Study of Resonance States in Unstable Nuclei Using Low-Energy Radioactive Nuclear Beams

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Proton resonance scattering on unstable nuclei
at energies below 5 MeV/nucleon

Introduction

Experimental study of unstable nuclei

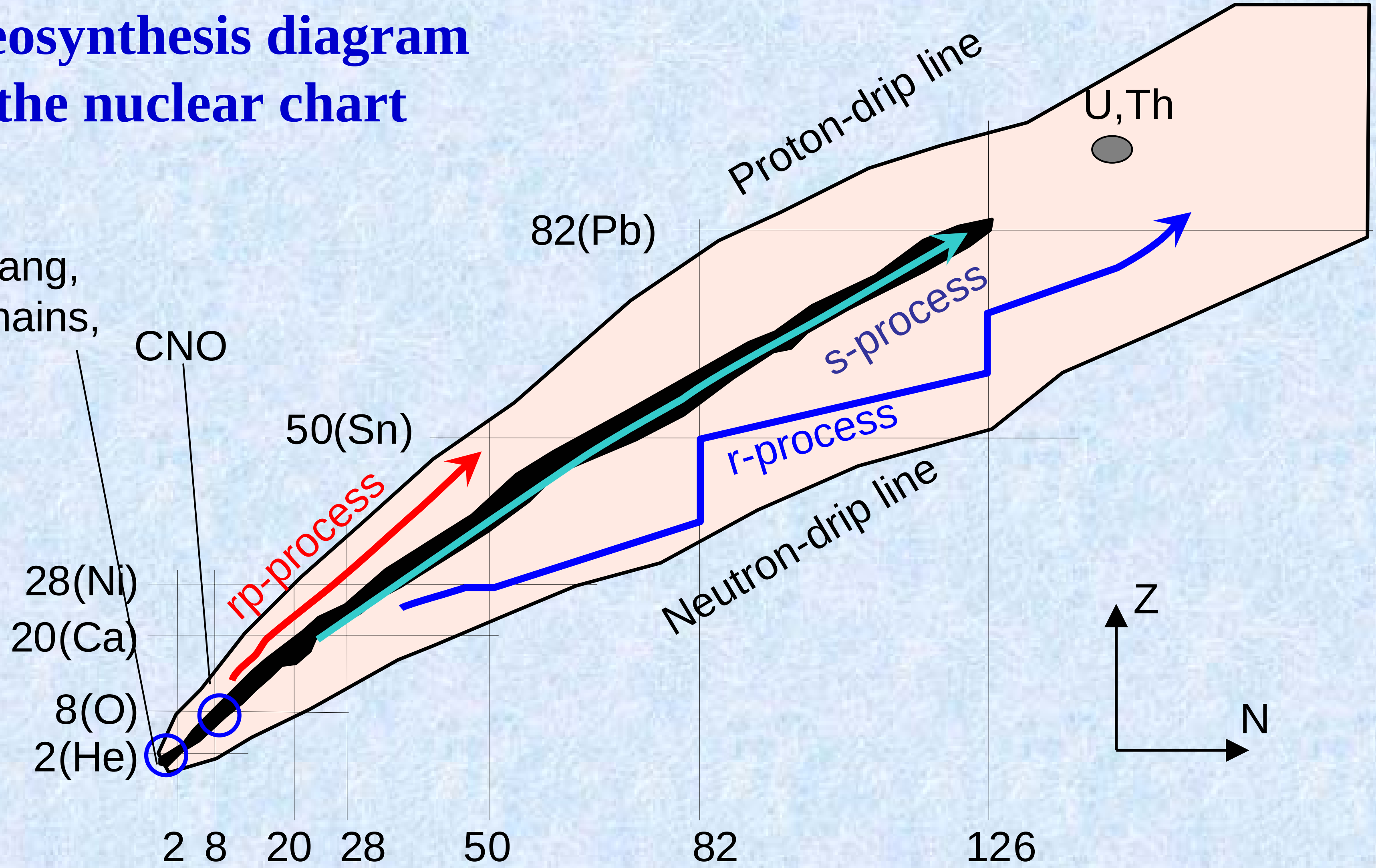
Developments of secondary beams of radioactive ions

Exotic nuclear structure (Neutron halo e.g. ^{11}LI)

Change of magic numbers in a neutron-rich region
(e.g. disappearance of the N=20 magic number)

Nuclear astrophysics

Nucleosynthesis diagram in the nuclear chart



Unstable nuclei play important roles in explosive nucleosynthesis under high-temperature & high-density conditions (supernova, nova & X-ray burst etc.)

Neutron-rich nuclei — Mass, lifetime, (n,γ) reaction rates → r-process

Proton-rich nuclei — (p,γ) reaction rates → rp-process

Low-energy Radioactive Nuclear Beams at E < 10 MeV/nucleon

Recently, techniques of producing low-energy radioactive nuclear beams have been developed largely at many facilities

Low energy nuclear reactions of unstable nuclei

- Nuclear spectroscopy
- Nuclear Astrophysics

Applied physics

- Implantation of radioactive ions into materials (material science, biology...)

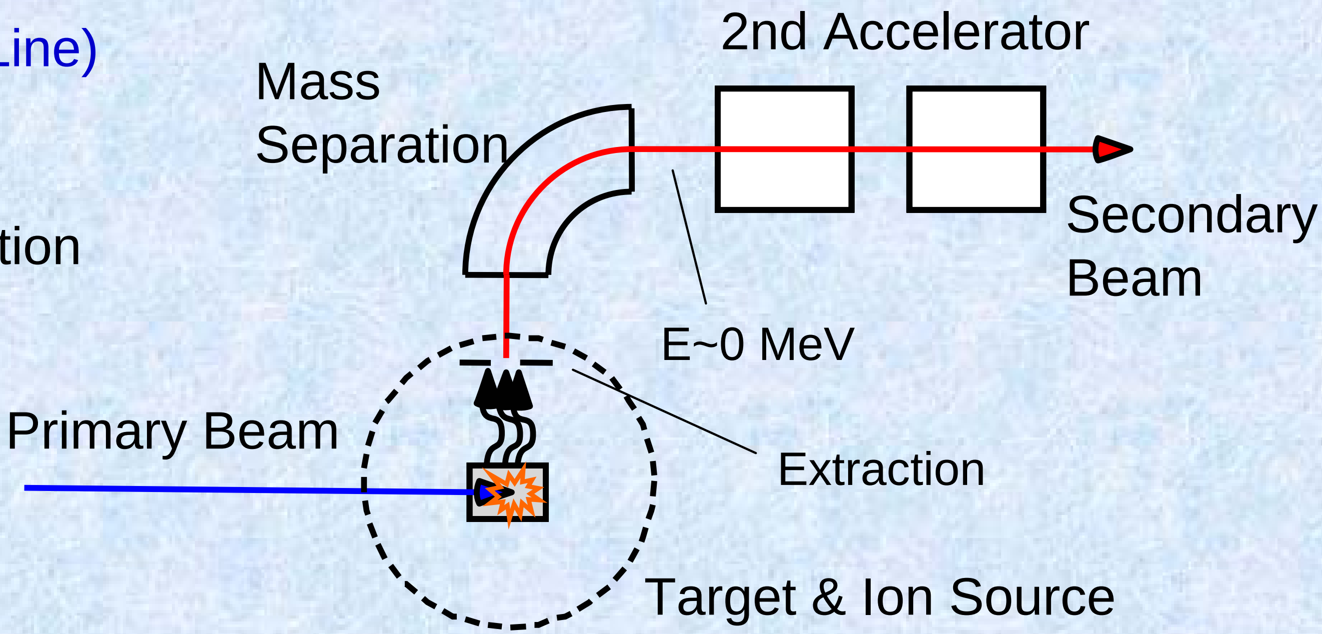
Production of Low-Energy Radioactive Beams

ISOL (Isotope Separator On-Line)

Reaction products stopped in the target
→ extraction & acceleration

Good beam quality.

Production efficiency depends on chemical properties and lifetime



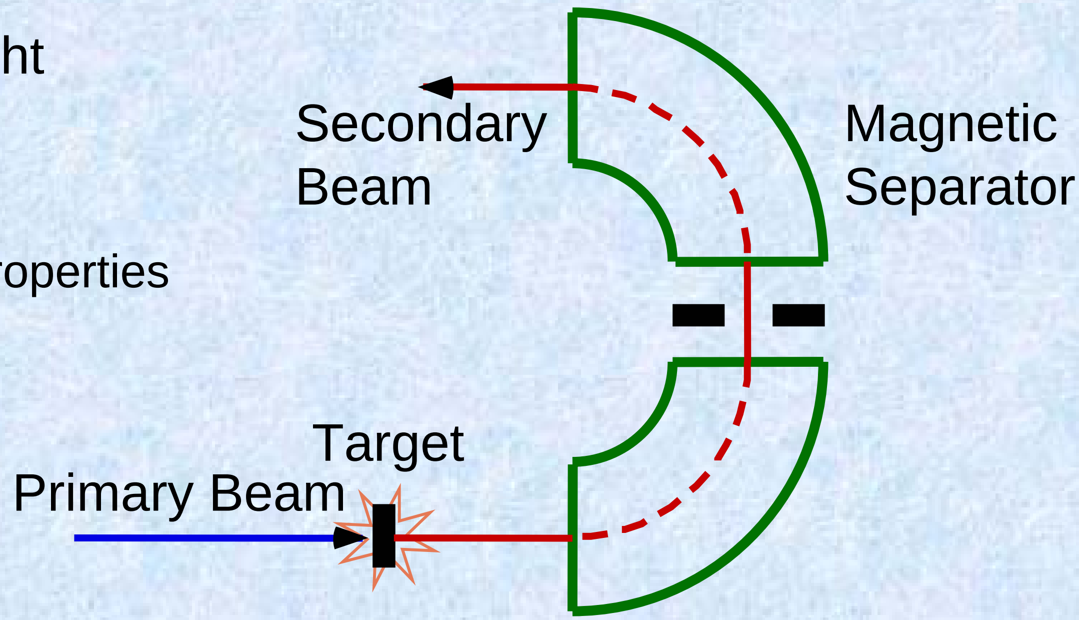
In-Flight Separator

Reaction products in flight are separated and used as beam particles

Independent of chemical properties

Beam quality not so good

Technically simpler than ISOL

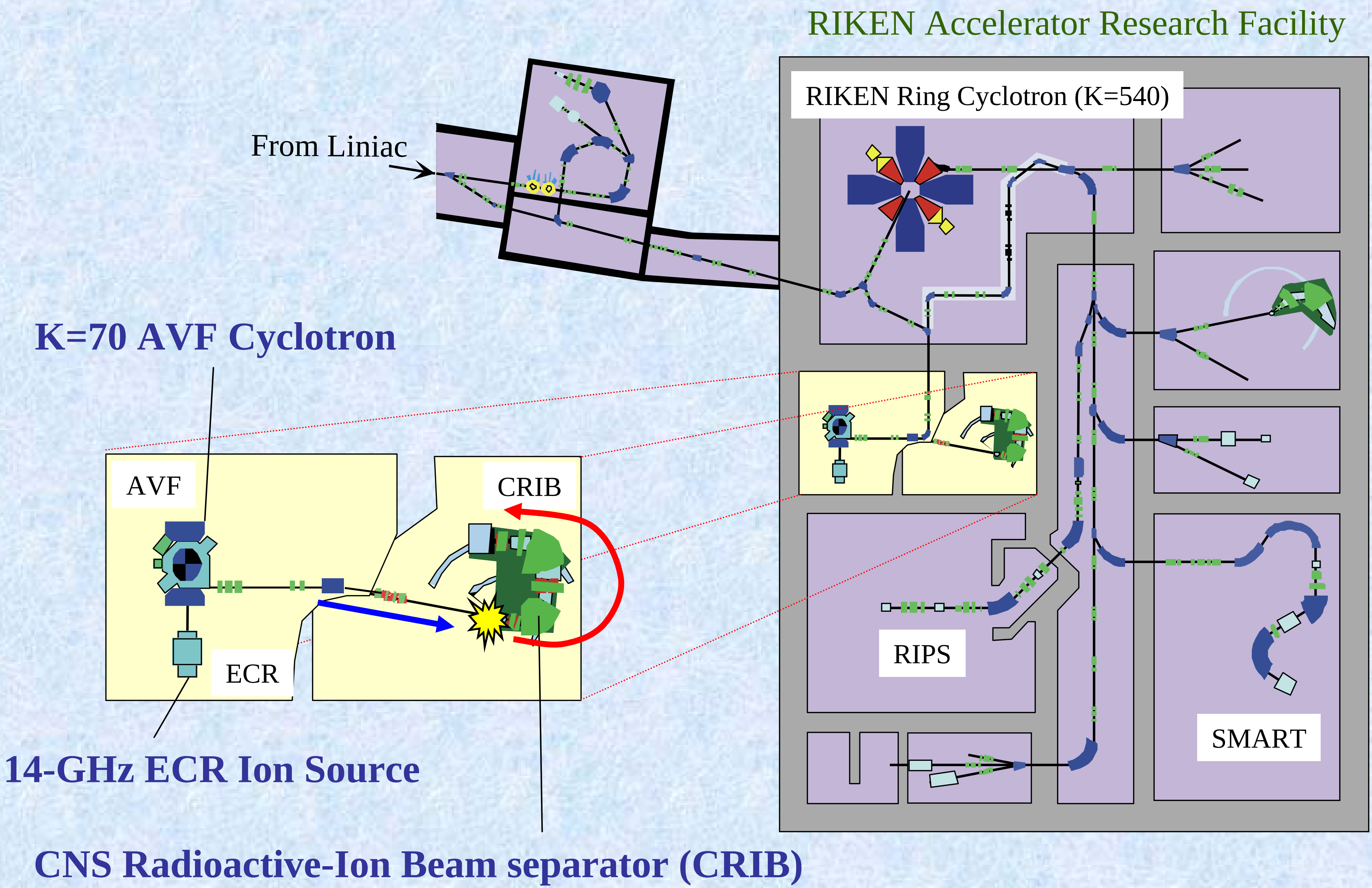


Usually for
high-energy beams (>~100 MeV/u)

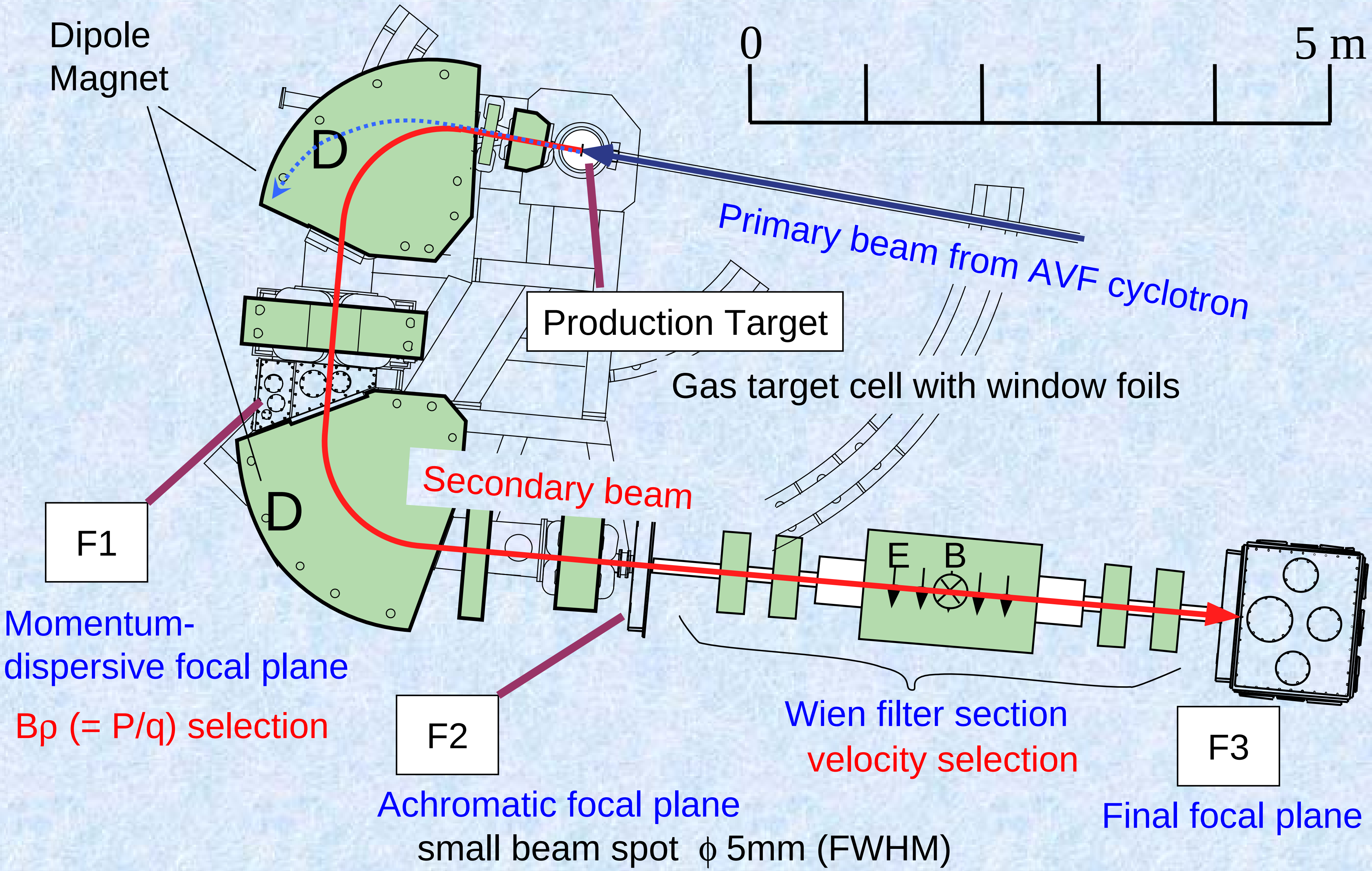
(also useful for low-energy beams)

CNS Low-energy In-flight Beam Line in RIKEN Facility

Center for Nuclear Study (CNS), University of Tokyo



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



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

(Z can be separated by energy-loss at degrader)

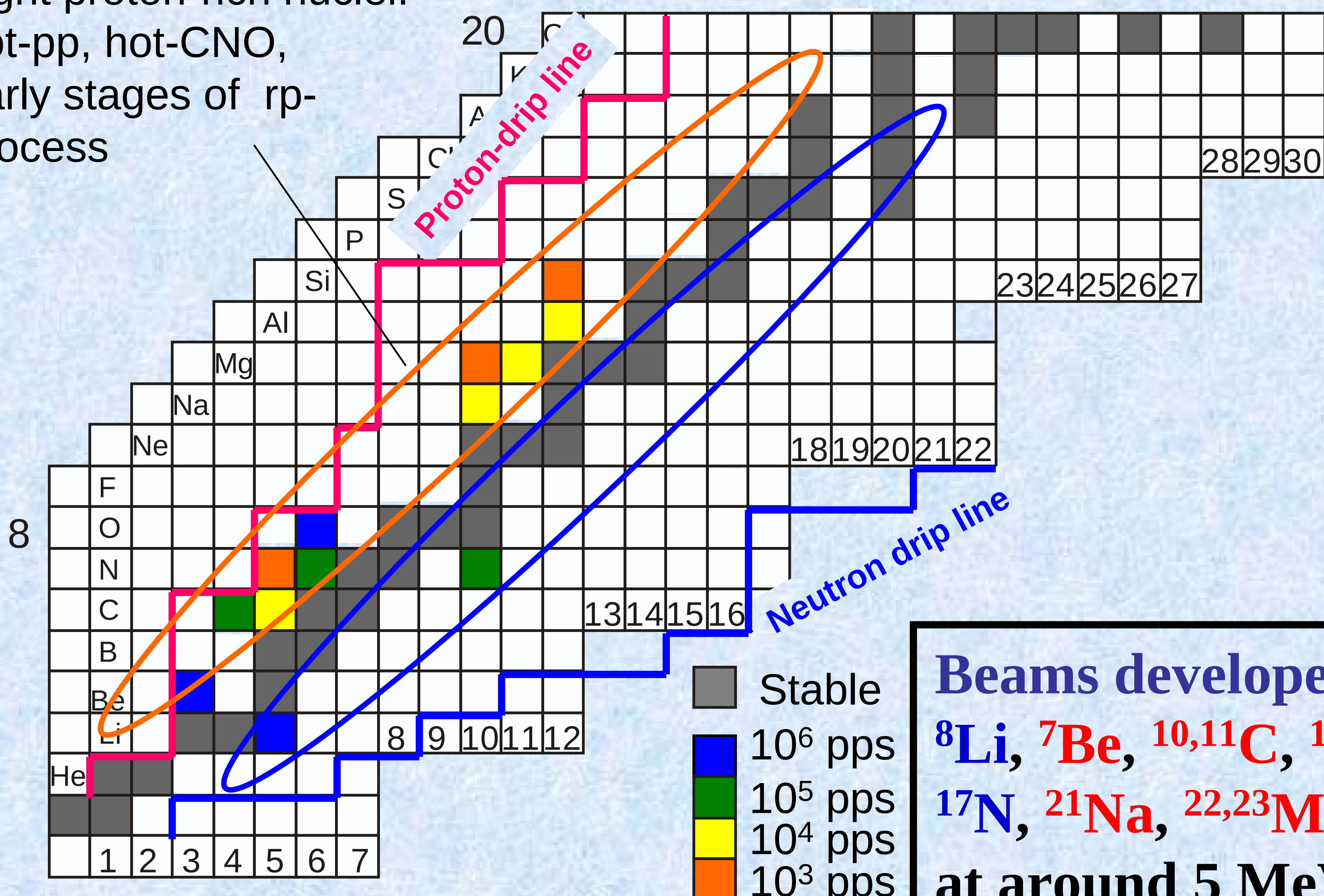
Production reactions for low-energy in-flight method

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



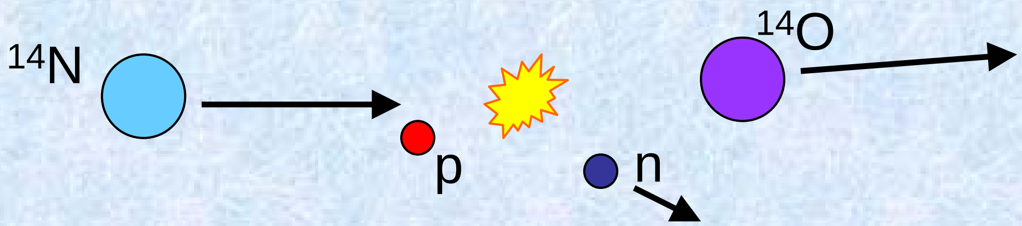
Beams developed so far:

^{8}Li, ^{7}Be, ^{10,11}C, ^{12,13}N, ^{14}O, ^{17}N, ^{21}Na, ^{22,23}Mg, ^{25}Al, ^{26}Si

at around 5 MeV/nucleon

Example: ^{14}O beam

- Reaction: $p(^{14}N,^{14}O)n$ (p,n) reaction in inverse kinematics
  $\sigma \sim 8$ mb
- Primary beam $^{14}N(6+)$ Intensity: 500 pnA (3×10^{12} particles/s)
  Energy: 8.4 A MeV



- Gas target (Proton target): Hydrogen-gas
  1 atm. & 2-cm thick (0.2 mg/cm^2)

  confined in a cell with two Havar foils

^{14}O secondary beam intensity: 10^6 particles/s

Study of unbound states in unstable nuclei

Proton/Neutron
Separation energy

$E_x \sim 10$ MeV

$^{A-1}Z + n$

$^{A-1}(Z-1) + p$

^{A}Z

Stable nucleus

$^{A-1}(Z-1) + p$

$E_x \sim < 1$ MeV

$^{A-1}Z + n$

^{A}Z

Neutron-rich nucleus near the drip line

Almost no bound excited states

$\rightarrow$ observed as resonances

Proton Elastic Resonance Scattering

$$A + p \rightarrow B^* \text{ (resonance)} \rightarrow A + p$$

Resonance observed in the low-energy proton elastic scattering

Recently applied to unstable nuclei

Low-energy beams are good for this process

Large cross sections

- ● For proton-rich nuclei: low-lying excited states
- ○ For neutron-rich nuclei: highly excited states (with $T=T_z+1$)

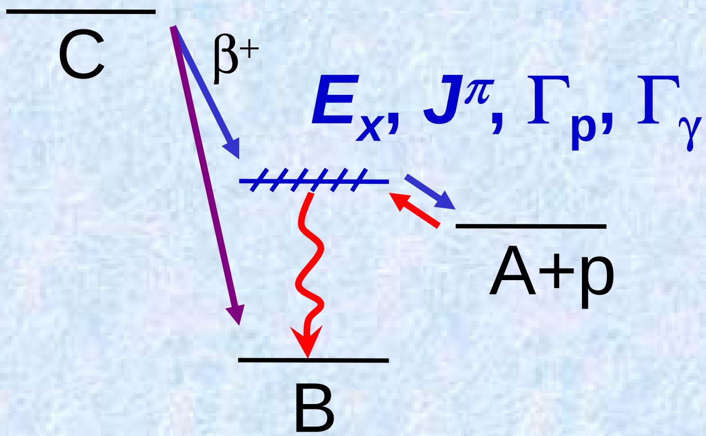
Study of proton resonances in proton-rich unstable nuclei

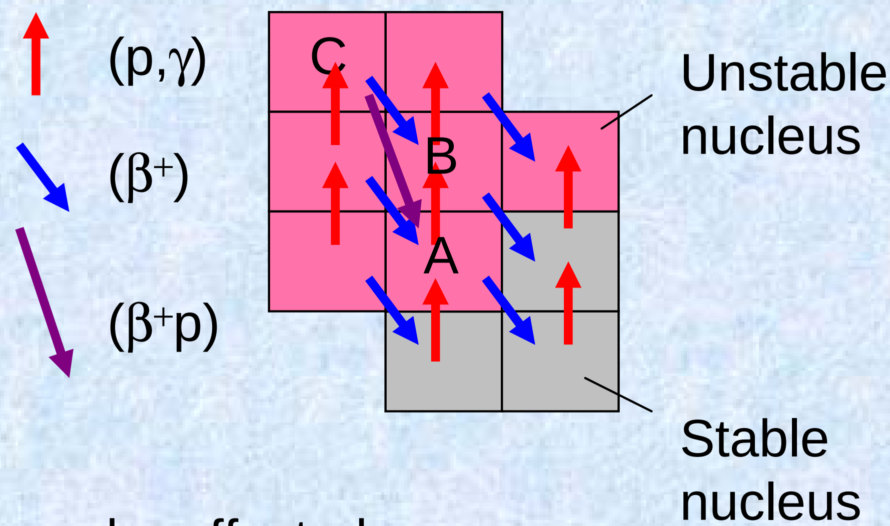
for explosive hydrogen burning in nuclear astrophysics

A(p, γ)B A & B are proton-rich unstable nuclei

Resonance level in nucleus B near the A+p threshold

- the **(p,γ)** reaction rates may be enhanced **A+p → B* → B+γ**





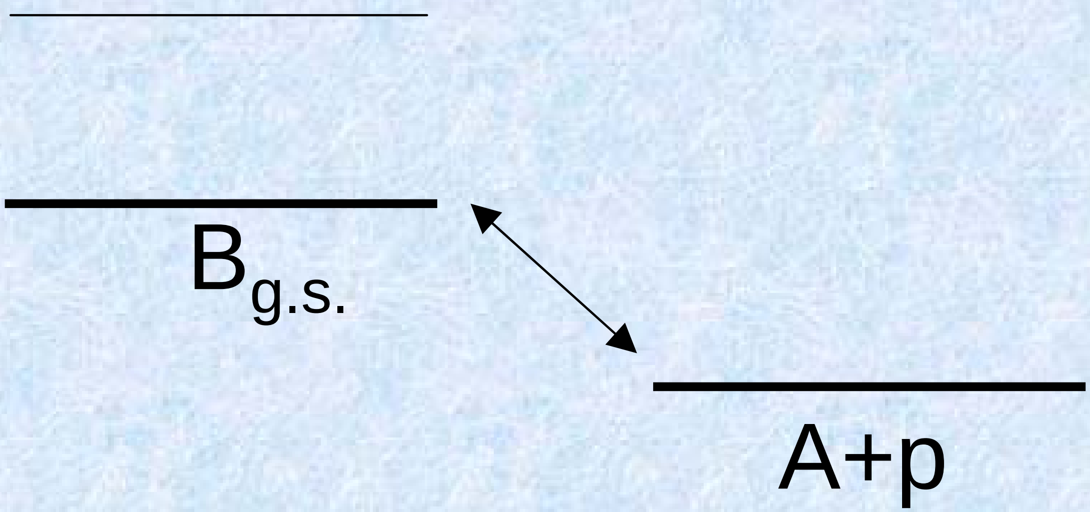
- Beta decay branches of parent nucleus C may be affected

$C(\beta^+)B^{(*)}$

$C(\beta^+)B^* \rightarrow A+p$ beta-delayed proton emission via resonances

Important to know experimental information on resonances to understand the reaction paths in explosive hydrogen burning

Unbound nuclei outside the proton drip line



The ground state of a nucleus as a proton resonance (unbound nucleus)

c.f. $^{15}F \leftrightarrow {}^{14}O+p$

Resonance energy = mass of nucleus

→ nuclear stability, mass formula

Comparison with levels in the neutron-rich mirror nucleus

→ Charge symmetry of nuclear force
Effects of Coulomb force in nuclear structure

Recent experiments at CNS (2002—2005)

Resonance search

$^{11}C(p,p)^{11}C$

$^{12}N(p,p)^{12}N$

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

Direct measurement

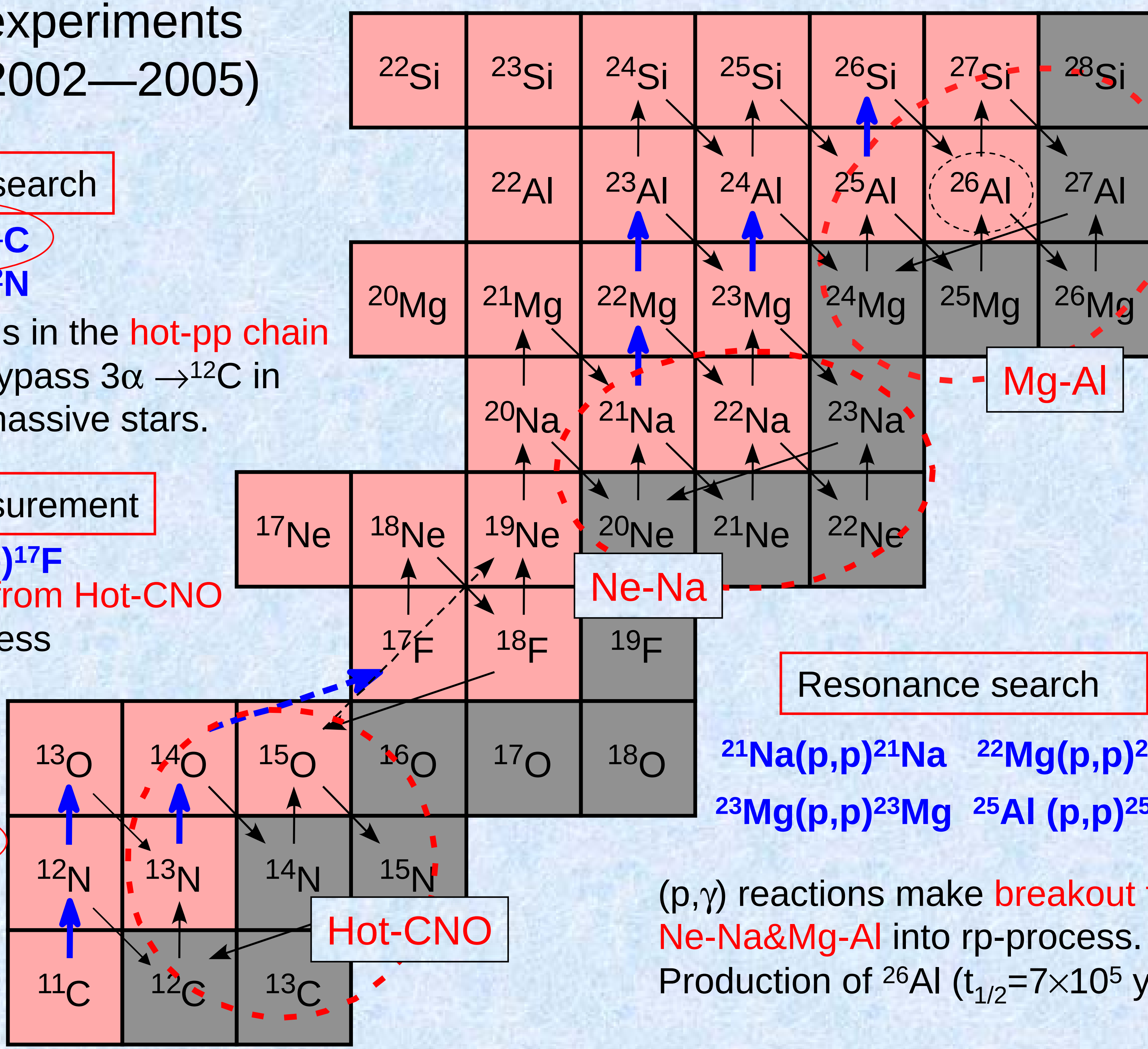
$^{14}O(\alpha,p)^{17}F$

breaks out from Hot-CNO into rp-process

Resonance search

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

Hot-CNO. Structure of $^{14}O^*$



Resonance search

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

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

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

Experiment of proton resonance scattering

A+p → B* → A+p

with a beam of unstable proton-rich nucleus "**A**"
& a proton target

In inverse kinematics

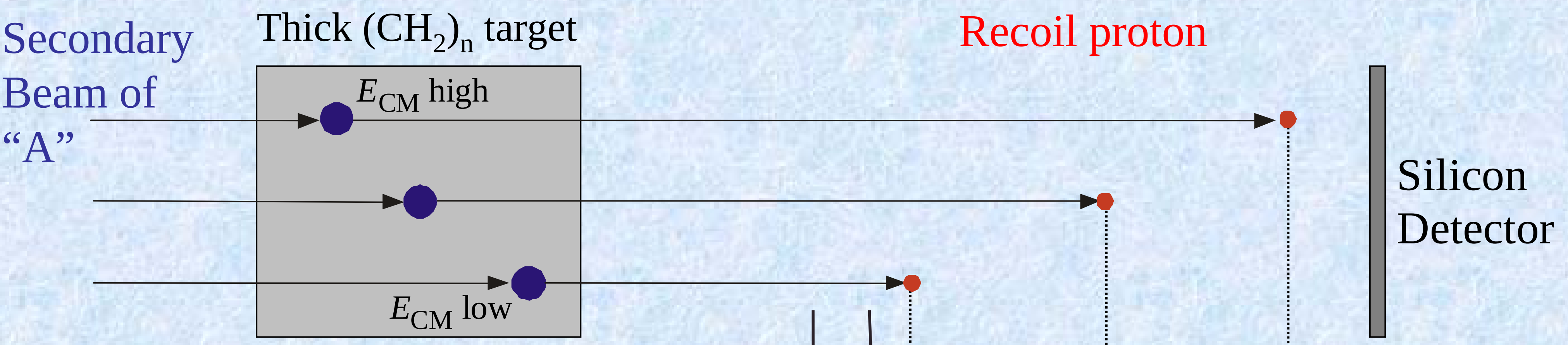
Experimental goals:

- To identify resonances in the excitation function $\frac{d\sigma}{d\Omega}(E_{\mathrm{CM}})$
- To determine resonance parameters E_R, Γ ($\sim\Gamma_p$), & J^{π}

Basic data for nuclear structure and astrophysical reaction rates

However, it is unable to measure Γ_γ , which is necessary
to deduce astrophysical (p,γ) reaction rates.

Thick-target method for A+p in inverse kinematics

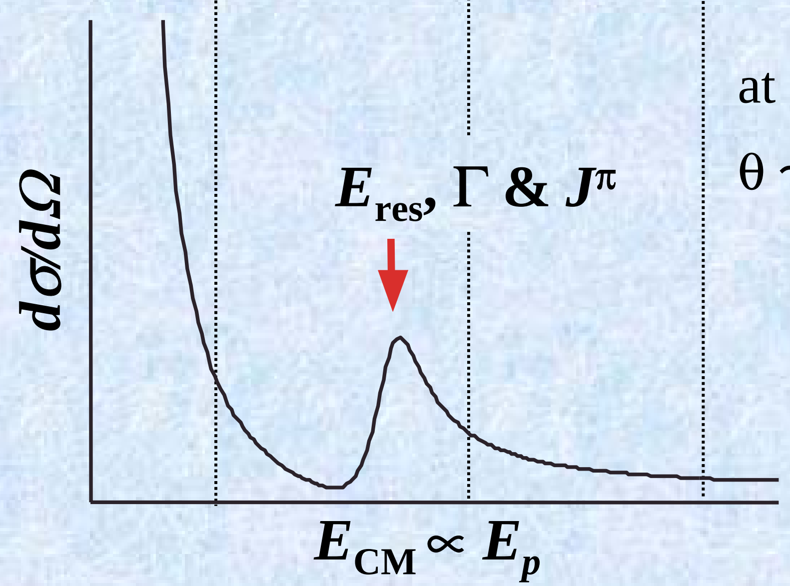


- **Thick proton target**

  Energy loss process of the beam

  Utilized to scan dσ/dΩ(*E*) automatically

  Without changing the beam energy before the target



Excitation function dσ/dΩ(*E*)

Proton yield → **dσ/dΩ**

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

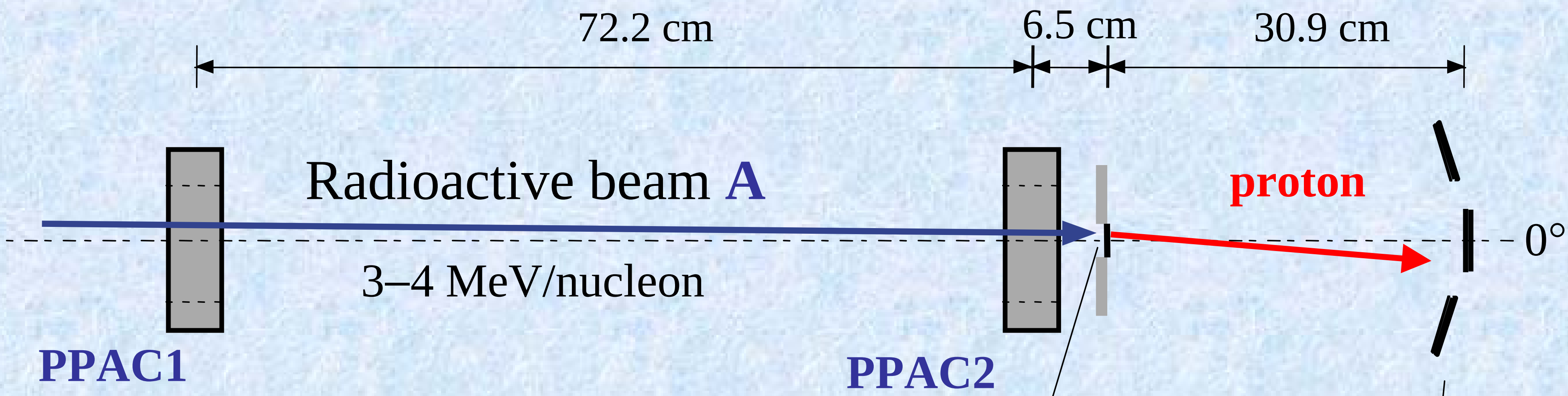
Counts per energy-bin

Target-thickness per energy-bin

Interference pattern of potential & resonance scattering

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

Target $(CH_2)_n$
ϕ 3 cm
~10 mg/cm^2

(C target for background subtraction)

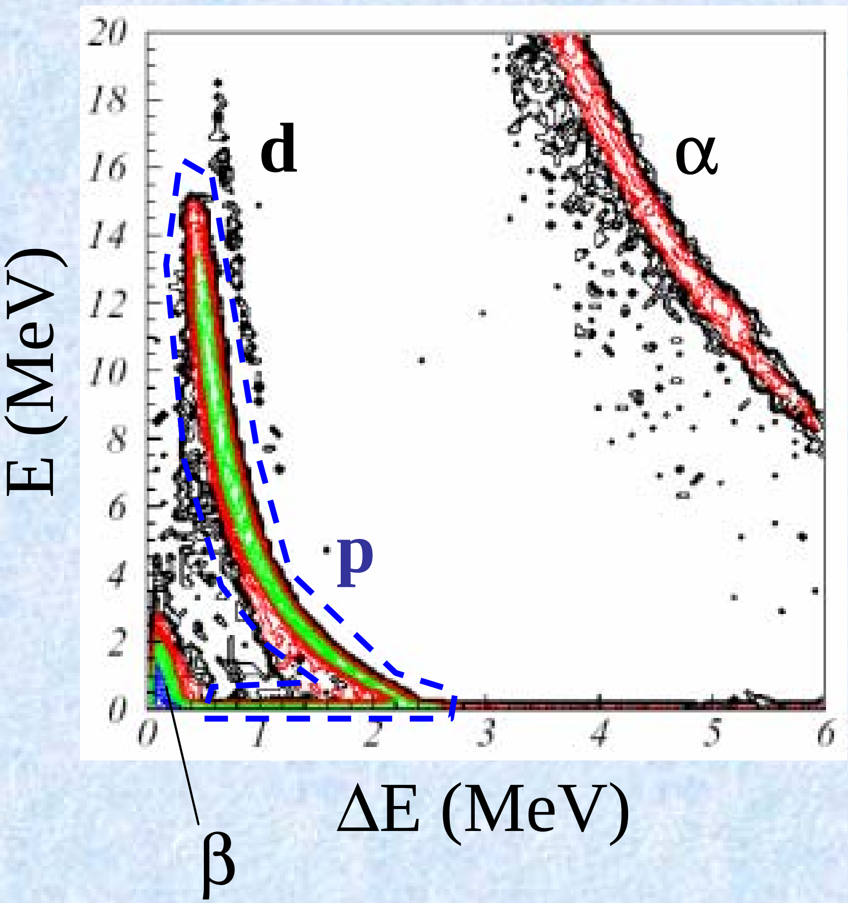
Telescopes of ΔE-E SSD

Area 50 × 50 mm^2
ΔE: 75 μm thick
16(x) + 16(y) strips → (x,y)
E: 1500 μm thick

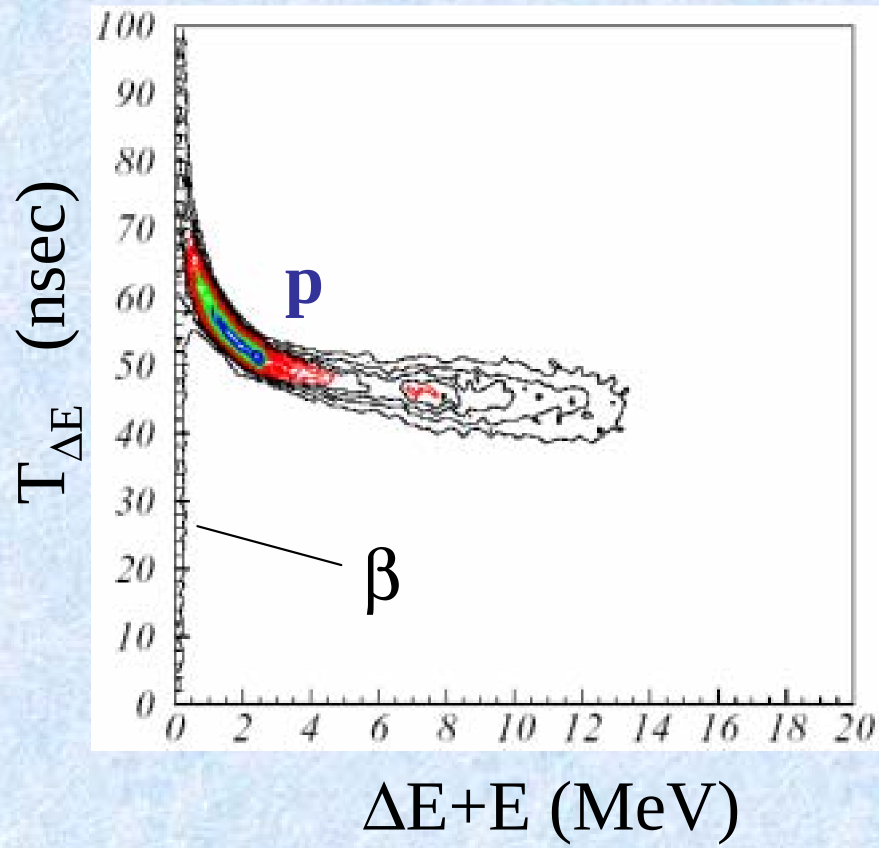
The beam stops in the target.
Recoil protons go out from the target.

Identification of Recoil Proton

ΔE vs. E



E vs. Timing



Reconstruction of CM Energy

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

A: mass number of projectile

E_p: proton energy (LAB)

By SSD

Resolution of 80 keV (FWHM)

θ_p: angle of proton (LAB)

By PPACs & SSD (double-sided strips)

Resolution of 0.5 deg (FWHM)

E_{CM} is deduced from E_p & θ_p on an event-by-event basis

(energy loss in the target taken into account)

E_p resolution of 80 keV

$\rightarrow$ E_{CM} resolution of ~20 keV (FWHM) at $\theta_p = 0$

Better than the invariant mass method used in radioactive beam experiments

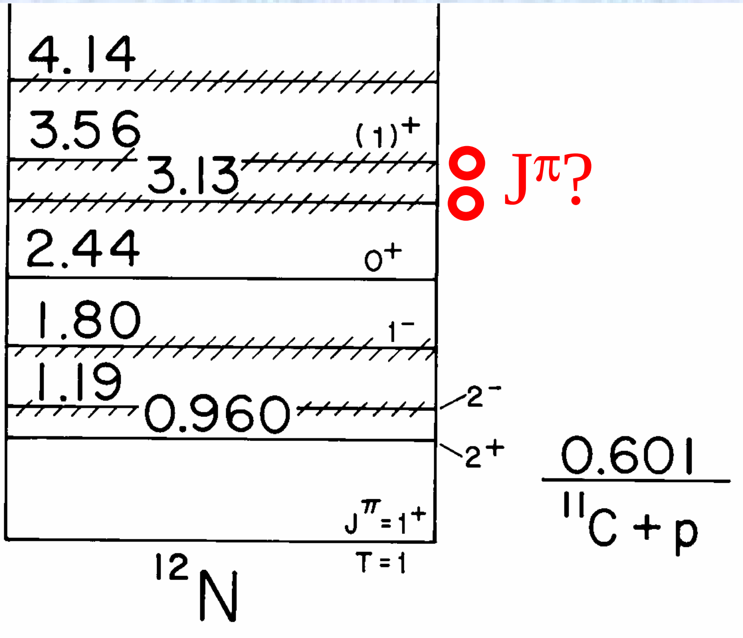
(Contribution from energy straggling of proton in the target is small.)

^{11}C+p experiment (for ^{12}N resonances)

To verify known values of E_R, Γ (~Γ_p), J^π for low-lying levels in ^{12}N

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

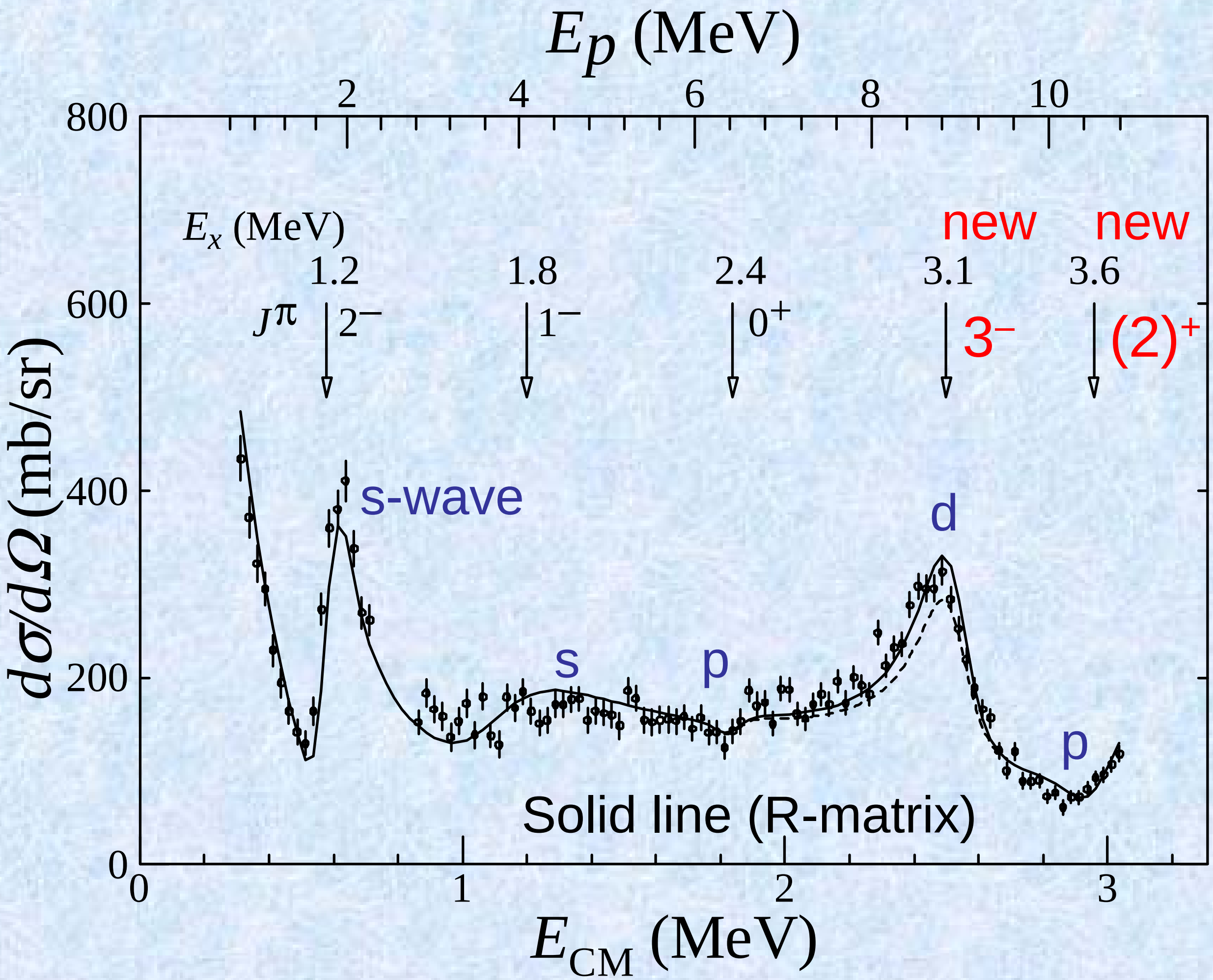
J^π values for the 3.13 & 3.56-MeV levels

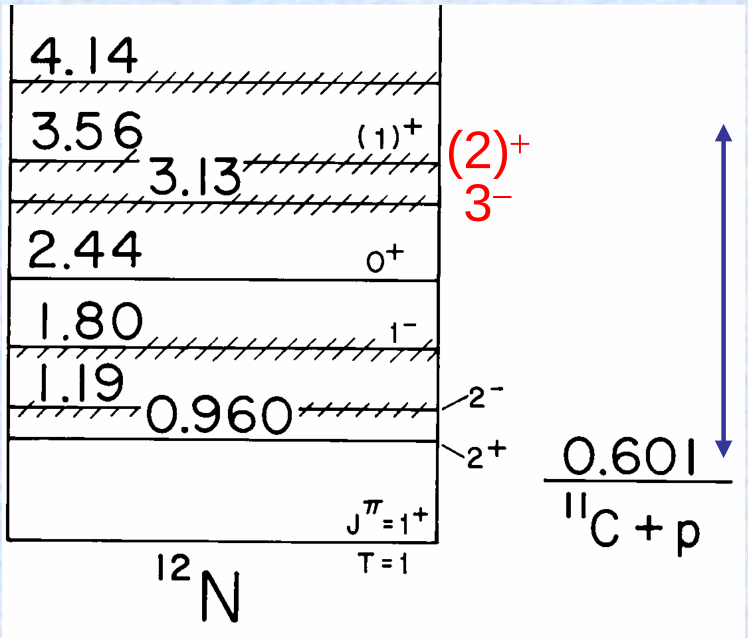


Result: ^{11}C+p (^{12}N resonances)

Resonances relevant to $^{11}C(p,\gamma)^{12}N$

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





E & Γ are consistent width known values.

The resonances at 0.96 & 1.2 MeV are important for the $^{11}C(p,\gamma)^{12}N$ reaction.

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

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

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

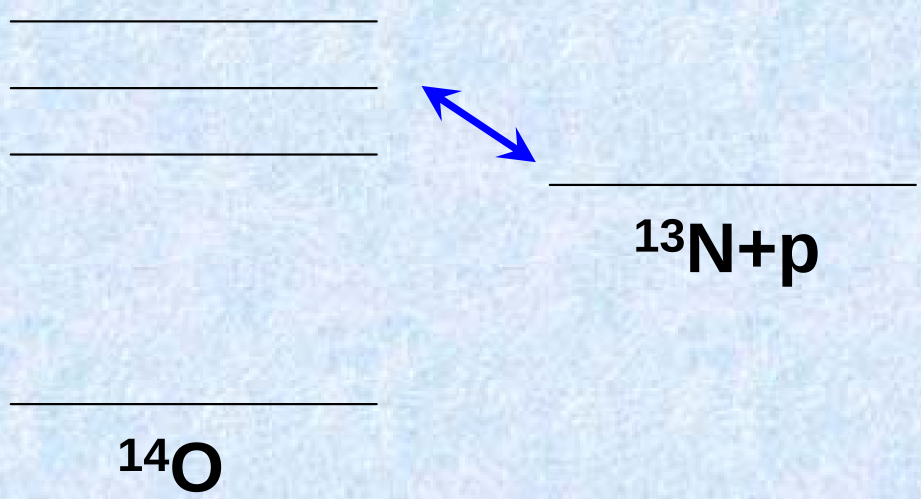
Isobaric Analog Multiplets

- T = 1 levels in A=14 nuclei (^{14}C, ^{14}N, ^{14}O)

  Charge independence & Effects of Coulomb force in nuclear structure

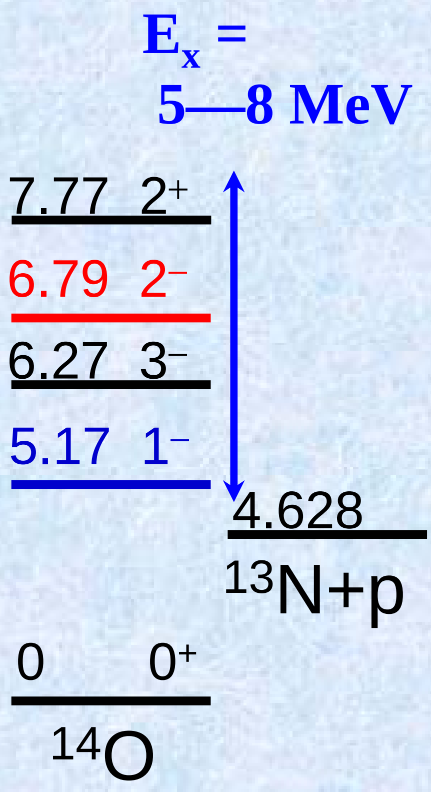
- Experimental information on ^{14}O is relatively poor

E_x & Γ of resonances to study the astrophysical ^{13}N(p,γ)^{14}O reaction rates in the Hot-CNO cycle



^{13}N+p result (^{14}O resonances)

Preliminary Data



The 1– resonance at 5.17 MeV dominates the astrophysical ^{13}N(p,γ)^{14}O reaction rates

Solid line: R-matrix

Energy resolution ~20 keV (FWHM)!

cf. ^{14}N(^{3}He,t)^{14}O reaction

Collaborators for CRIB experiments

Kyushu-Univ., Japan

CNS, Univ. of Tokyo, Japan

RIKEN, Japan

KEK, Japan

Chung-Ang, Univ., Korea

Ewha Woman's Univ., Korea

ATOMKI, Hungary

Sao-Paulo Univ., Brazil

Summary

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

Low-energy in-flight separator method

with intense primary beams and a large-acceptance separator

Technically simpler than ISOL

Complementary to ISOL

Experiments on proton-rich nuclei

^{11}C+p, ^{13}N+p ....

Other projects in near future:

p-resonance scattering on neutron-rich nuclei

a-resonance scattering on unstable nuclei