Coulomb dissociation for astrophysics studies

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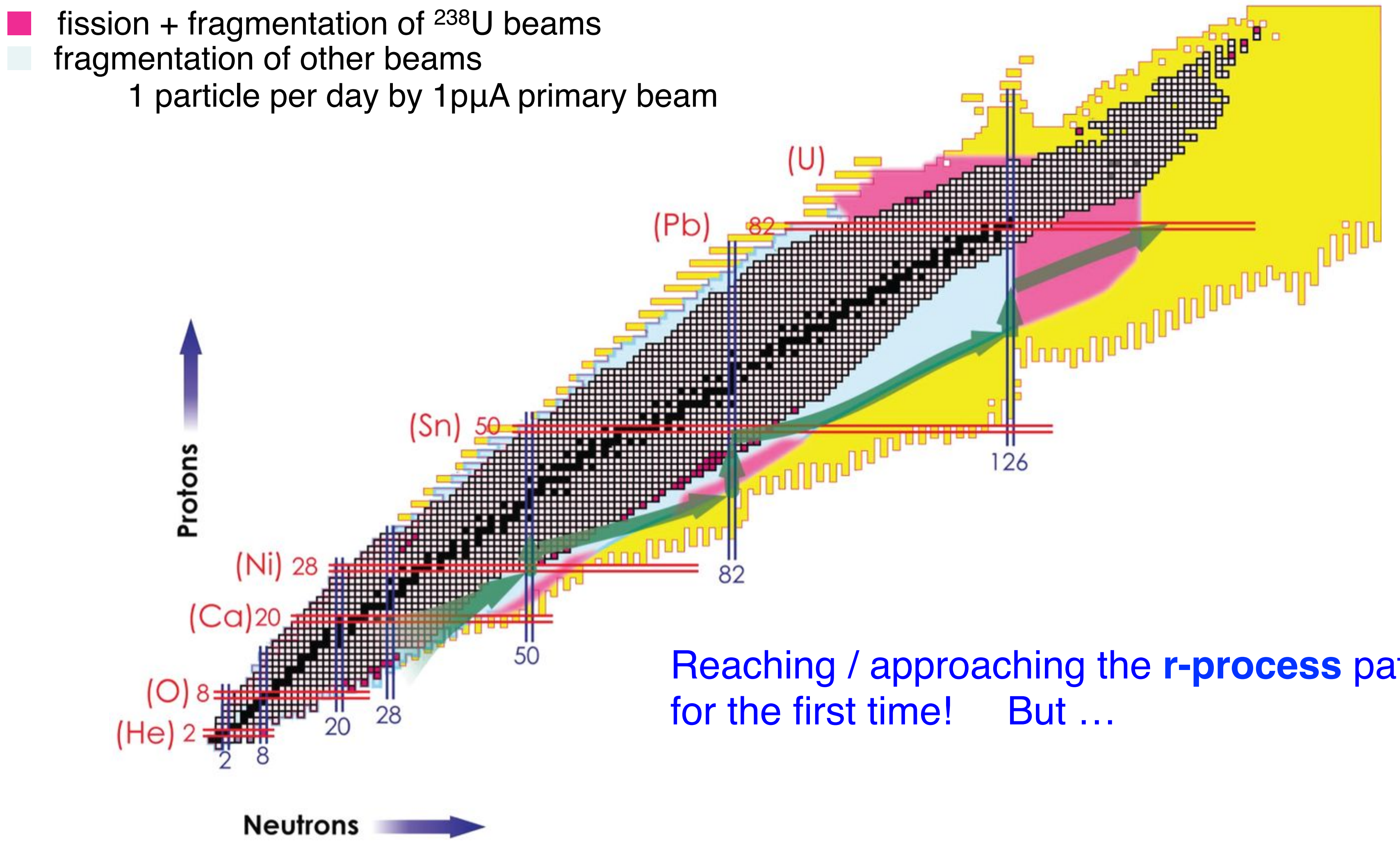
1. Introduction

2. Coulomb dissociation

3. At RIKEN RIBF

first **X**USTIPEN: X=J

Nuclear chart potentially covered by RIKEN RIBF (beams of short-lived nuclei)



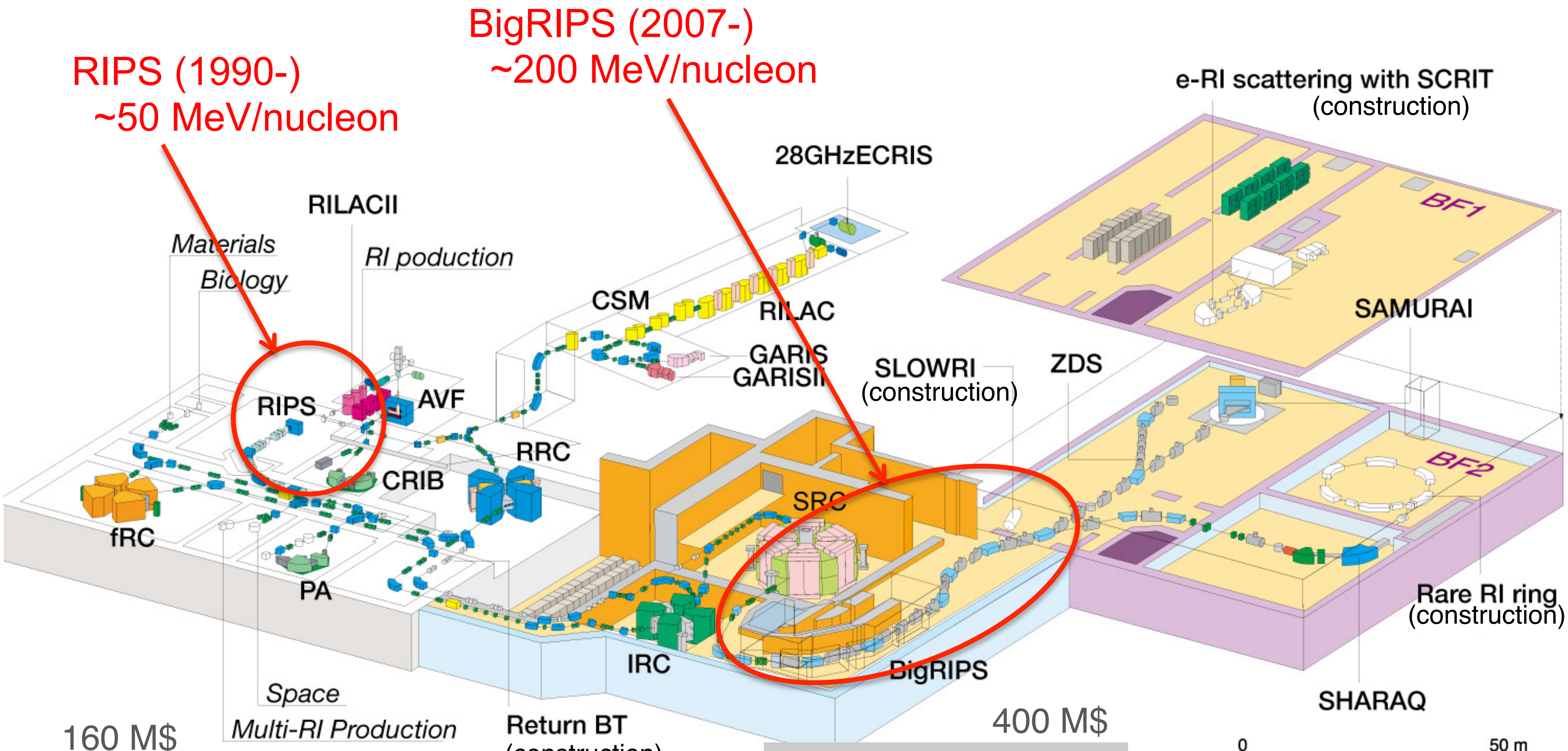
Reaching / approaching the **r-process** path for the first time! But …

Motobayashi T , and Sakurai H Prog. Theor. Exp. Phys. 2012;2012:03C001

PTEP Progress of Theoretical and Experimental Physics

RIKEN RIBF (RI Beam Factory) -- fragmentation-based RI bems (1990- / 2007-)

RIBF – a new generation RIB facility in operation
with world highest capability of providing RI beams in coming years!



160 M$

135 MeV/nucleon
for light nuclei (1986-)

400 M$

345 MeV/nucleon
up to U (2006-)

experimental
equipment

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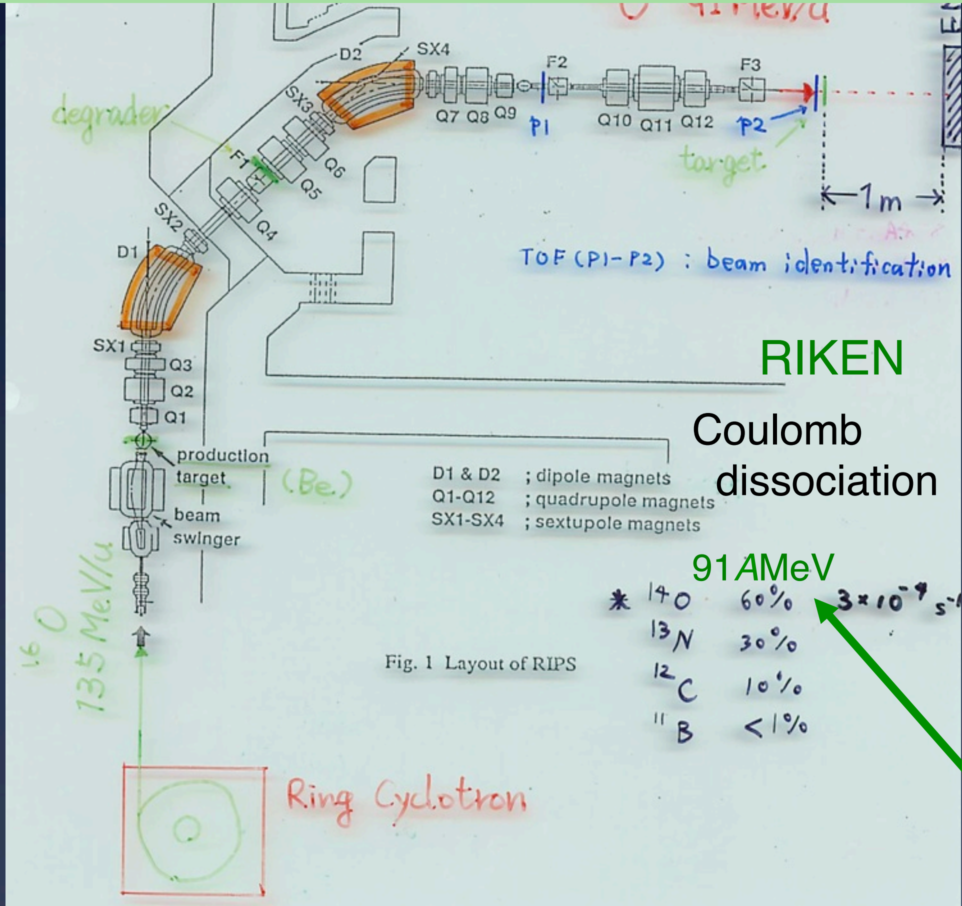
Two early experiments with RI beams are for the astrophysical reaction $^{13}N(p,\gamma)^{14}O$

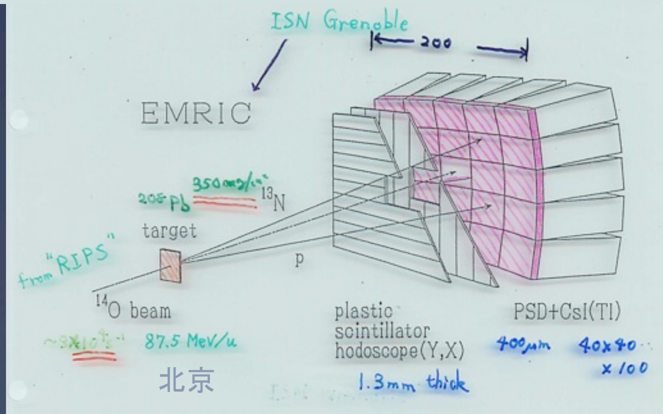


RIKEN

Coulomb dissociation

91 AMeV

* ^{14}O	60%	3×10^{-9} s
^{13}N	30%	
^{12}C	10%	
^{11}B	<1%	



Coulmob dissociation
^{14}O+Pb
→ ^{13}N+p+Pb
RIKEN

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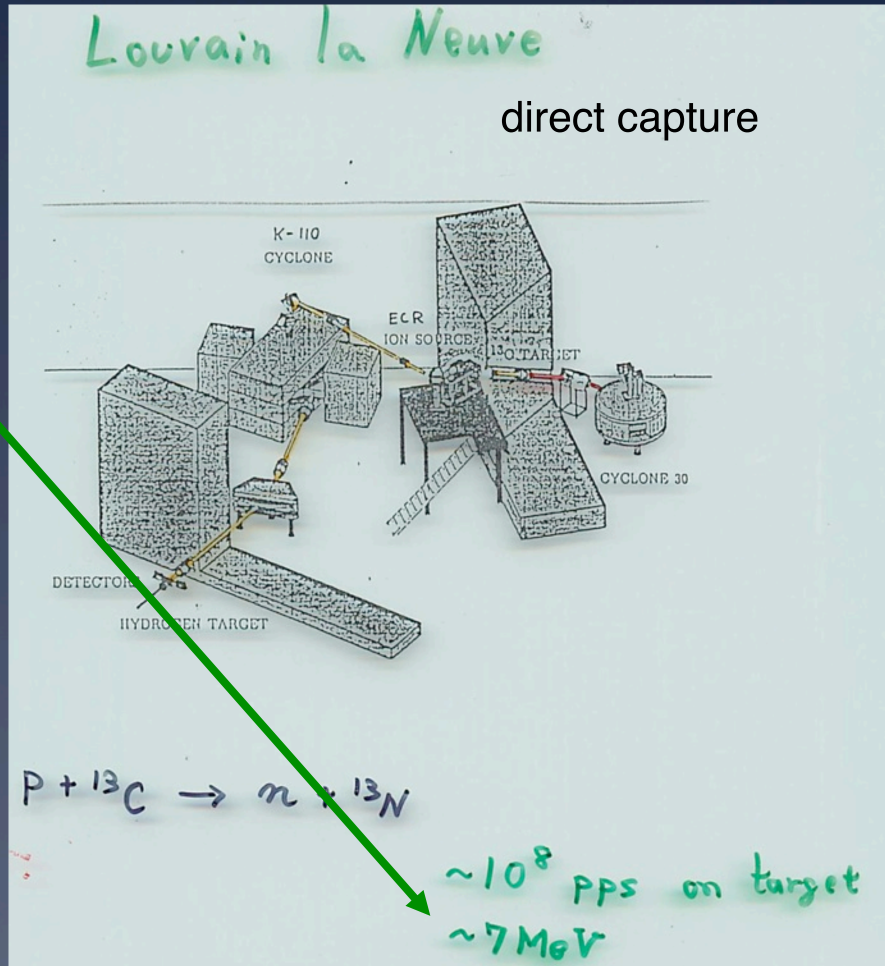
Direct measurement
$^{13}N+^{1}H \rightarrow ^{14}O+\gamma$
Louvain la Neuve



direct capture

Results by direct capture / Coulomb dissociation agree. ➔CNO-hot CNO boundary

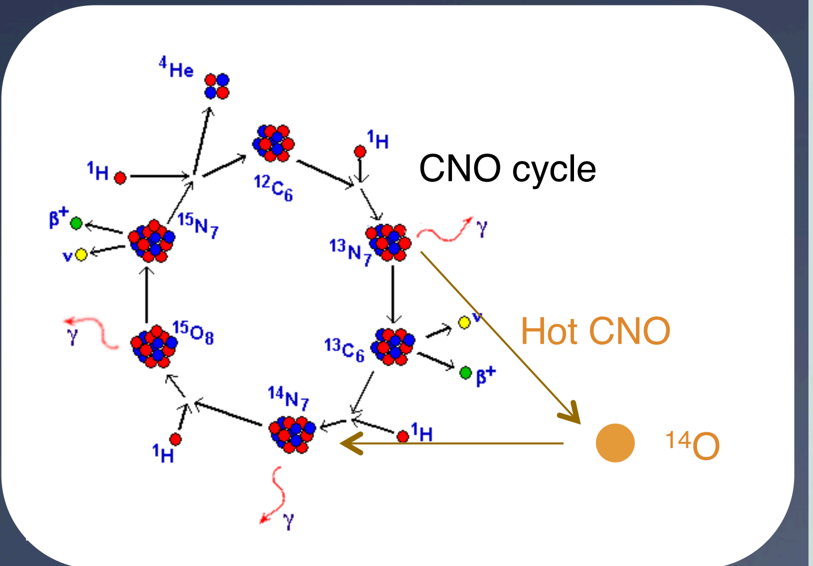
Γ_γ	present	(p,γ)
^{14}O (1^-)	3.1 ± 0.6 eV	$(3.8 \pm 1.2)^*$ (3.2) 3.4 ± 0.9
^{13}N $(1/2^+)$	0.59 ± 0.18 eV	$0.50 \pm 0.04^*$ eV

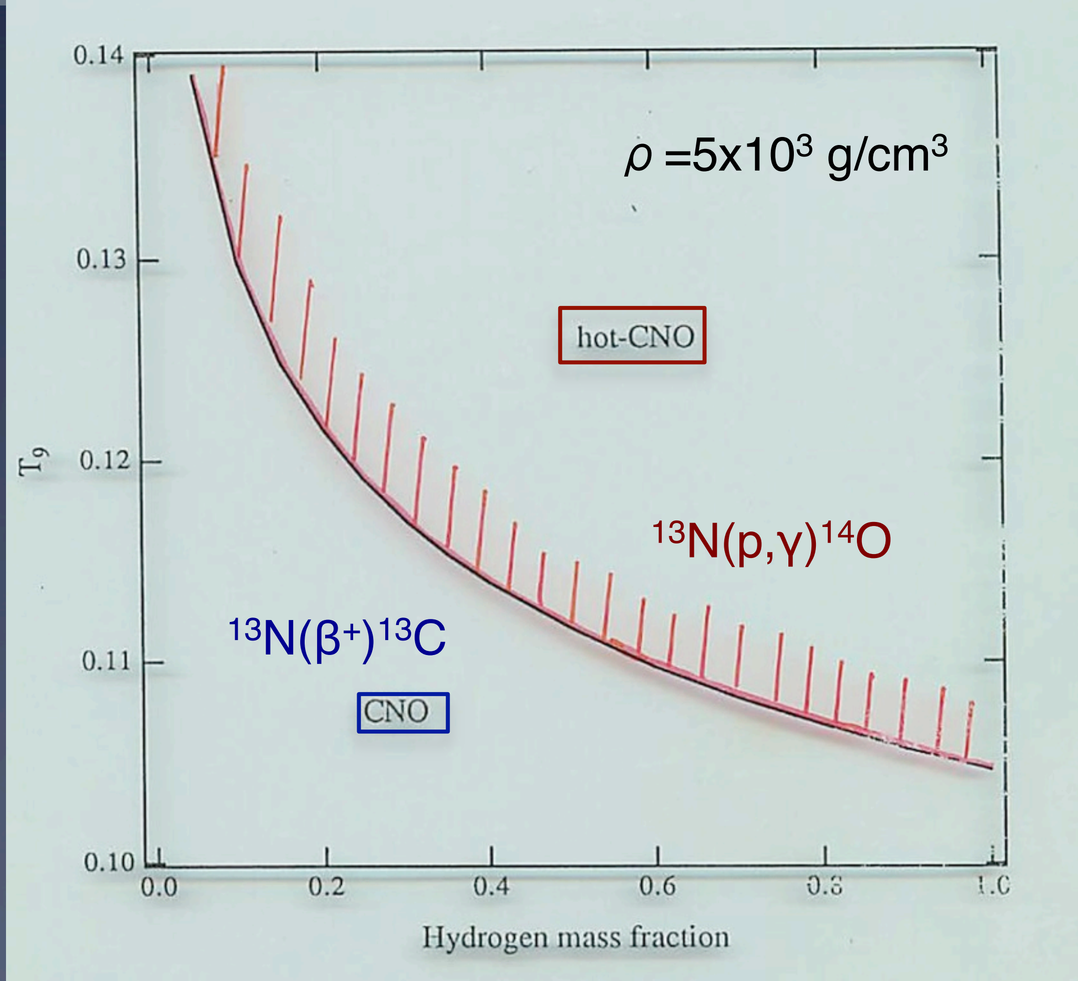
$^{12}C(p,\gamma)^{13}N$

reaction rate ← $\omega\Gamma_\gamma$, E_0

$$\langle \sigma v \rangle \propto \omega\Gamma_\gamma (kT)^{-3/2} \exp\left[-\frac{E_0}{kT}\right]$$

$$P_{12} = \rho_1 \rho_2 \langle \sigma v \rangle$$





Indirect methods for determination of astrophysical σ

to overcome

- small cross sections (low yield, low S/N …)
- weak RI beams – for reactions involving short-lived nuclei
- electron screening
- …

Indirect methods for determination of astrophysical σ

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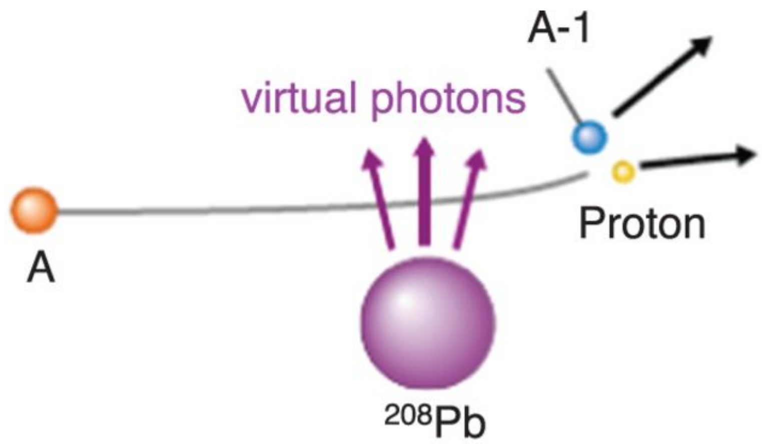
- …

by

- Coulomb dissociation
- ANC* determination
- Trojan-horse (quasi-free reaction)
- Spectroscopy of resonant states
- …..

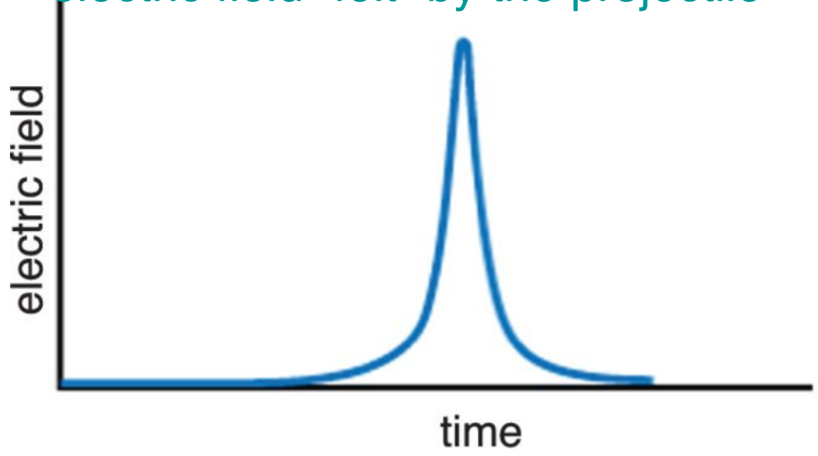
Schematic picture of the Coulomb dissociation.

(γ Trojan Horse)

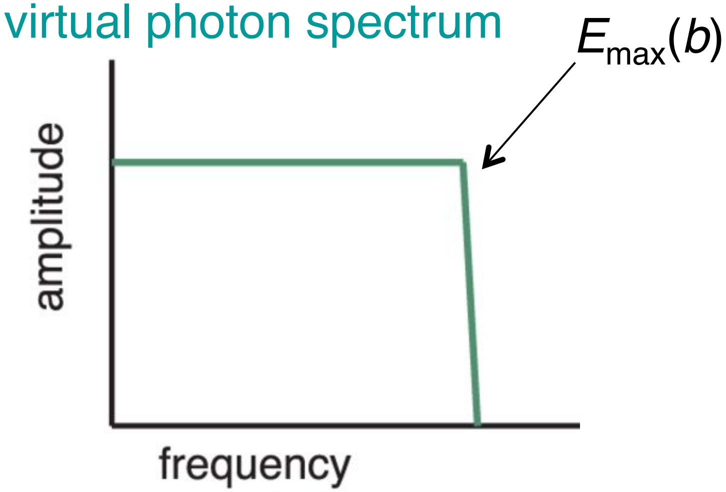


Fermi, Z. Phys. 29 (1924) 315

electric field “felt” by the projectile



virtual photon spectrum

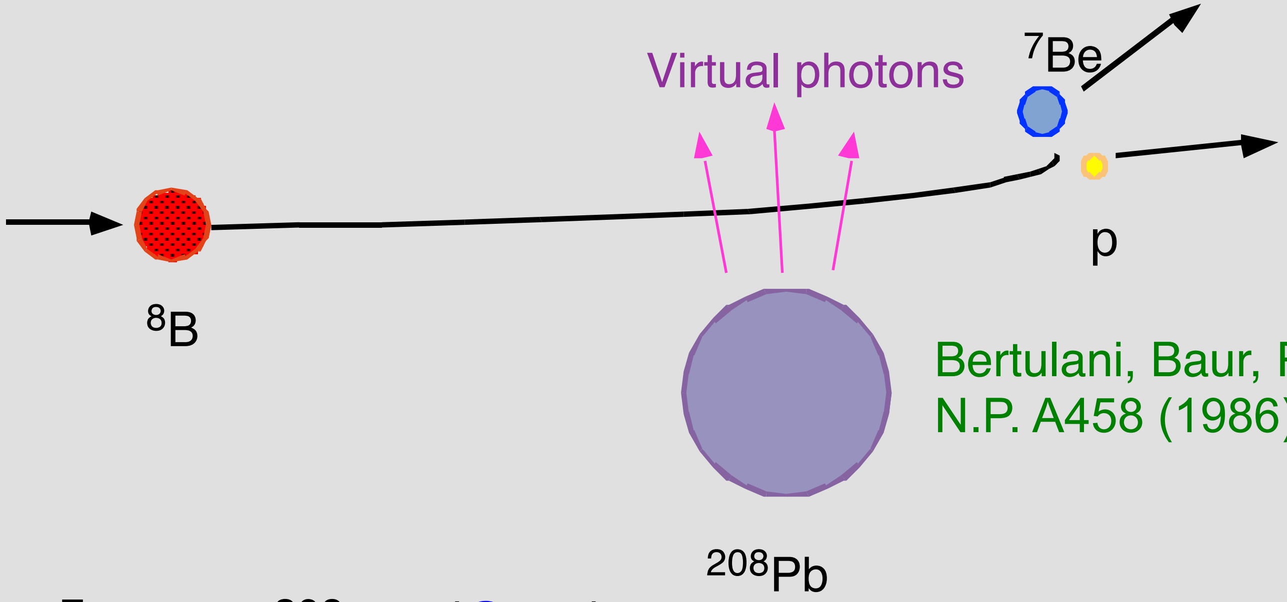


“Fast beam” can cover the energy range of nuclear excitation.

Motobayashi T , and Sakurai H Prog. Theor. Exp. Phys. 2012;2012:03C001

PTEP
Progress of Theoretical and Experimental Physics

Coulomb dissociation   successfully applied to astrophysical capture reactions



Bertulani, Baur, Rebel
N.P. A458 (1986) 188

^{8}B+^{208}Pb -> ^{7}Be+p+^{208}Pb (C.D.)

↓ virtual photon theory or DWBA

^{8}B(γ,p)^{7}Be (abs.)

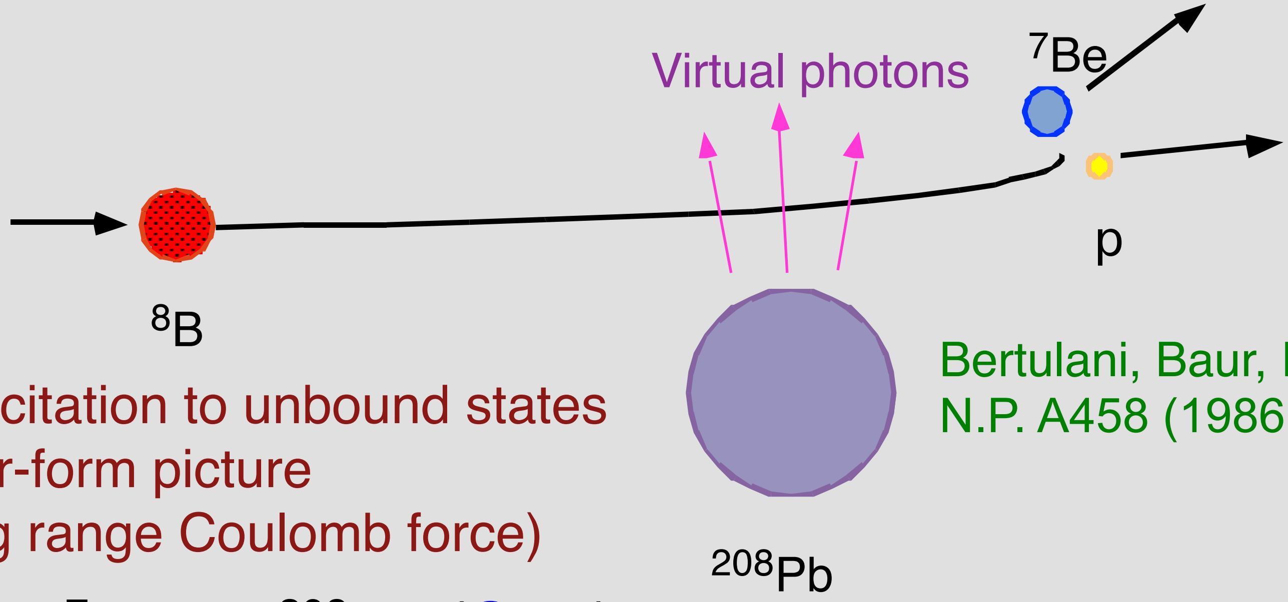
↓ detailed balance

^{7}Be(p,γ)^{8}B (capt.)

large σ, thick target (intermediate energy)

experiments with weak RI beams

Coulomb dissociation successfully applied to astrophysical capture reactions



Bertulani, Baur, Rebel
N.P. A458 (1986) 188

= Coulomb excitation to unbound states
(in the prior-form picture
-- long range Coulomb force)

^{8}B+^{208}Pb -> ^{7}Be+p+^{208}Pb (C.D.)

↓ virtual photon theory or DWBA

^{8}B(γ,p)^{7}Be (abs.)

↓ detailed balance

^{7}Be(p,γ)^{8}B (capt.)

large σ, thick target (intermediate energy)

experiments with weak RI beams

Coulomb dissociation efficient tool ← σ enhancement and experimental advantages

detailed balance

$$\sigma_{(\gamma,\mathrm{p})} = \frac{(2j_7+1)(2j_1+1)}{2(2j_8+1)} \frac{k_{17}^2}{k_\gamma^2} \sigma_{(\mathrm{p},\gamma)}$$

100 ~ 1000 for inverse process

virtual photon number (intermediate energy)

$$\left(\frac{d\sigma}{dE_\gamma}\right)_{\mathrm{C.D.}} = \frac{n}{E_\gamma} \sigma_{(\gamma,\mathrm{p})}$$

100 ~ 1000 for inverse process

thick target

charged particle detection

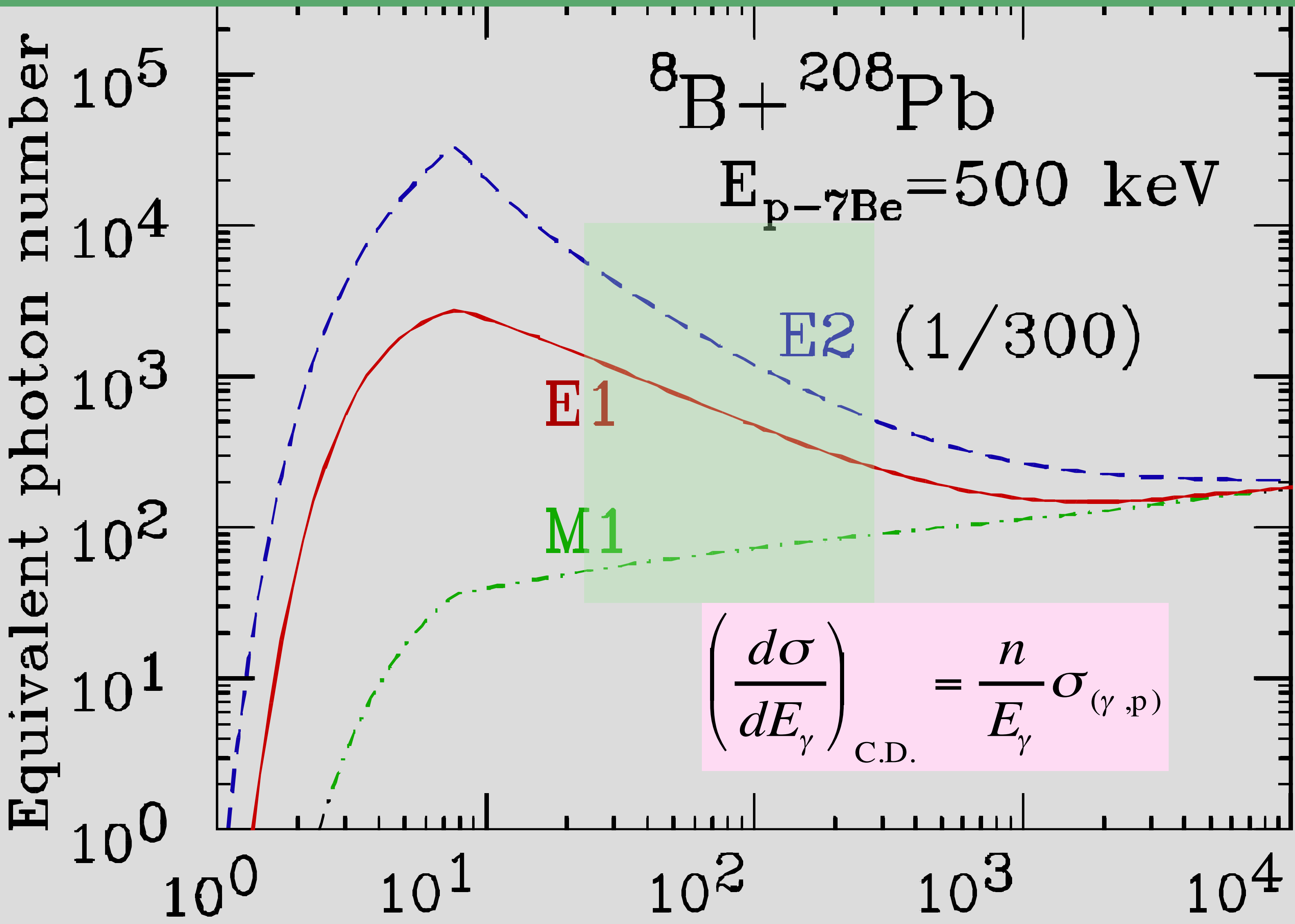
but

Indirect --- nucl. force / higher order / E2 / 3 body /relativistic…

← reaction theory

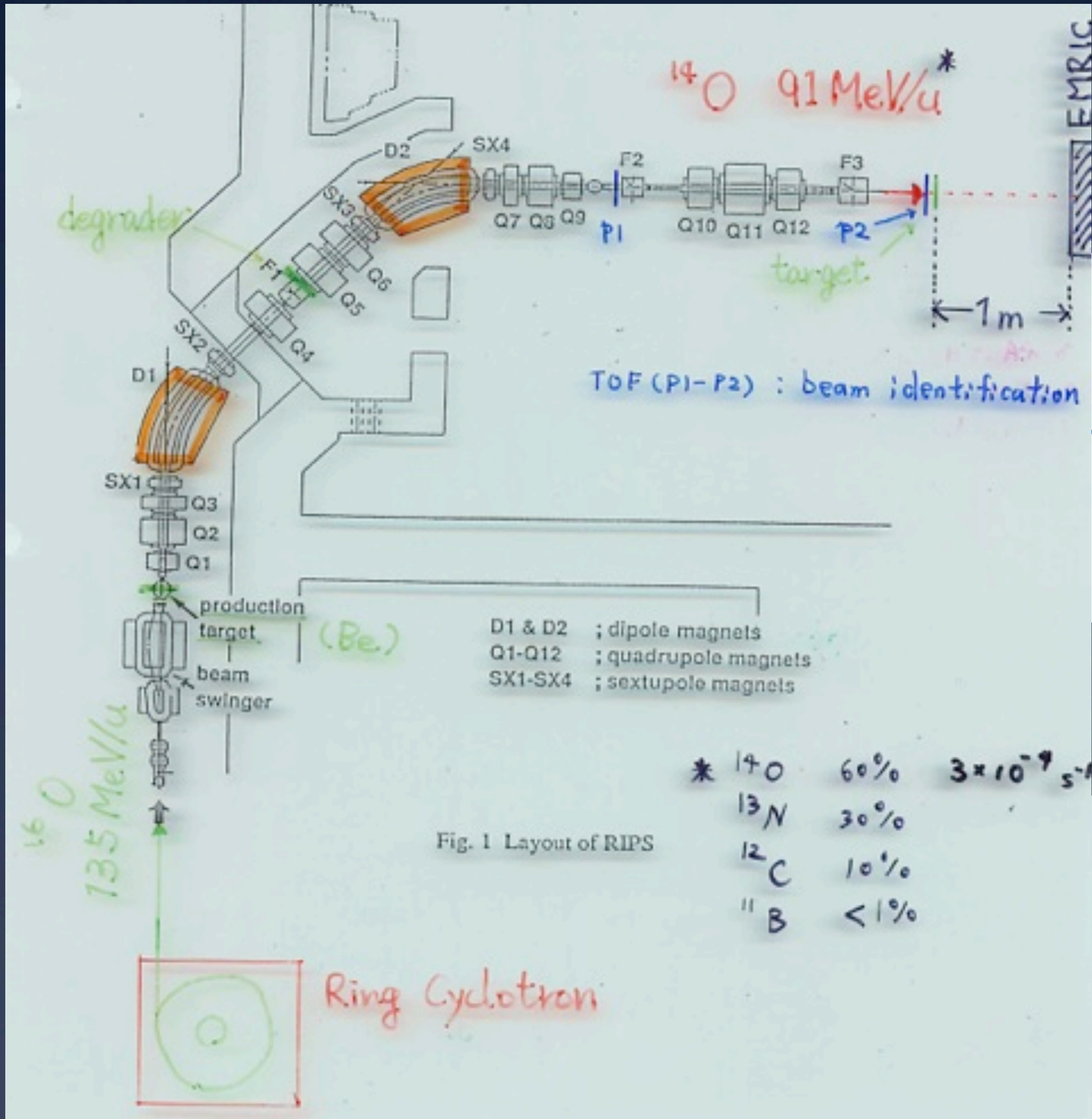
only for (x,γ) to the ground state / only E1 (or E2) practical

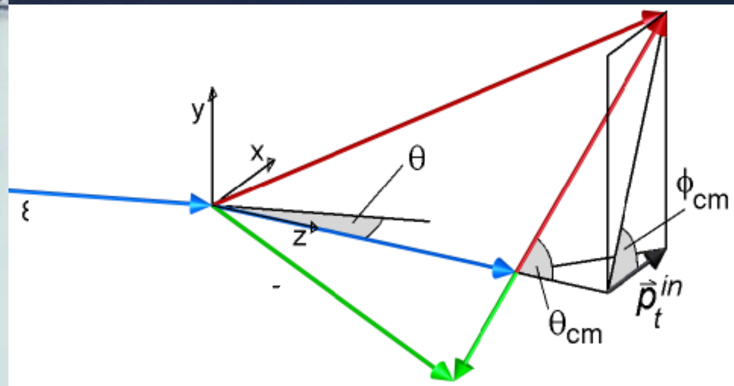
Virtual photon intensity depends on the multipolarity.

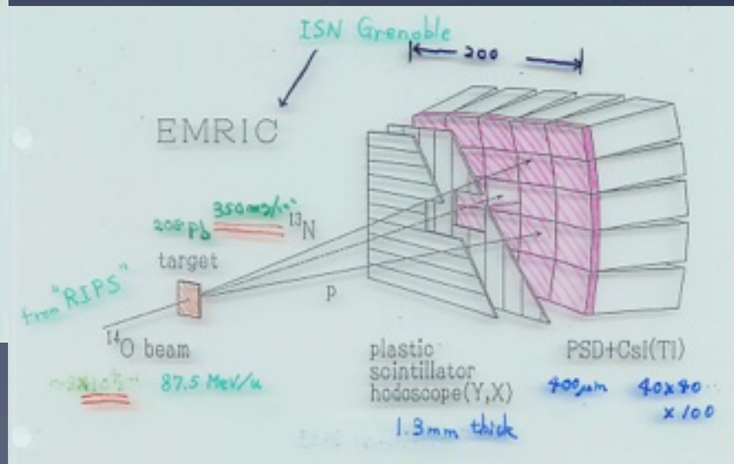


$$\left(\frac{d\sigma}{dE_\gamma}\right)_{C.D.} = \frac{n}{E_\gamma}\sigma_{(\gamma,p)}$$

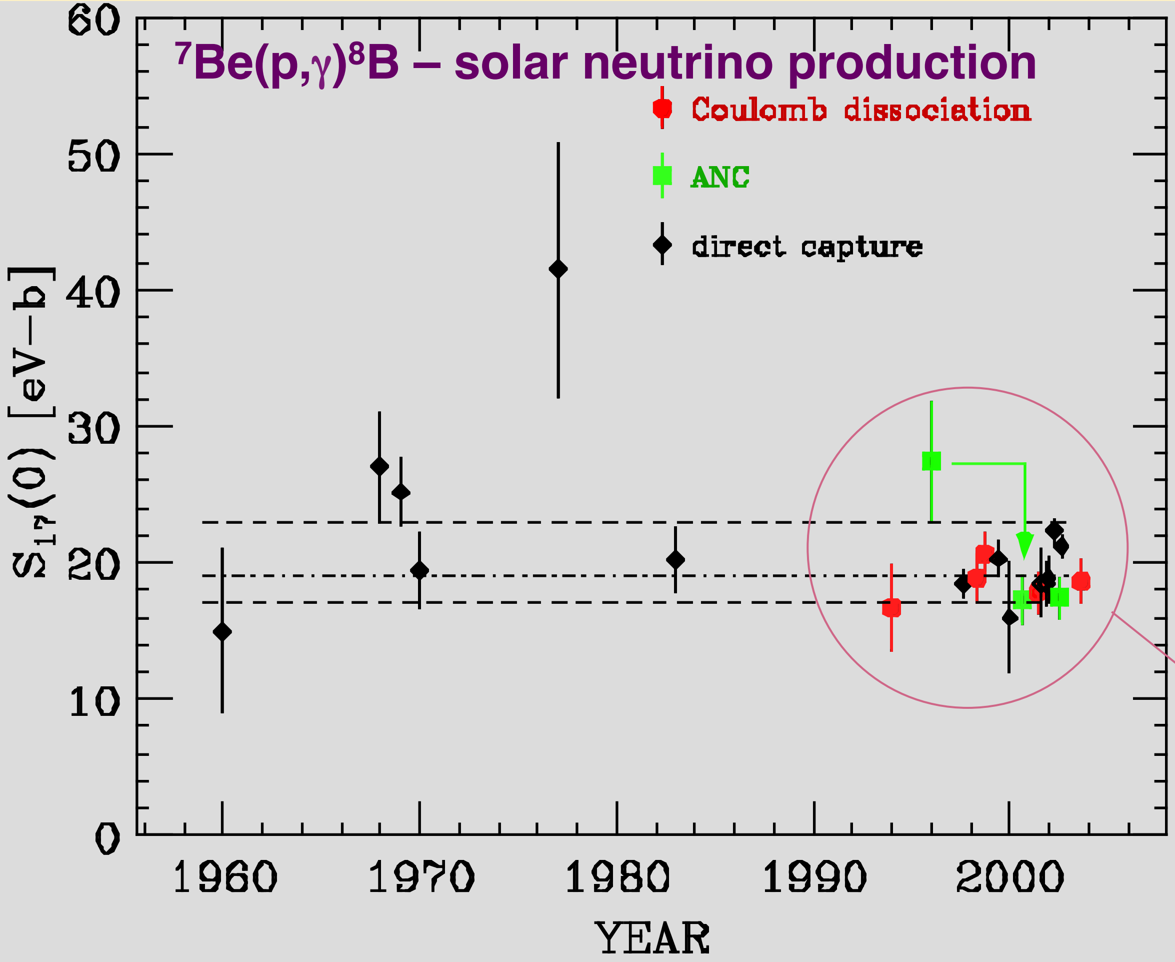
Typical setup - $^{13}N(p,\gamma)^{14}O$ or ^{14}O dissociation



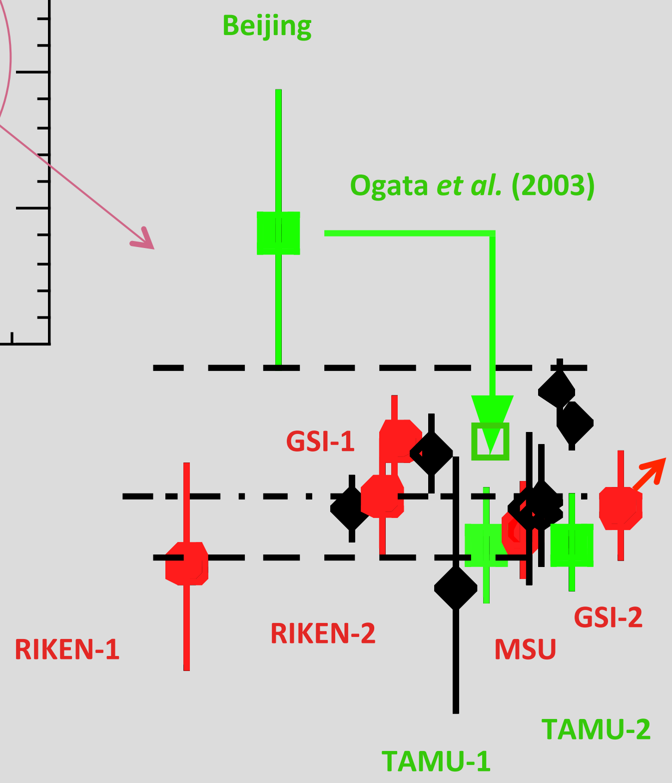




Recommended values change as experimental and theoretical development



S_{17} at E=0



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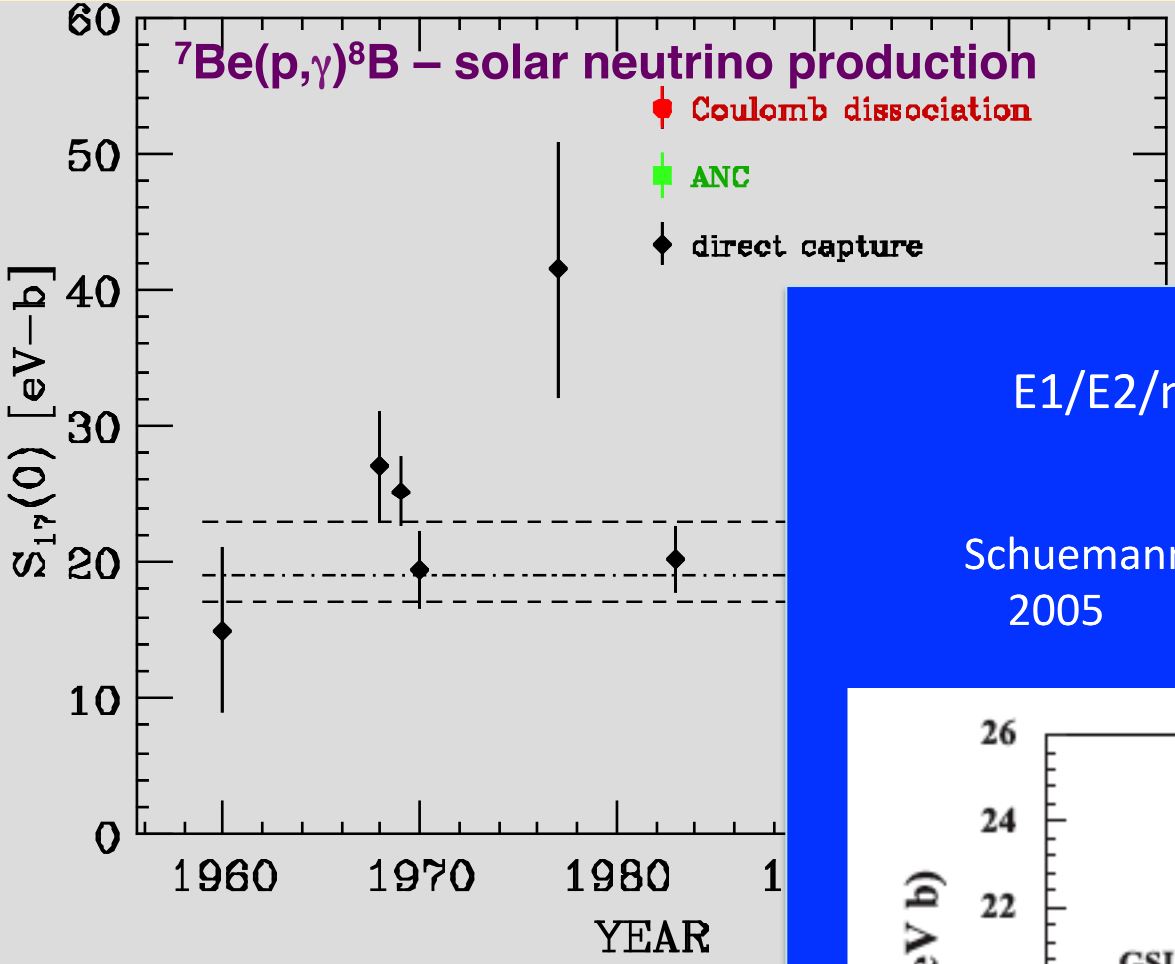
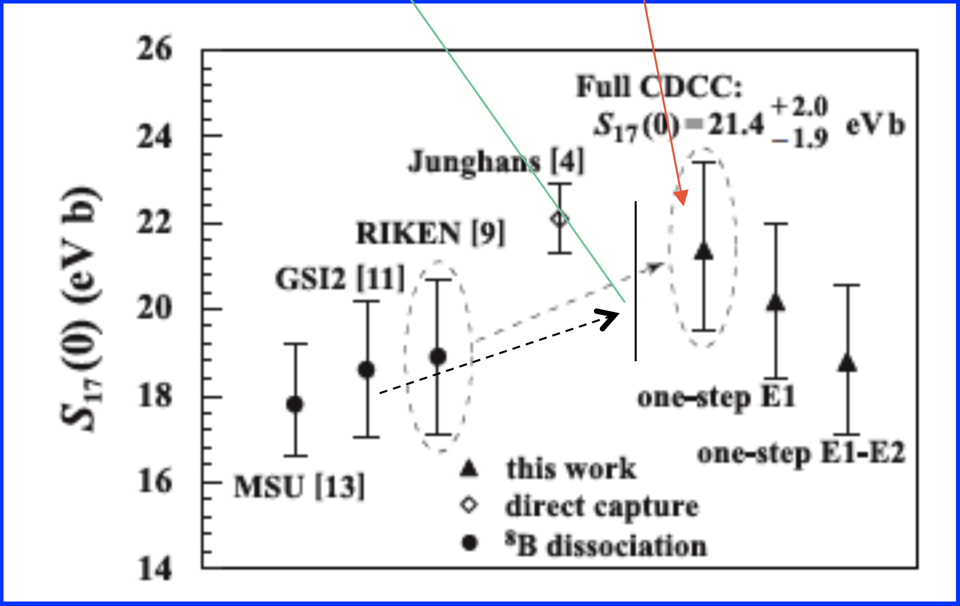


S_{17} at E=0

E1/E2/nucl. interference

Ogata *et al.* (CDCC)

Schuemann *et al.* 2005



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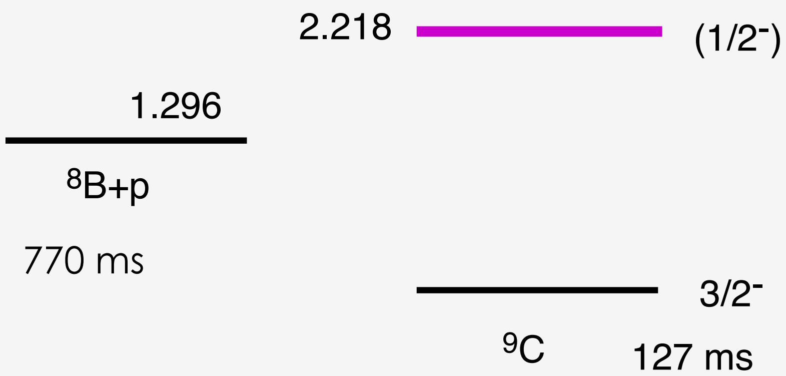
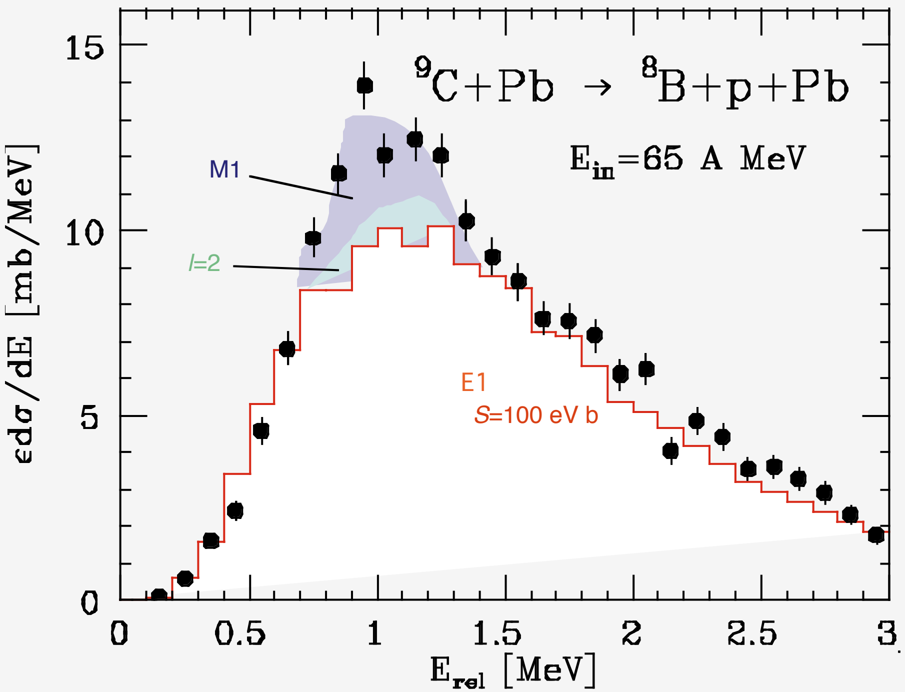
Example 3

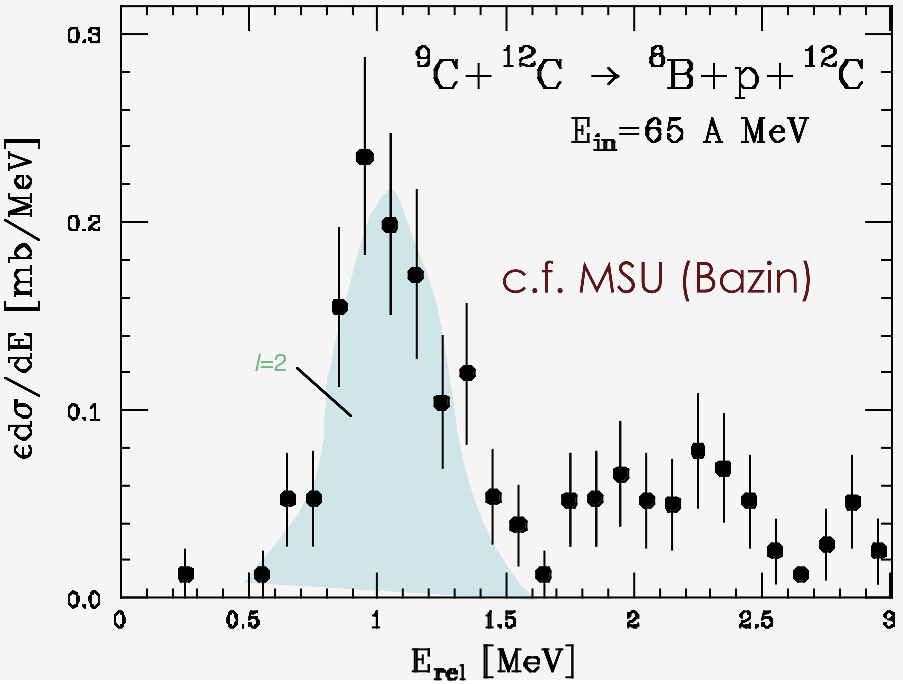
$^8B(p,\gamma)^9C$ in hot pp chain

direct- and resonant-capture

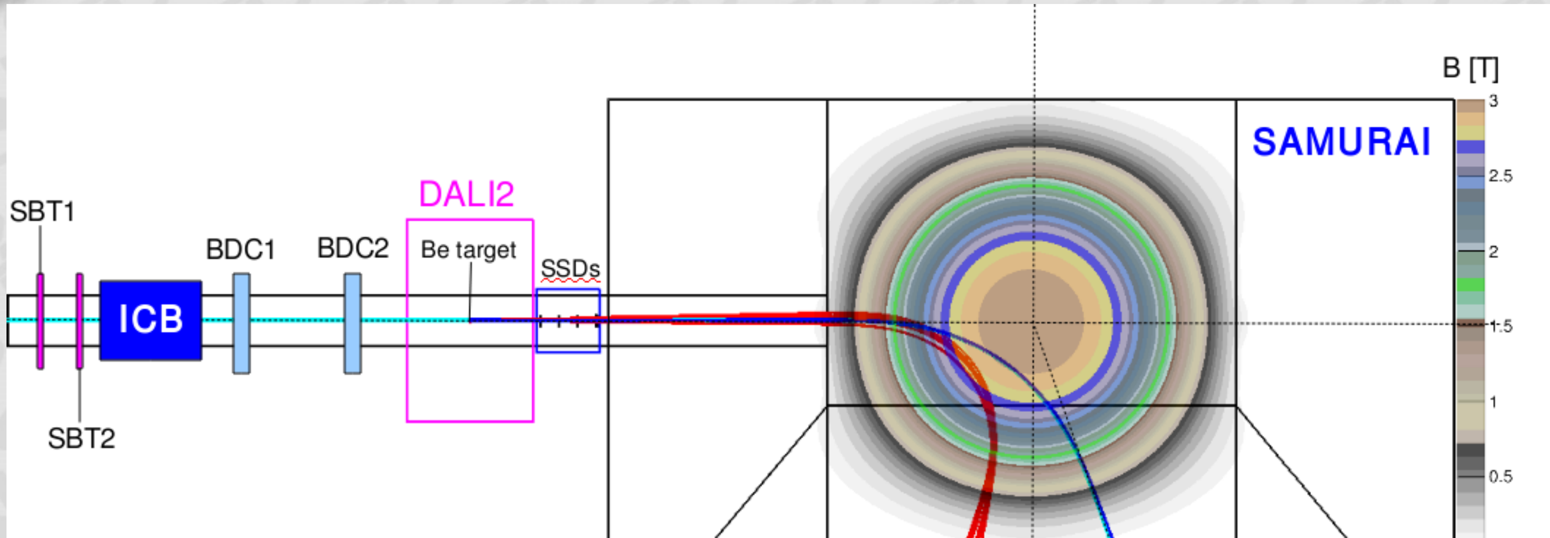


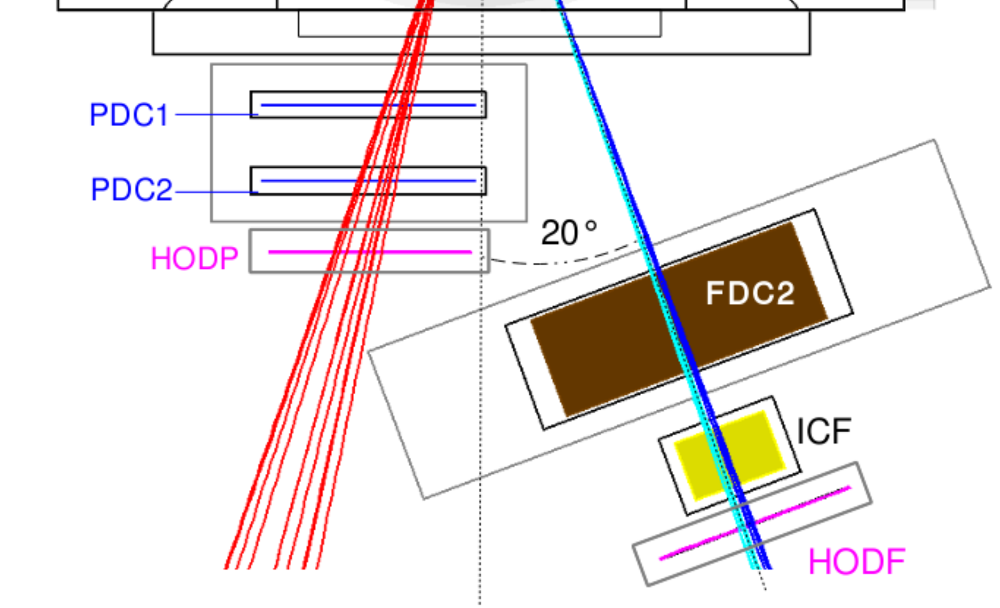
A plan at RIBF using SAMURAI
better resolution
with higher statistics





Trajectories for p-HI type invariant-mass experiments with SAMURAI

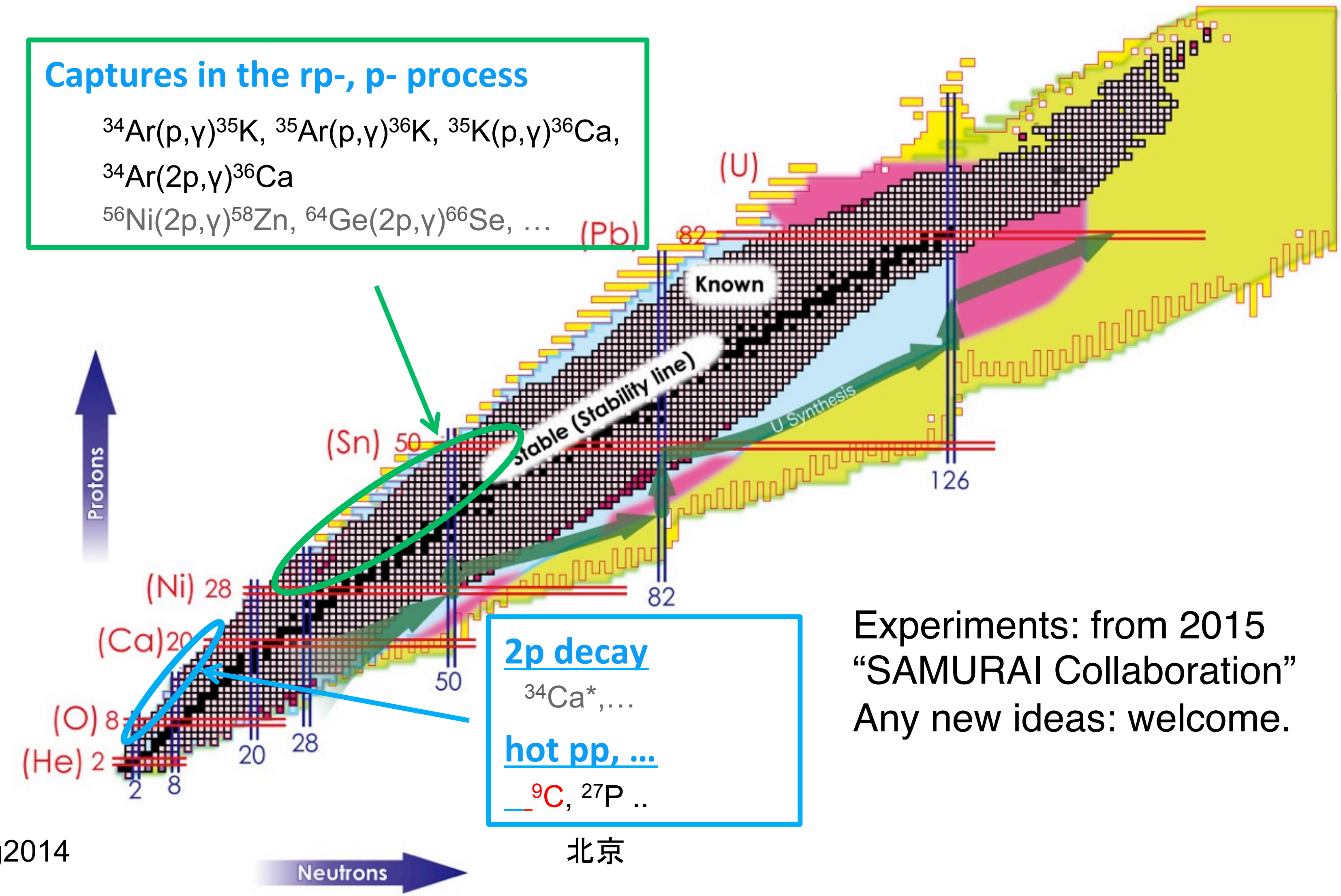




Possible experiments in the first stage

Captures in the rp-, p- process

^{34}Ar(p,γ)^{35}K, ^{35}Ar(p,γ)^{36}K, ^{35}K(p,γ)^{36}Ca,
^{34}Ar(2p,γ)^{36}Ca
^{56}Ni(2p,γ)^{58}Zn, ^{64}Ge(2p,γ)^{66}Se, …



2p decay

^{34}Ca*,…

hot pp, …

^{9}C, ^{27}P ..

Experiments: from 2015
“SAMURAI Collaboration”
Any new ideas: welcome.

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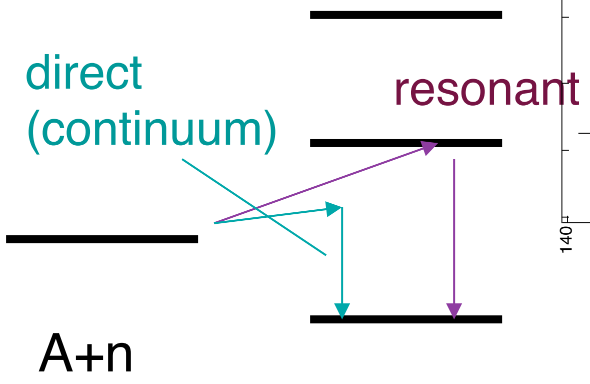
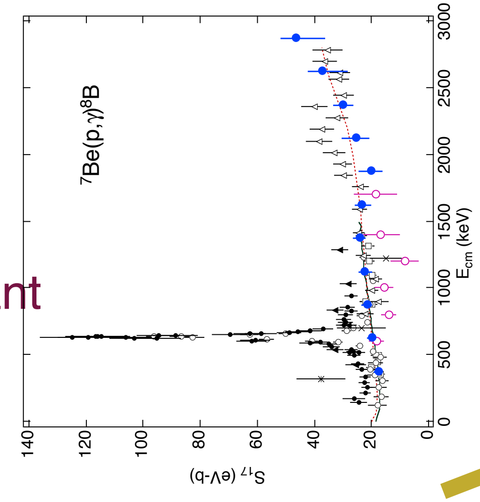
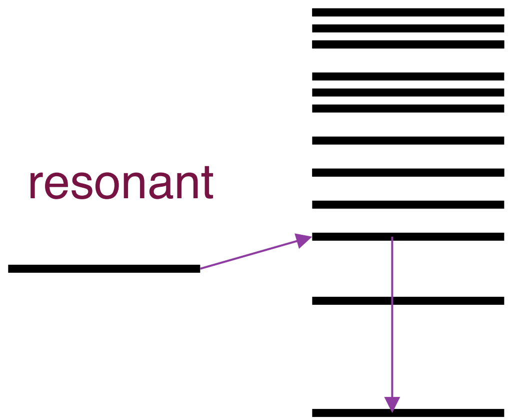
Situation depends much on the region in the nuclear chart.

(n,γ) (or (p,γ)) – radiative capture







level density: low

light nuclei

closed shell

near the drip line

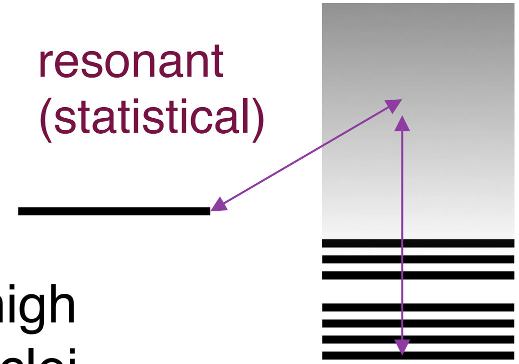
Cross section (σ), lifetime

Direct measurement

Indirect methods

Coulomb dissociation, ANC,….

mass (Q), lifetime
level density ..



level density: high

heavier nuclei

If the Brink Hypothesis is applicable, γ-ray strength function is obtained by Coulomb dissociation. Utsunoiya (Konan U.)

c.f. Uberseder et al., PRL 112 (2014) 211101

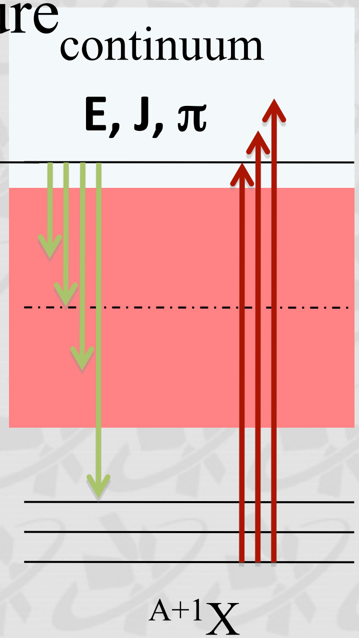
Radiative neutron capture

$^{A}X(n,\gamma)^{A+1}X$

$n+^{A}X$

$$f_{X\lambda}(\varepsilon_\gamma)\downarrow = \frac{T_{X\lambda}(\varepsilon_\gamma)}{2\pi}\varepsilon_\gamma^{-(2\lambda+1)}$$

$$\varepsilon_\gamma < S_n$$



Photoneutron emission

$^{A+1}X(\gamma,n)^{A}X$

$$f_{X\lambda}(\varepsilon_\gamma)\uparrow = \frac{\varepsilon_\gamma^{-2\lambda+1}}{(\pi\hbar c)^2}\frac{\langle\sigma_{X\lambda}^{abs}(\varepsilon_\gamma)\rangle}{2\lambda+1}$$

$$\varepsilon_\gamma > S_n$$

$$\sigma_{X\lambda}^{\gamma n}(\varepsilon_\gamma) = \sigma_{X\lambda}^{abs}(\varepsilon_\gamma)\times\frac{T_n}{T_n+T_\gamma}$$

Brink Hypothesis

$$f_{X\lambda}(\varepsilon_\gamma)\uparrow \cong f_{X\lambda}(\varepsilon_\gamma)\downarrow$$

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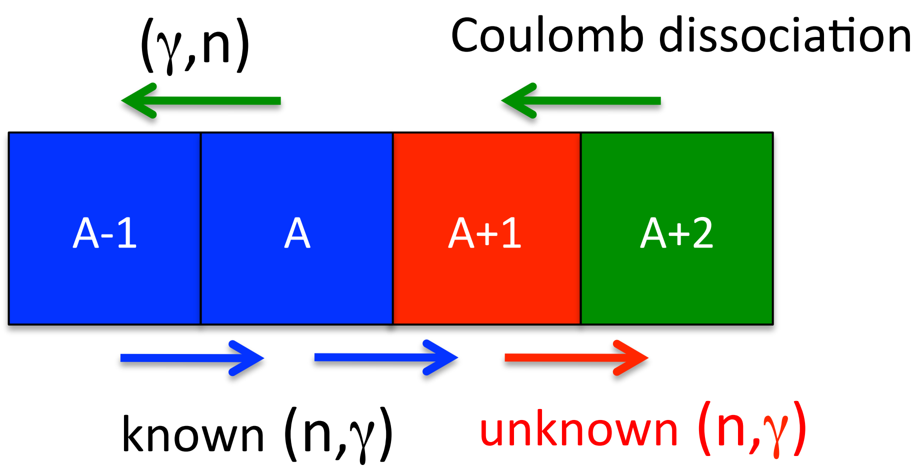
Courtesy of H. Utsunomiya

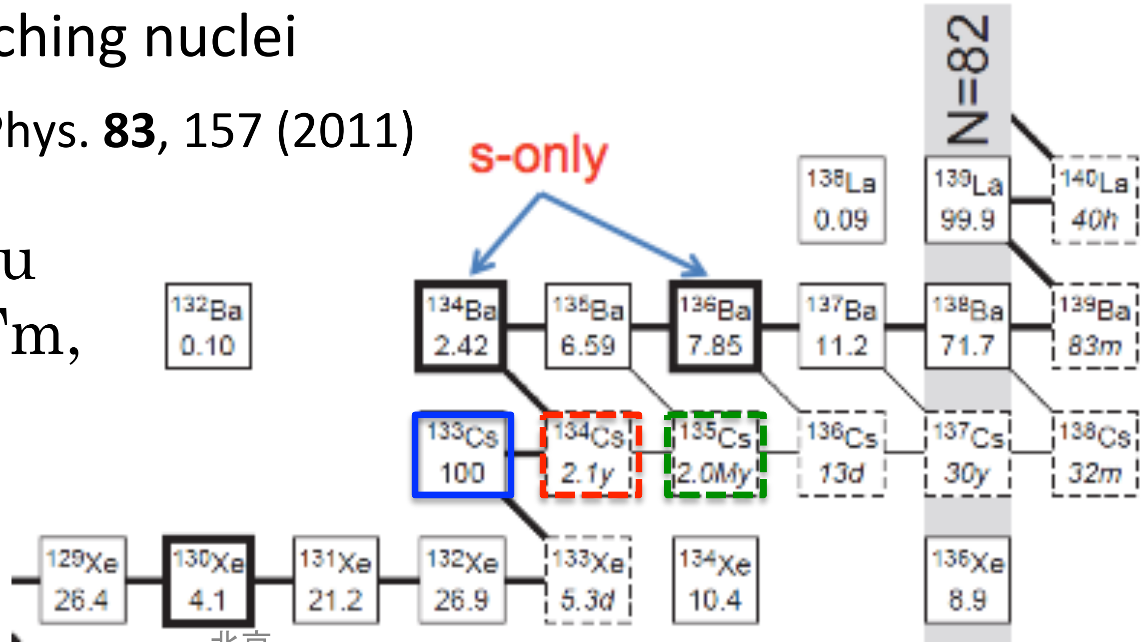
γSF Method with Coulomb dissociation



Important **s-process** branching nuclei

F. Käppeler *et al.*, Rev. Mod. Phys. **83**, 157 (2011)

^{134}Cs, ^{135}Cs, ^{154}Eu, ^{155}Eu
^{160}Tb, ^{163}Ho, ^{170}Tm, ^{170}Tm,
^{179}Ta, ^{204}Tl



Courtesy of H. Utsunomiya


NIC-XIV will be in Japan!
Nuclei in the Cosmos
hosted by NAOJ* and RIKEN
in 2016
* National Astronomical Observatory of Japan
c.f.
OMEG2015 at Beijing
Origin of Matter and Evolution of Galaxies
June 24-27, 2015

Summary

RIKEN RIBF (running)

highest capability of RI beam production

Coulomb dissociation

efficient (but limited) tool for astrophysical (p,γ) and (n,γ)

Coulomb dissociation at RIBF

1) Studies with improved conditions (statistics, resolution, ..)
2) Studies of heavier system
   e.g. (n,γ) in the r-process (in addition to rp-process cases)
3) Studies of statistical (n,γ) reactions

OMEG @Beijing (2015), NIC @~Tokyo (2016)


Thank you
谢谢你
ありがとうございました
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