$^{22}Na+\alpha/p$ 共振散射的实验研究

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创新群体年度进展汇报
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内 容

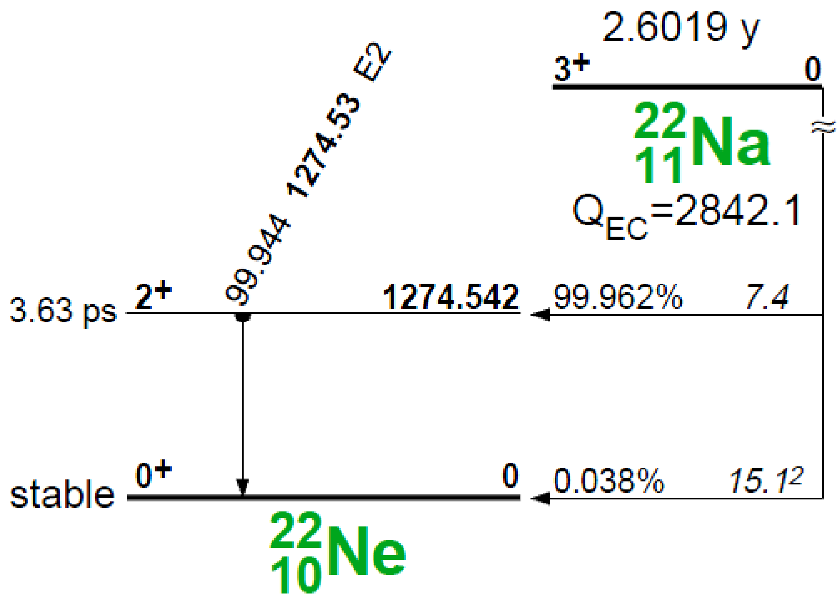
- 科学意义
- 厚靶实验方法简介
- CRIB 实 验
- 初步结果
- 讨 论

Orgueil meteorites and Ne-E problem

Fell on May 14, 1864, a few minutes after 8 pm, near Orgueil in southern France. About 20 stones fell over an area of several square miles.

In 1972，Black found that in Orgueil meteorites the abundance ratio of $^{20}Ne/^{22}Ne$ is less than 1.5，much lower than that of 9.8 on earth, this is the so-called **Ne-Extraordinary problem**。Geoch. Cosmochim. Acta V36, 347(1972)

^{22}Na production somewhere



The relatively short half-life and the 1.275 MeV γ-ray make the ^{22}Na a possibly sensitive probe for the diagnosis of nearby Nova outbursts from the Sun.

Gamma-ray production in Novae

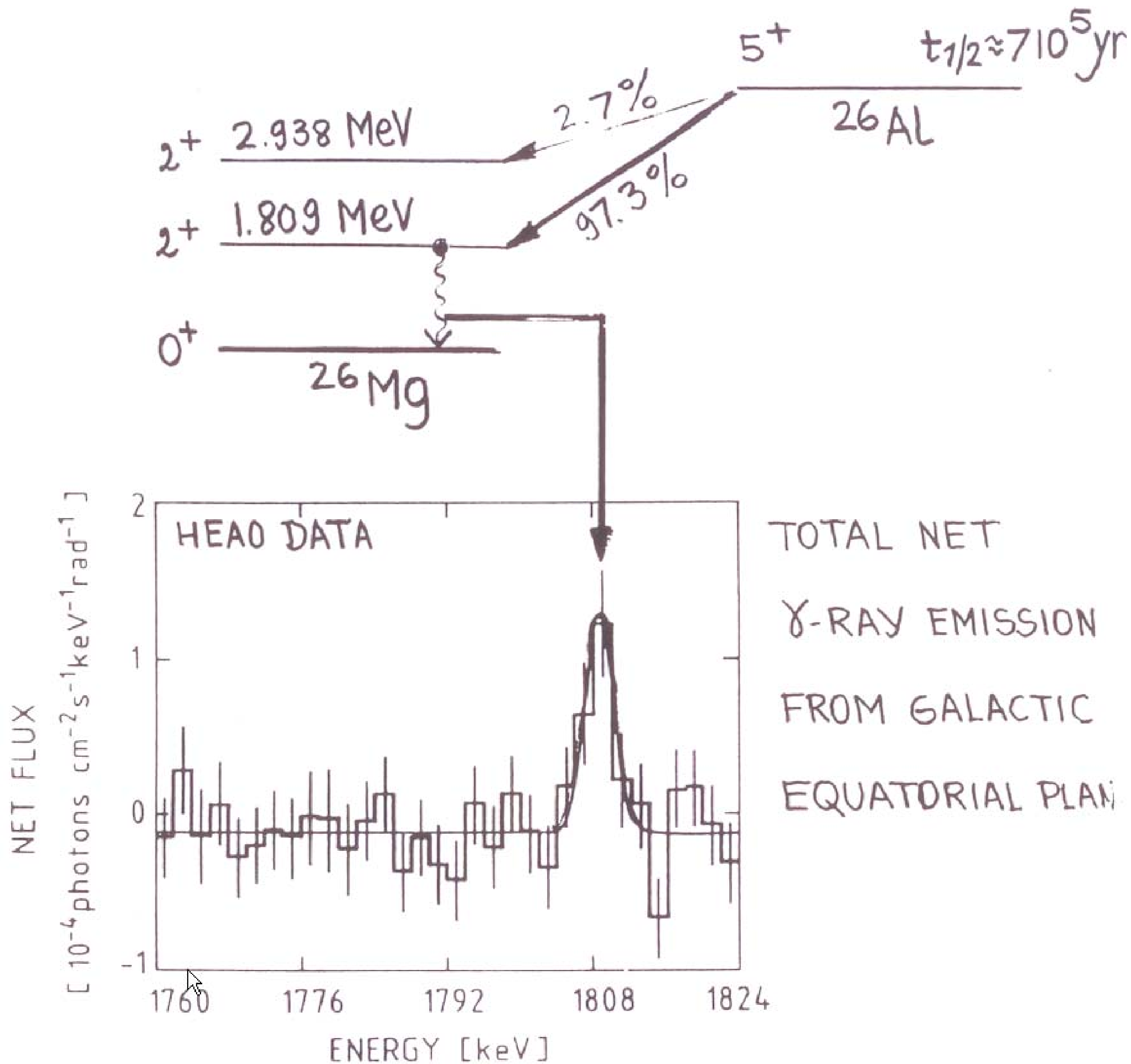
- Clayton & Hoyle Ap. J. **494** (1974)
  – direct observation of γ-rays in novae ejecta

Nucleus	τ	Emission	Nova type
^{13}N	862 s	511 keV	CO ONe
^{18}F	158 m	511 keV	CO ONe
^{7}Be	77 d	478 keV	CO
^{22}Na	**3.75 yr**	**1275 keV**	**ONe**
^{26}Al	1.0×10^{6} yr	1809 keV	ONe

- Intensity of an observed γ-ray flux would provide a ***strong*** constraint on novae modelling.

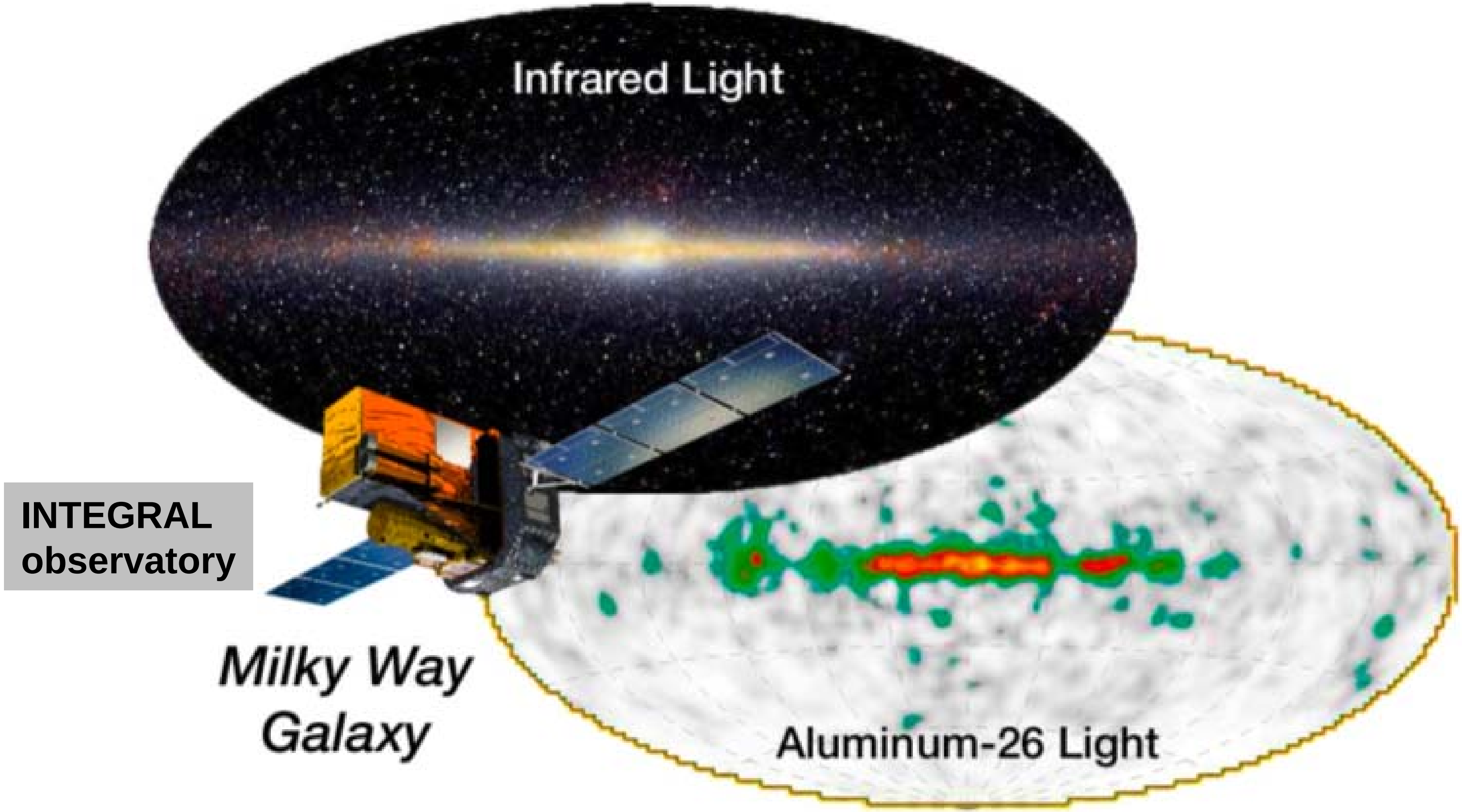
INTEGRAL: launched Oct '02

International Gamma-Ray Astrophysics Laboratory
European Space Agency
http:// www.esa.int/science/integral



5+
t1/2≈7 10^5 yr
26 AL
2.7%
97.3%
2+ 2.938 MeV
2+ 1.809 MeV
0+
26 Mg
HEAO DATA
TOTAL NET
γ-RAY EMISSION
FROM GALACTIC
EQUATORIAL PLAN
NET FLUX
[10^-4 photons cm^-2 s^-1 keV^-1 rad^-1]
2
1
0
-1
1760
1776
1792
1808
1824
ENERGY [keV]

Milky Way seen by ^{26}Al γ-ray at satellite observatory



total of about 3 solar masses
of ^{26}Al in our galaxy

^{22}Na γ-ray observation

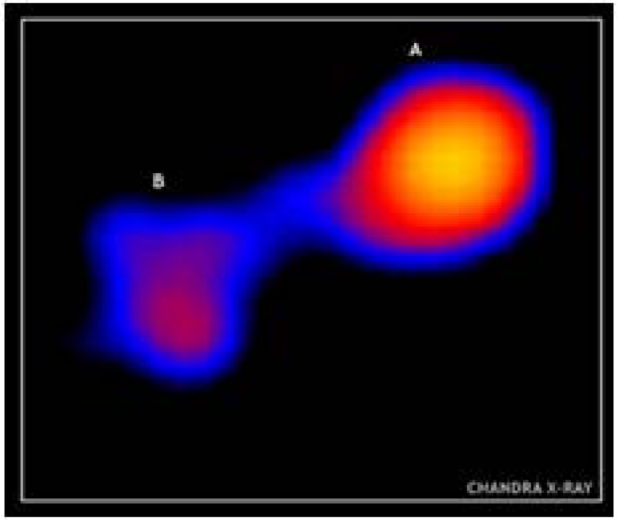
COMPTEL aboard CGRO observed five nearby Ne-type novae

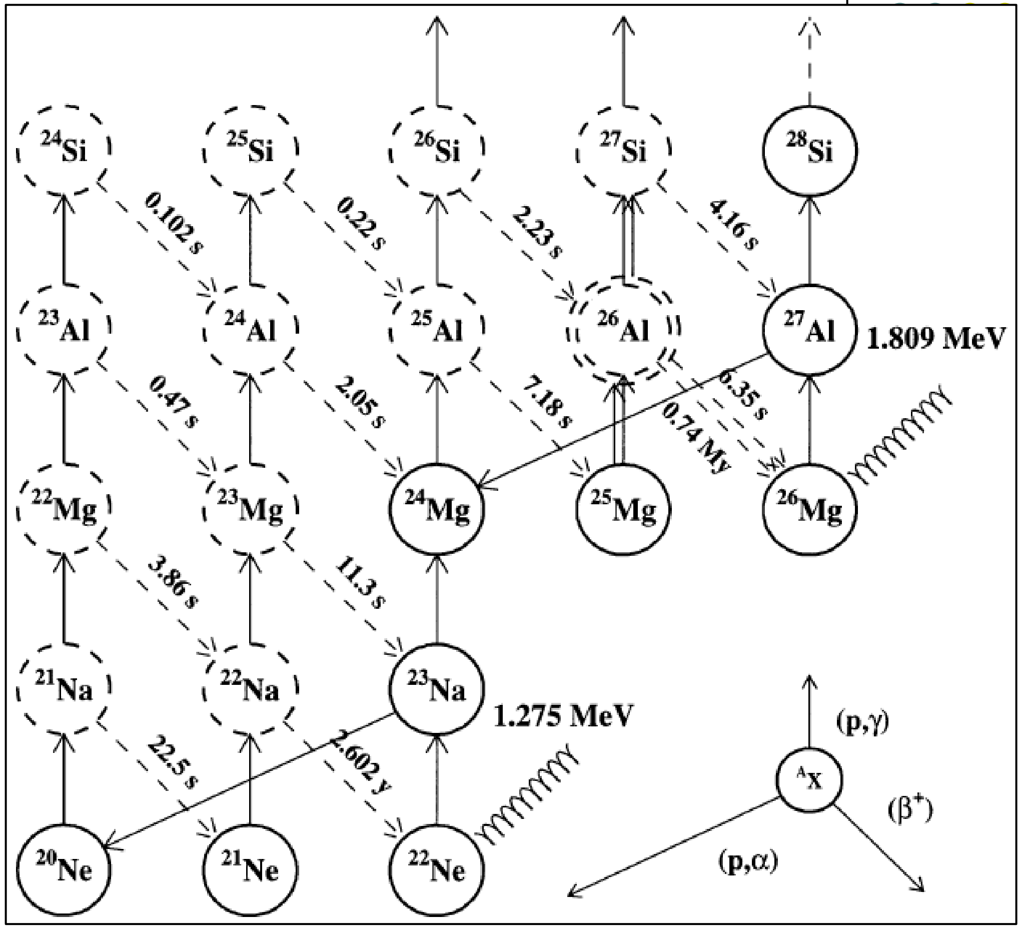
^{22}Na: only an upper limit of 3.7×10^{-8} $M_\odot$ of ejected ^{22}Na by any nova in the Galactic disk.

CGRO (NASA), since 1991

What happened to the ^{22}Na?

Classic Nova





Thermonuclear outburst takes place on the surface of a white dwarf component in a close binary system

银河系每年粗略估计有20至60颗新星出现的经验，估计出现率为每年40颗

Main nuclear paths in the synthesis of ^{22}Na

Synthesis of ^{22}Na in ONe novae

- $^{20}Ne(p,\gamma)^{21}Na(p,\gamma)^{22}Mg(\beta+)^{22}$**Na**

  or

- $^{20}Ne(p,\gamma)^{21}Na(\beta+)^{21}Ne(p,\gamma)^{22}$**Na**

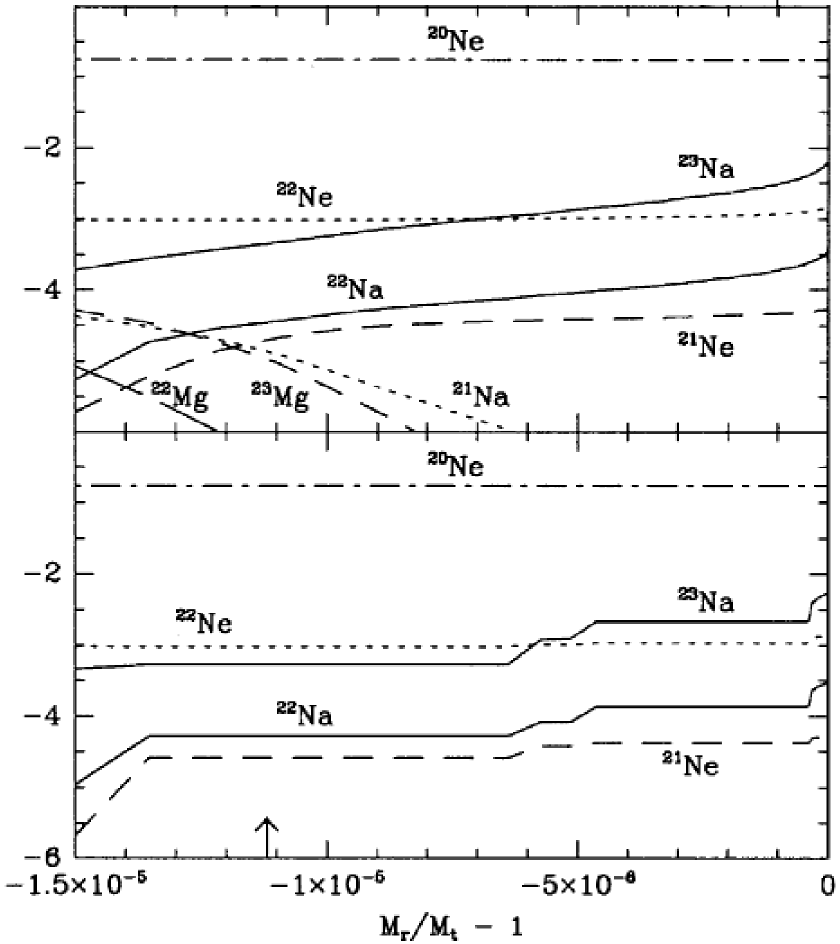
Four reactions that control the synthesis of ^{22}Na:

$^{20}Ne(p,\gamma)^{21}Na$

$^{21}Ne(p,\gamma)^{22}Na$

$^{21}Na(p,\gamma)^{22}Mg$

$^{22}Na(p,\gamma)^{23}Mg$



José et al., APJ, 520:347-360(1999)

NP1012-AVF11 Dec., 2010 **RIKEN 8th NP-PAC meeting**

Spokesperson: Youbao Wang

Study of resonant elastic/inelastic scattering of ^{22}Na+p relevant to the astrophysical ^{22}Na(p,γ)^{23}Mg reaction

S. J. Jin[1,*], Y. B. Wang[1], J. Su[1], S. Q. Yan[1], Y. J. Li[1], Z. H. Li[1], B. Guo[1], G. Lian[1], S. Zeng[1], X. X. Bai[1], W. P. Liu[1], S. Kubono[2], H. Yamaguchi[2], D. Kahl[2], J. Hu[2], H. S. Jung[3], J. Y. Moon[3], T. Terenishi[4], H. W. Wang[5], H. Ishiyama[6], H. Iwasa[7], H. Komatsubara[8]

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[3] *Department of Physics, Chung-Ang University, Seoul 156-756, Republic of Korea*

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[5] *Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China*

[6] *High Energy Accelerator Research Organization(KEK), 1-1 Oho, Tsukuba, Ibaraki 319-1195, Japan*

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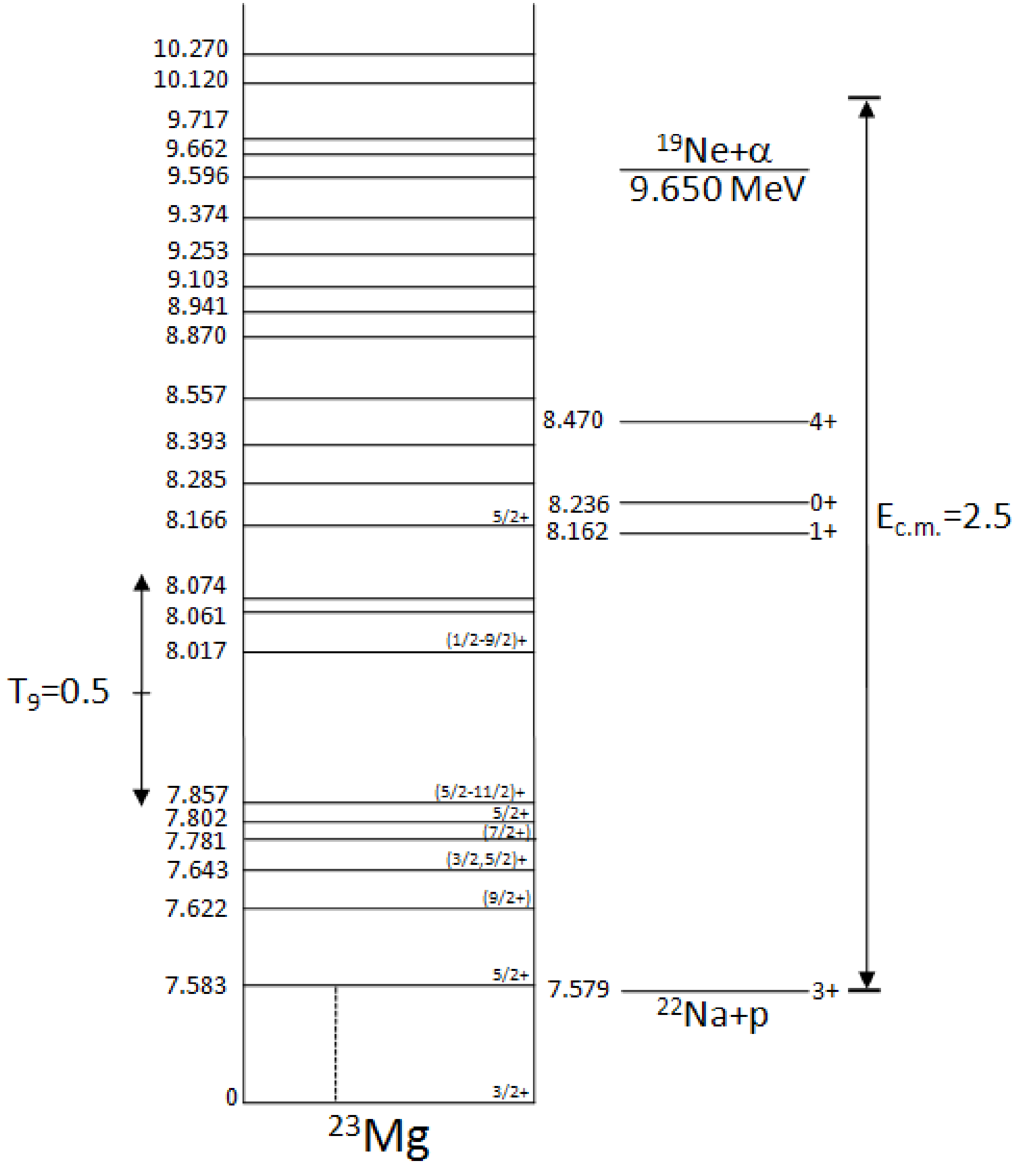
[8] *Department of Physics, University of Tsukuba, Tsukuba 305-8571, Japan*

Motivations of the ^{22}Na+p measurement



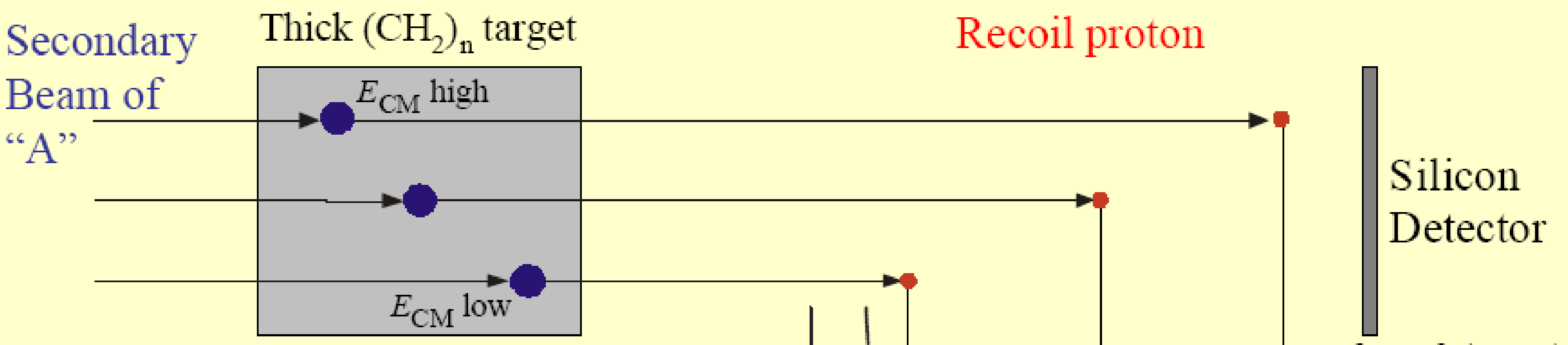
- To map the relevant resonances in ^{23}Mg over larger excitation energy region using ^{22}Na+p channel with a well-developed thick target method
- To deduce the resonance parameters including energy、spin/parity and proton width for ^{22}Na(p,γ)^{23}Mg reaction and for level systematics
- To develop ^{22}Na secondary beam for studies of ^{22}Na(α,α) and ^{22}Na(α,p)

Nearly 30 energy levels are missing up to 9.7MeV comparing with ^{23}Na

Introduction of TTIK method

- General introduction
- Our previous TTIK works
- CRIB experiment

Thick-target method for A+p in inverse kinematics

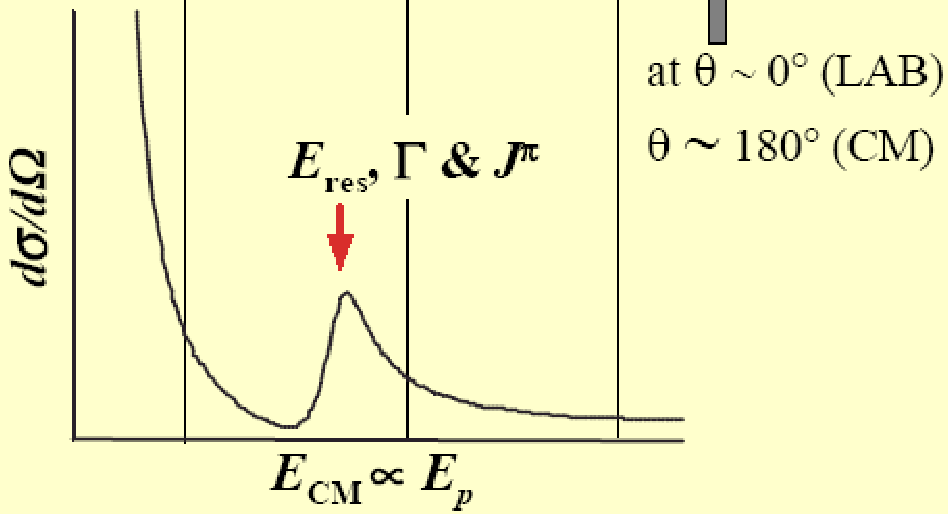


- **Thick proton target**

  Energy loss of the beam

  Scanning $d\sigma/d\Omega(E)$ automatically

  Without changing the beam energy before the target



Excitation function $d\sigma/d\Omega(E)$

Proton yield → $d\sigma/d\Omega$

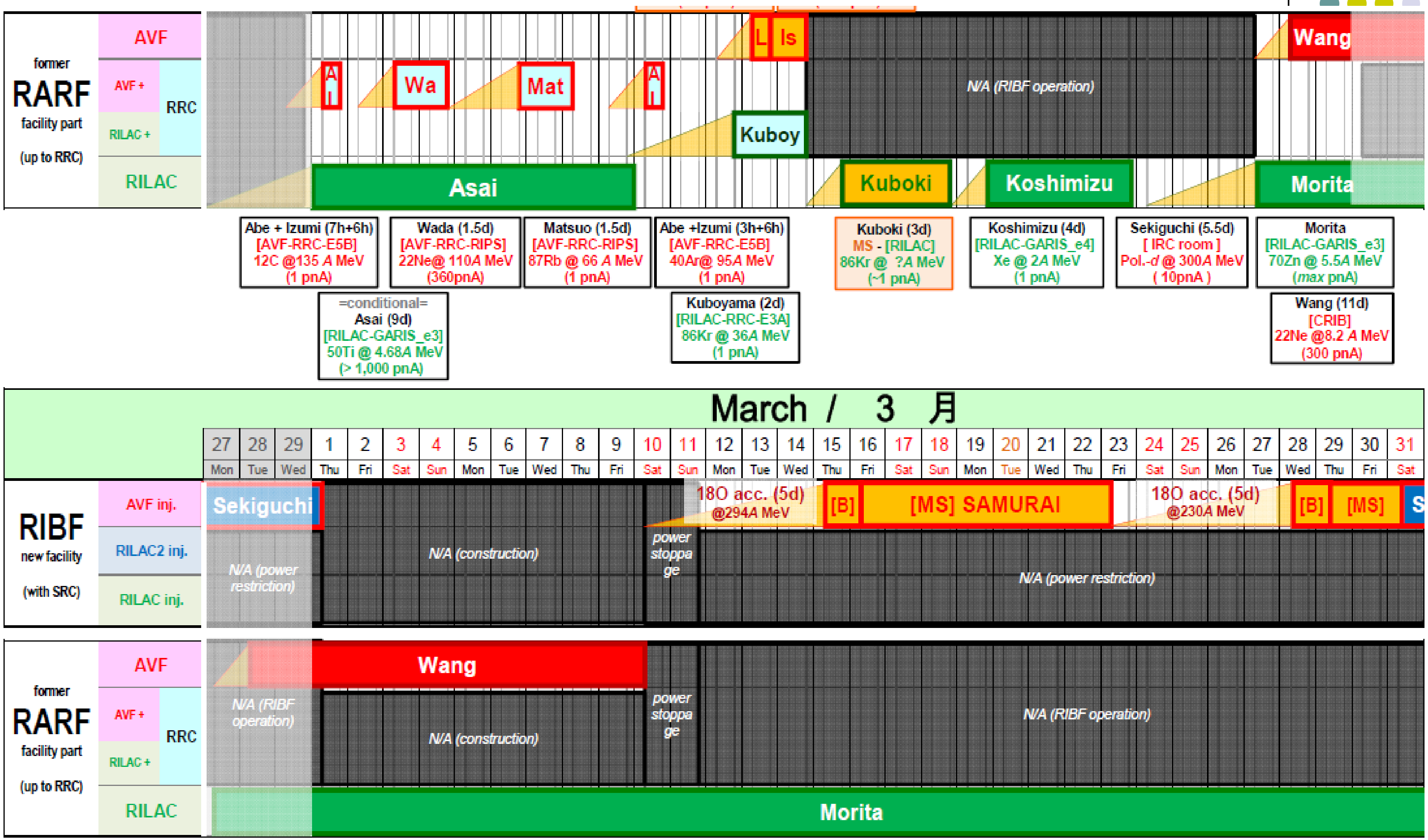
$$\frac{dN}{dE} \propto \frac{d\sigma}{d\Omega} \cdot \frac{dx}{dE} \cdot d\Omega$$

Counts per energy-bin

Target-thickness per energy-bin

Interference pattern of potential & resonance scattering

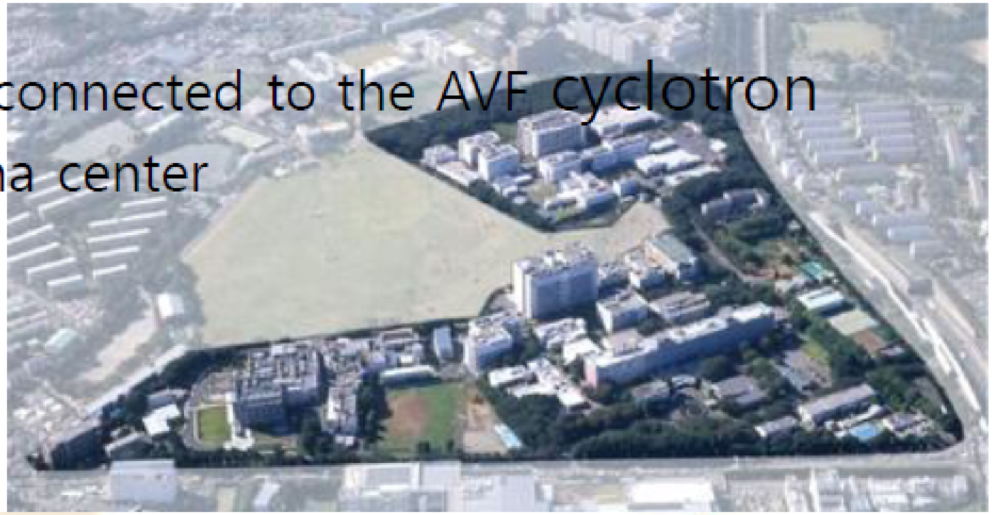
Beam-time allocation

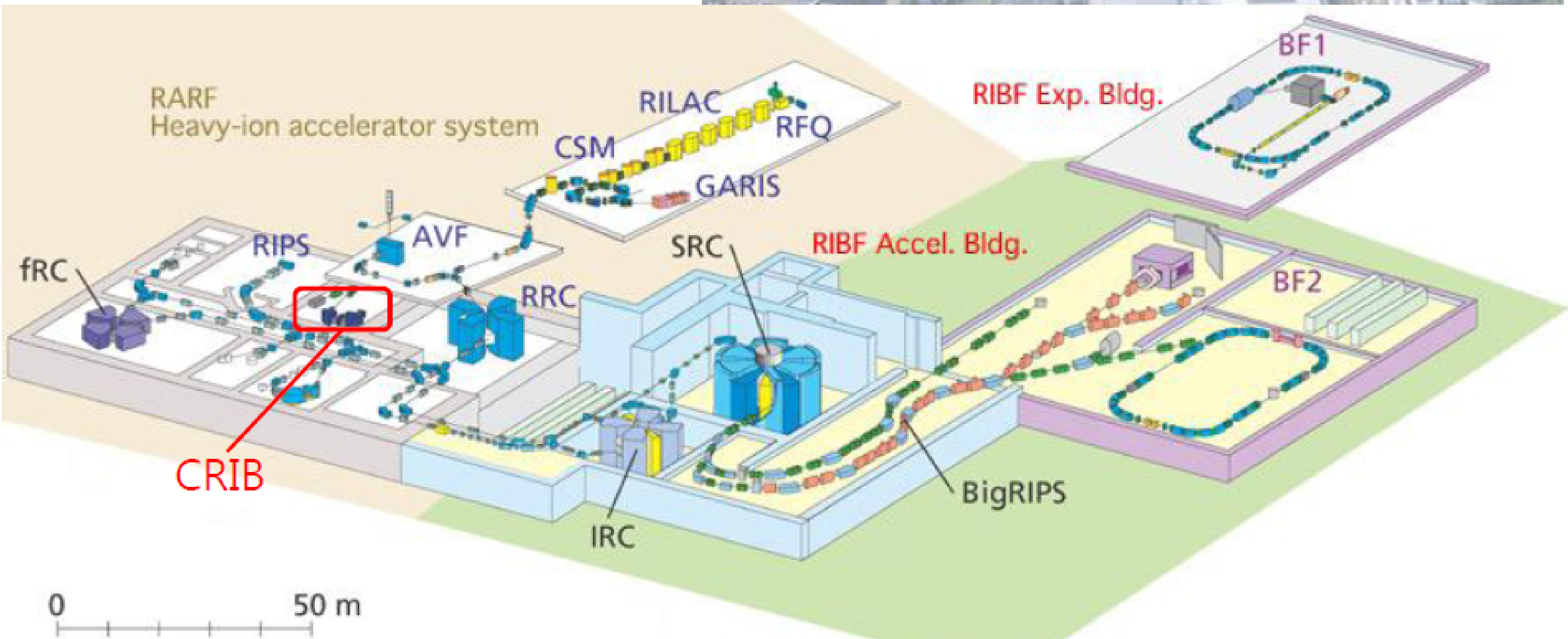


Beam time: Feb. 28 – Mar.10, 2012

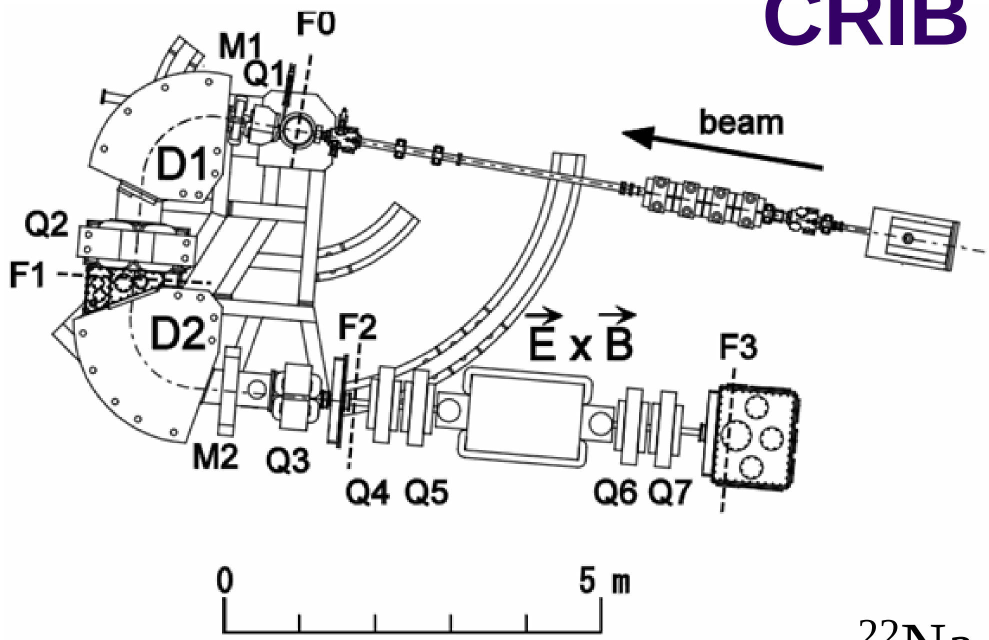
▪ CRIB in RIBF of RIKEN

- CRIB is in the "old" building, connected to the AVF cyclotron
- E7 experimental hall at Nishina center





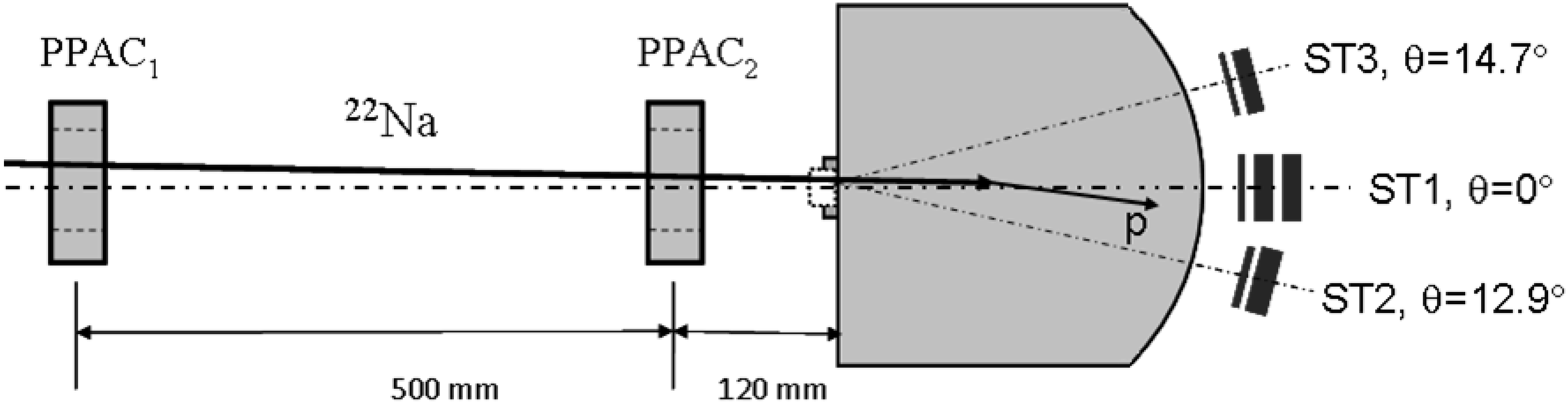
CRIB facility at CNS



^{22}Na beam production conditions

Primary beam	$^{22}Ne^{7+}$
Energy	6.1 MeV/A
Intensity	500 enA
Production reaction	$^{22}Ne(p, n)^{22}Na$
Production target	^{1}H gas, 1.15 mg/cm^2 (LN_2-cooled, 400 Torr, 90K, 80 mm in length

Experimental setup at F3 chamber

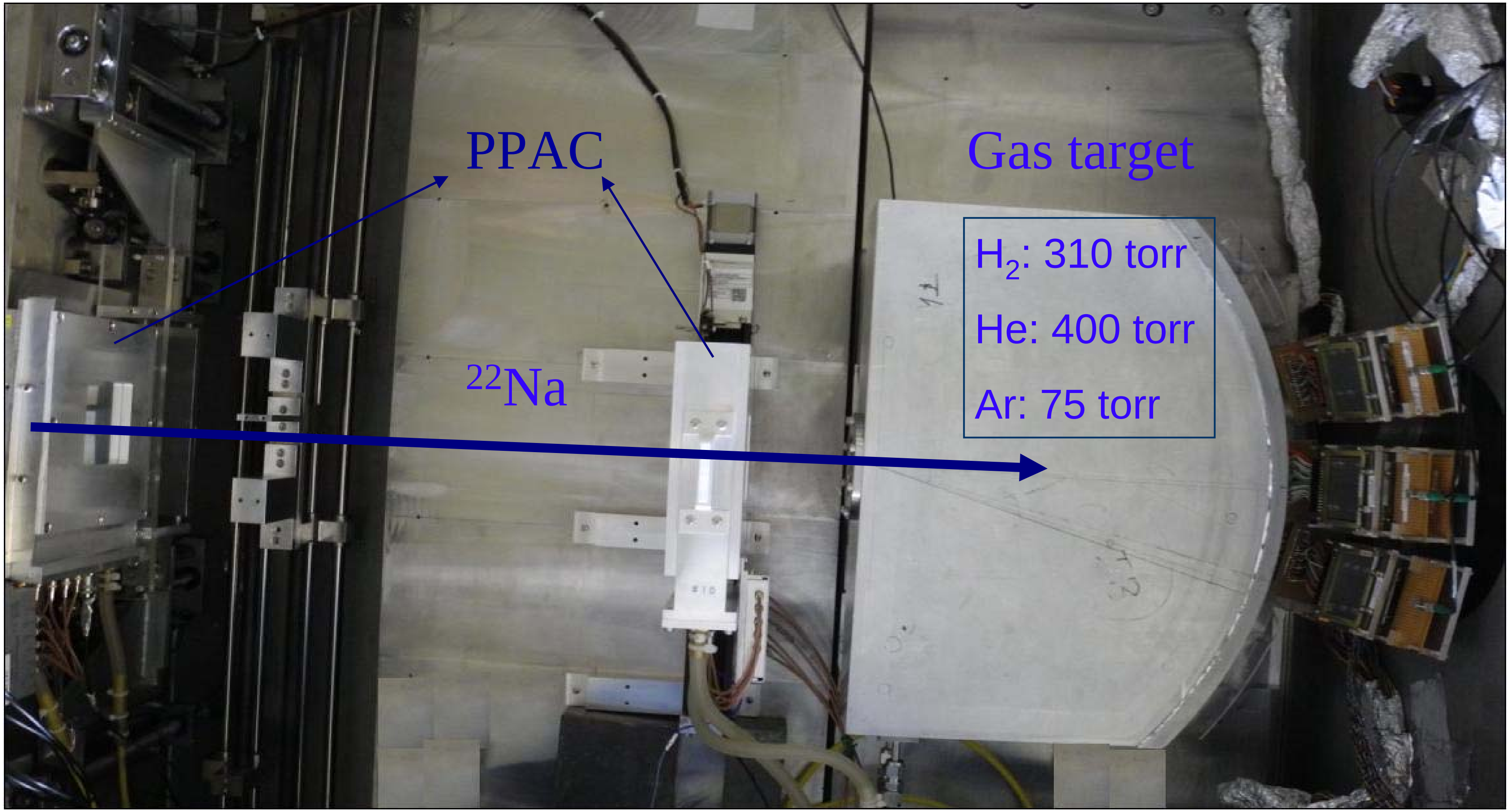


^{22}Na: 37.1 MeV (in gas)
2.5 × 10^5 pps (on target)

Gas target
Length: 300 mm
Windows: 2.5 μm Havar (front),
26.5 μm Mylar (back).

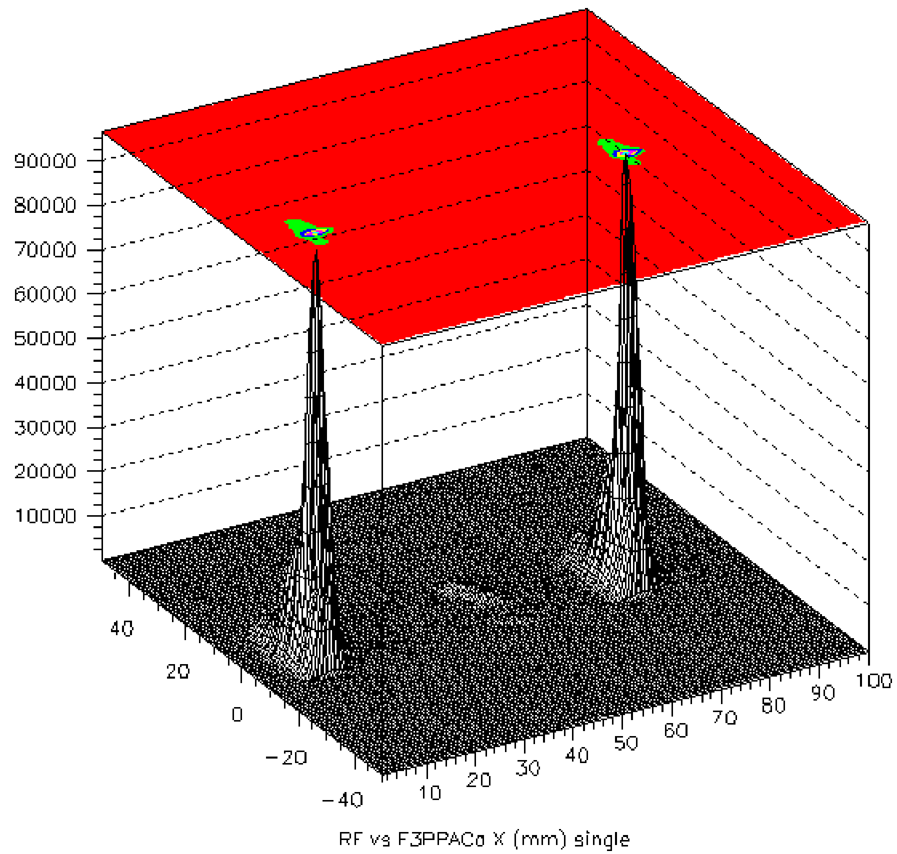
Silicon Telescopes
DSSSD+SSD
50×50 mm^2

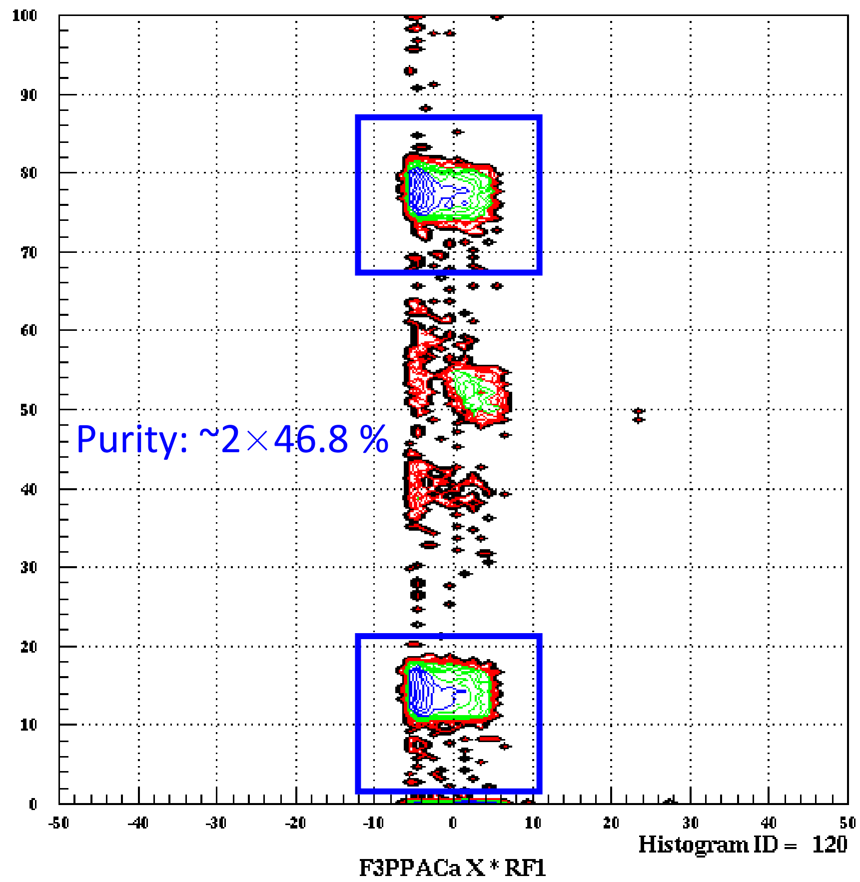
Setup for ^{22}Na+p/α

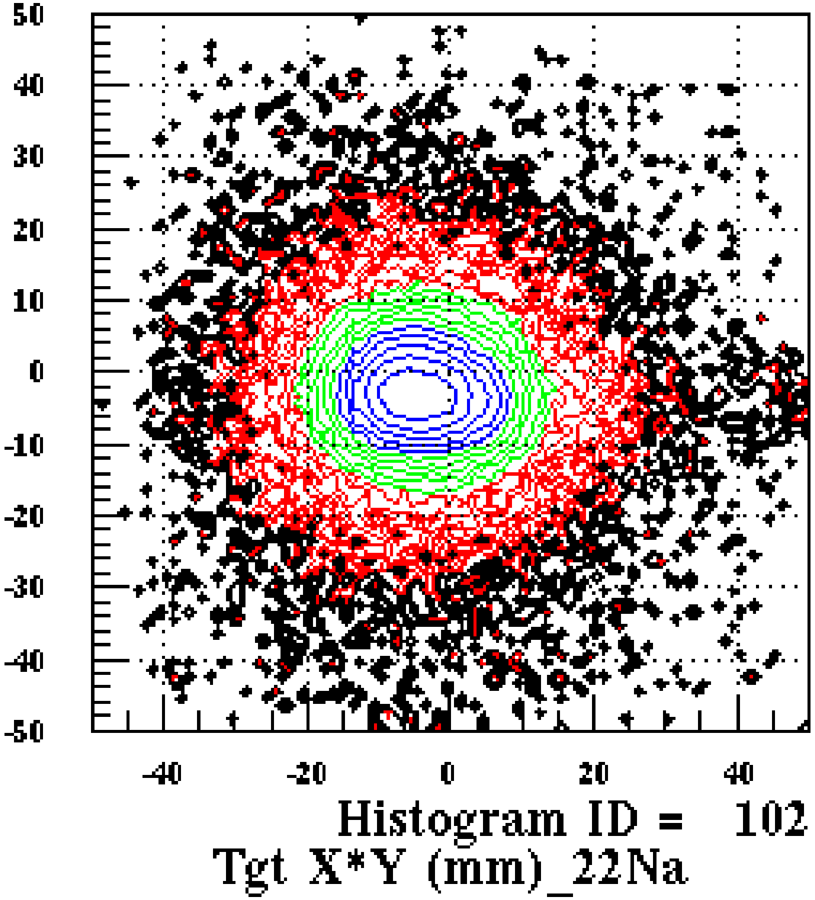


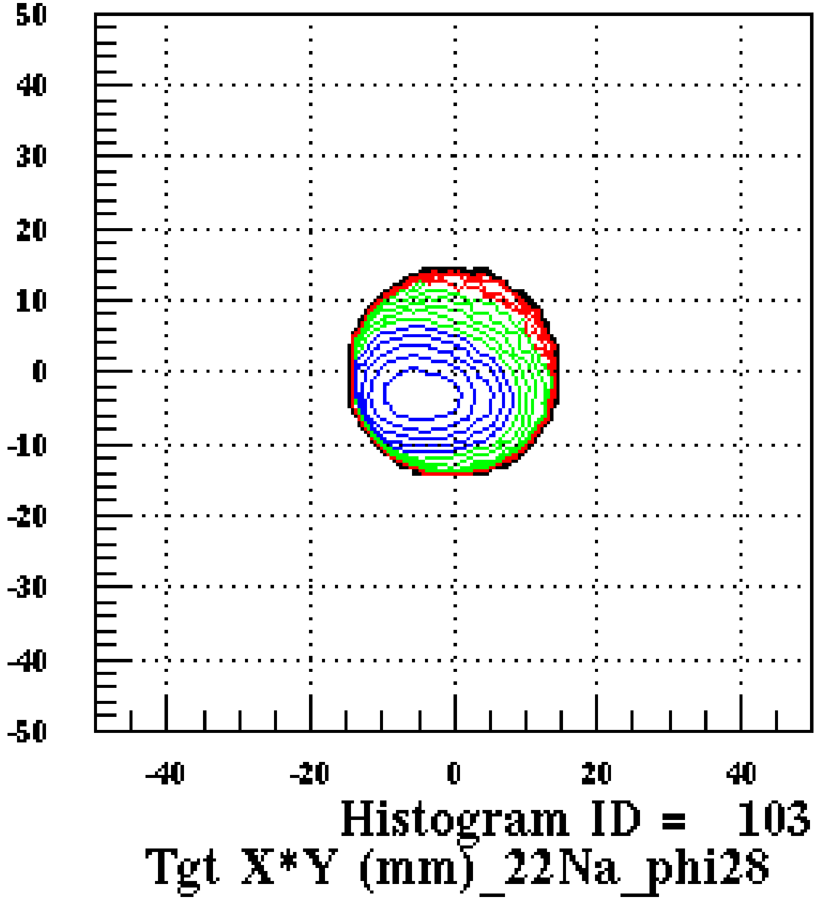
^{22}Na RIB production

At F3, with ±50 kV of Wien Filter



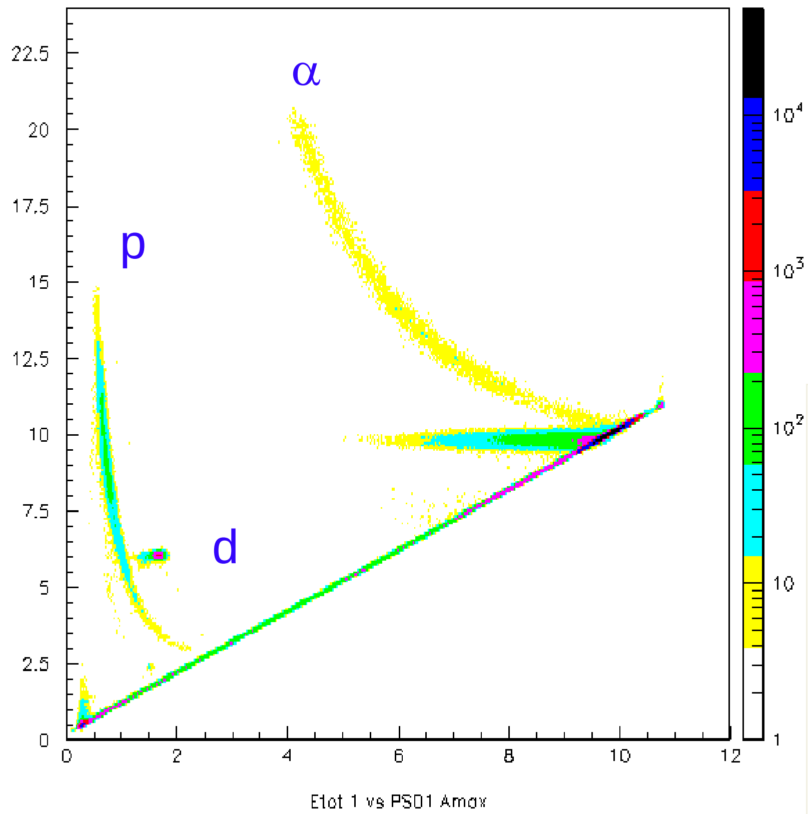


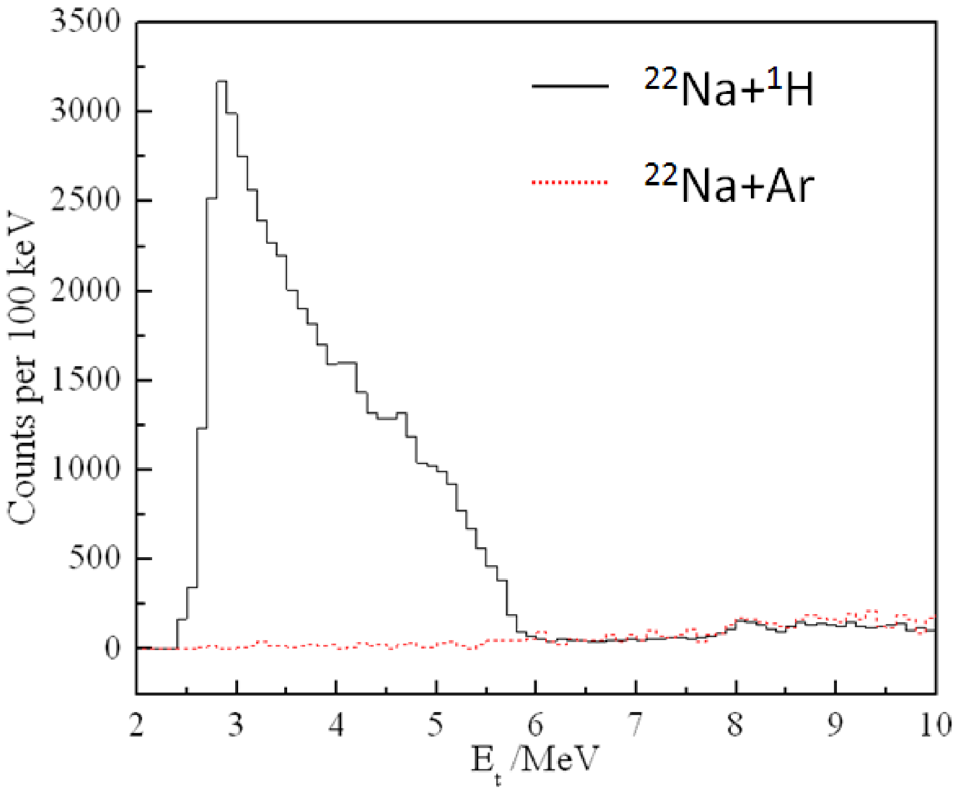




Beam size on target position by extrapolation

Light recoils from ^{22}Na+p





Proton spectrum from ^{22}Na(p,p) and background

Data Analysis

- **Kinematics reconstruction on an event by event basis.**

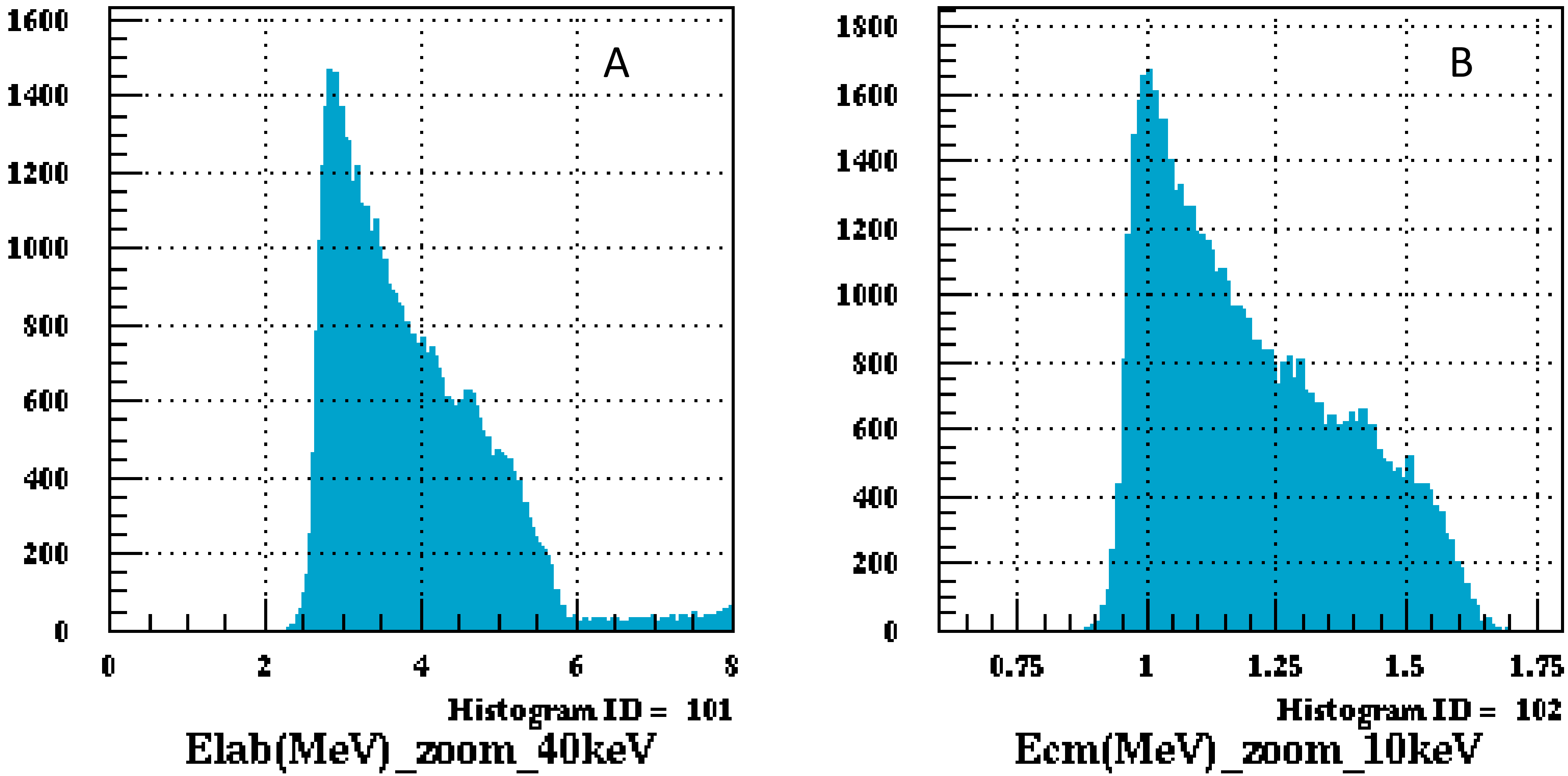
  Beam profile by PPACs (Energy and trajectory)

  Proton energy and scattering angle from ΔE-E telescope

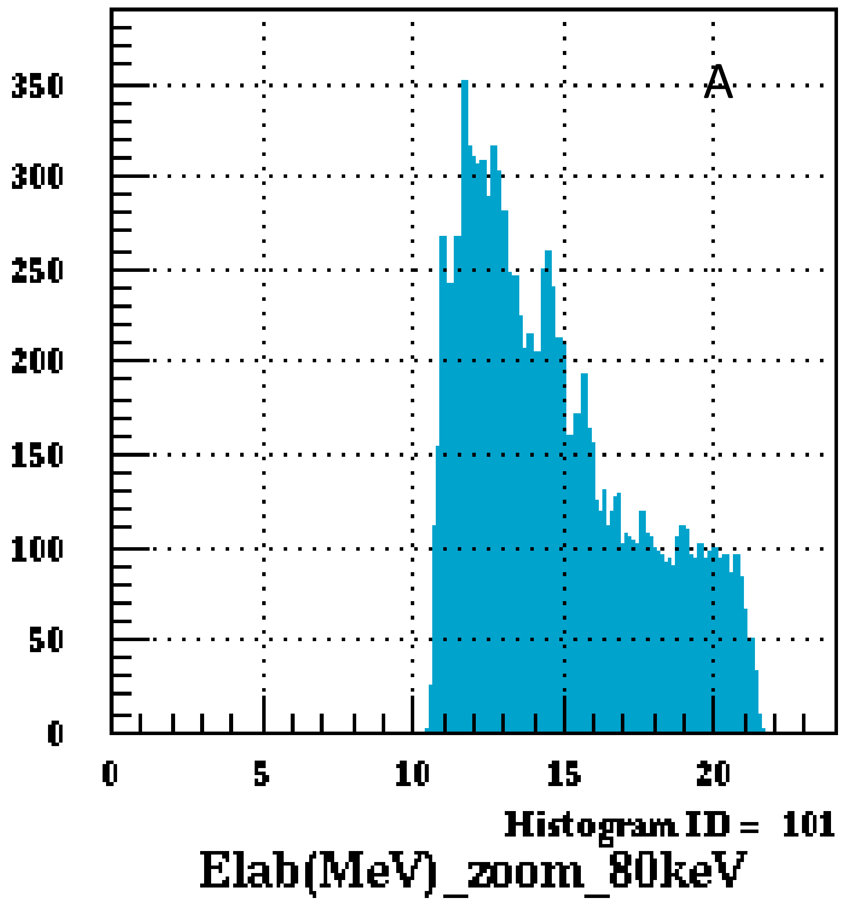
$$E_{p,\alpha} = \frac{m_{^{22}Na} \times m_{p,\alpha}}{m_{^1H}(m_{^{22}Na} + m_{^1H})}\left(\cos\theta_{lab} + \sqrt{\gamma^{-2} - \sin^2\theta_{lab}}\right)^2 E_{cm}$$

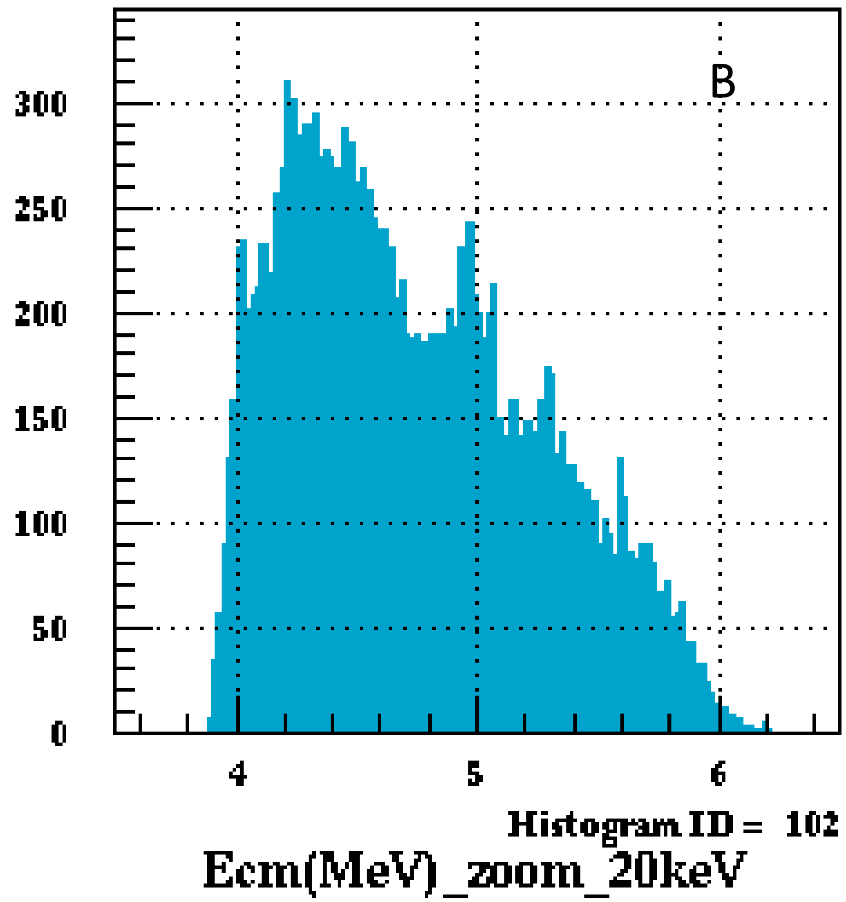
where

$$\gamma = \sqrt{\frac{m_{^{22}Na} \times m_{p,\alpha}}{m_{^1H} \times m_{^{22}Na,^{19}Ne}} \times \frac{E_{cm}}{E_{cm} + Q_{p,\alpha}}}$$



Proton spectrum from $^{22}Na(p,p)$, before(A) and after(B) kinematic reconstruction, respectively





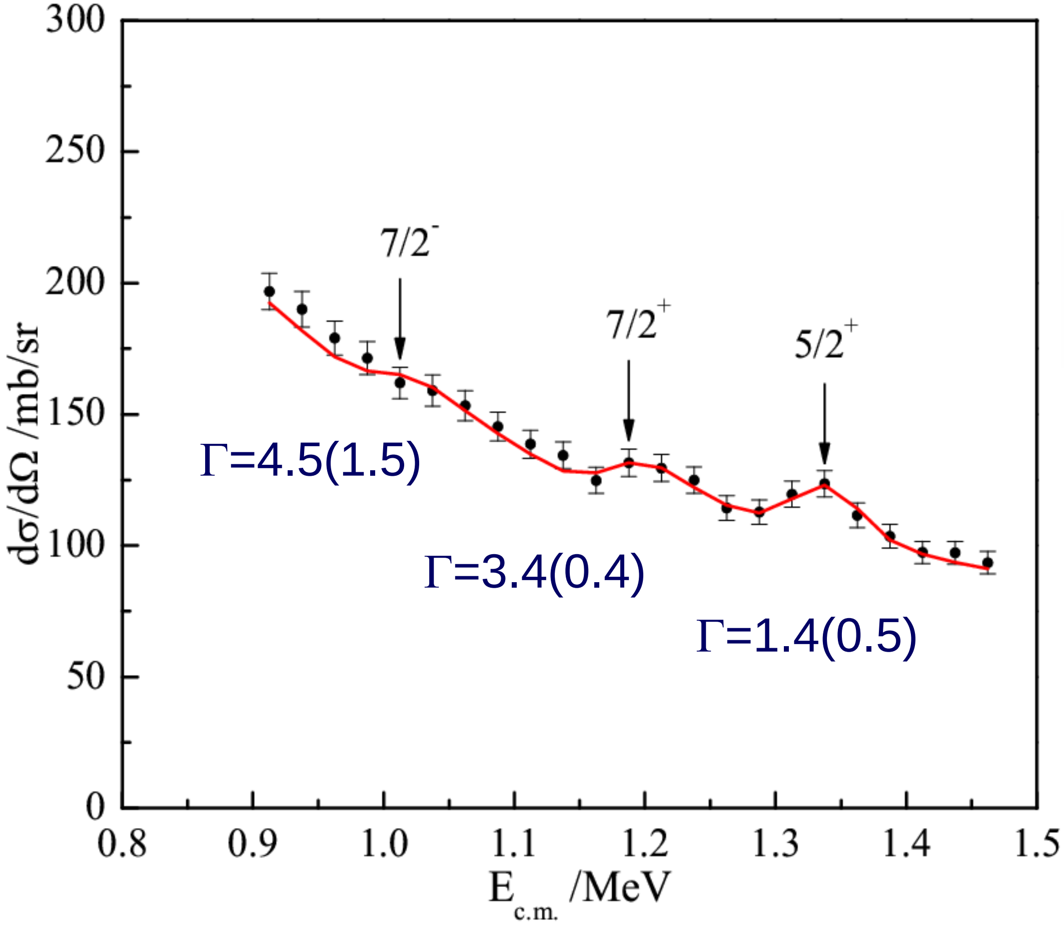
Alpha spectrum from $^{22}Na(\alpha,\alpha)$, before(A) and after(B) kinematic reconstruction, respectively

Differential Cross Section

$$\frac{d\sigma}{d\Omega}(E_{cm},\Delta\Omega) = \frac{N(E_{cm},\Delta\Omega)}{N_{beam}\times n_{eff}(E_{cm})\times\Delta\Omega}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{c.m.} = \frac{1}{4\cos\theta_0}\left(\frac{d\sigma}{d\Omega}\right)_{lab}$$

Excitation function of ^{22}Na(p,p) from ST1

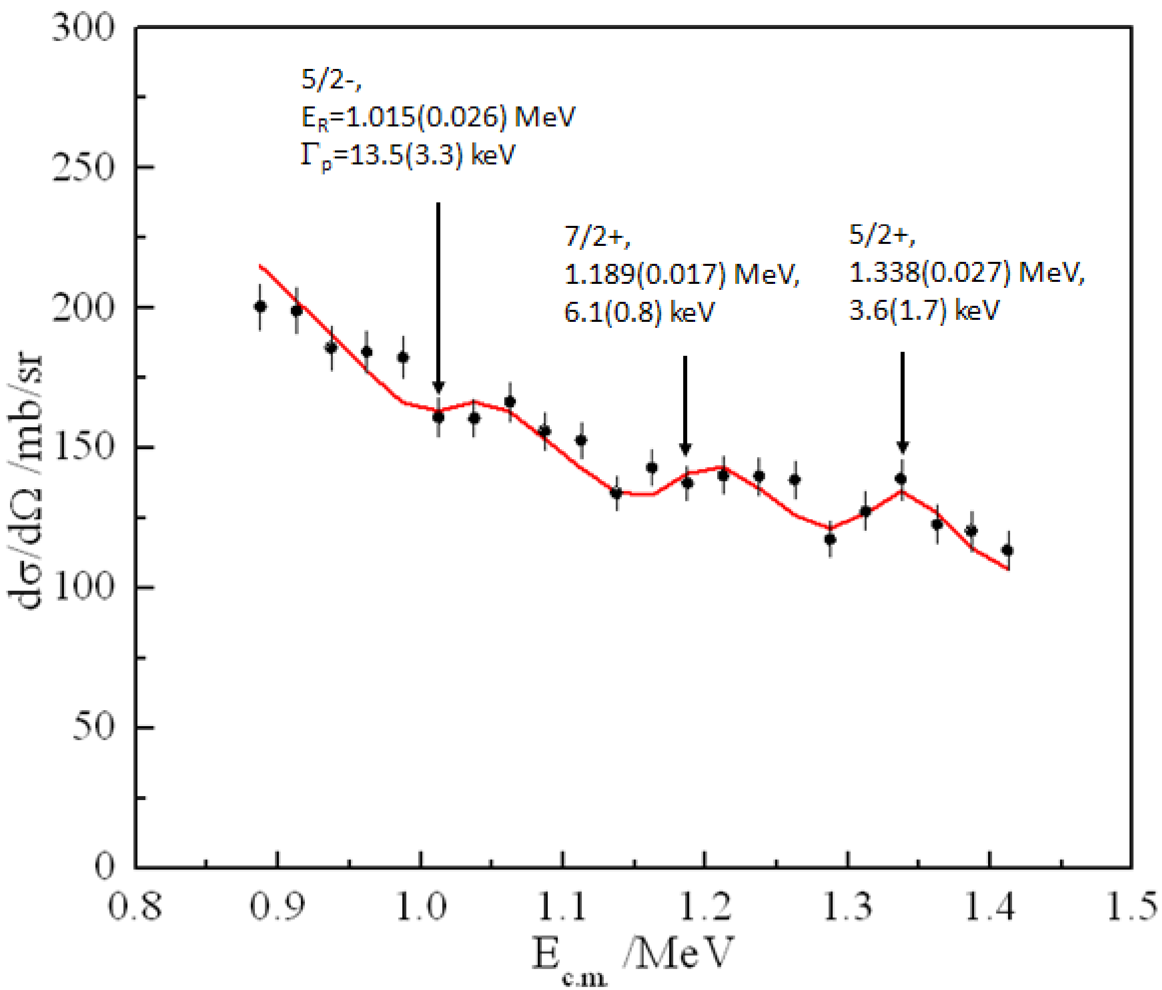


- **Multi-level R- matrix analysis**

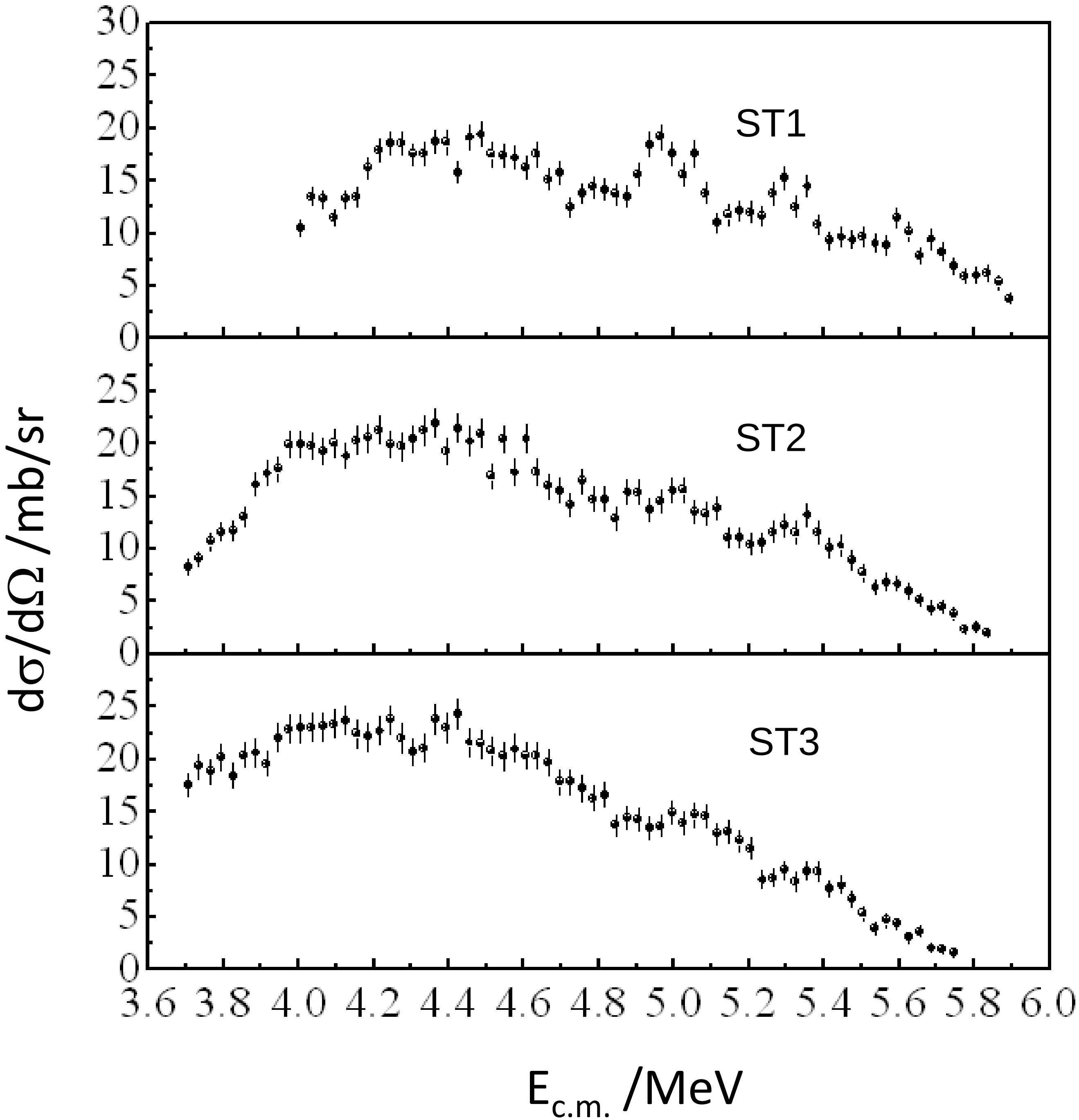
$$R_{cc} = \sum_{\lambda} \frac{\gamma_{\lambda c}^2}{E_\lambda - E}, \qquad \Gamma_{\lambda c} = 2P_c(E)\gamma_{\lambda c}^2$$

3 narrow resonances observed with deduced E_R, J^π, and Γ_p

Excitation function for ST3



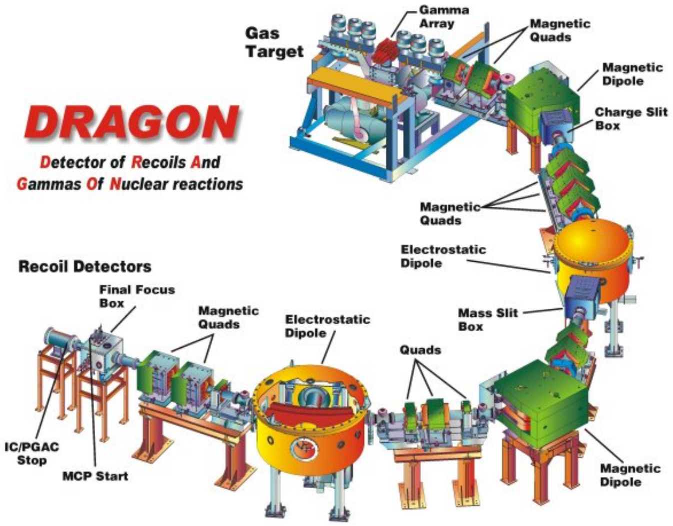
$^{22}Na+\alpha$ Excitation Function

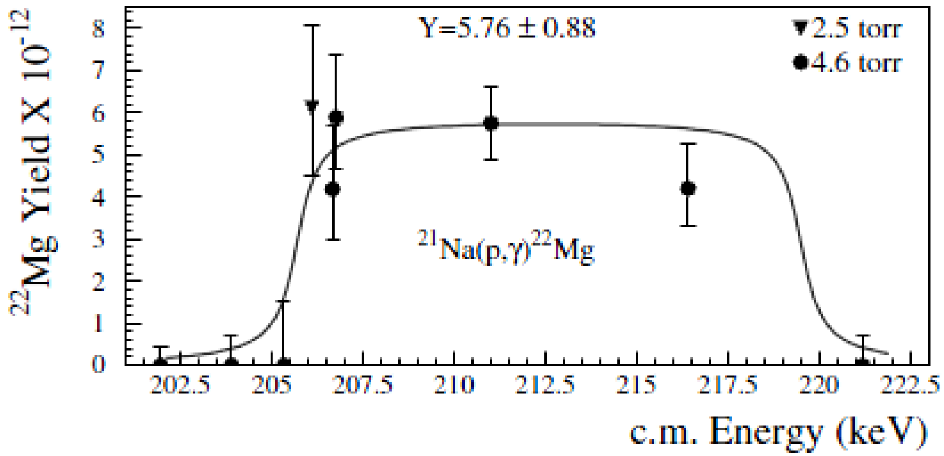


Discussion

- Status of other experimental measurements
- Level Systematics

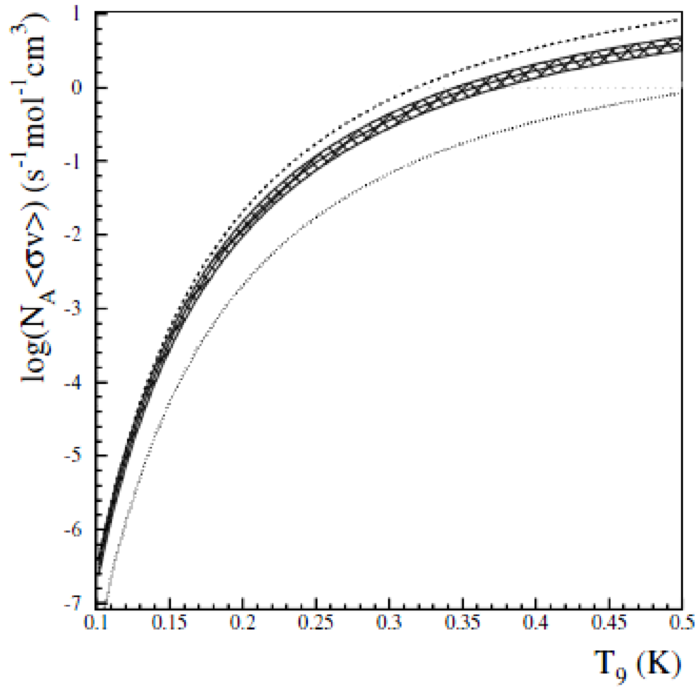
^{21}Na(p,γ)^{22}Mg reaction measurement at DRAGON





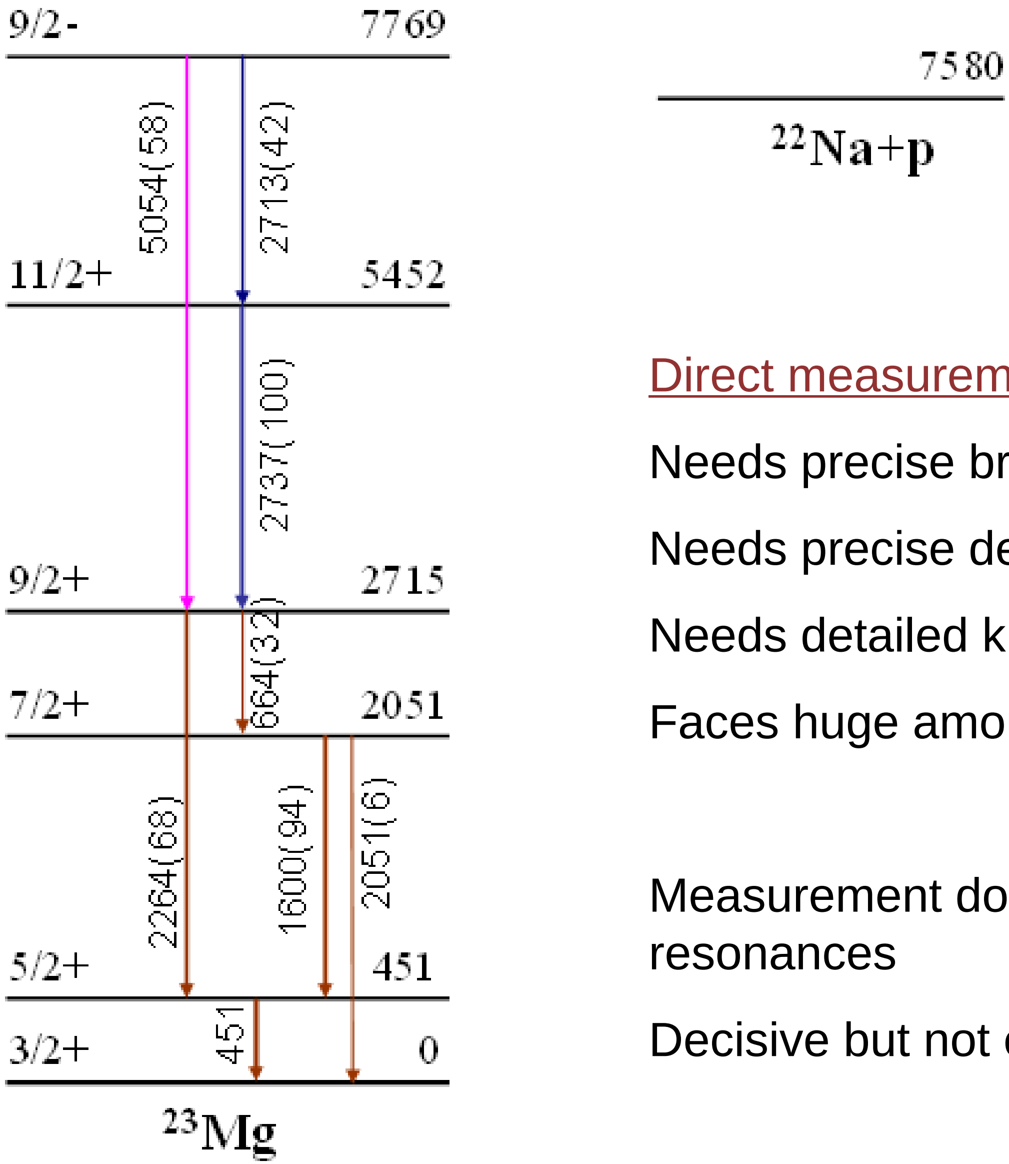
$$Y = \frac{\lambda^2}{2}\frac{M+m}{m}\omega\gamma\left(\frac{dE}{dx}\right)^{-1}$$

$$N_A\langle\sigma v\rangle = 1.54\times10^{11}(\mu T_9)^{-3/2}\omega\gamma\,\exp\left[-11.605\,\frac{E_R}{T_9}\right],$$



Bishop et al., PRL90, 162501(2003)

Decay scheme of ^{23}Mg



<u>Direct measurement:</u>

Needs precise branching ratios

Needs precise detection efficiency

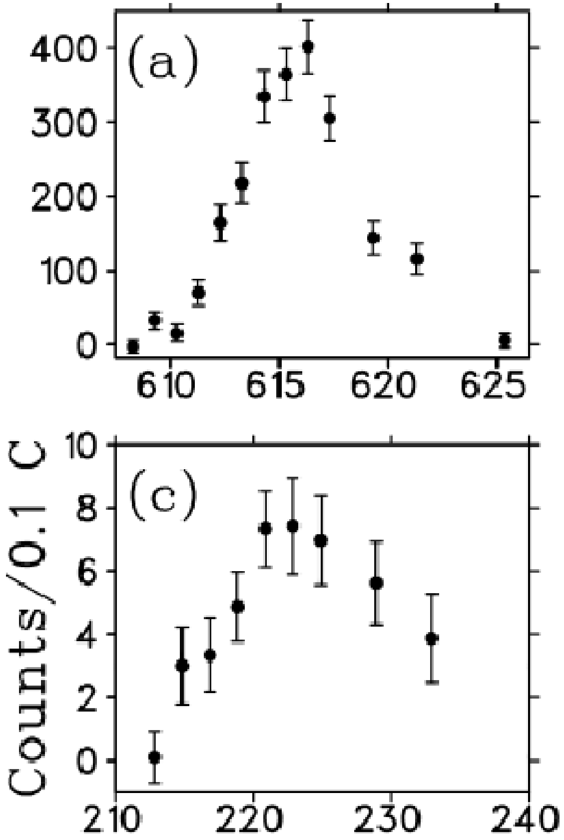
Needs detailed knowledge of stopping power

Faces huge amounts of background

Measurement done usually around the known resonances

Decisive but not exclusive!

Direct measurements of $^{22}Na(p,\gamma)^{23}Mg$ reaction



E_R (keV)	$\omega\gamma_{previous}$ (meV)	$\omega\gamma_{present}$ (meV)	Ratio present : previous
198	≤ 4 *	≤ 0.50	0.1
211	1.8 ± 0.7 1	$5.5^{+1.6}_{-0.9}$	3.1
232	2.2 ± 1.0 *	≤ 0.65	0.3
287	15.8 ± 3.4 1	38 ± 8	2.4
453	68 ± 20 2	161 ± 21	2.4
608	235 ± 33 2	573^{+100}_{-72}	2.4

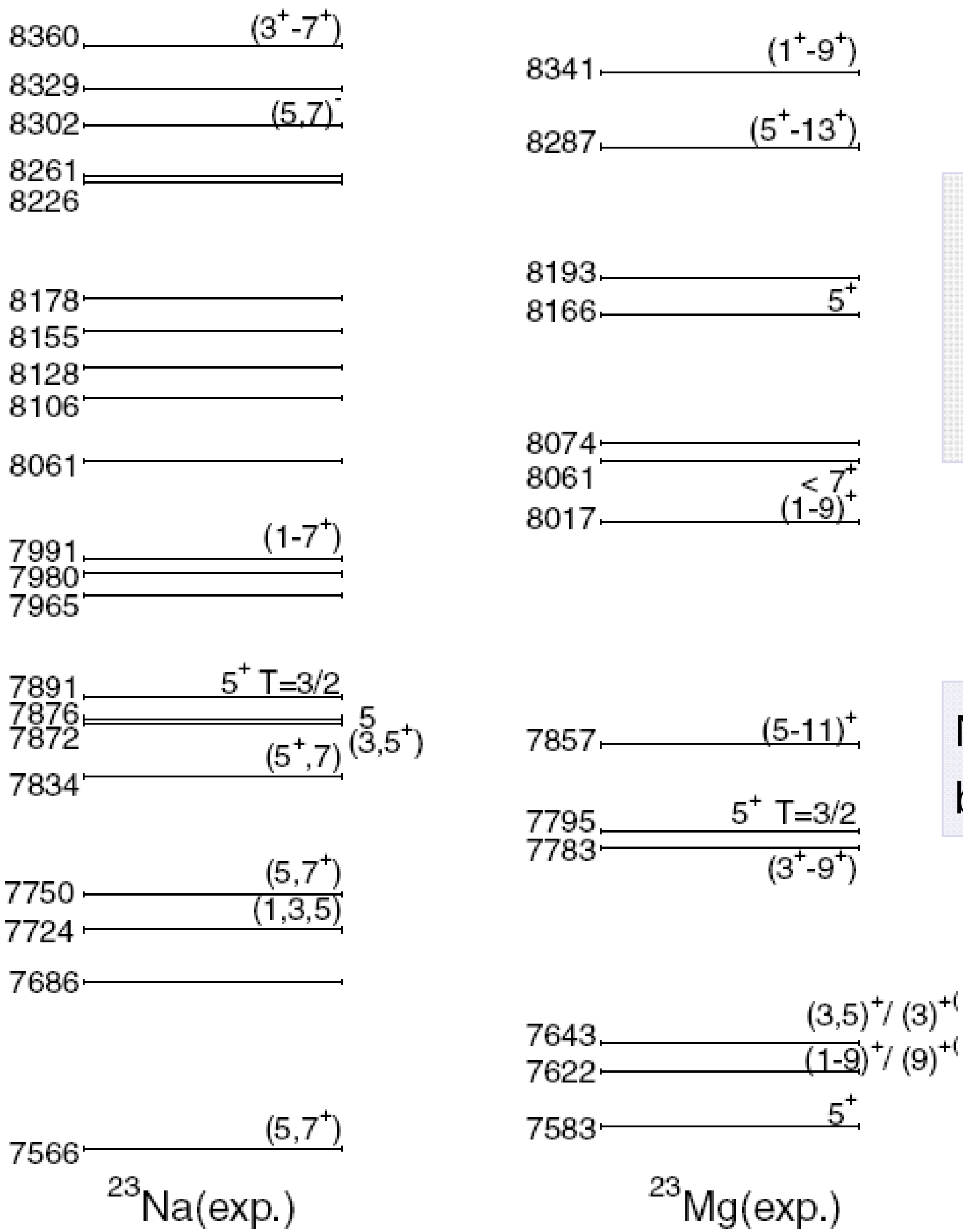
^{22}Na consumption increases by factors of 2 to 3

A.L.Sallaska *et al.*, PRL105,152501(2010)

Earlier similar studies:

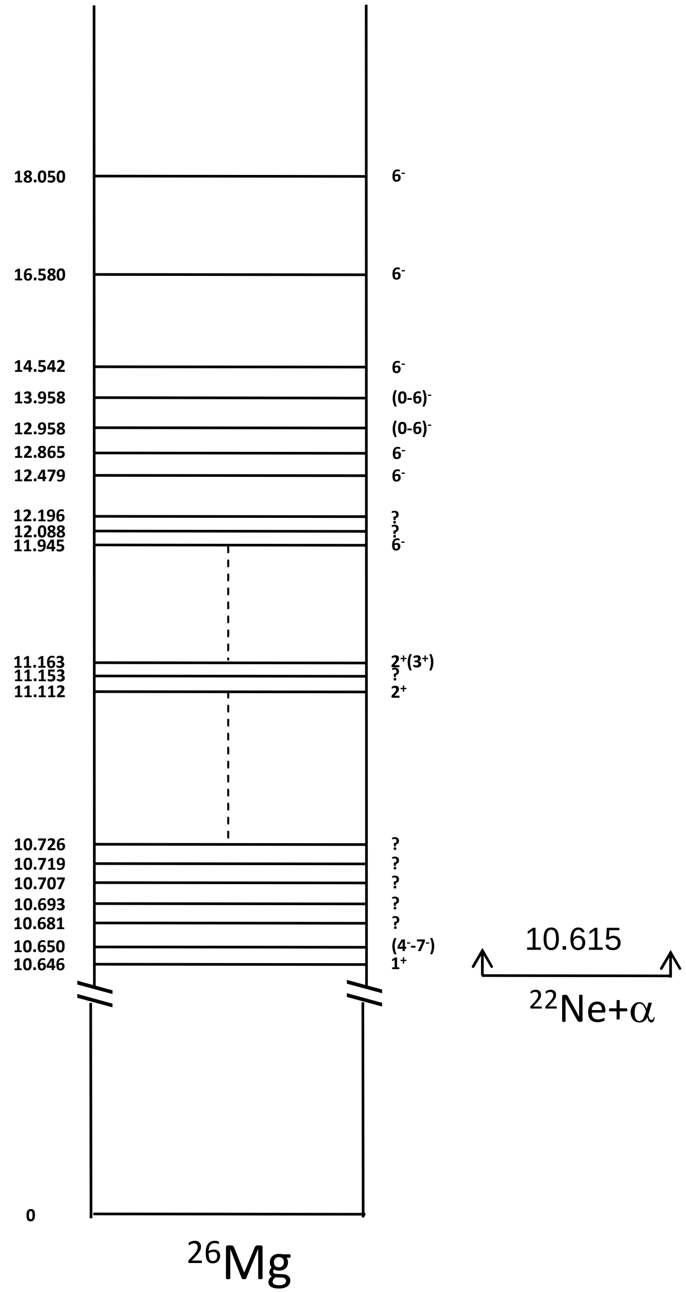
F. Stegmüller *et al*., NPA**601**, 168(1996)

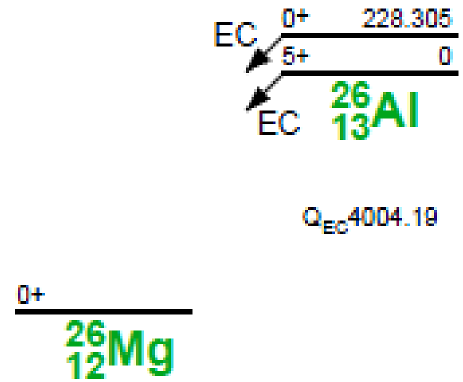
S. Seuthe *et al.*, NPA**514**, 471(1990).

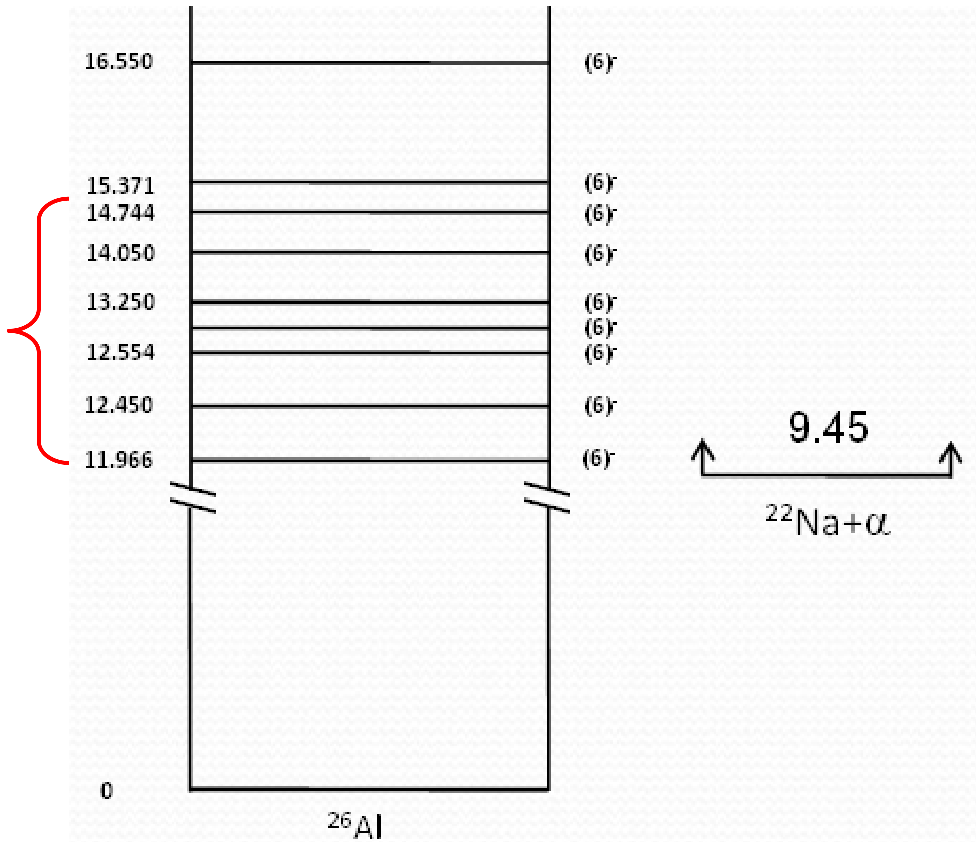


Known ^{23}Mg states above S_p=7578 keV

Note: spins are multiplied by 2 just for clarity!

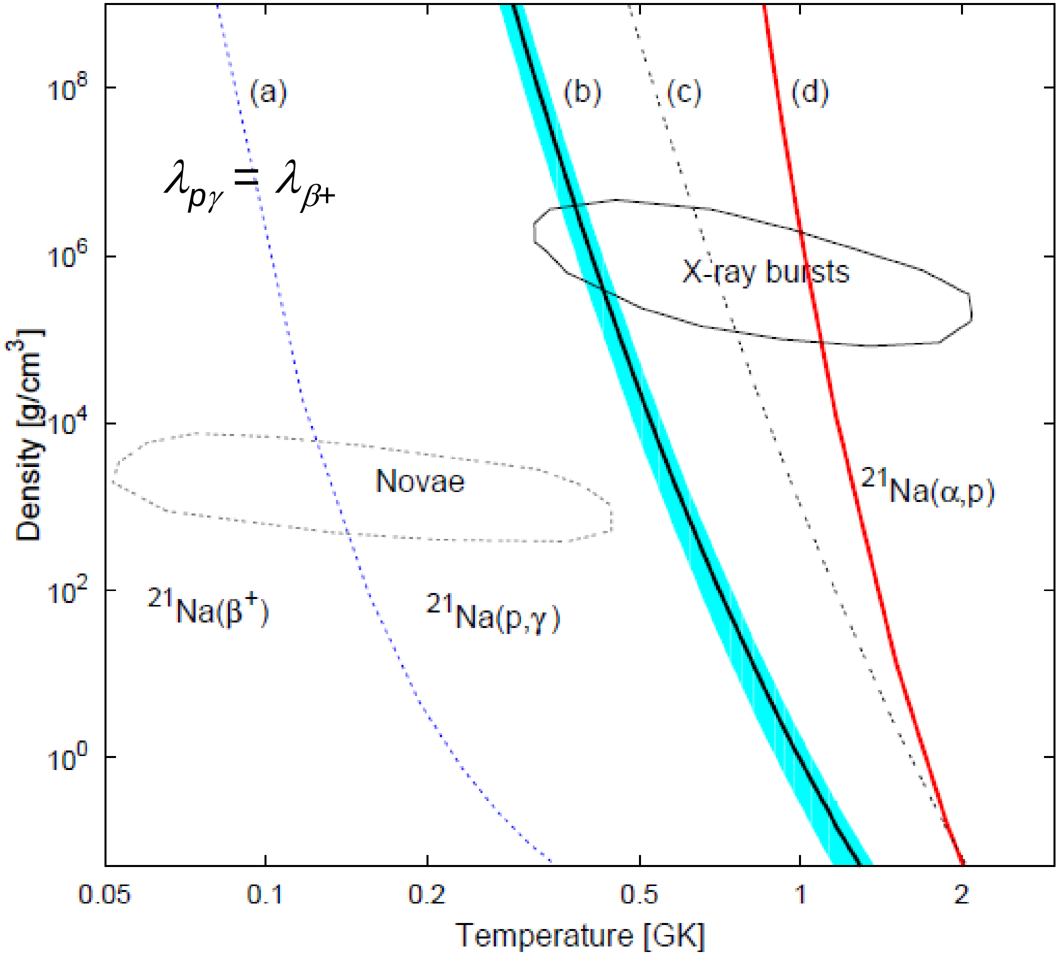

18.050
6-
16.580
6-
14.542
6-
13.958
(0-6)-
12.958
(0-6)-
12.865
6-
12.479
6-
12.196
?
12.088
?
11.945
6-
11.163
2+(3+)
11.153
?
11.112
2+
10.726
?
10.719
?
10.707
?
10.693
?
10.681
?
10.650
(4--7-)
10.646
1+
0
26Mg
10.615
22Ne+α

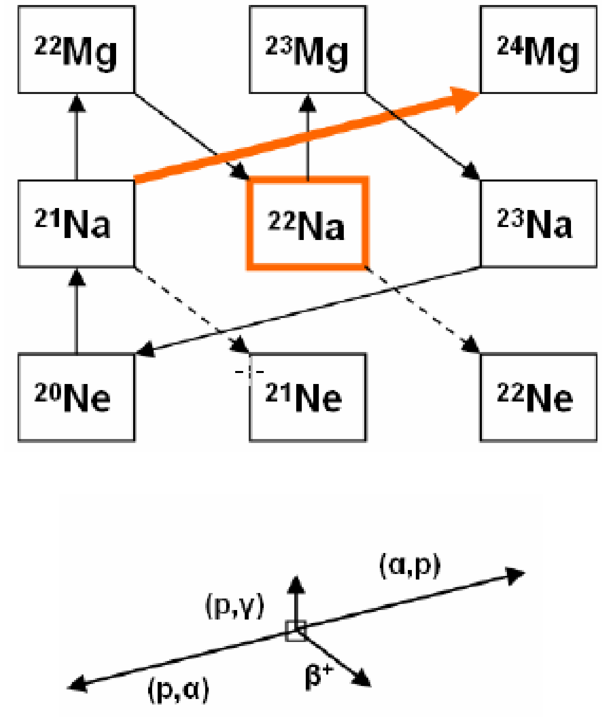

EC
0+
228.305
5+
0
EC
26 13 Al
QEC4004.19
0+
26 12 Mg


16.550
(6)-
15.371
(6)-
14.744
(6)-
14.050
(6)-
13.250
(6)-
(6)-
12.554
(6)-
12.450
(6)-
11.966
(6)-
0
26Al
9.45
22Na+α

^{21}Na(p,γ) and ^{21}Na(α,p)

(b,c,d) $\lambda_{\alpha p} = \lambda_{\beta+}$ using different (α,p) rates





X_{4He} = 0.28, X_{1H} = 0.7 and 0.02 of heavier isotopes

Summary

- The excitation functions of $^{22}Na+p$ and $^{22}Na+\alpha$ resonant scattering were measured with a high-quality ^{22}Na radioactive beam.
- Resonant structures were observed from the ex. func. of $^{22}Na+p/\alpha$ resonant scattering.
- Detailed analysis is in progress.

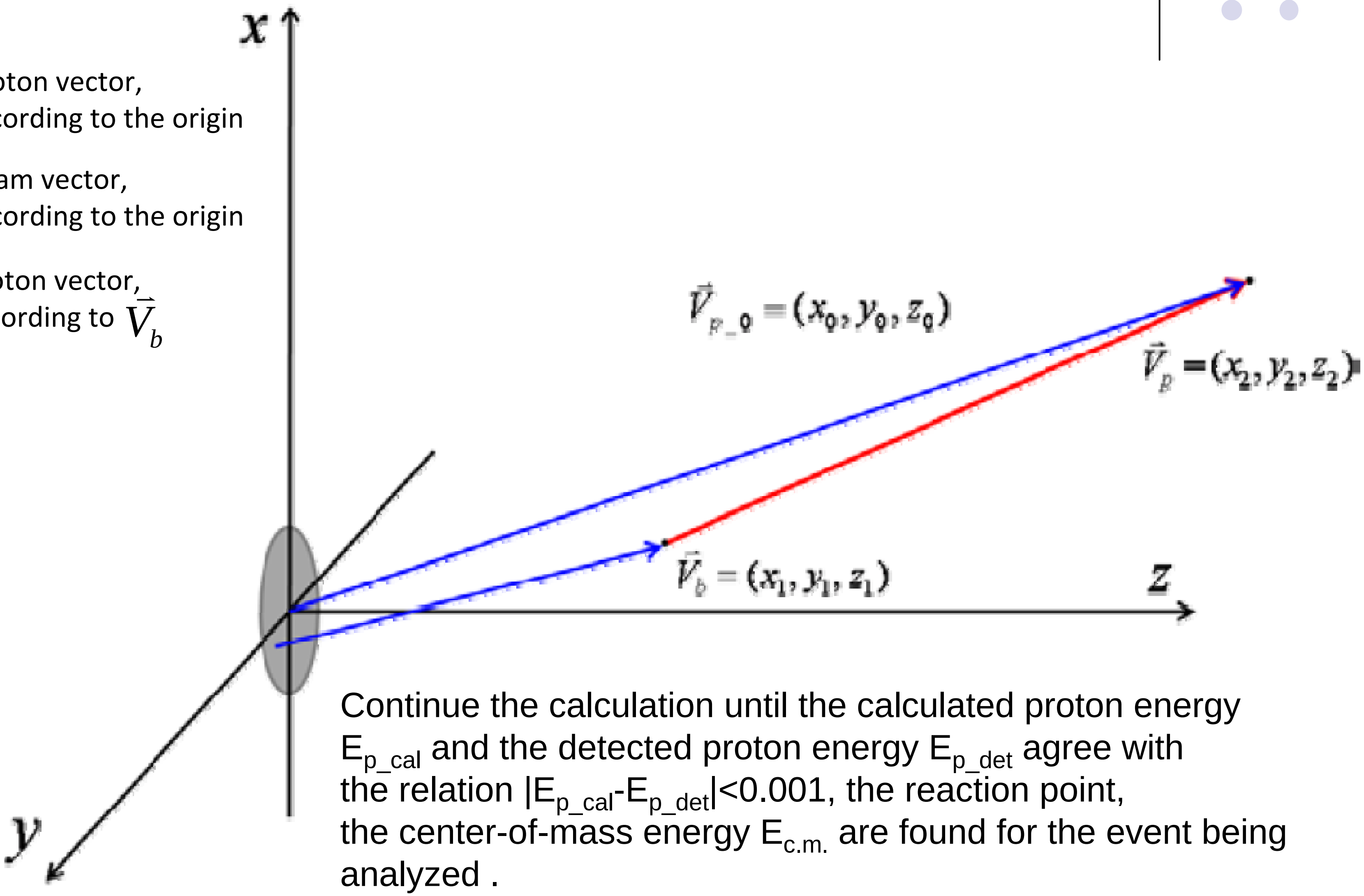
Thank you!

$$\cos\theta = \frac{\vec{V}_b \cdot \vec{V}_p}{\left|\vec{V}_b\right|\left|\vec{V}_p\right|} = \frac{x_1x_2 + y_1y_2 + z_1z_2}{\sqrt{x_1^2 + y_1^2 + z_1^2}\sqrt{x_2^2 + y_2^2 + z_2^2}}$$

$\vec{V}_{p\_0}$: proton vector, according to the origin

$\vec{V}_b$: beam vector, according to the origin

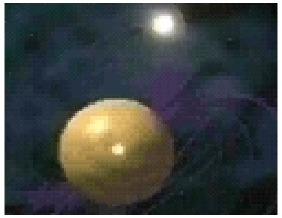
$\vec{V}_p$: proton vector, according to $\vec{V}_b$



Continue the calculation until the calculated proton energy E_{p_cal} and the detected proton energy E_{p_det} agree with the relation $|E_{p\_cal}-E_{p\_det}|<0.001$, the reaction point, the center-of-mass energy $E_{c.m.}$ are found for the event being analyzed .

X-RAY BURSTERS & X-RAY PULSARS

semi-detached binary system:



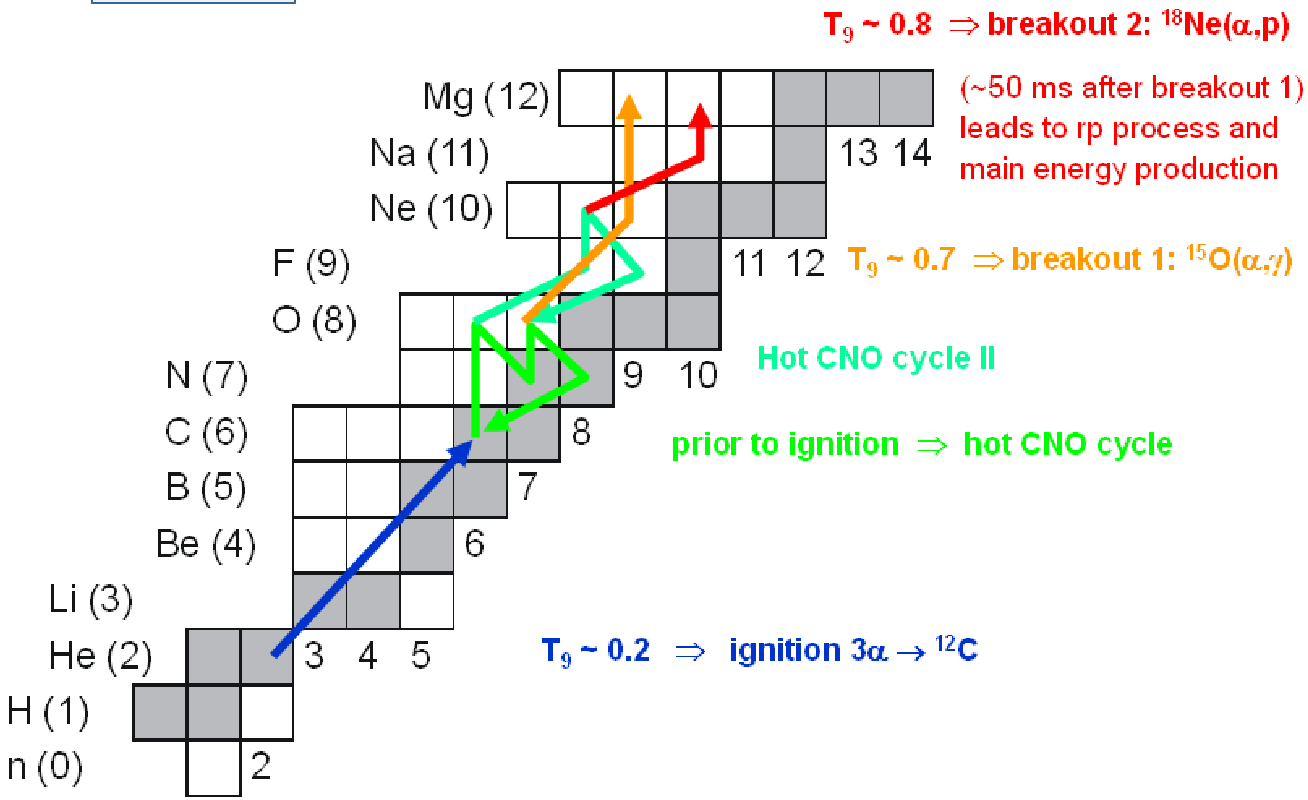
Neutron star + less evolved star

$T \sim 10^9$ K
$\rho \sim 10^6$ g cm^{-3}

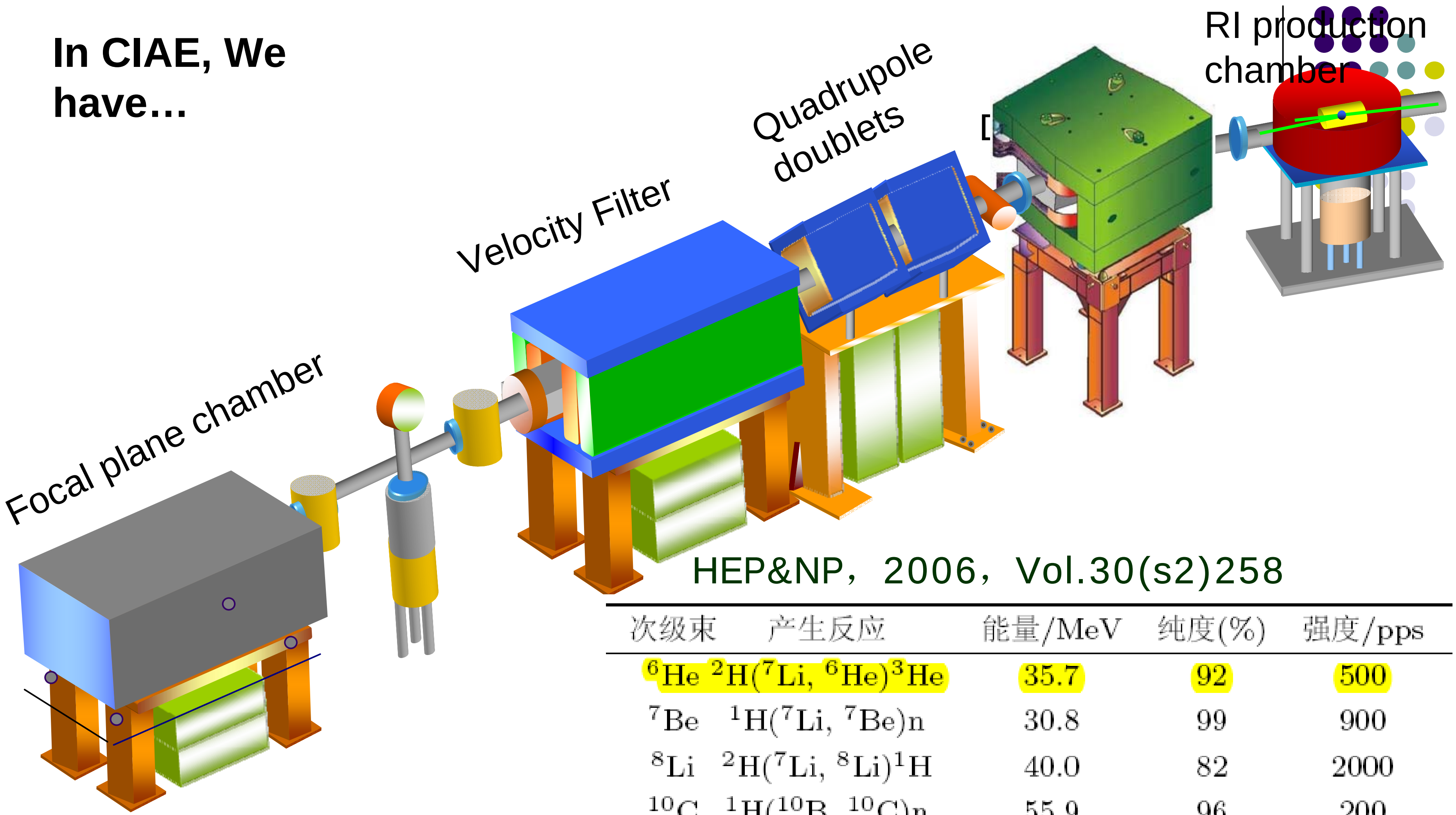
burst ignition

(α,p) and (p,γ) reactions on proton-rich nuclei

nucleosynthesis up to A ~ 80-100 mass region



In CIAE, We have…



HEP&NP，2006，Vol.30(s2)258

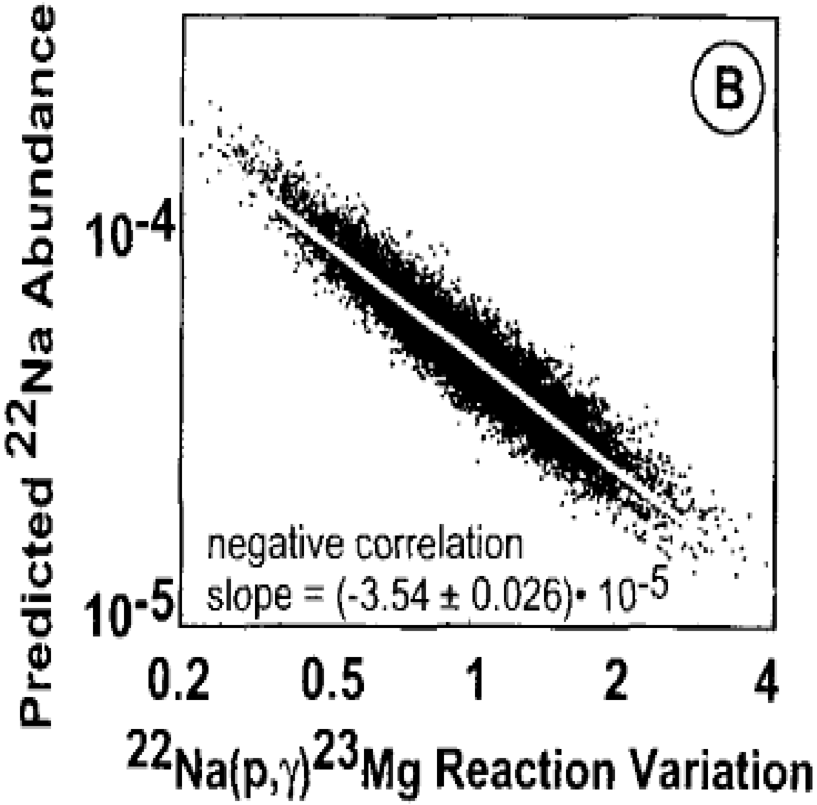
次级束	产生反应	能量/MeV	纯度(%)	强度/pps
^{6}He	^{2}H(^{7}Li, ^{6}He)^{3}He	35.7	92	500
^{7}Be	^{1}H(^{7}Li, ^{7}Be)n	30.8	99	900
^{8}Li	^{2}H(^{7}Li, ^{8}Li)^{1}H	40.0	82	2000
^{10}C	^{1}H(^{10}B, ^{10}C)n	55.9	96	200
^{11}C	^{1}H(^{11}B, ^{11}C)n	63.4	80	1000
^{13}N	^{2}H(^{12}C, ^{13}N)n	57.8	92	1200
^{15}O	^{2}H(^{14}N, ^{15}O)n	66.0	91	1500
^{17}F	^{2}H(^{16}O, ^{17}F)n	76.1	90	3000
^{18}F	^{3}He(^{16}O, ^{18}F)^{1}H	75.7	85	600

Relevant Publication of local TTIK works

1. **Angular distribution of ^{6}He+p elastic scattering**
   LIU Xin, Wang You-Bao et al., Chin. Phys. C36, 716-720(2012)
2. **Excited states in ^{18}Ne studied via ^{17}F+p**
   JIN Sun-Jun, WANG You-Bao et al.,
   Chin. Phys. Lett. Vol. 27, 032102(2010)1-4
3. **Elastic resonance scattering of ^{13}N+p and ^{17}F+p**
   Y.B. Wang, B.X. Wang et al., Nucl. Phys. A834, 100c-102c(2010)
4. **Simulation and analysis of ^{13}N+p elastic resonance scattering**
   WANG You-Bao, QIN Xing et al., Chin. Phys. C33, 181-186(2009)
5. **^{13}N+p elastic resonance scattering via a thick-target method**
   Y.B. Wang, B.X. Wang et al., Phys. Rev. C77, 044304(2008)
6. **Levels in ^{13}N examined by ^{12}C+p elastic resonance scattering with thick target**
   QIN Xing, WANG You-Bao et al., Chin. Phys. C32, 957-961(2008)
7. **A Setup for resonance scattering reactions with thick target**
   WANG Youbao, WANG Baoxiang et al., HEP&NP, Vol.30(S2), 202 (2006). (In Chinese)

^{22}Na abundance v.s. ^{22}Na(p,γ)^{23}Mg reaction

Significant nuclear uncertainties affect this rate (a factor ranging from 3 to 6 for T8>1), which turns out to be crucial in deriving ranges of ^{22}Na production during nova outbursts.



Hix et al. Nucl. Phys. A718 (2003) 620c-622c

Narrow resonances

$$\langle\sigma v\rangle_{12} = \left(\frac{2\pi}{\mu_{12}kT}\right)^{3/2} \hbar^2 (\omega\gamma)_R \exp\left(-\frac{E_R}{kT}\right)$$

rate entirely determined by "**resonance strength**" $\omega\gamma$ and **energy of the resonance E_R**

resonance strength

(= integrated cross section over resonant region)

$$\omega\gamma = \frac{2J+1}{(2J_1+1)(2J_T+1)} \frac{\Gamma_1\Gamma_2}{\Gamma}$$

(Γ_i values at resonant energies)

experimental info needed

- partial widths Γ_i
- spin **J**
- energy E_R