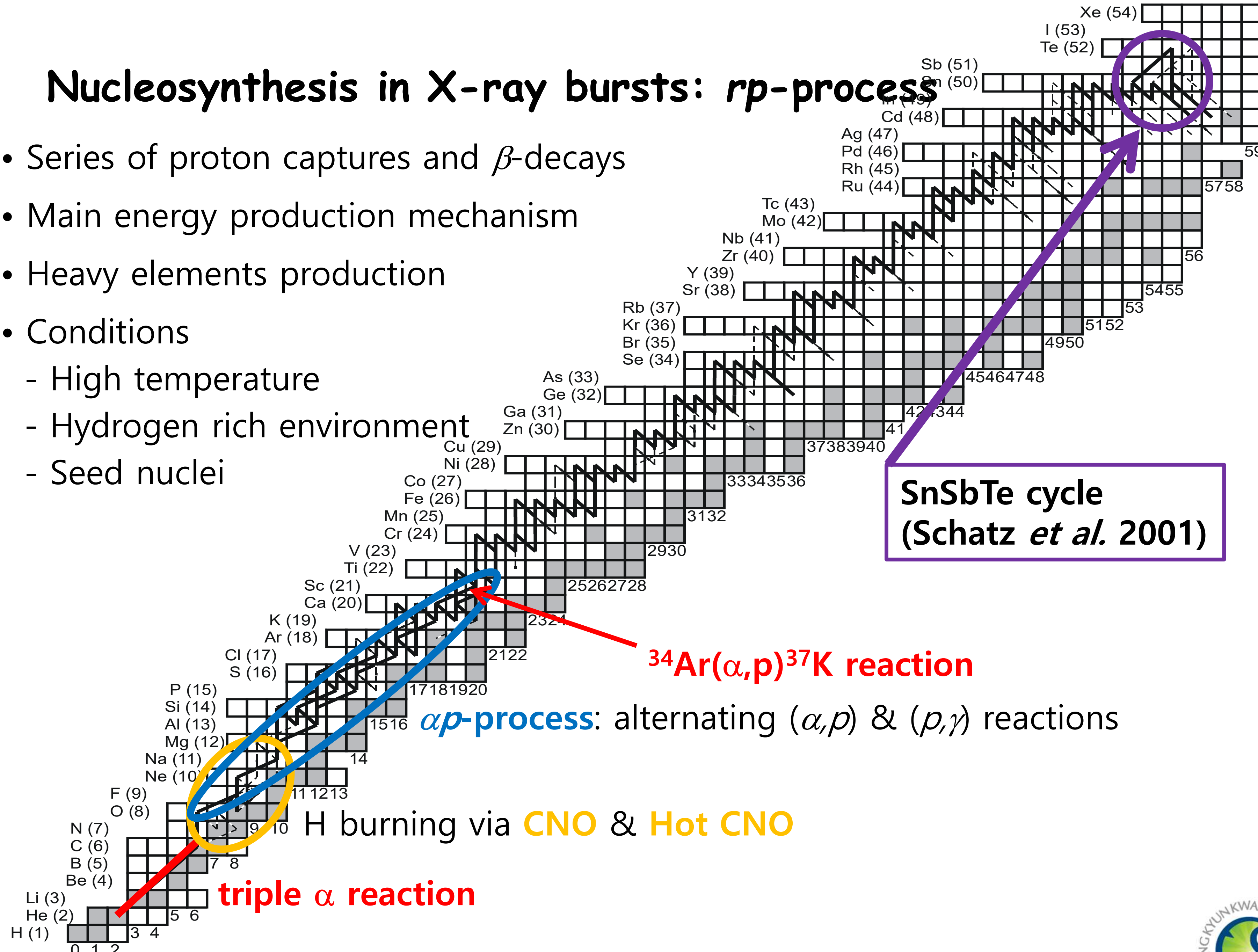
Proton branching ratios of ^{23}Mg levels
Phys. Rev. C 105, 025801 (2022)

Proton branching ratios in ^{22}Mg for X-ray bursts
Eur. Phys. J. A 59, 112 (2023)

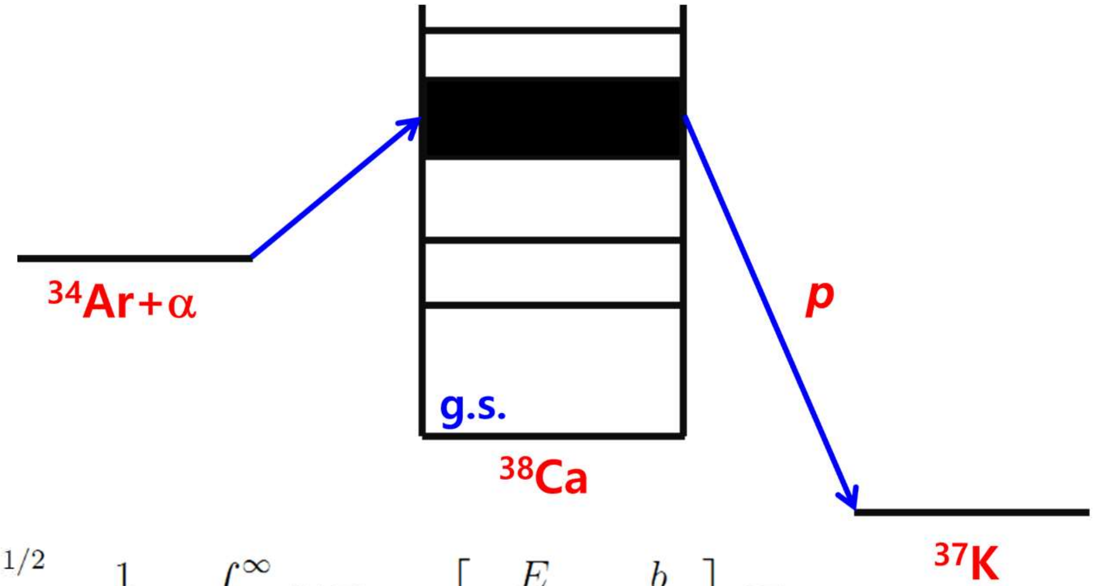
Gold-backing CaF target

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



^{38}Ca energy levels for ^{34}Ar(a,p)^{37}K rates



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

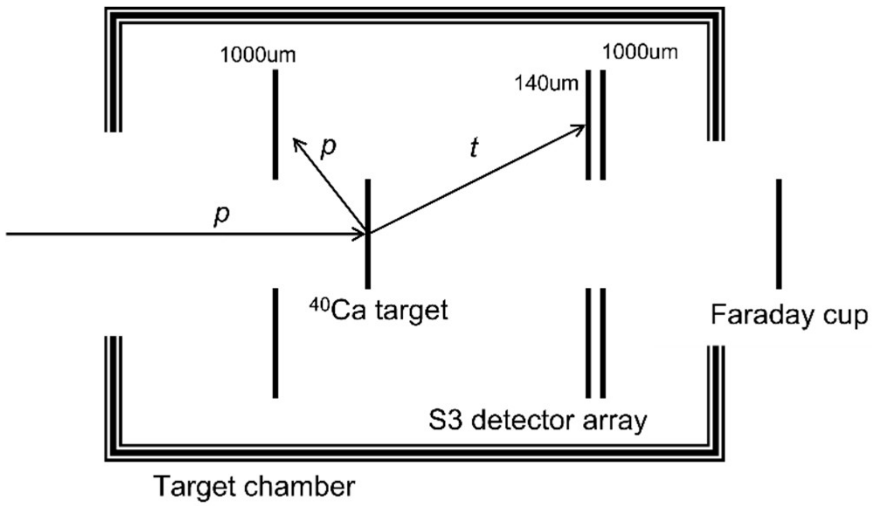
- reaction rate ∝ $\exp(-E/kT)\cdot\exp(-b/E^{1/2})$

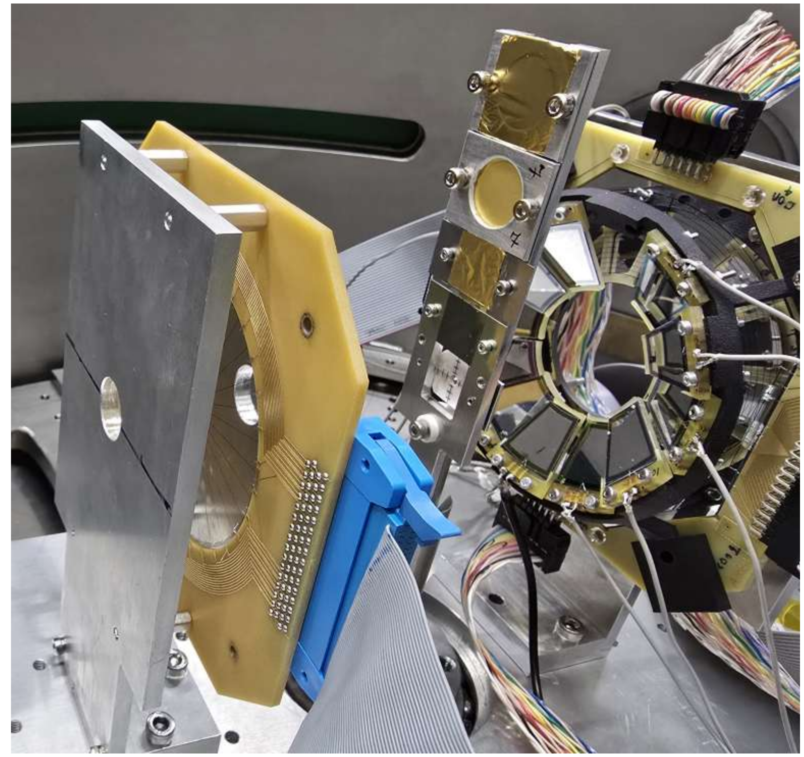
→ strongly localized in energy

- X-ray burst temperatures: 1-2 GK

→ Properties of ^{38}Ca energy levels at ***E_x* = 6-9 MeV** are important

$^{40}Ca(p,t)^{38}Ca$ Experimental Setup





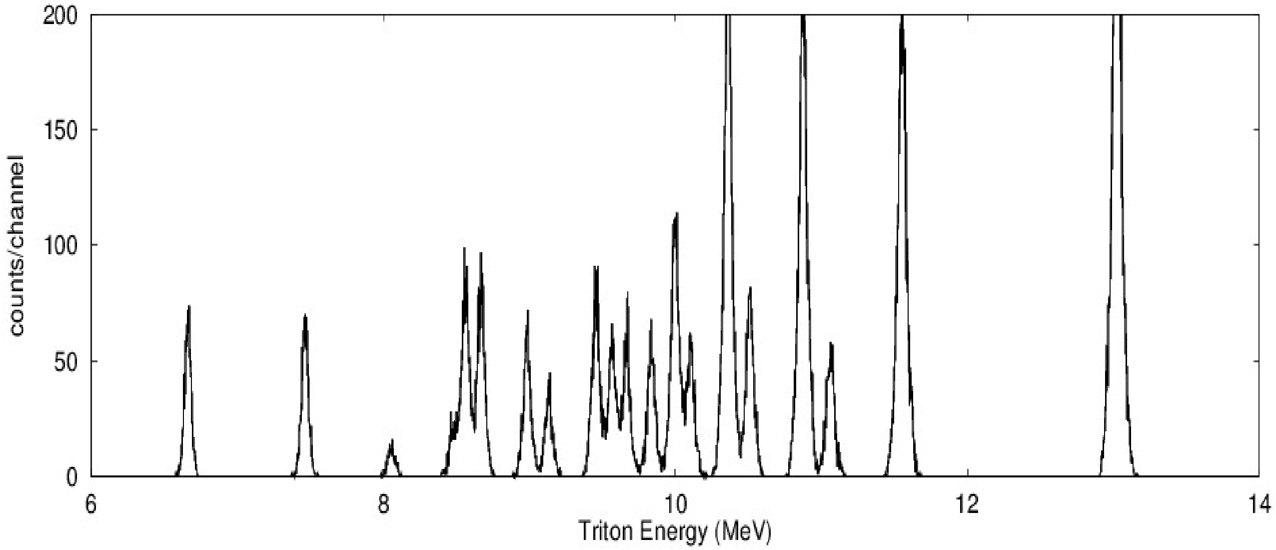
- proton beam:
  - at the energy of **36 MeV (→ 30.5 MeV)** from the tandem accelerator
  - about 0.2 nA of beam current

- target: CaF_2 solid targets

- forward angle: ΔE-E silicon detector telescope for particle ID
  - a **140 um-thick (→ 50-75 um-thick)** energy loss layer backed by a 2000 um-thick residual energy layer
  - Type S3 from Micronsemiconductor Ltd. (CD type detector)
  - 24 annular strips, recoiling particles will be at various angles simultaneously

- backward angle: silicon strip detector for decay protons

Yield estimation



- recoiling tritons from the $^{40}Ca(p,t)^{38}Ca$ reaction will be identified
  - energy range of tritions: 6 – 20 MeV
  - energy range of the excitation energies in ^{38}Ca: **0 – 9 MeV (→ 0 – 4 MeV)**

- at 0.2 pnA of beam intensity, more than 5,000 counts will be accumulated in 3 days of beamtime for the ground state of ^{38}Ca

- experimental angular distributions of identified ^{38}Ca levels will be compared with DWBA calculations for spin assignments

- astrophysical $^{34}Ar(a,p)^{37}K$ and $^{37}K(p,g)^{38}Ca$ reaction rates will be calculated

$^{19}F(p,t)^{17}F$ measurement for the $^{13}N(\alpha,p)^{16}O$ reaction

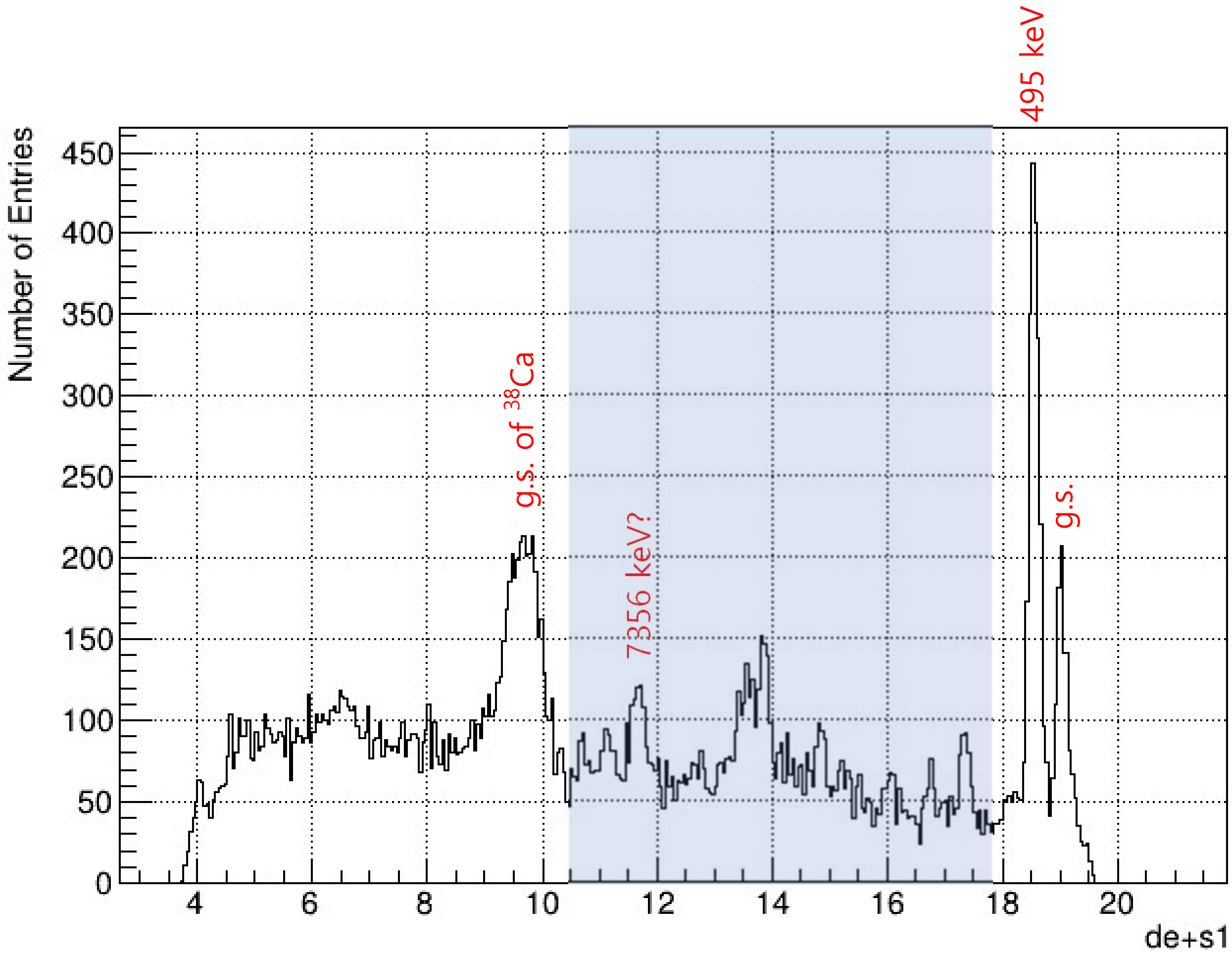
• presolar grains such as type X and type C shows the evidence for initial ^{44}Ti
→ suggests that the grains are formed in Core-Collapse Supernovae

• low $^{14}N/^{15}N$ and $^{12}C/^{13}C$ ratios found in the grains: at odds with predictions from theoretical models

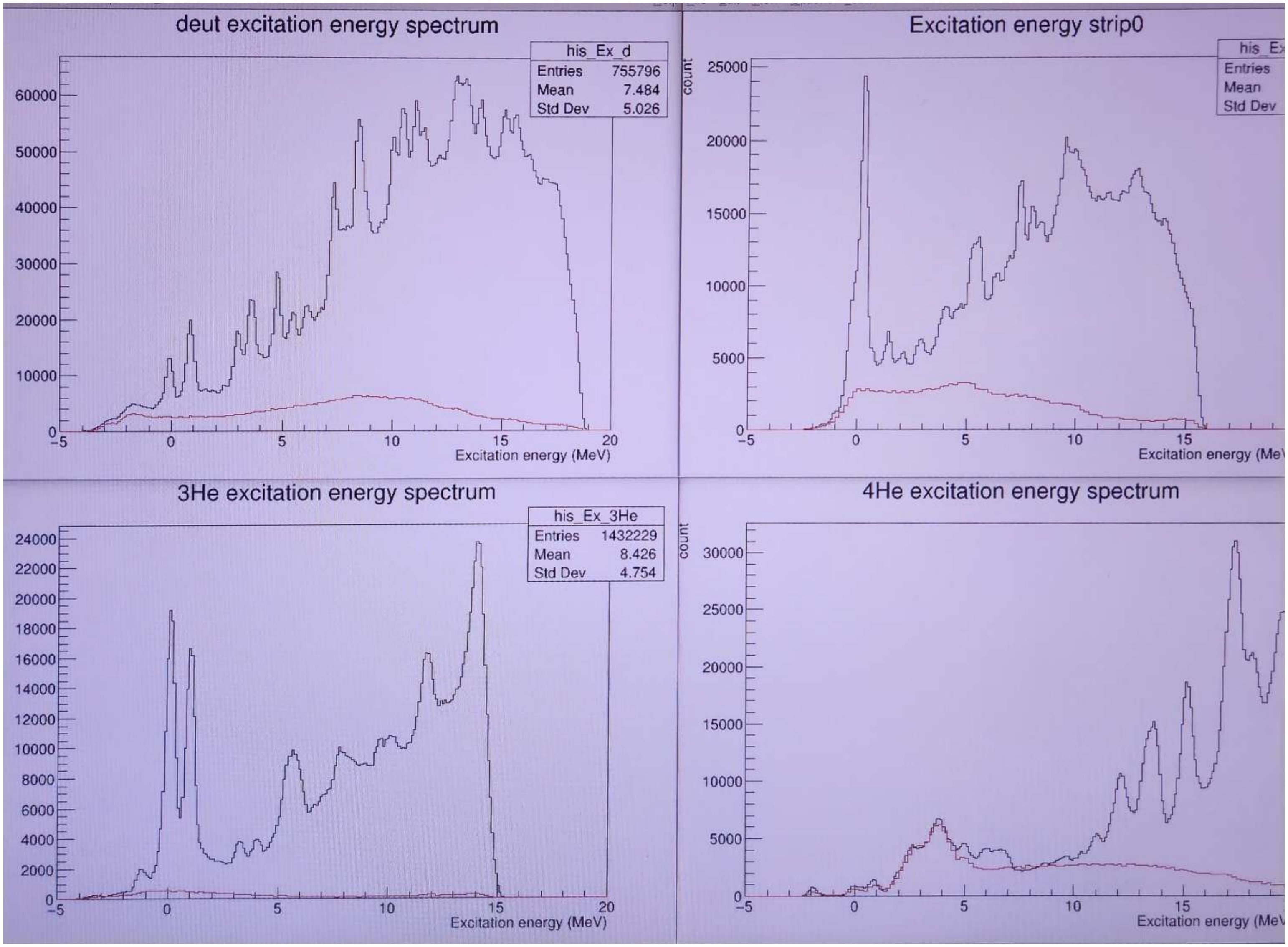
• new supernova models incorporating the ingestion of hydrogen into the helium shells are proposed

• $^{13}N(a,p)^{16}O$ reaction: directly affect ^{13}C, ^{13}N and ^{16}O abundances under these conditions
→ charged particle decay widths of ^{17}F energy levels are needed

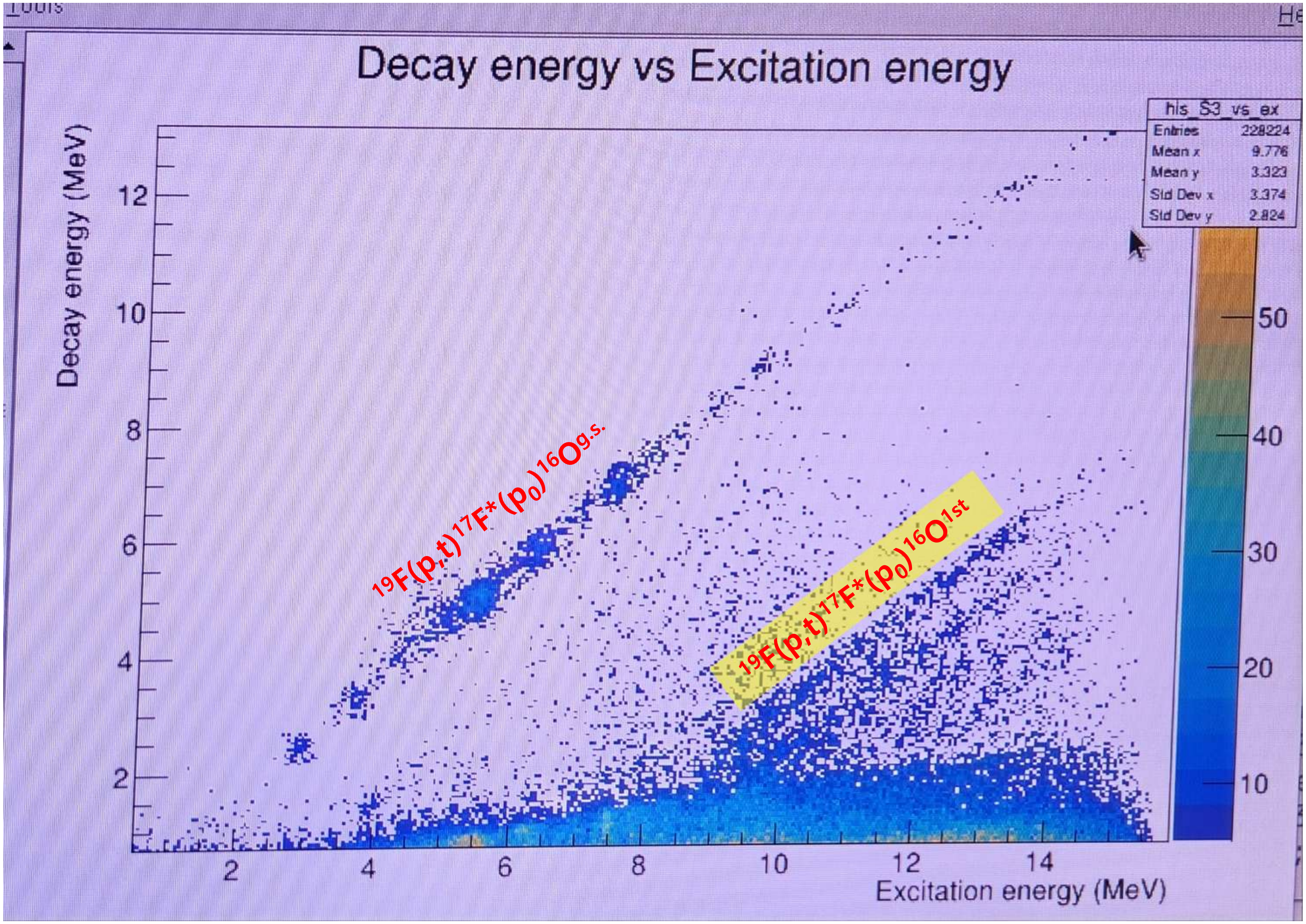
Trition energy spectrum



Background run



Decay energy vs E_{ex}



Thank you!

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(RIKEN Nishina Center)

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