Low-energy radioactive beam experiments for nuclear astrophysics

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Main subject:

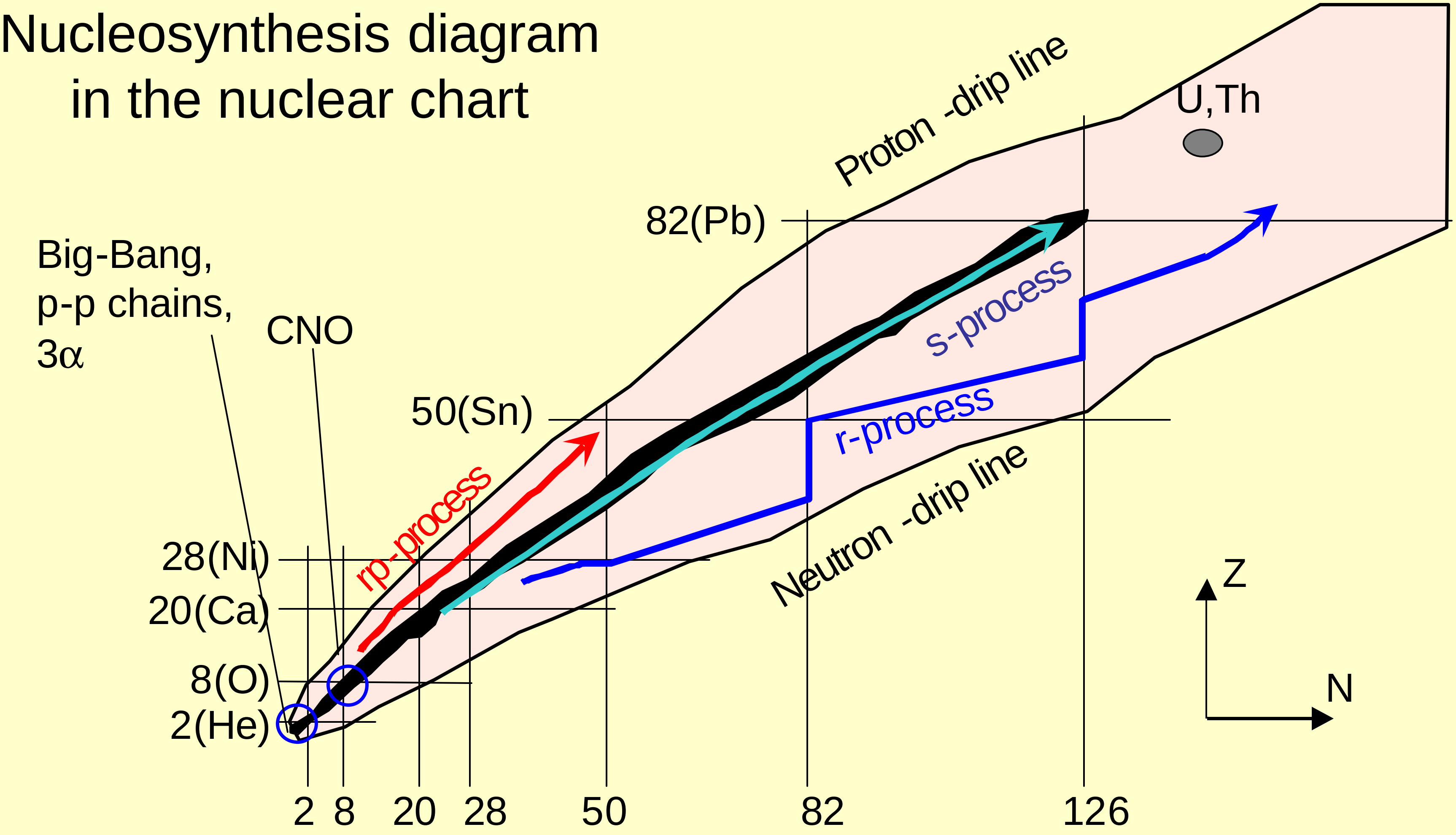
Recent experimental studies using low-energy radioactive beams at CNS

Production of low-energy radioactive nuclear beams

Basic concepts on stellar reaction cross section

Experimental techniques of measuring resonance scattering to study explosive hydrogen burning

Nucleosynthesis diagram in the nuclear chart



r-process (rapid neutron capture process) plays a crucial role to produce heavy elements like Uranium and Thorium in super nova explosion.

rp-process (rapid proton capture process) is important in energy generation and nucleosynthesis at high-temperature hydrogen-rich explosive conditions like nova and X-ray burst.

Unstable (neutron- or proton-rich) nuclei play important roles in explosive conditions!

Production of radioactive nuclear beams

Two major techniques for radioactive beam production

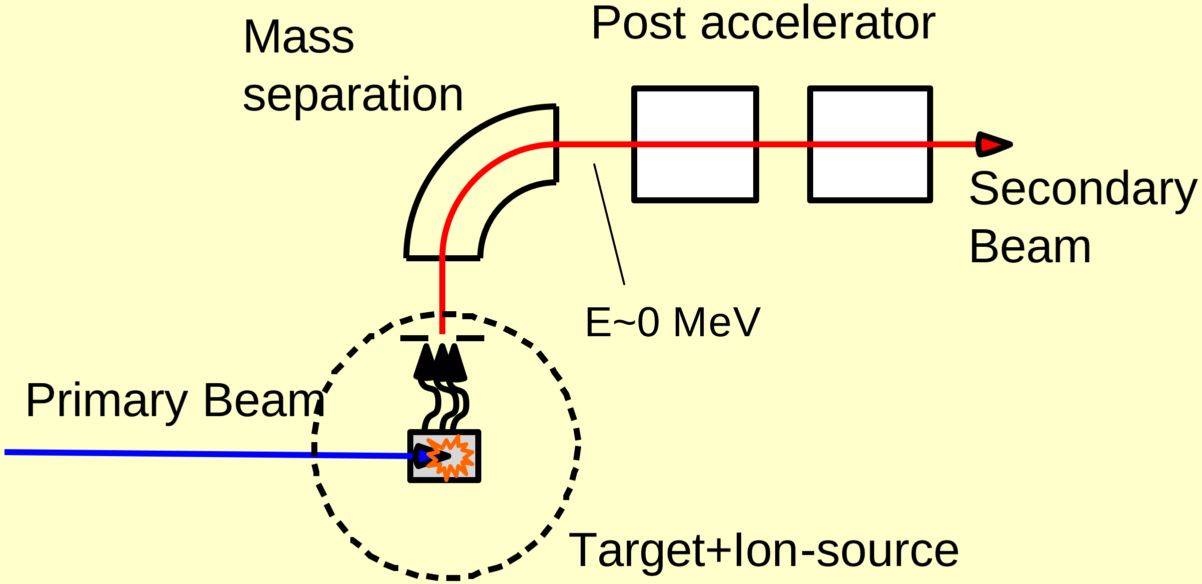
1. ISOL (Isotope Separator On-Line)

Reaction products are produced and stopped in a thick production target, which is part of an ion source. The reaction products are re-ionized and re-accelerated as a secondary beam

Good beam quality

Extraction efficiency depends on life time & chemical property

Post-accelerator is necessary



Good for low-energy experiments (for nuclear astrophysics)

Two techniques for radioactive beam production

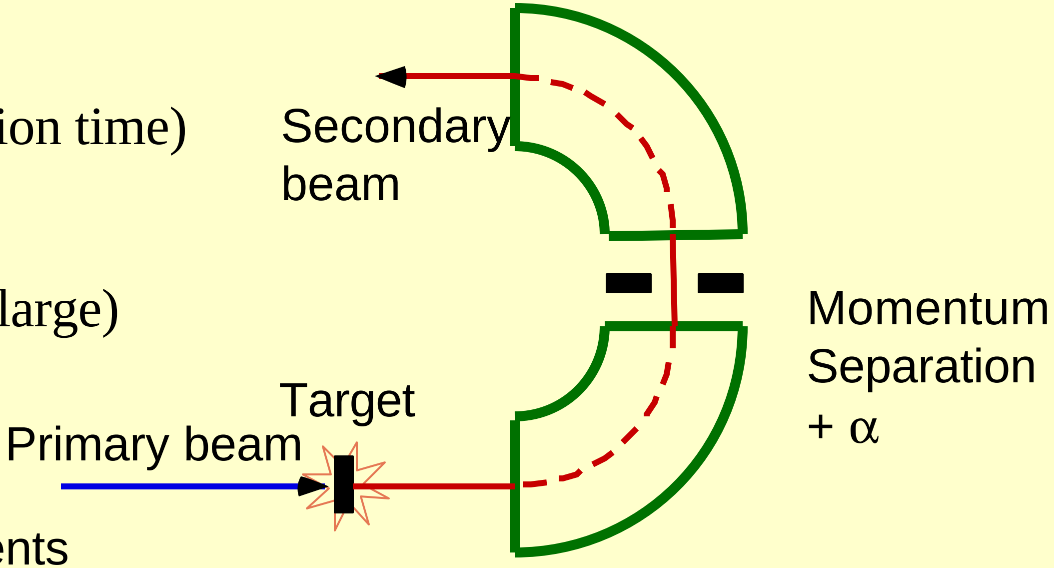
2. In-Flight Method

Reaction products are emitted from the target into forward angles.
Particles are separated “in-flight” by a separator to have a secondary beam.

Independent of chemical properties

No problem with life time
(life time >> beam transportation time)

Bad beam quality
(energy & angular spreads are large)



Good for high-energy experiments

-Projectile-fragmentation reaction at E > 100 MeV/nucleon is
efficient for production of unstable nuclei far from the stability line
- Target can be thick.

Application to low-energy beams is also useful.

Radioactive Nuclear Beam Facilities

Low-energy (mostly < 5 MeV/nucleon)

ISOL

Leuvan-la-Neuve, TRIUMF, ORNL, SPIRAL, REX ISOLDE, TRIAC…

In-flight

NotreDame, TexasA&M, CNS……

Direct measurements of stellar reactions (at $E < 1$ MeV)

Indirect study of stellar reaction by various low-energy reactions

In future projects, development of high intensity beams (> 10^9 pps) and upgrade of beam energy (> 10 MeV/nucleon) are planed.

High-energy, In-flight (> ～ 100 MeV/nucleon)

GANIL, GSI, RIKEN, MSU….

Structure, decay, & excitation properties of neutron- and proton-rich nuclei

Coulomb dissociation method for stellar (p,γ) reaction rates

At future facilities (RIBF, RIA, FAIR…), mass, life-time, decay branches for extremely neutron-rich nuclei will be studied for the r-process.

Low-energy beam facility at Center for Nuclear Study (CNS), U-Tokyo

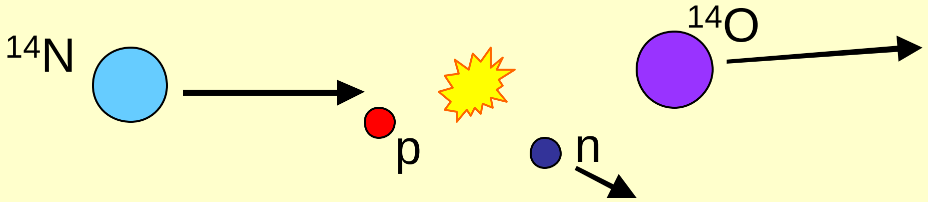
CRIB (CNS low-energy Radioactive-Ion Beam separator) 2000~

Low-energy in-flight method

With low-energy high-intensity heavy-ion primary beams
and a large-acceptance particle separator

For example: ^{14}O beam can be produced by

- Primary beam ^{14}N (6+) Intensity 500 pnA (3×10^{12} particles/s)
Energy 8.4 MeV/nucleon
- p(^{14}N,^{14}O)n reaction Inverse-kinematics (heavy beam + light target)
Cross section ~ 8 mb

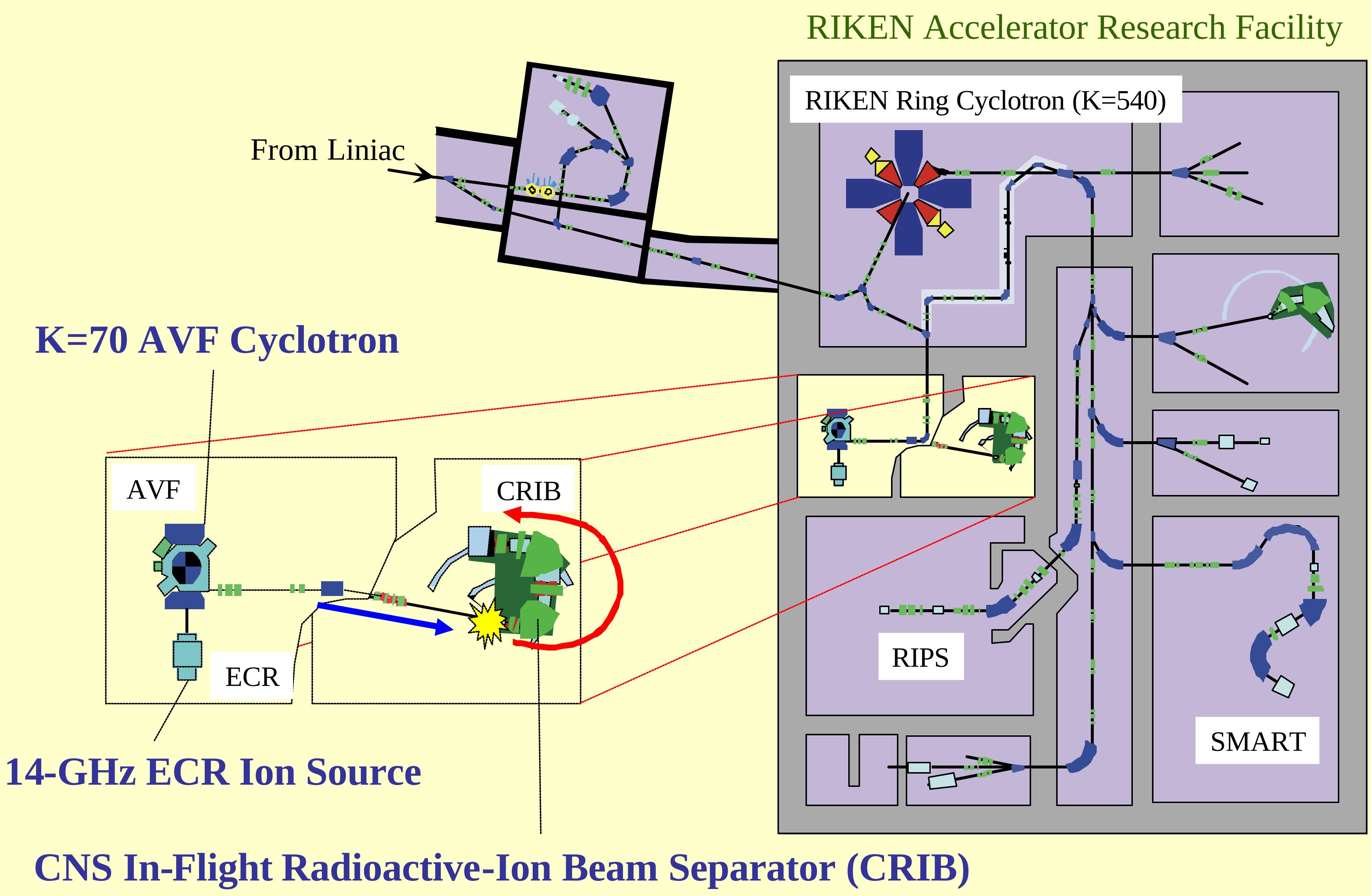


Kinematically
focused into
forward angles

- Hydrogen target Methane gas CH_4 in a cell with window foils
1atm. 2 cm (0.3 mg/cm^2)

Energy < 7 MeV/nucleon
^{14}O intensity 2´10^{6} particles/sec
(10^{7} is possible with a thicker target)

CNS Low-Energy Radioactive-Beam Line in RIKEN Facility



CNS In-Flight Radioactive-Ion Beam Separator (CRIB)

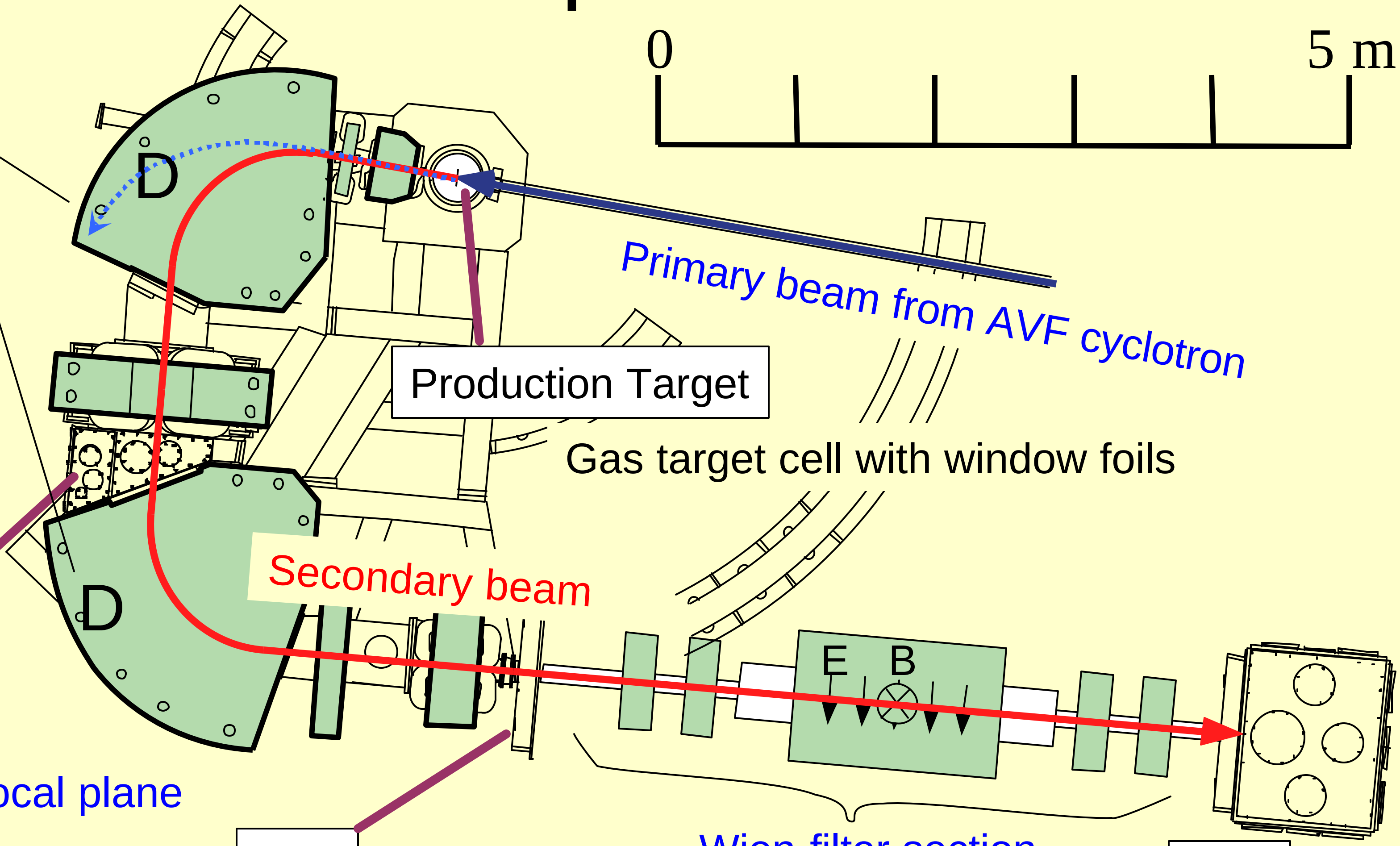
RIKEN AVF (azimuthally varying field) cyclotron

K = 70 MeV
Extraction radius 0.714 m
Total weight 110 ton

$$E_{\max} = K \frac{q^2}{A}$$

Modifications & improvements (flat-top cavity, maximum energy upgrade etc) are made by CNS.

CRIB separator



Dipole Magnet

Primary beam from AVF cyclotron

Production Target

Gas target cell with window foils

Secondary beam

F1

Momentum-dispersive focal plane

P/q selection

F2

Achromatic focal plane

small beam spot (ϕ1cm)
slit & degrader

Wien filter section

velocity selection

F3

Final focal plane

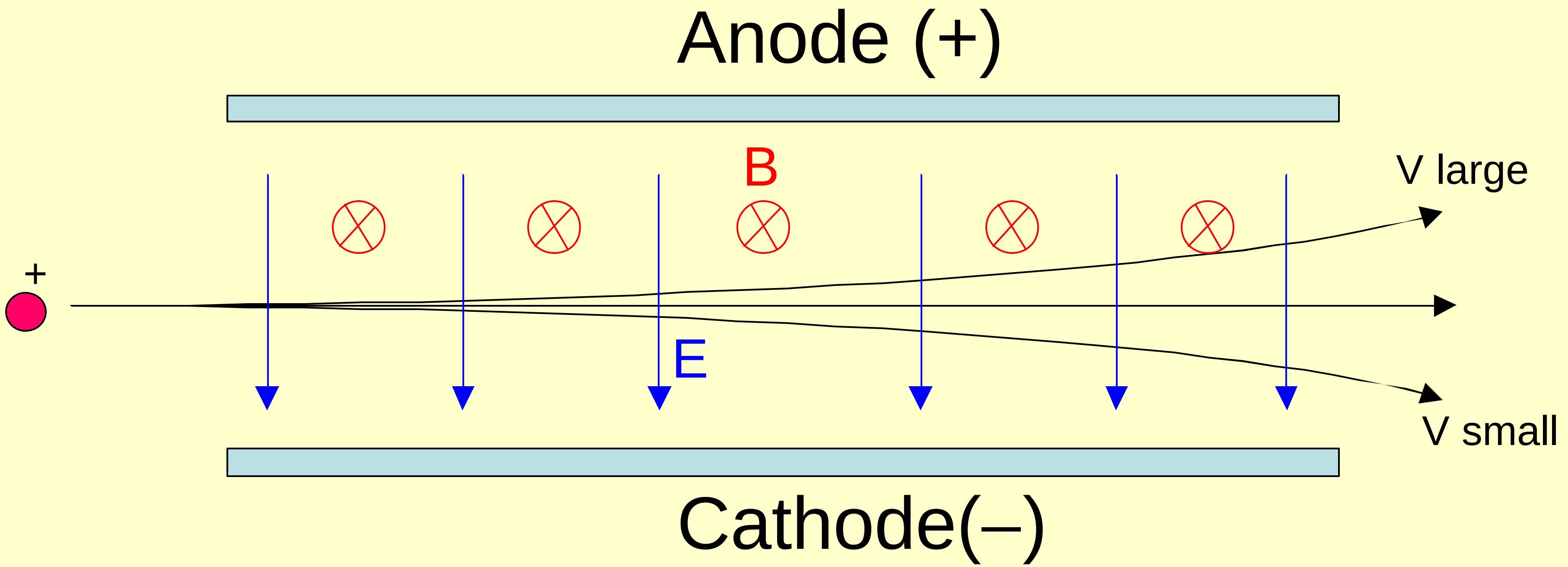
slit
Exp. setup

P/q =const. & v = const. → m/q selection

(Z can be separated by using degrader)

Wien Filter

Length of electrodes 1.5 m
Max E field ±200 kV / 8 cm
Max B field 3 kGauss



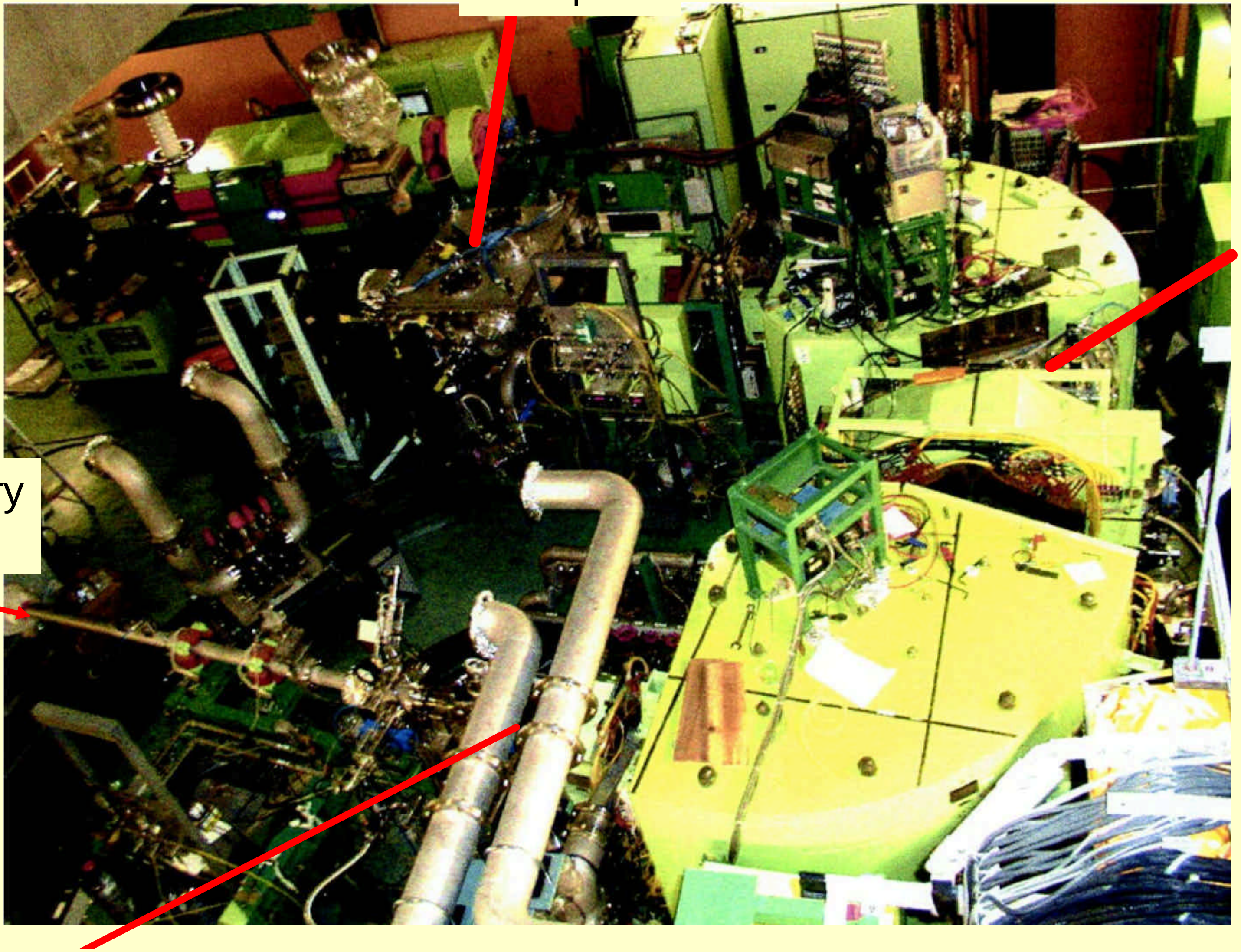
Lorentz force $qE = qvB$

$$v = \frac{E}{B}$$

Velocity selection
Independent of charge and mass

CRIB

In the RIKEN Accelerator Facility



F2:
Achromatic
focal plane

F1:
Dispersive
focal plane

Primary
beam

Target

Production reactions for CRIB (low-energy in-flight method)

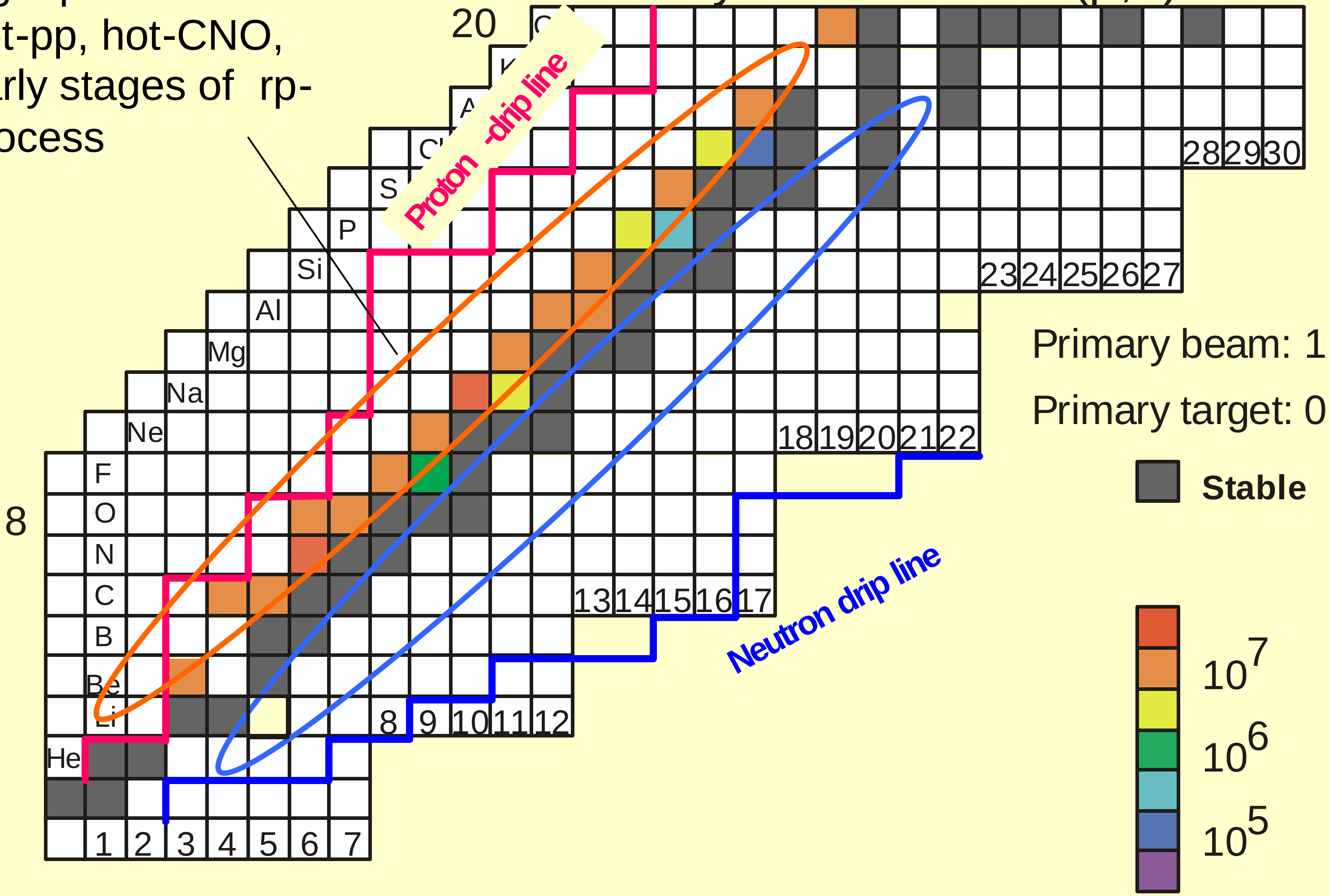
Heavy-Ion beam + light-ion target

Proton-rich nuclei: (p,n), (p,d), (d,n), (d,t), (^{3}He,n)….

Neutron-rich nuclei: (d,p), (d,^{3}He)…..

Light proton-rich nuclei:
hot-pp, hot-CNO,
early stages of rp-process

Intensity Prediction for (p,n) reactions



Primary beam: 1 pμA

Primary target: 0.1 mg/cm^2

Radioactive Beams Produced by CRIB (A<20)

(p,n) reactions ↖

^{7}Be 10^{6} pps

^{10}C 1.6×10^{5} pps

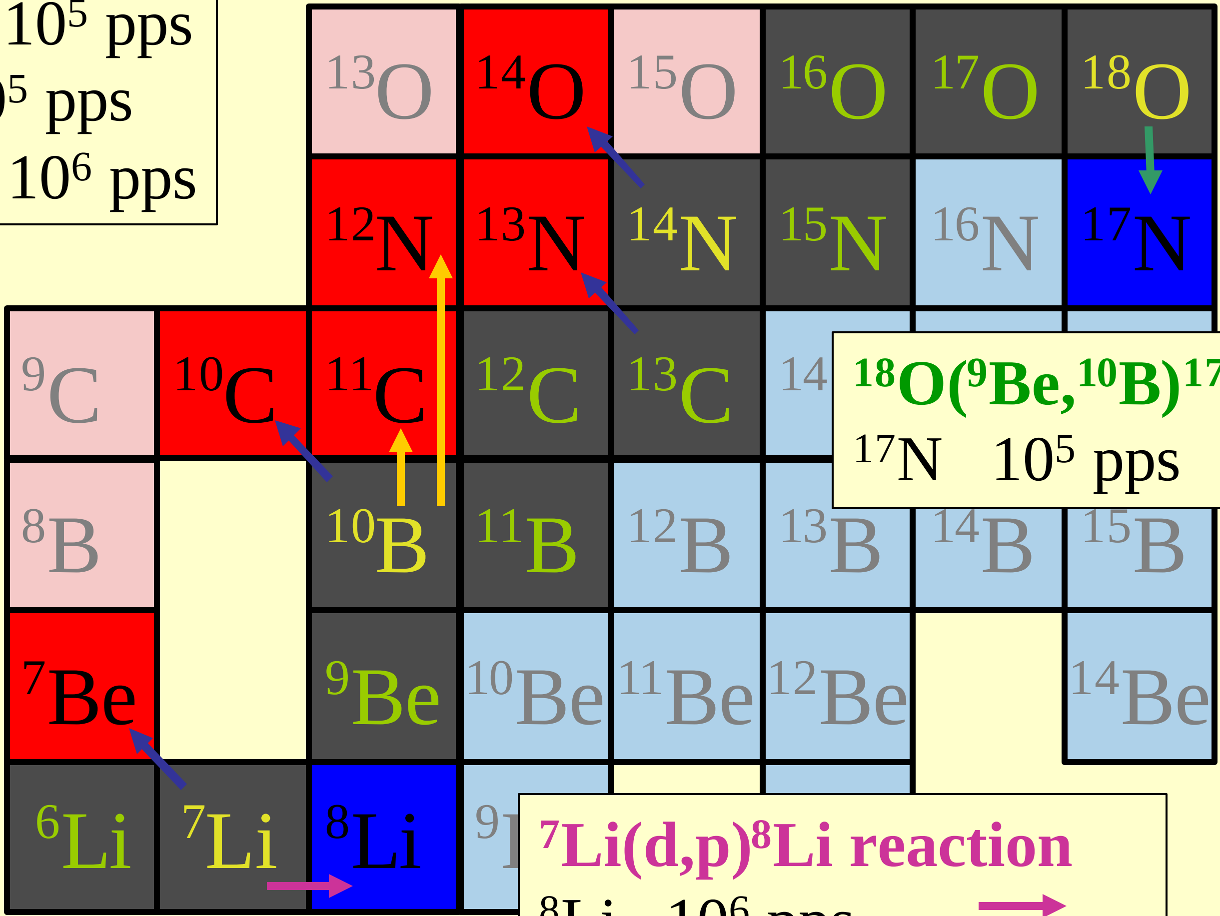
^{13}N 2×10^{5} pps

^{14}O 1.7×10^{6} pps

(^{3}He,n) & (^{3}He,np) reactions ↑

^{12}N 2.5×10^{3} pps

^{11}C 1.7×10^{4} pps



^{18}O(^{9}Be,^{10}B)^{17}N reaction

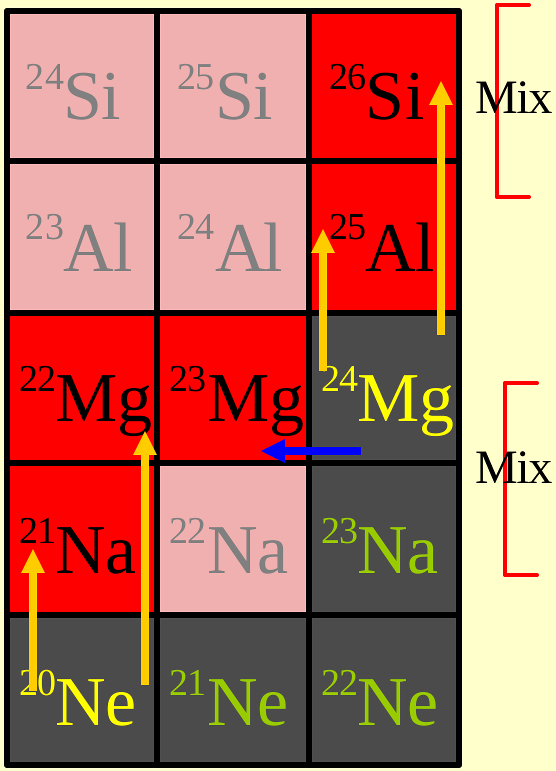
^{17}N 10^{5} pps ↓

^{7}Li(d,p)^{8}Li reaction

^{8}Li 10^{6} pps →

■ Stable nuclei

Radioactive Beams Produced by CRIB (A>20)



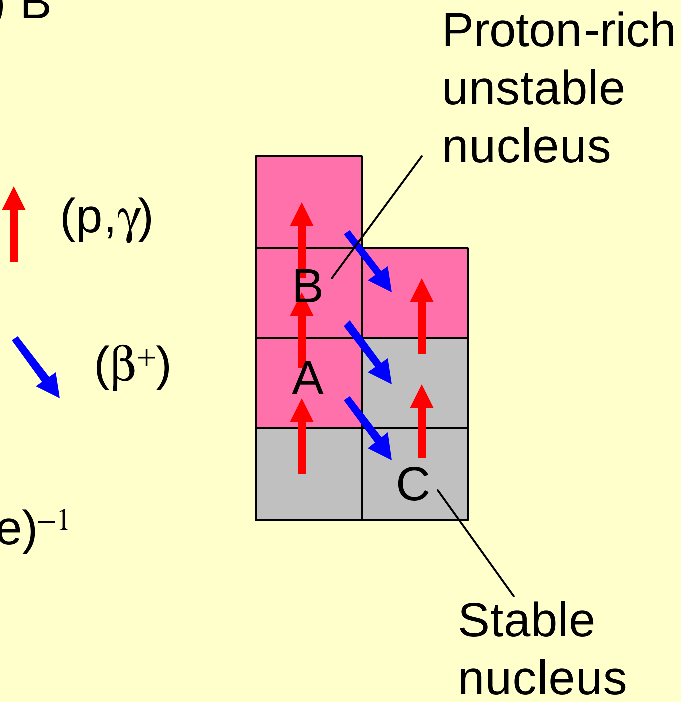
Secondary Beam	Primary Beam	Reaction	Target	Intensity	Purity
^{21}Na 4.2 *A* MeV	^{20}Ne^{8+} 200 pnA	**(^{3}He,np)**	^{3}He gas 0.25 mg/cm^{2}	**2.3×10^{4} pps**	**12 %**
^{22}Mg 4.6 *A* MeV	^{20}Ne^{8+} 200 pnA	**(^{3}He,n)**	^{3}He gas 0.25 mg/cm^{2}	**6.6×10^{3} pps**	**3 %**
^{25}Al 4.0 *A* MeV	^{24}Mg^{8+} 125 pnA	**(^{3}He,np)**	^{3}He gas 0.25 mg/cm^{2}	**1.2×10^{4} pps**	**6 %**
^{26}Si 4.0 *A* MeV	^{24}Mg^{8+} 125 pnA	**(^{3}He,n)**	^{3}He gas 0.25 mg/cm^{2}	**3×10^{3} pps**	**1.5 %**
^{23}Mg 4.0 *A* MeV	^{24}Mg^{8+} 125 pnA	**(d,t)**	D_2 gas 0.33 mg/cm^{2}	**3.2×10^{4} pps**	**12 %**

Hydrogen burning in stars

Quiet burning in stars	pp-chains, CNO cycle etc.
Explosive burning in nova or X-ray burst	Hot-CNO,..., rp-process

Radiative proton capture reaction on nucleus A $\quad$ A(p, γ) B

If A is a proton-rich unstable nucleus, A(p,γ)B reaction competes with beta decay A(β^+)C



A(p,γ)B	A(β^+)C
Reaction rate	Decay rate = (life time)$^{-1}$

Important to study (p,γ) reaction rates on proton-rich nuclei to understand explosive hydrogen burning

Formalism of reaction cross section

At low energies, the cross section can be approximated by

$$s(E) = E^{-1}\exp(-2ph)S(E)$$

where $\propto \pi\bar{\lambda}^2$

Probability for penetration through the Coulomb barrier (for the A+p system)

$$\eta = \frac{Z_1 Z_2 e^2}{\hbar v}$$ Coulomb parameter

S(*E*): Astrophysical S-factor

lower E → smaller σ(E)

Direct (non-resonant) capture A+p→B+γ *S*(*E*) varying slowly with *E*

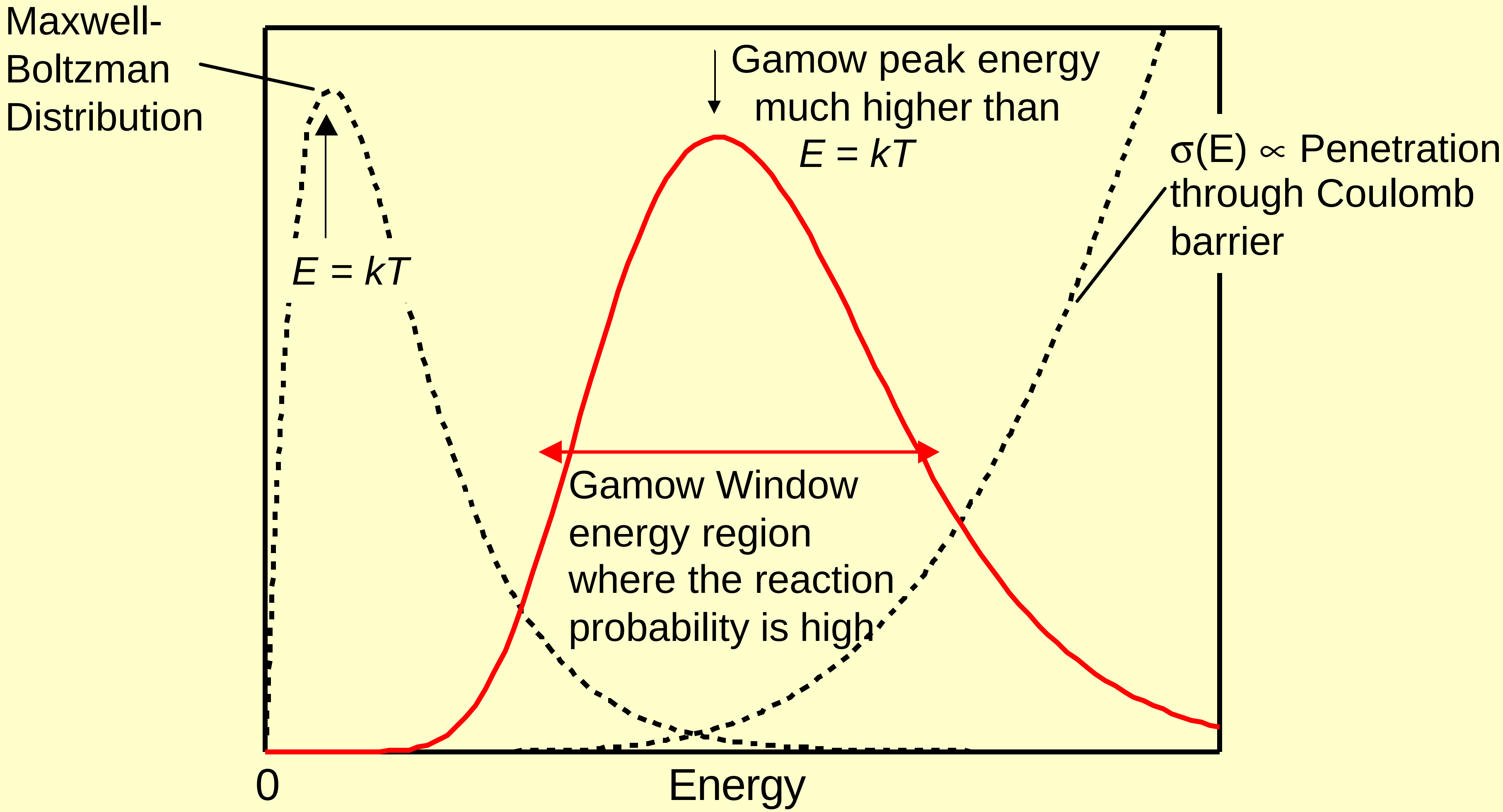
Resonant capture A+p→B* →B+γ *S*(*E*) enhanced very much around resonance energy

Resonance contributions are important

Non-resonant reaction rate

Reaction rate

$$\langle \sigma v\rangle \propto \int_0^\infty \sigma(E)E\exp\left(-\frac{E}{kT}\right)dE = \int_0^\infty \exp\left(-\frac{E}{kT}\right)\exp(-2\pi\eta)S(E)dE$$



Maxwell-
Boltzman
Distribution

Gamow peak energy
much higher than
E = *kT*

σ(E) ∝ Penetration
through Coulomb
barrier

E = *kT*

Gamow Window
energy region
where the reaction
probability is high

0

Energy

Resonant capture cross section

Breit-Wigner formula for an isolated resonance

A+p → B* → B+γ

$$\sigma(E) = \pi \lambda\!\!\!^{-2} \omega \frac{\Gamma_p \Gamma_\gamma}{(E - E_R)^2 + (\Gamma/2)^2}$$

where

$w = (2J+1)/(2J_1+1)/(2J_2,+1)$ Spin J_1, J_2, J of A, p, B*

$\Gamma_p, \quad \Gamma_g$ Proton & Gamma partial widths

$\Gamma = \Gamma_p + \Gamma_g + \ldots$ Total width

Maximum cross section at $E = E_R$ $\quad s_{\mathrm{BW}}(E_R) \propto \frac{\Gamma_p \Gamma_g}{\Gamma^2}$

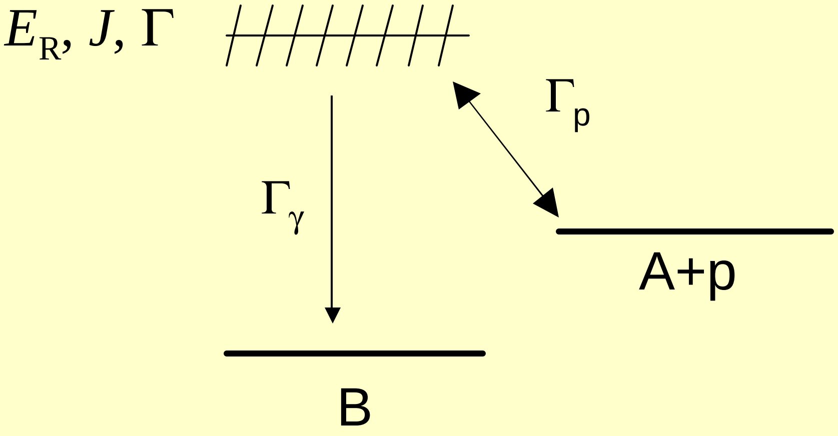
Reaction rate

$$\langle \sigma v \rangle \propto \int_0^\infty \sigma(E) E \exp\left(-\frac{E}{kT}\right) dE \propto \omega \frac{\Gamma_p \Gamma_\gamma}{\Gamma} \exp\left(-\frac{E}{kT}\right)$$

Low-lying resonances (E~0) are important!

For stellar (p,γ) reactions of interest, often $\Gamma \sim \Gamma_p >> \Gamma_\gamma$

Study of resonances above proton threshold



A+p → B*

- $\xrightarrow{\Gamma p}$ A+p elastic resonance scattering
- $\xrightarrow{\Gamma \gamma}$ B+γ resonance capture reaction of interest

(no other channels in this example)

Because of $\Gamma_p \gg \Gamma_\gamma$, the resonance scattering is much easier to measure than the resonance capture reaction .

Resonance scattering experiment is useful to study the resonance

→ resonance information E_R, J, $\Gamma \sim \Gamma_p$

(However, Γ_γ can not be determined experimentally.)

Experiments with radioactive beams to study (p,γ) reactions

Direct measurement with radioactive beams at energies < ~ 1 MeV

$^{13}N(p,\gamma)^{14}O$ Leuvain-la-Neuve

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

beam intensity > 10^8 pps required!

Indirect studies with larger cross sections

Resonance search: (at low-energy facilities)

$^{13}N+p\rightarrow{}^{14}O^*\rightarrow{}^{13}N+p$ for $^{13}N(p,\gamma)^{14}O$

Coulomb breakup: (at high-energy facilities)

$^{14}O + Pb \rightarrow {}^{13}N + p$ for $^{13}N(p,\gamma)^{14}O$

(absorption of virtual photons $^{14}O+\gamma\rightarrow{}^{13}N+p$)

ANC (Asymptotic Normalization Coefficient) method (low-energy)

$^{7}Be(d,n)^{8}B$ can simulate direct proton capture $^{7}Be(p,\gamma)^{8}B$

Experiments at CNS
(2002—2005)

Resonance search

$^{11}\mathrm{C}(p,p)^{11}\mathrm{C}$
$^{12}\mathrm{N}(p,p)^{12}\mathrm{N}$

(p,γ) reactions in the hot-pp chain which may bypass 3α →^{12}C in metal-poor massive stars.

Direct measurement

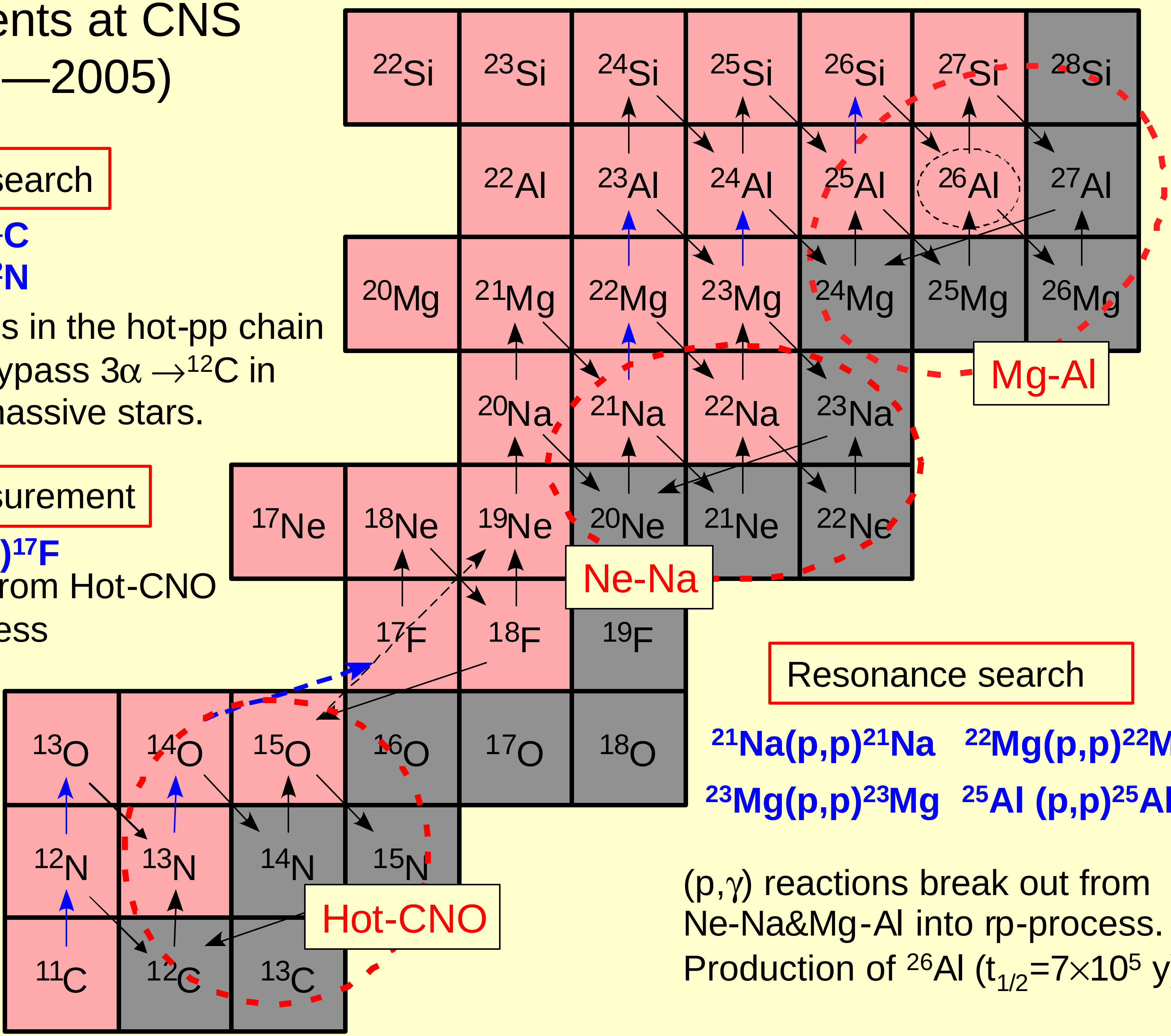
$^{14}\mathrm{O}(\alpha,p)^{17}\mathrm{F}$

breaks out from Hot-CNO into rp-process

Resonance search

$^{13}\mathrm{N}(p,p)^{13}\mathrm{N}$

Hot-CNO.
Resonances at higher energies



Resonance search

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

$^{23}\mathrm{Mg}(p,p)^{23}\mathrm{Mg}$ **$^{25}\mathrm{Al}\ (p,p)^{25}\mathrm{Al}$**

(p,γ) reactions break out from Ne-Na&Mg-Al into rp-process.
Production of ^{26}Al ($t_{1/2}=7\times10^{5}$ y)

Experimental technique
for the A+p elastic resonance scattering

A: proton-rich unstable nucleus

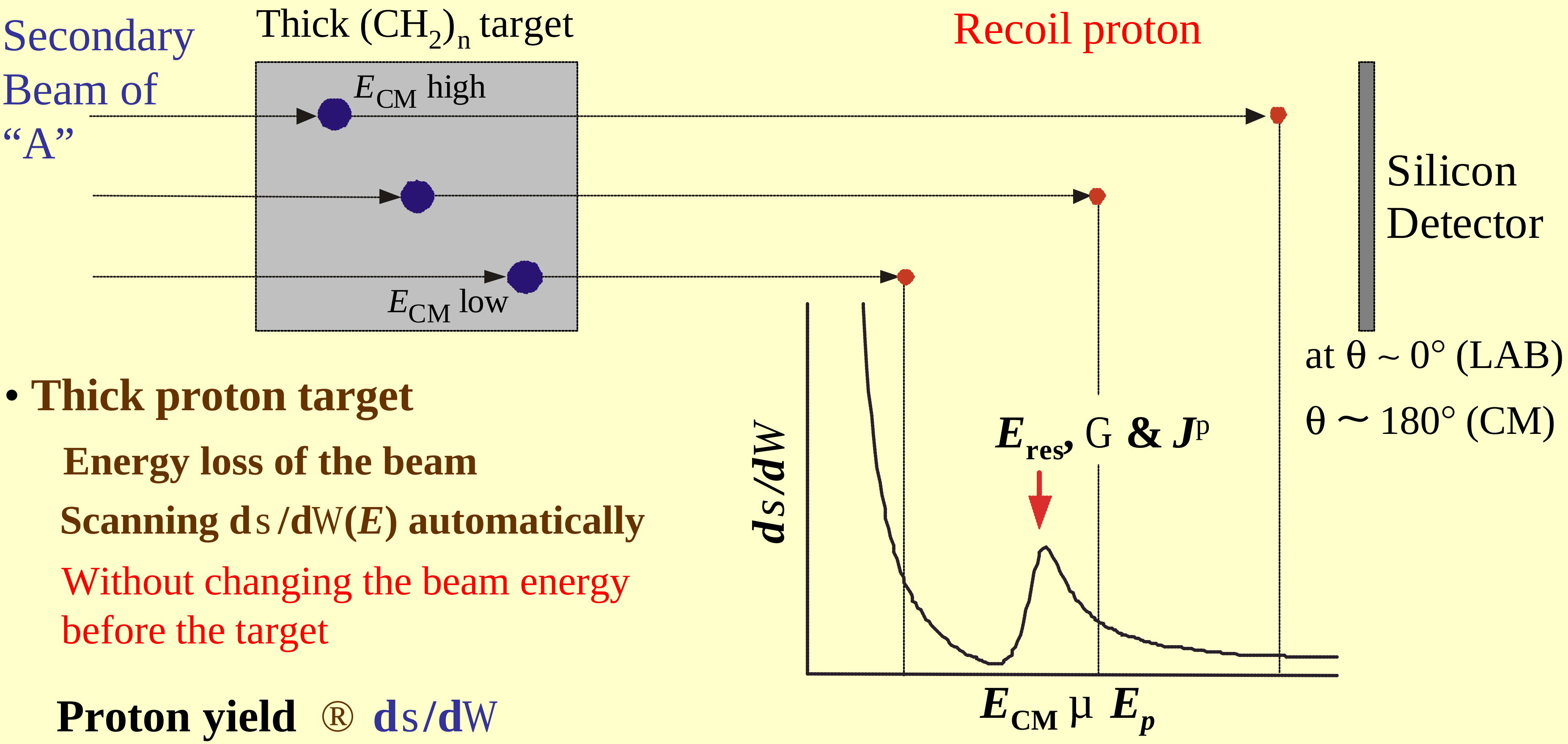
a low-energy beam of $E < \sim 4$ MeV/nucleon

p: proton

a target of polyethylene $(CH_2)_n$

In inverse kinematics

Thick-target method for A+p in inverse kinematics



- **Thick proton target**

  Energy loss of the beam

  Scanning ds /dW(*E*) automatically

  Without changing the beam energy before the target

Proton yield ® **ds/dW**

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

Counts per energy-bin

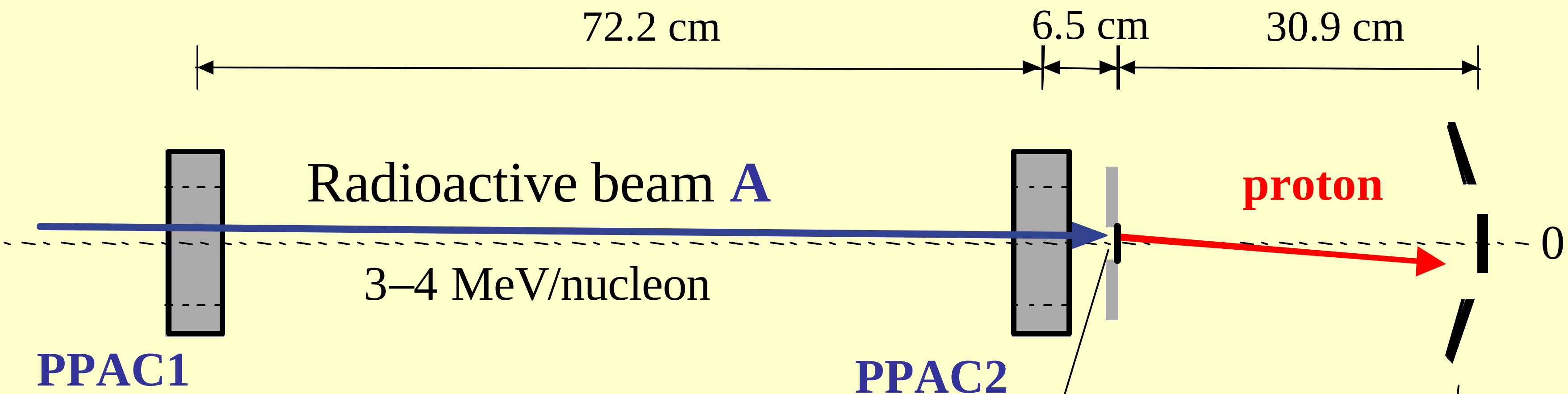
Target-thickness per energy-bin

Excitation function dσ/dΩ(*E*)

Interference pattern of potential & resonance scattering

Setup for A+p

at CRIB F2 or F3



PPAC1

(Parallel-Plate Avalanche Counter)

Area: 100 × 100 mm^2

Position (x,y) -> angle

Timing -> TOF

PPAC2

Target $(CH_2)_n$

ϕ 3 cm

~10 mg/cm^2

(C target for background subtraction)

Telescopes of DE-E SSD

Area 50 × 50 mm^2

ΔE: 75 μm thick

16 ×16 strips → (x,y)

E: 1500 μm thick

The beam stops in the target.

Recoil protons come out from the target.

Reconstruction of CM Energy

$$E_{\mathrm{CM}} = \frac{1}{4\cos^2 q_p} \frac{A+1}{A} E_p$$

A: mass number of projectile

E_p: energy of proton in LAB

By SSD

Resolution of 100 keV (FWHM)

q_p: angle of proton in LAB

By PPACs & SSD (double-sided strips)

Resolution of 0.5 deg (FWHM)

E_{CM} is deduced from E_p & q_p on an event-by-event basis
(energy loss in the target taken into account)

E_p resolution of 80 keV
→ E_{CM} resolution of 20 keV (FWHM) at $q_p = 0$

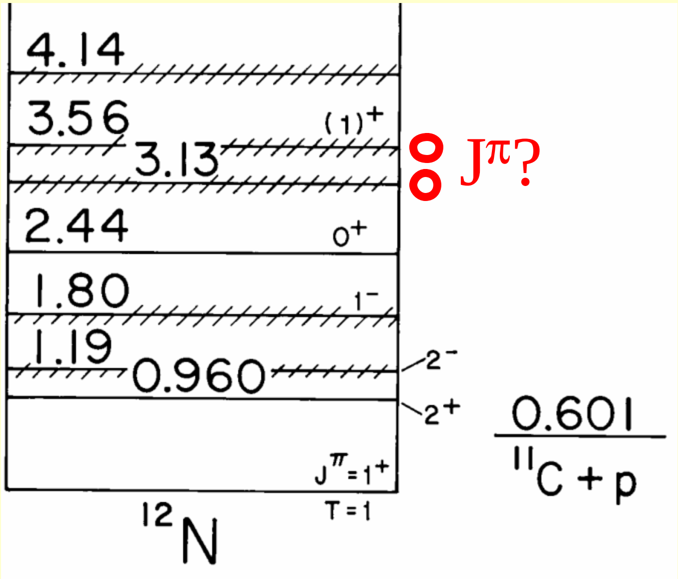
(Contribution from energy straggling of proton in the target is small.)

^{11}C+p Experiment

J^{π} for the 3.13 & 3.56-MeV levels ?

Verifying known values of E_R, Γ (~Γ_p), J^{π}

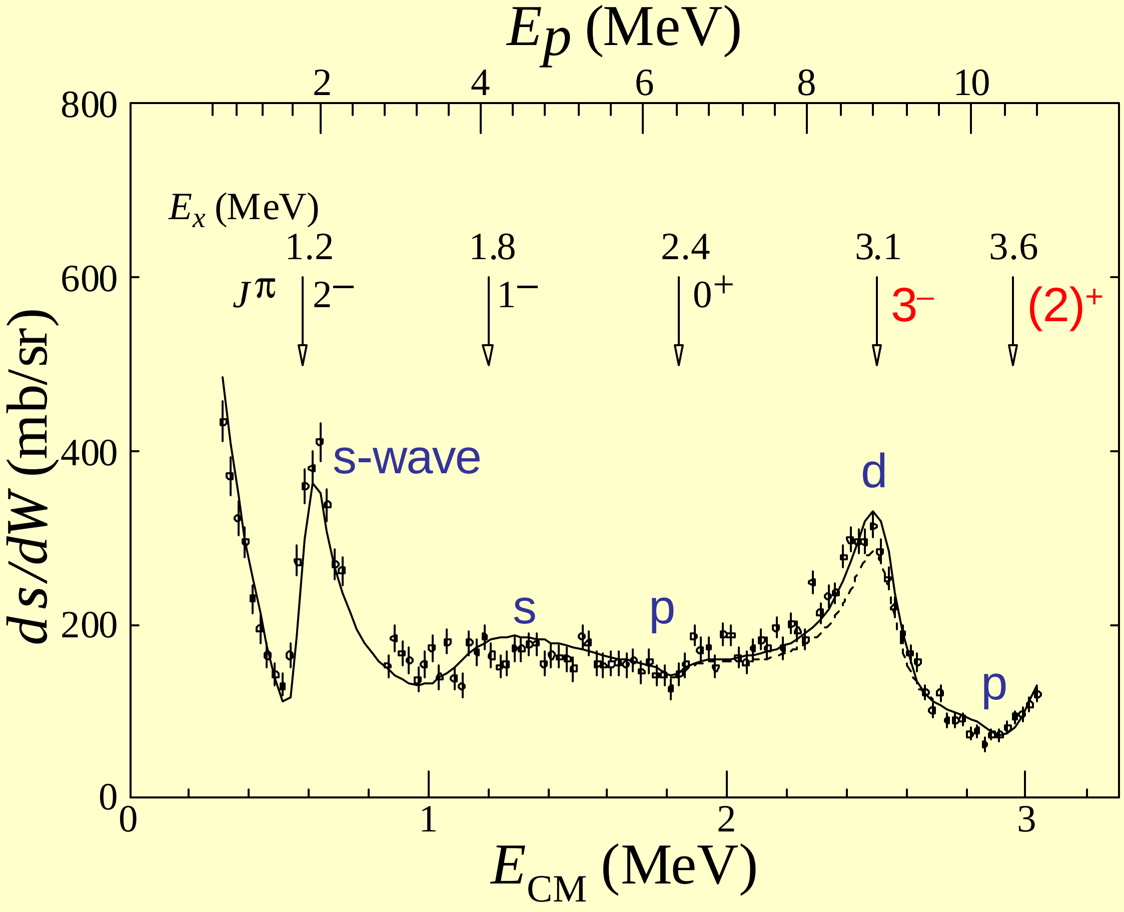
For the astrophysical $^{11}C(p,g)^{12}N$ reaction rates (Hot-PP)



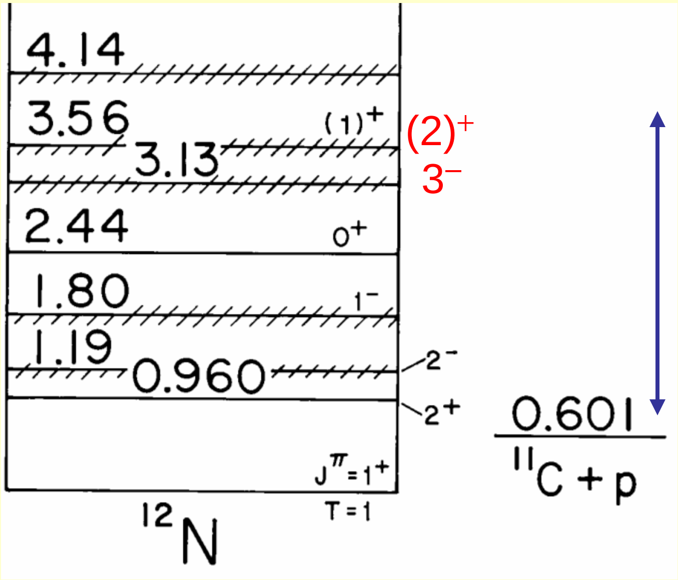
Result: ^{11}C+p (^{12}N*) elastic resonance scattering

Resonances relevant to ^{11}C(p,γ)^{12}N

T. Teranishi et al., PLB 556 (2003) 27



Solid line (R-matrix)



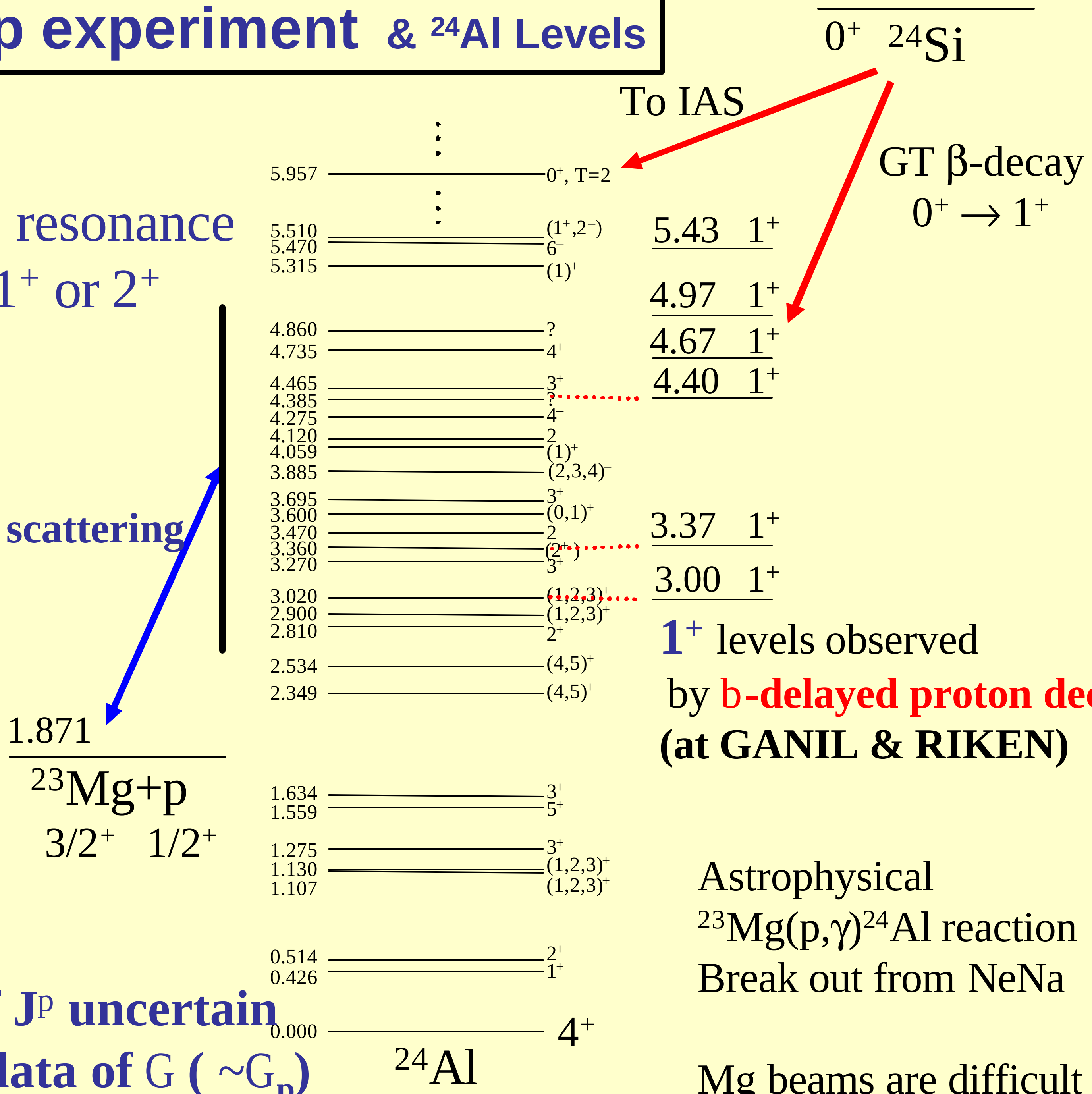
E & Γ are consistent width known values.

The 2 $^+$ level at 0.96 MeV & 2$^-$ level at 1.2 MeV are important for the ^{11}C(p,γ)^{12}N reaction.

J$^\pi$ = 3$^-$ newly assigned to the 3.13-MeV level

does not contribute to the (p,g) reaction so much because of the M2 transition 3$^-$ → 1$^+$(g.s).

^{23}Mg+p experiment & ^{24}Al Levels



s-wave resonance

$\rightarrow 1^+$ or 2^+

Elastic scattering

1^+ levels observed

by **b-delayed proton decay**

(at GANIL & RIKEN)

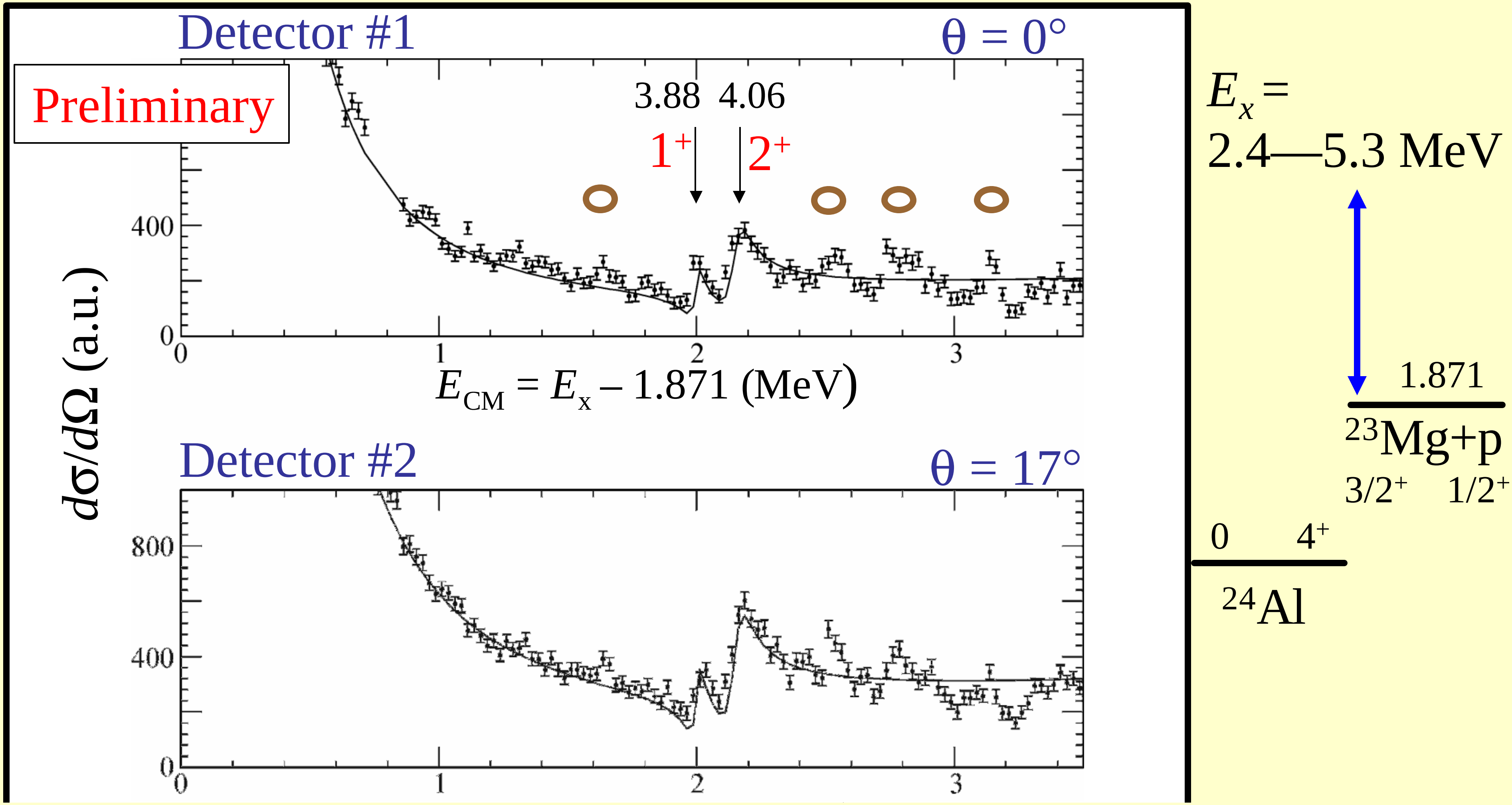
Astrophysical
^{23}Mg(p,γ)^{24}Al reaction
Break out from NeNa

Many of J^p uncertain

No exp data of G **(** ~G$_p$**)**

Mg beams are difficult for ISOL

Spectra of ^{23}Mg+p (^{24}Al*)



Solid line: R-matrix fit

s-wave assumed for levels at

E_x = 3.88 MeV & 4.06 MeV (J^π not well known before)

Peak height depends on *J* value.

® **1^+ for 3.88 MeV & 2^+ for 4.06 MeV (preliminary)**

^{24}Al Levels

Above Proton Threshold of E_x = 1.871 MeV

Latest Compilation
NPA633(1998)1

Ex (MeV)	J^π
2.349	$(4,5)^+$
2.534	$(4,5)^+$
2.810	2^+
2.900	$(1—3)^+$
3.020	$(1—3)^+$
3.270	3^+
3.360	$(2)^+$
○ 3.470	2
3.600	$(0,1)^+$
3.695	3^+
○ 3.885	$(2—4)^-$
○ 4.059	$(1)^+$
4.120	2
4.275	4^-
4.385	
4.465	3^+
4.735	4^+
4.860	

No exp data of G

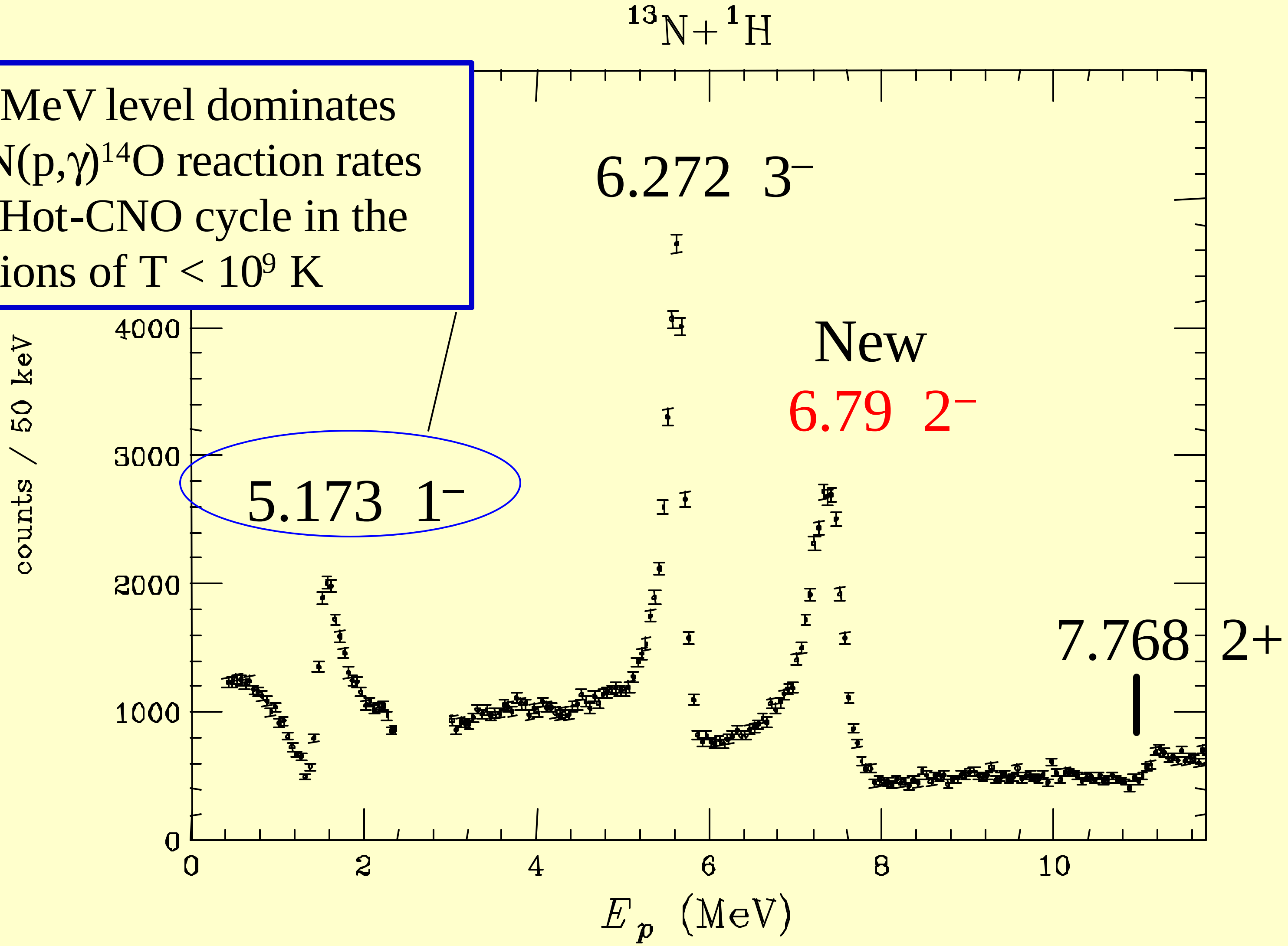
^{24}Si(β)^{24}Al*→^{23}Mg+p
PRC63(2002)024307

Ex (MeV)	J^π
3.00	1^+
3.37	1^+
○ 4.40	1^+
○ 4.67	1^+
○ 4.97	1^+

Preliminary result of ^{23}Mg+p exp.

1^+ Γ ~ 40 keV
2^+ Γ ~ 60 keV

^{13}N+p experiment (preliminary) for ^{14}O resonances



5.173 MeV level dominates the ^{13}N(p,γ)^{14}O reaction rates in the Hot-CNO cycle in the conditions of $T < 10^9$ K

6.272 3^-

New

6.79 2^-

5.173 1^-

7.768 2+

Proton-resonance scattering is a powerful tool to study nuclear structure of light unstable nuclei!

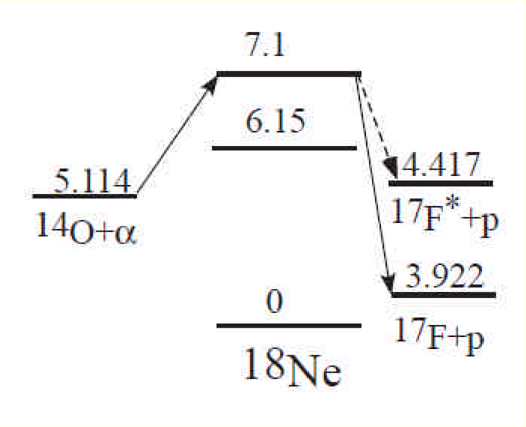
Energy resolution 20 keV (FWHM)!

Outlook

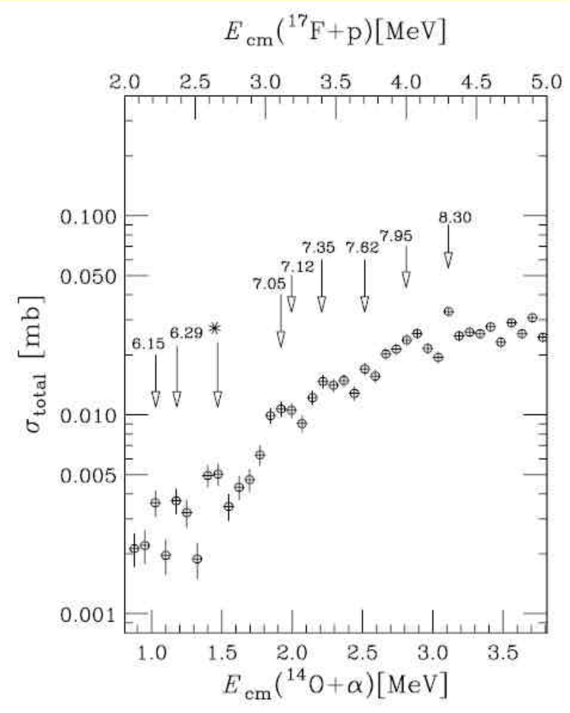
Direct measurement of stellar (α,p) or (p,α) reactions relevant to explosive hydrogen burning (rp-process) will be studied!

$^{14}O(\alpha,p)^{17}F$ break out from the hot-CNO cycle

^{14}O beam + thick He target



$\Gamma_\alpha << \Gamma_p$



Preliminary result
M. Notani et al., NPA746(2004)113c

Summary

Low-energy radioactive beams are useful to study
resonance states close to the particle threshold in unstable nuclei.

Low-energy In-flight method at CNS

with intense primary beams and a large acceptance separator

Technically simpler than and complementary to ISOL

Many beams were developed in a short period

Experiments on proton-rich nuclei relevant to the explosive hydrogen burning