Nuclear Astrophysics with low-energy RI beams

Lecture by
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What will be covered in this lecture

- Experimental nuclear astrophysics
- Astrophysical reaction study with unstable nuclei (radioactive isotope; RI) … What does it mean?
- Low energy RI beam production (ISOL/in-flight).
  - ◆In particular, CRIB of CNS, the Univ. of Tokyo
- Physics cases, using methods to study astrophysical reactions with RI beams
  - ◆Direct measurement
  - ◆Resonant scattering with thick-target method in inverse kinematics (TTIK)
  - ◆The active target, as an advanced form of TTIK
  - ◆Indirect method (e.g. Trojan Horse Method)

How to simulate "stars"

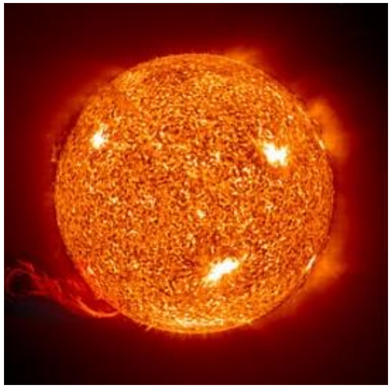
Stars…interesting objects to study, may evolve, explode, and create elements

Our sun…important energy source of our life

However,

- Interior of the sun/stars…we cannot see directly.
- We need a theoretical model, observational and experimental evidences (especially nuclear reaction rates) to understand them completely.

The sun



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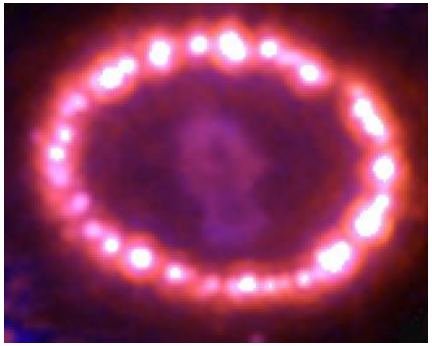
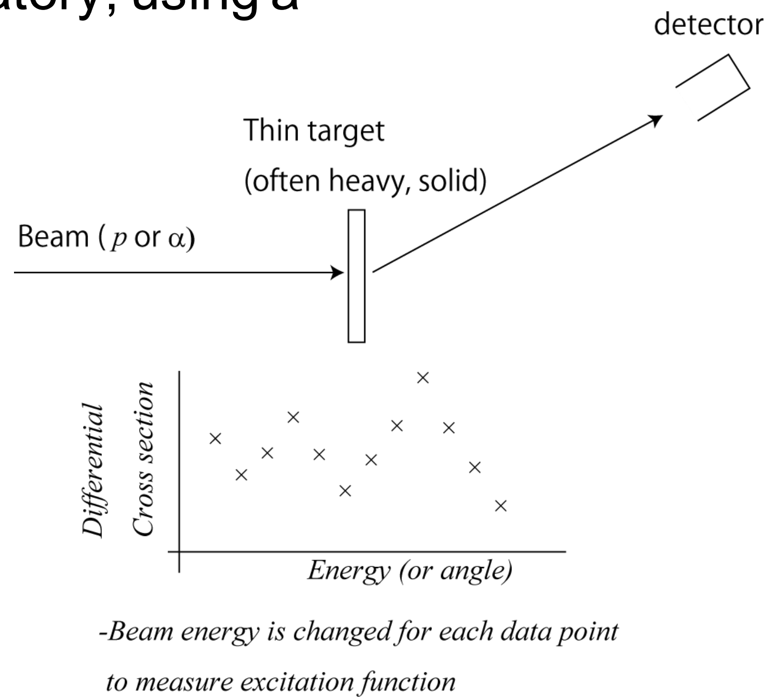


Nuclear physics experiment to astrophysical simulation

- What we can measure?

reaction cross section vs energy.

- ◆ Make the stellar reaction at laboratory, using a beam and a target.
- ◆ Cross section…target thickness, number of beam particle, number of detected particle, scattering angle, solid angle of the detector.



What we need for the simulation:

reaction rate vs temperature

T-dependence

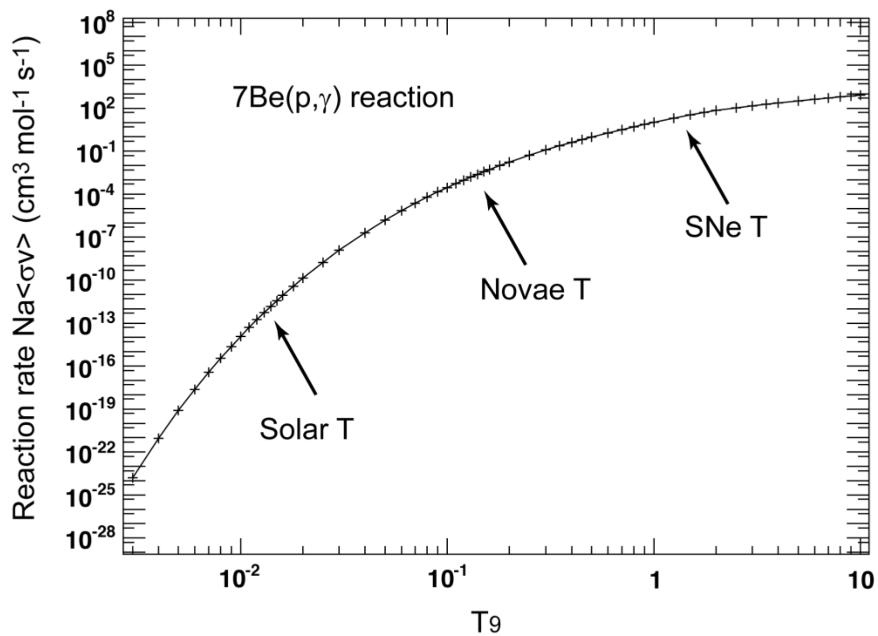
- To study thermonuclear reaction cross sections (or rates)→ To understand stars/nucleosynthesis

  [“thermo”nuclear reaction… nuclear reaction thermally induced by the environmental heat (such as in stars)]
- $^{7}Be(p,\gamma)$…a capture reaction to make ^{8}B (just an example)
- Reaction rates…Much dependent on T

- Compound nucleus…

^{8}B structure (resonance) is also important.

We need experiments!



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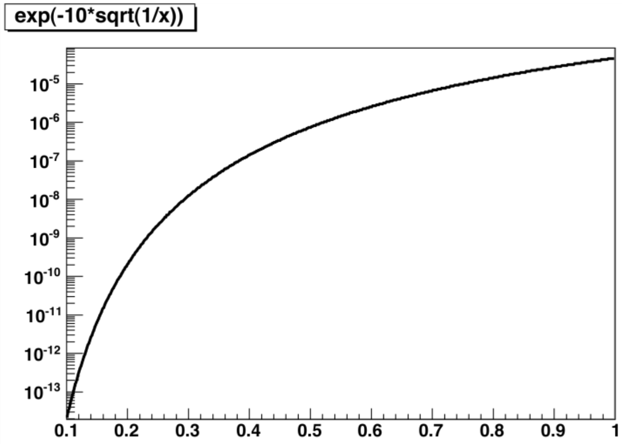
Quantum tunneling

- The large E-dependence of the cross section…because of the tunneling probability to penetrate the Coulomb barrier of the nucleus.
- Tunneling probability of square potential well:

$$P \propto \exp(-2\kappa\Delta r)$$

$$\kappa = \frac{\sqrt{2m|V-E|}}{\hbar}, \Delta r; \text{width of the potential}$$

- Coulomb potential:



$$P = \exp(-2\pi\eta)$$

$$\eta = \frac{Z_1 Z_2 e^2}{\hbar v} \propto Z_1 Z_2 \left(\frac{\mu}{E}\right)^{1/2}$$

η: Sommerfeld parameter

μ: reduced mass

Astrophysical S-factor

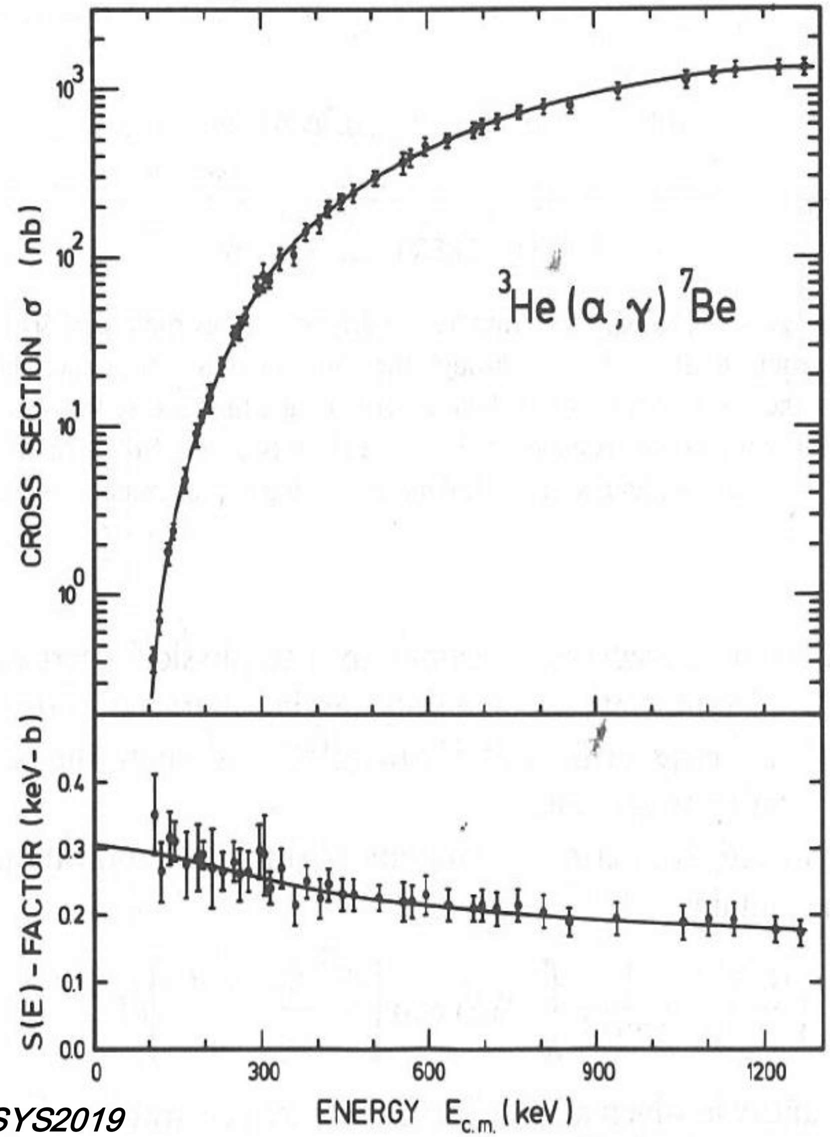
- Normalization for the large energy dependence:

Introducing *S(E)*, instead of cross section

$$\sigma(E) = \frac{S(E)}{E}\exp\{-2\pi\eta\}$$

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

- $1/E$…geometrical factor (λ^2)
- A flat E-distribution can be obtained by using *S(E)*.



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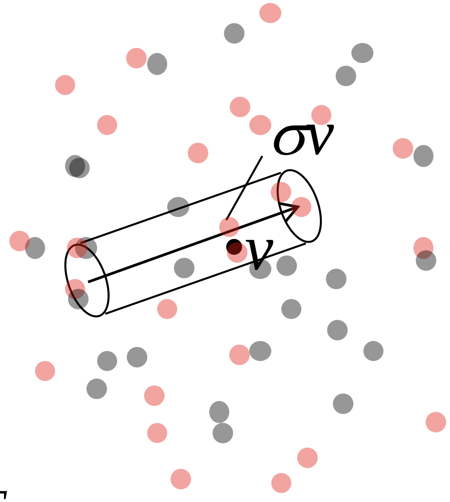
Reaction rate

- Reaction rate per particle pair <σv>

  a particle and the other particle collide with a relative velocity v, and the cross section σ(v).

  How much is the averaged rate of reactions?

  - ◆ Maxwell-Boltzmann distribution
  - ◆ Coulomb barrier (use S-factor)
  - ◆ Barrier penetrability b



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

$$b = (2\mu)^{1/2} \pi e^2 Z_1 Z_2 / \hbar$$

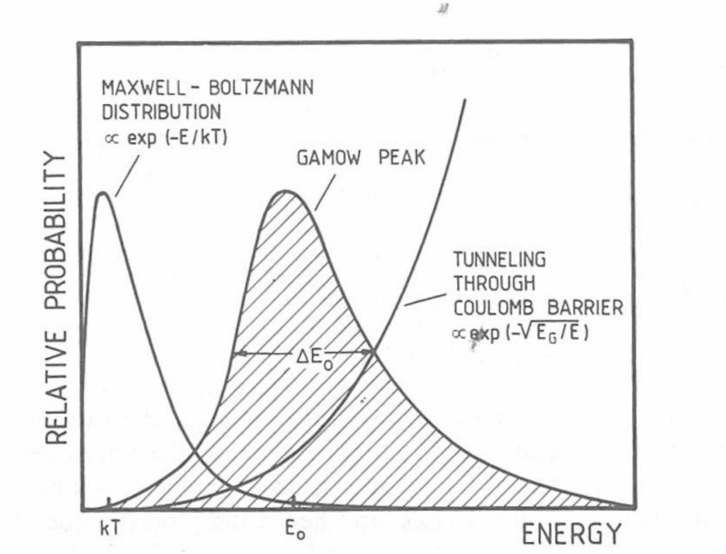
- Total reaction rate… $r = N_x N_y < \sigma v >$

  Exp. cross section ⇒ we can evaluate production rate of newly synthesized nuclides

T and E, more in detail

- What's the relation between T and E?
  - ◆ Boltzmann distribution…. kT ⇔ E
  - ◆ However, the cross section in much dependent on E, due to the tunneling effect.

    tunneling probability $\propto \exp(-\sqrt{1/E})$
  - ◆ Gamow peak (at Gamow energy)is the realistic energy at which the nuclear reactions take place.



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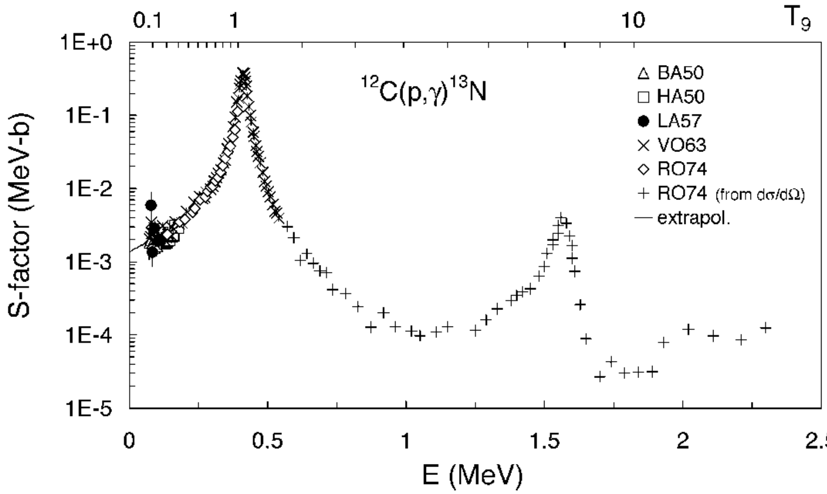
Resonant reaction

- Sometimes the reaction is dominated by resonant reactions.
- We only need to know resonance parameters (E, Γ, J^{π}) and apply the resonant reaction formula:



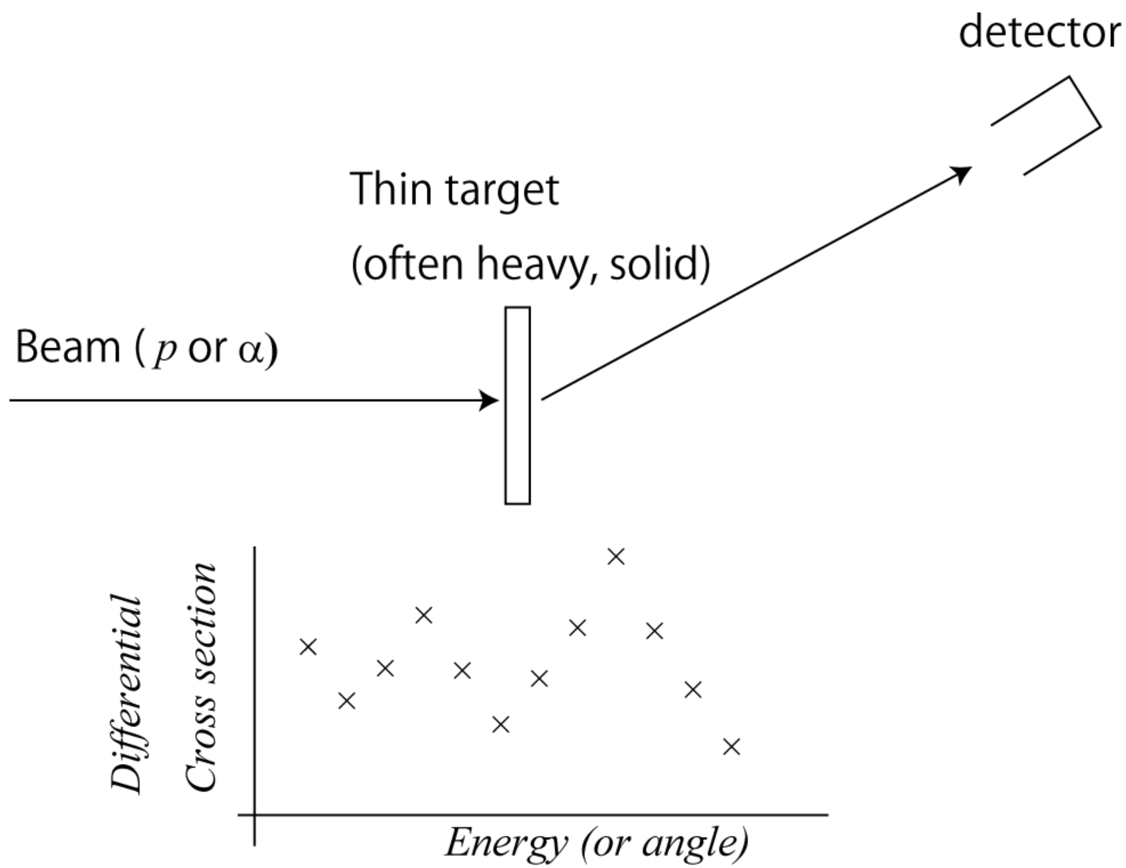
$$\sigma(E) = \pi \lambda\!\!\!^{-}{}^2 \frac{2J+1}{(2J_1+1)(2J_2+1)}(1+\delta_{12})\frac{\Gamma_a \Gamma_b}{(E-E_0)^2+(\Gamma/2)^2}$$

$$\sigma(E=E_0) \propto \frac{\Gamma_a \Gamma_b}{\Gamma^2}\text{(max.c.s.)}, \int_0^{\infty}\sigma(E)dE \propto \frac{\Gamma_a \Gamma_b}{\Gamma}\text{(integrated c.s.)}.$$

If $\Gamma_a \ll \Gamma_b$, the integrated c.s. $\propto \Gamma_a \Gamma_b/(\Gamma_a+\Gamma_b) \sim \Gamma_a$

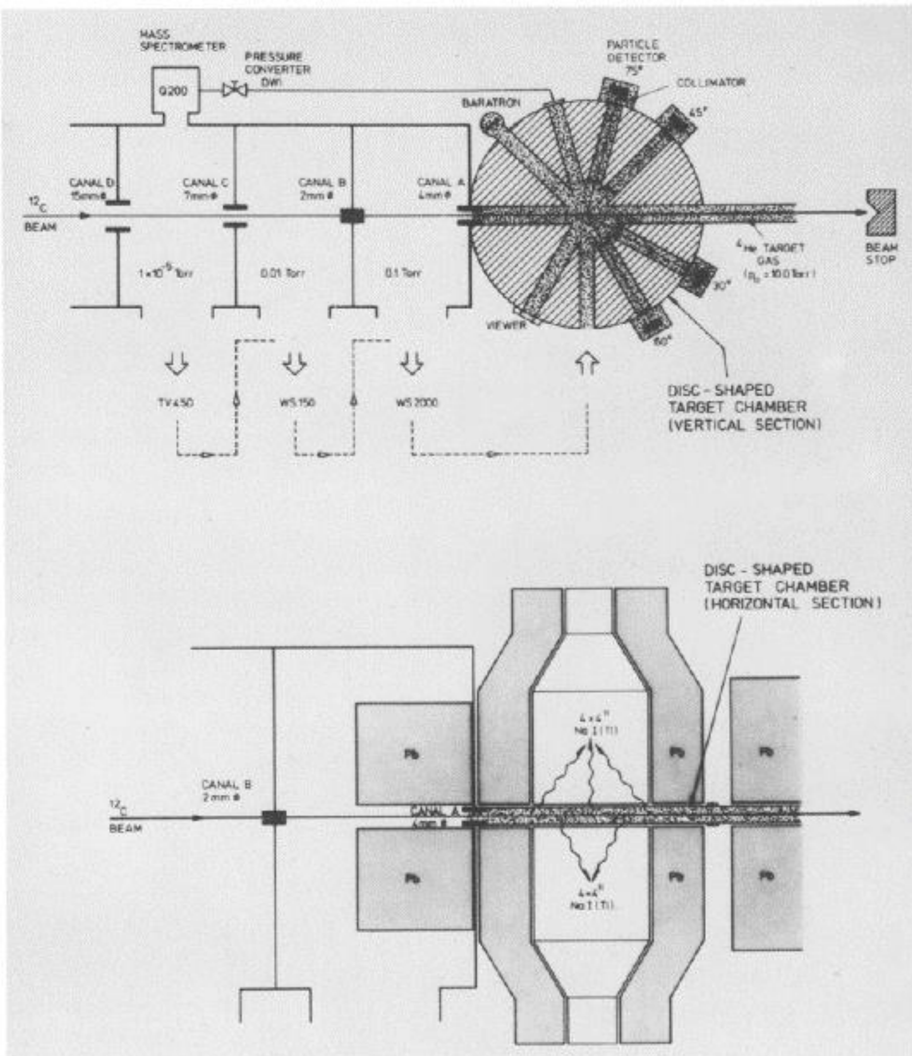
($\Gamma_\gamma \ll \Gamma_p$ for low-energy (p,γ) reactions.)

“Traditional” measurement



-Beam energy is changed for each data point
to measure excitation function

Example: $^{12}C(\alpha,\gamma)^{16}O$

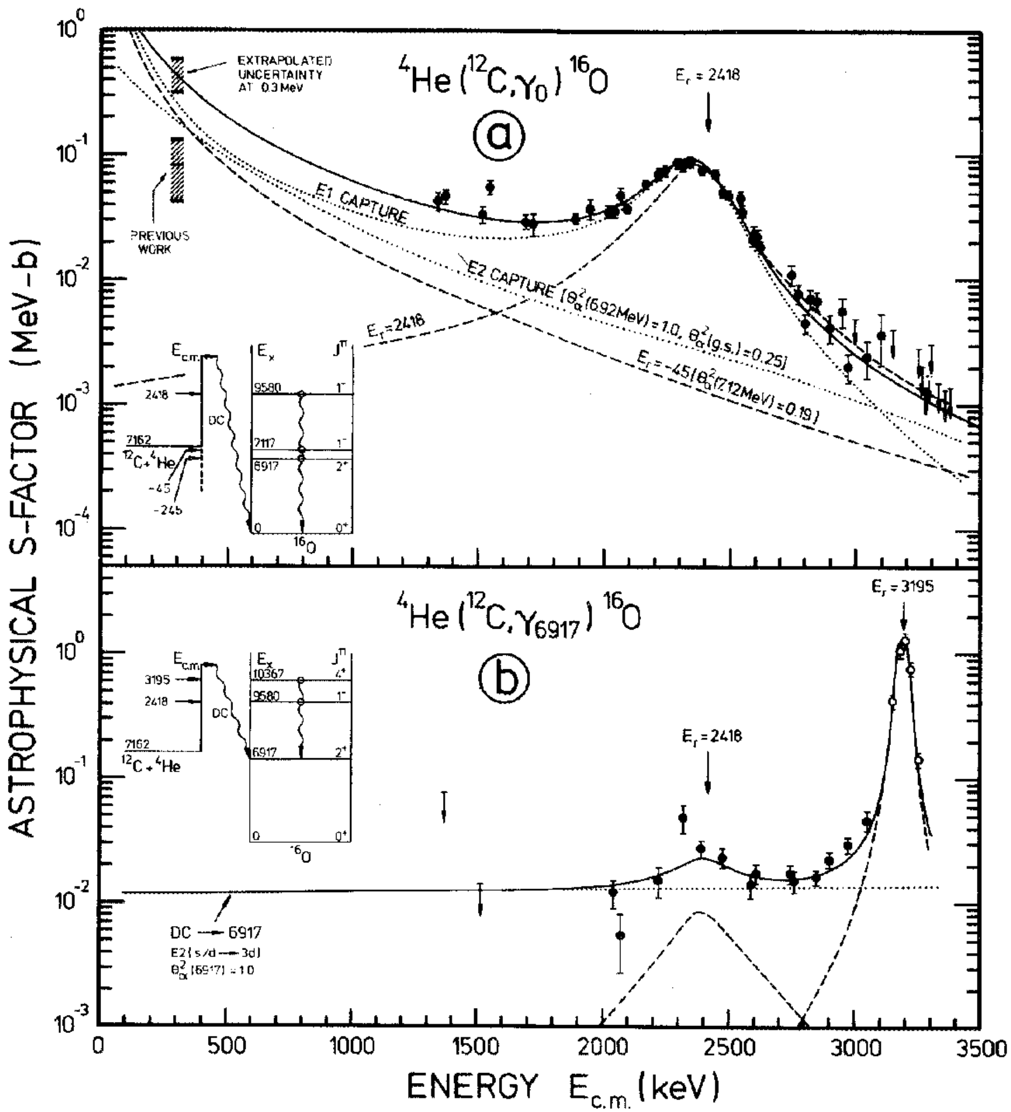


Kettner et al. (1986) @Bochum

- ^{12}C beam (50μA, down to 0.5 MeV)
- Windowless ^{4}He target, differential pumping, 10 Torr
- Si detectors to measure elastic scattering (beam intensity normalization)
- NaI detectors to measure γ-rays

Measuring ^{16}O is also possible, in principle (e.g. Kyushu Univ.), but very few and low-energy ^{16}O must be separated from the intense ^{12}C beam.

$^{12}C(\alpha,\gamma)^{16}O$

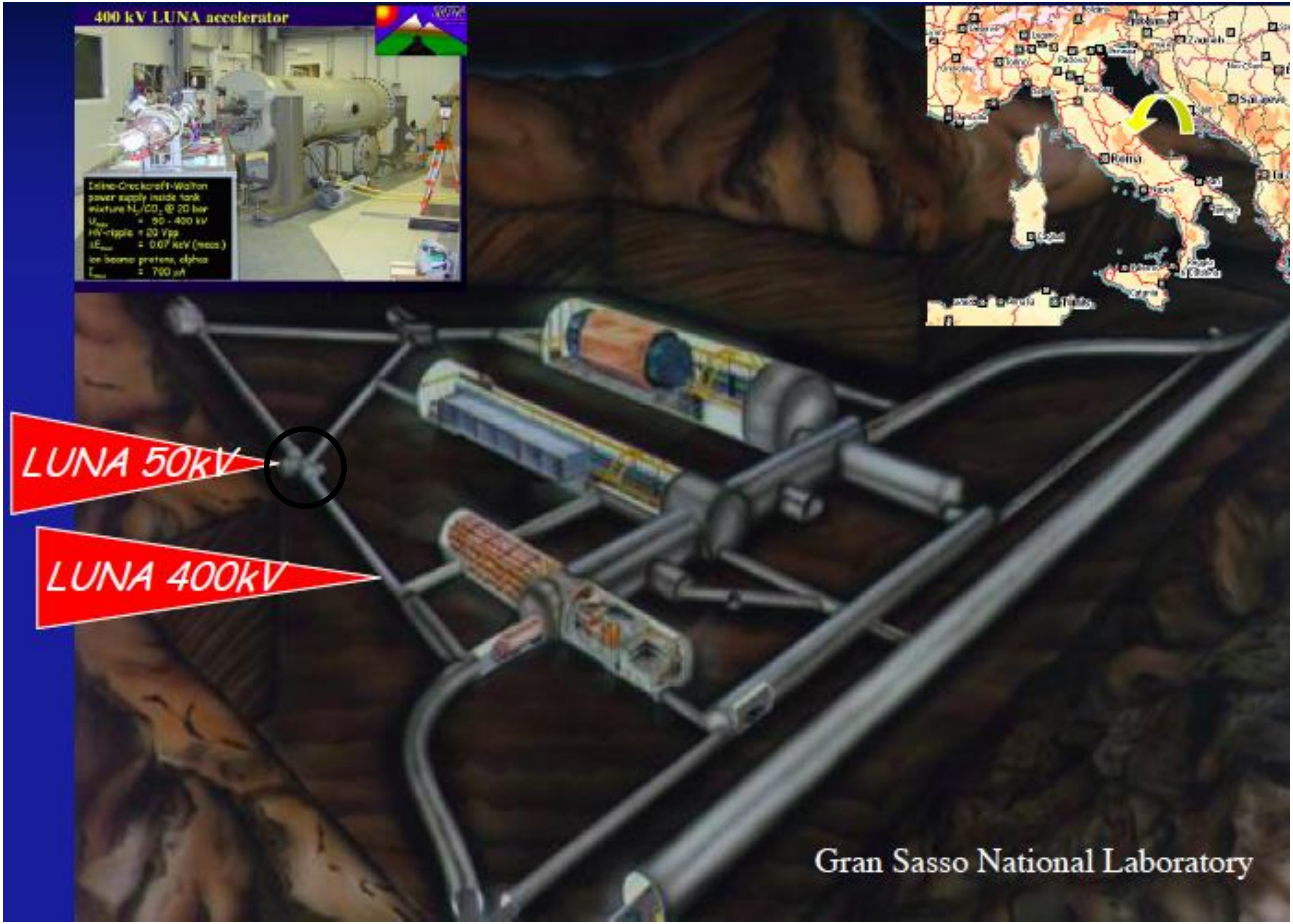


•Measurements have been performed at the energy close to E_{cm}=1MeV (σ～nb).

⇔

AGB star Gamow energy~300 keV

•Background from cosmic γ-rays… requires us a low-background environment.



400 kV LUNA accelerator
power supply inside tank
HV-ripple = 20 Vpp
LUNA 50kV
LUNA 400kV
Gran Sasso National Laboratory

Underground (p,γ) reaction measurement

$^{17}O(p,\gamma)$ by LUNA collaboration

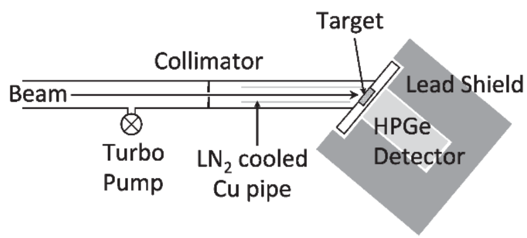
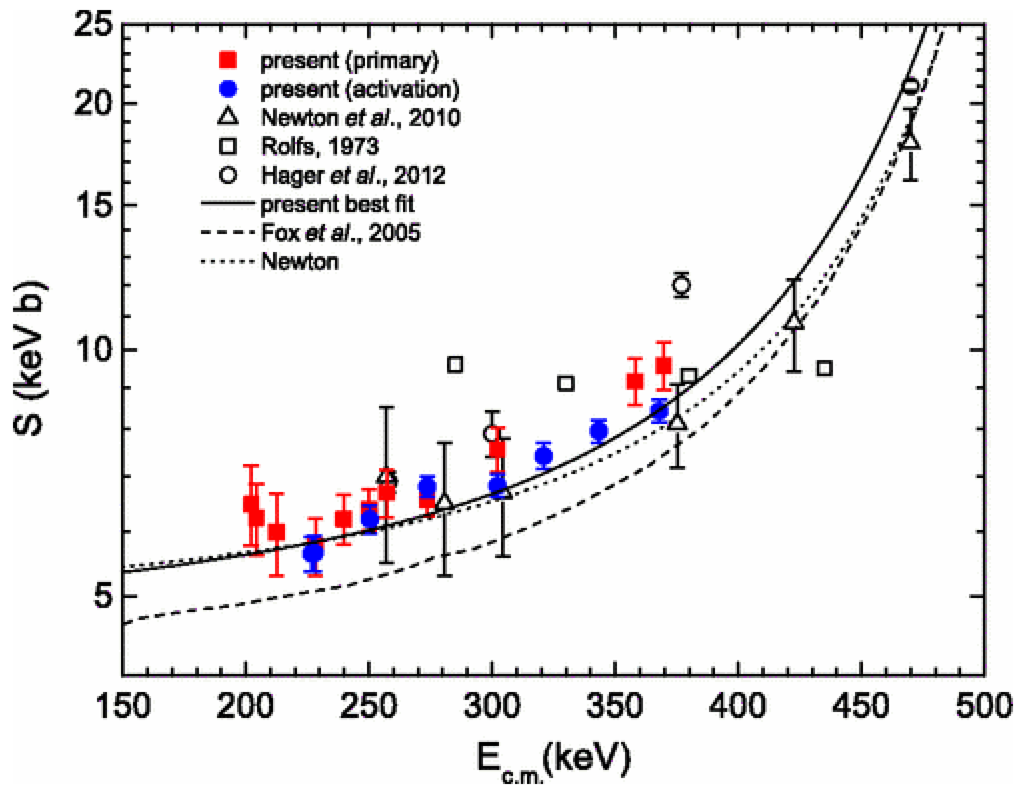


FIG. 2. Sketch of the experimental setup used for the prompt γ-ray detection, consisting of a HPGe detector placed in close geometry to the target, tilted at an angle of 55° with respect to the beam axis.



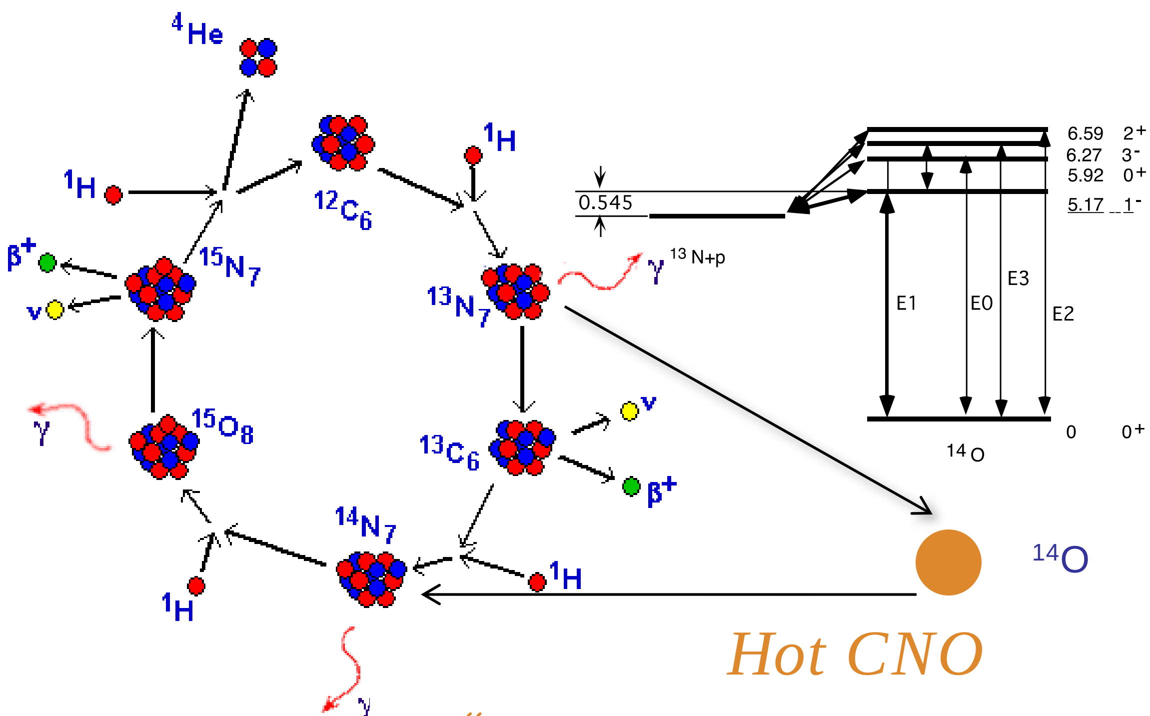
Beam: 200uA proton

Target: isotope-enriched Ta_2O_5

Underground background reduction: 1/2500

Astrophysical reactions involving RI

- Example: ^{13}N(p,γ)…Cold CNO cycle to Hot CNO cycle. $\tau_{1/2}(^{13}\mathrm{N})$=10 min, $\tau_{1/2}(^{14}\mathrm{O})$=1 min.



"Entrance" of explosive burning process

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Difficulty of RI-beam experiments

- **Beam intensity**

Astrophysical reactions often have small cross section.

Typical RI beam intensity…10^5 pps

Can be much more, or much less, depending on the RI.

Light ion beam intensity…$>10^{14}$ pps

1-hour beamtime for light ion…100,000 years for RI.

(Stars do not mind waiting for a long time, but we do.)

- **Limitation on available nuclides/energy**

High quality RI beams are not available for all nuclides.

Projectile fragmentation…covers a great variety of nuclides, but basically at high energy (not astrophysical energy).

A challenge for our intelligence.

But don’t worry too much

- RI in stars… often important in high temperature (explosive) phenomena. The reaction cross section is not too small in that case.

- What if the cross section is very small and it involves very rare isotopes?

The measurement would be extremely difficult, but that reaction should not be relevant for the universe.

Methods and typical energy for astrophysical reaction study

- Direct method…measure the reaction as it is [Gamow energy (keV-MeV)]
- Indirect methods
  - ◆ANC [peripheral reaction, <10 MeV/u]
  - ◆Coulomb Breakup [can be high, 10~100 MeV/u]
  - ◆Trojan Horse Method [motion of nucleon, ~5 MeV/u]
  - ◆Surrogate [10-50 MeV]
- Studying property of resonances
  - elastic scattering [excitation energy (~few MeV/u)]
  - transfer reaction [10-100 MeV/u]

Low energy: 1~10 MeV/u is suitable for the methods discussed in this lecture. CRIB(U-Tokyo) is a facility to provide such low energy RIB.

Methods of RI-beam production

- Offline separation (lifetime> days)

  Only available for long-lived RI (^{7}Be etc).

- Online methods

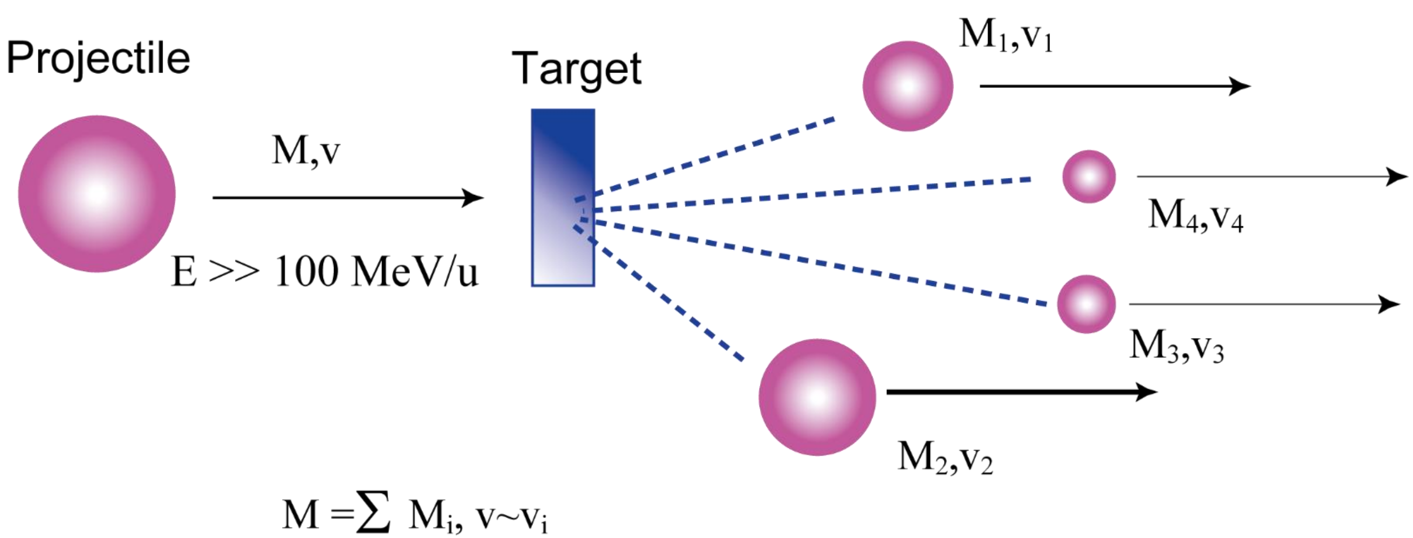
  ◆ISOL(isotope separator on-line) (lifetime >10ms)…low energy, good quality beam, suitable for astrophysics. (In spite of the limitation by the chemical property of ions and reacceleration.)

  ◆in-flight production/separation (lifetime >μs)

  - Fragmentation…high energy (>50 MeV/u)
  - direct reaction…main topic of this lecture
  - fusion/fission

Kinematics in Projectile fragmentation

- Fragmentation…the velocity of fragments is nearly equal to the projectile velocity.
  "persistence of velocity".
- Orientation peaked to the forward angle.
- Small momentum transfer between fragments.



Low-energy RIB with in-flight method

- The fragmentation is not possible at low energy machines (<<50 MeV/u).
- Direct nuclear reaction such as (p, n) reaction can be used as the RI-beam production mechanism.
  - Texas A&M MARS, U-Tokyo CRIB, IMP RIBLL1 INFN-LNL(Italy, Padova) EXOTIC, Florida RESOLUT

(p,n) reactions…reaching to 100mb/sr.

(^{3}He,n) reactions…order of 10mb/sr.

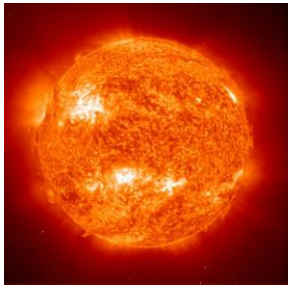
High energy fragmentation…μb~mb/sr (depending on how far from the stability line.)

Why low-energy RI beam?

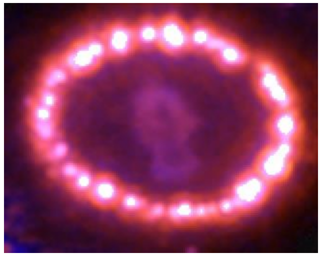
- Stellar astrophysical reactions :

  T ~ 10^6-10^9 K (typically keV to a few MeV).

  ⇒ Low energy is not bad energy! (Good for astrophysics and structure study.)



The Sun



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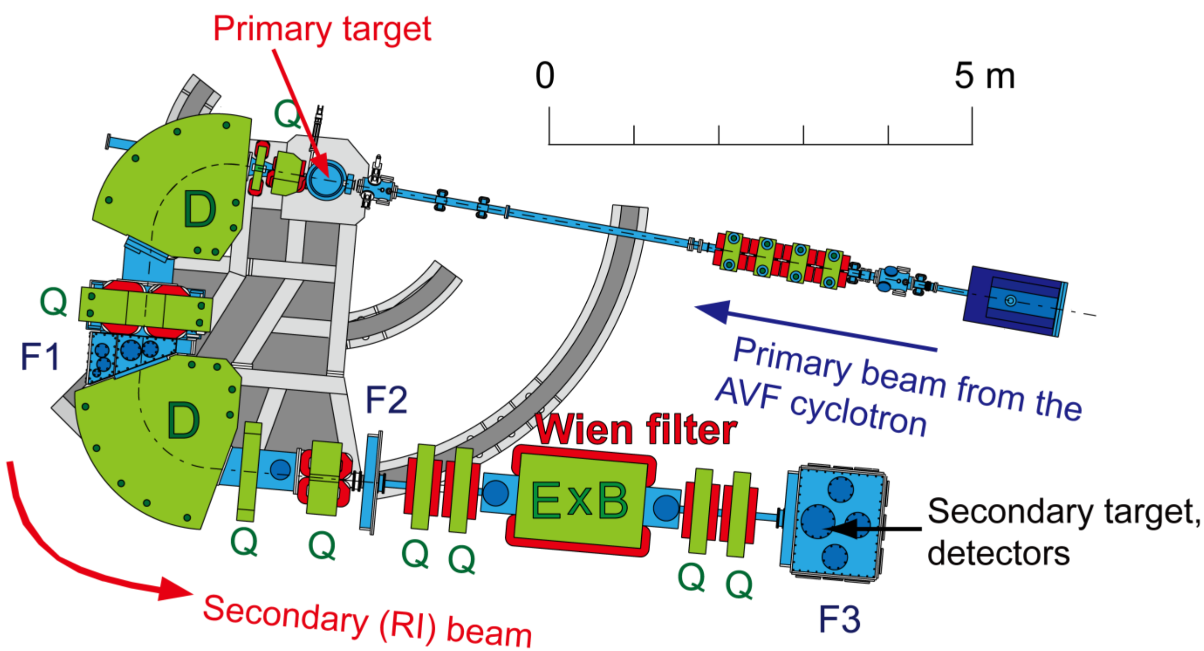
•Nucleosynthesis proceeds through unstable nuclei in some processes(pp chain, CNO cycle, r-, rp-, processes etc.)

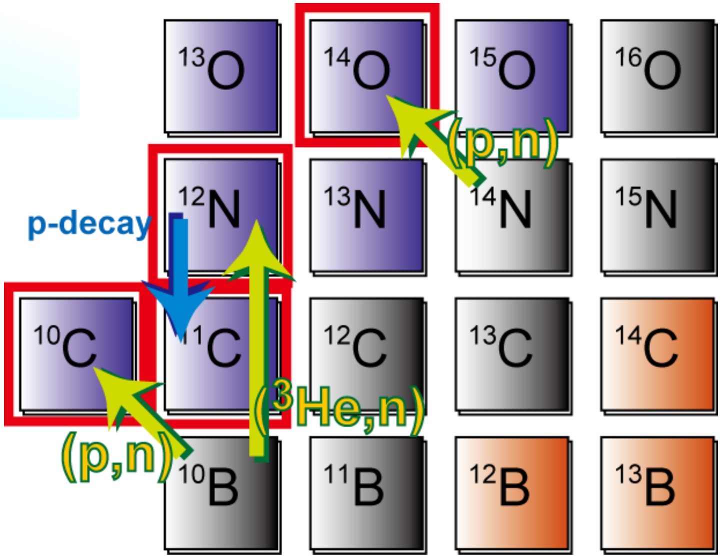
CRIB

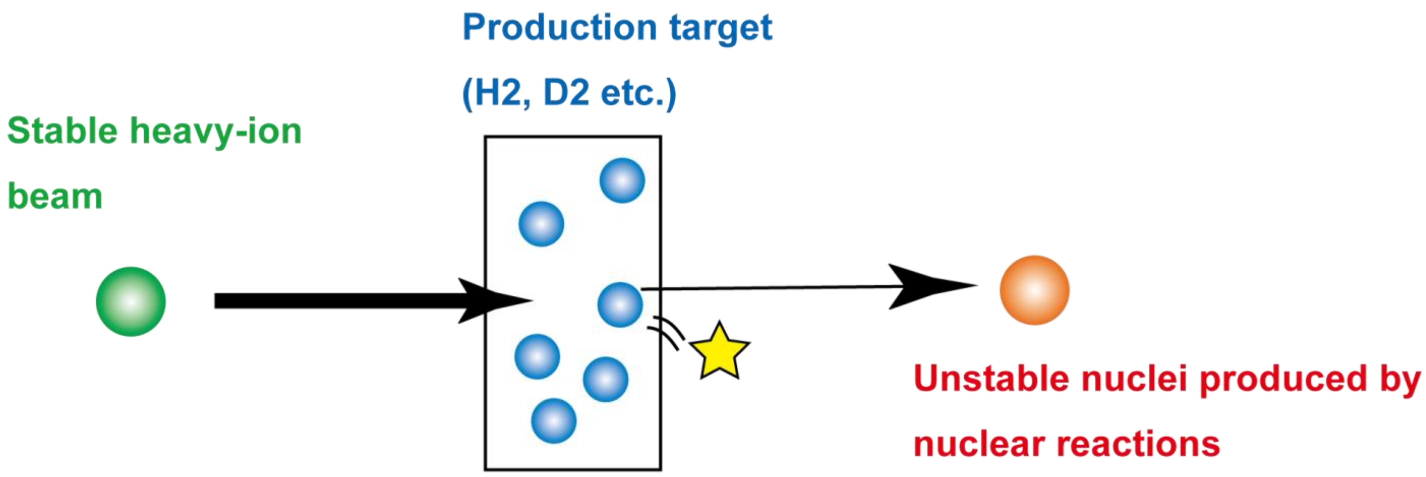
- CNS Radio-Isotope Beam separator , constructed and operated by CNS, Univ. of Tokyo, located at RIBF (RIKEN Nishina Center).
  - Low-energy(<10MeV/u) RI beams by in-flight method.
  - Primary beam from K=70 AVF cyclotron.
  - Momentum (Magnetic rigidity) separation by “double achromatic” system, and velocity separation by a Wien filter.
  - Orbit radius: 90 cm, solid angle: 5.6 msr, momentum resolution: 1/850.



In-flight low-energy RI beam Production

2-body reactions such as (p,n), (d,p) and (^{3}He,n) in inverse kinematics are mainly used for the production….large cross section (>10mb/sr)





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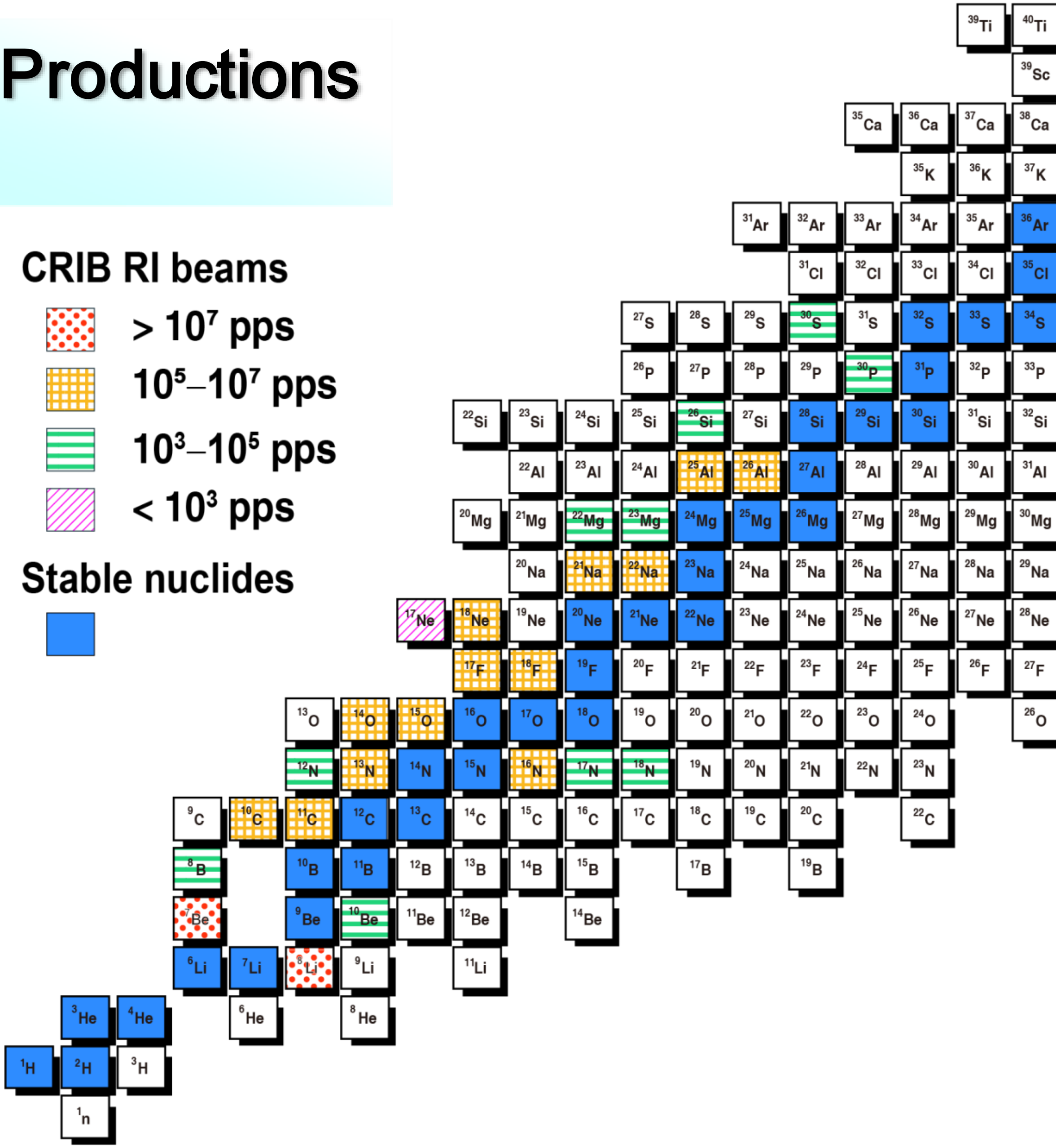
Low-Energy RI beam Productions at CRIB

Many RI beams have been produced at CRIB: typically 10^4-10^6 pps

Higher intensity for ^{7}Be beam with cryogenic H_2 target: 3 x 10^8 pps.



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Historical experiment: ^{13}N(p,γ)

VOLUME 67, NUMBER 7 PHYSICAL REVIEW LETTERS 12 AUGUST 1991

Determination of the ^{13}N(p,γ) ^{14}O Reaction Cross Section Using a ^{13}N Radioactive Ion Beam

P. Decrock,[2] Th. Delbar,[1] P. Duhamel,[3] W. Galster,[1] M. Huyse,[2] P. Leleux,[1] I. Licot,[1] E. Liénard,[1] P. Lipnik,[1] M. Loiselet,[1] C. Michotte,[1] G. Ryckewaert,[1] P. Van Duppen,[2] J. Vanhorenbeeck,[3] and J. Vervier[1]

[1]*Institut de Physique Nucléaire and Centre de Recherches du Cyclotron, Université Catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*

[2]*Instituut voor Kern- en Stralingsfysika, Katholieke Universiteit Leuven, B-3001 Leuven, Belgium*

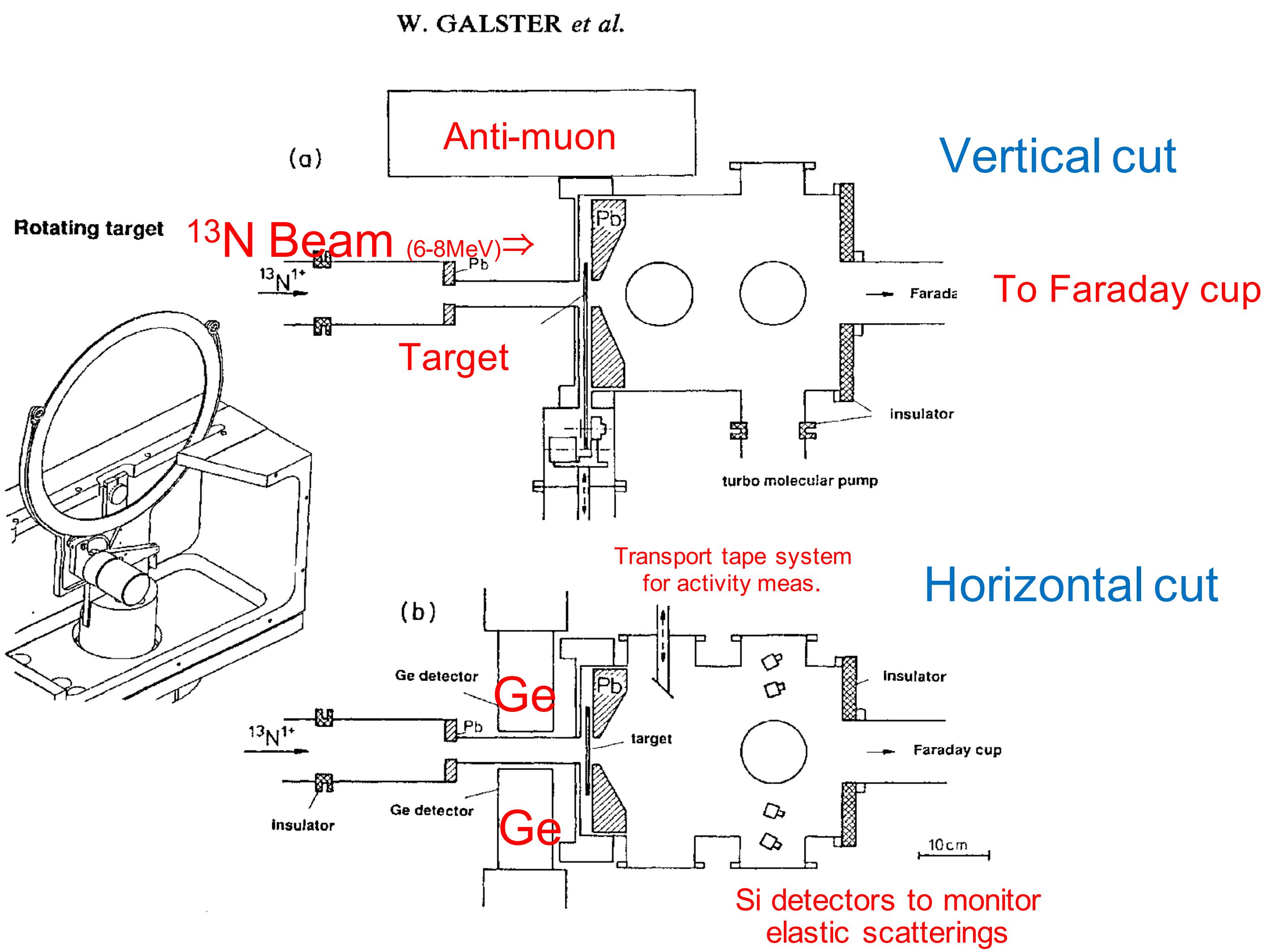
[3]*Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, B-1050 Bruxelles, Belgium*

(Received 2 May 1991)

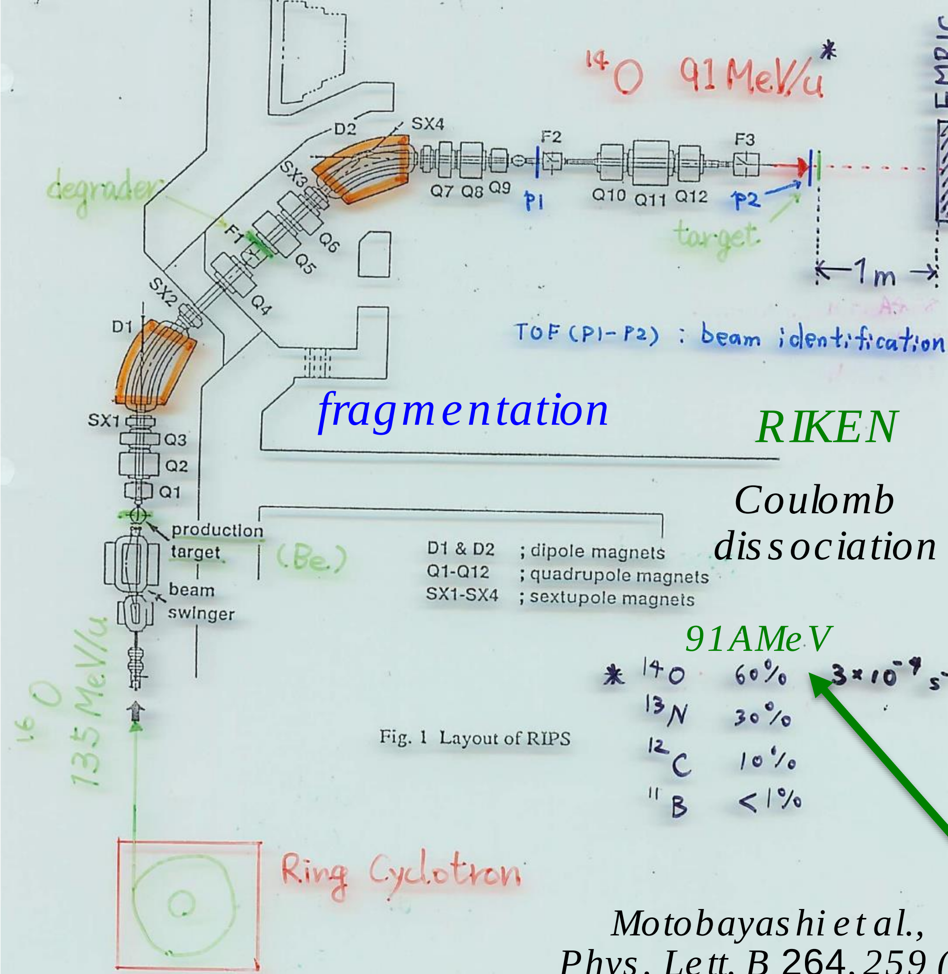
The cross section for the astrophysically important ^{13}N(p,γ)^{14}O reaction has been measured directly with an intense (3×10^8 particles/s) and pure (>99%) 8.2-MeV ^{13}N radioactive ion beam. The average value, for the 5.8–8.2-MeV ^{13}N energy range, is 106(30) μb. The partial γ width of the resonance which occurs in this reaction at a center-of-mass energy of 0.545 MeV has been deduced to be 3.8(1.2) eV. It is compared with theoretical predictions and indirect determinations.

- The first astrophysical reaction measurement with RI beam
- Direct measurement of ^{13}N(p,γ) around 0.545 MeV resonance in ^{14}O.

Setup [Galster et al., PRC 1991]



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



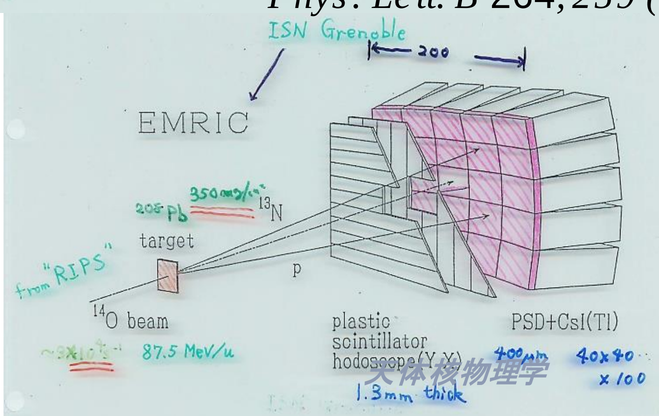
fragmentation

RIKEN

Coulomb dissociation

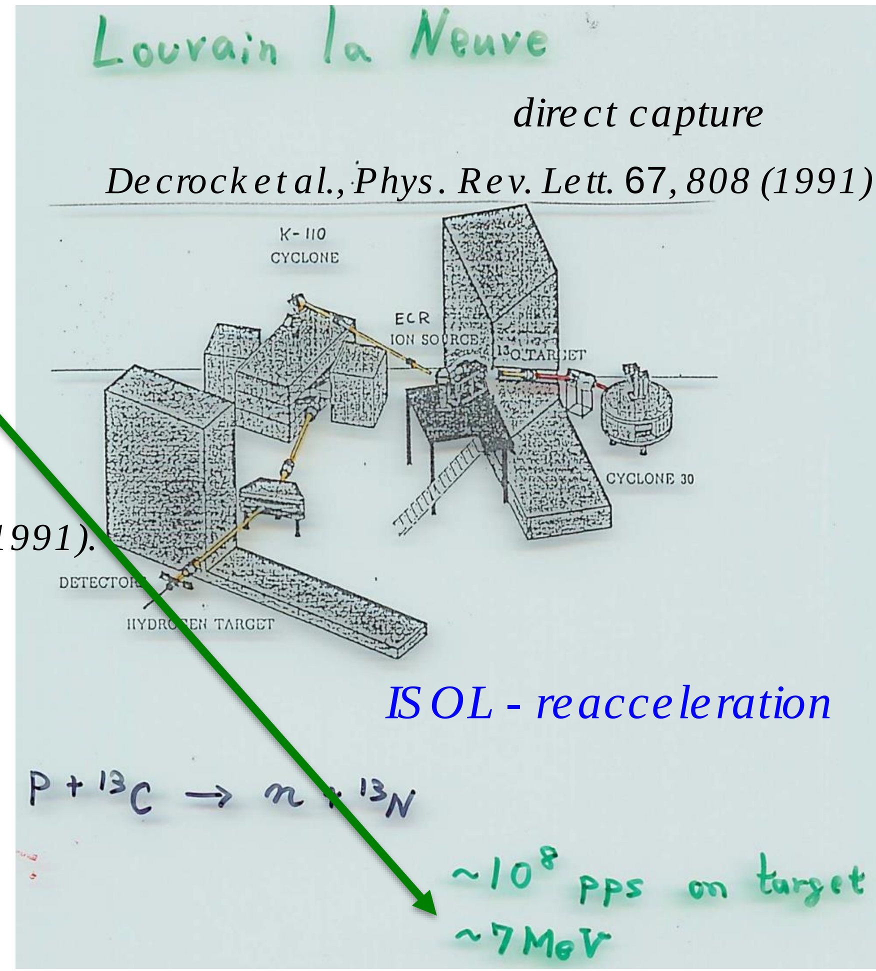
91AMeV

Motobayashi et al., Phys. Lett. B 264, *259 (1991).*



RIKEN
$^{14}O + Pb \rightarrow$
$^{13}N + p + Pb$

2018



direct capture

Decrock et al., Phys. Rev. Lett. 67, *808 (1991)*

ISOL - reacceleration

Coulomb dissociation v.s. direct capture

$^{13}N(p,\gamma)^{14}O$ (1^-)

	C.D. RIKEN ('91)	Direct Louvan ('91)	ratio
beam(s^{-1})	3×10^4	3×10^8	10^{-4}
σ	10 mb	100 μb	10^2
target	350 mg/cm^2	200 μg/cm^2	60
efficiency	0.5	2×10^{-3}	350
data taking	36 h	30 h	1.2
total counts	1.5×10^4	85	180

Results

Two new experiments were performed at the same period, but with different methods.

Γ_γ	Japanese (C.D.) present	Belgian (direct) (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

- Successful! … The two experiments (direct/indirect) yielded consistent Γ_γ values.

Summary of Lecture #1

- Nuclear physics experiment is essential for understanding stars and nucleosynthesis

- Difficulty…
  - ◆ Stable nuclei: too low cross section
  - ◆ Unstable nuclei: short lifetime of the nuclei

- RI beam production technique …enabled us to study stellar reactions in hot environment.

Lecture #2

- How to make RI beam experiments for astrophysical reactions?
- Thick target method in inverse kinematics
  - ◆Principle
  - ◆Application

Direct measurement of astrophysical (capture) reactions with unstable nuclei…

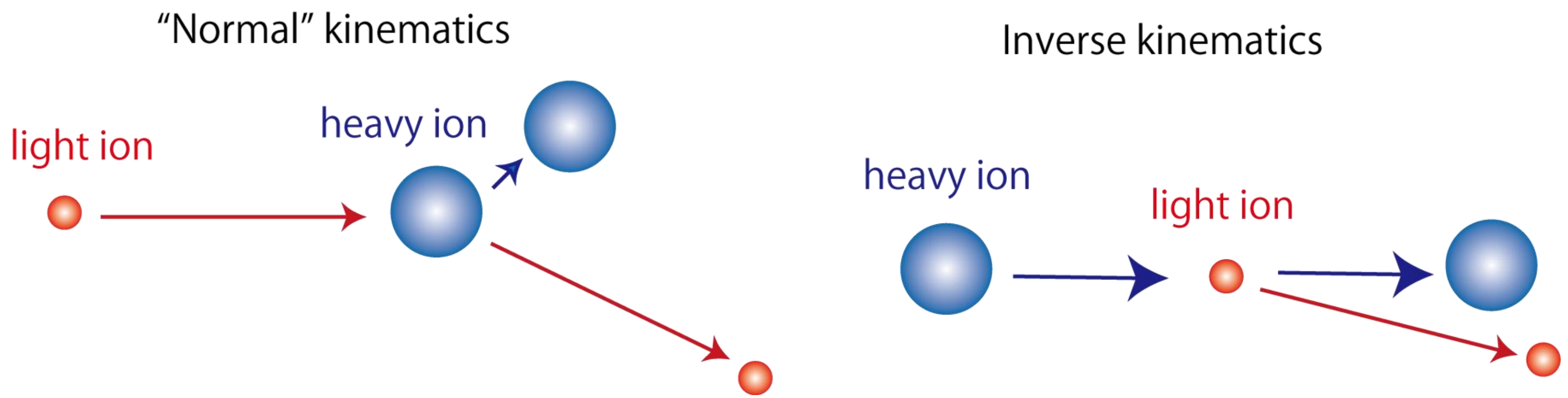
- Works for at least relatively intense RI beams, such as (^{13}N, ^{7}Be).

- But still not easy for others, such as ^{15}O(α, γ), because of the low RI beam intensity/reaction cross section.

Then, what can we do?

1. Use "indirect" methods (Coulomb dissociation, ANC, Trojan Horse Method, …)
2. Use TTIK (Thick target in inverse kinematics, I will discuss on this)
   - Direct measurement with a thicker target ⇒More efficient measurement.
   - Resonant scattering⇒High cross section (~100 mb/sr), to study resonances.

Inverse kinematics



Features of (ideal) inverse kinematics:

Heavy ion as the beam…keep going forward.

Light ion as the target…tend to be scattered to forward angle (compared to the normal kinematics).

1. Inverse kinematics at RI-beam production…The produced RI is already like a beam (cf. ISOL).

2. Inverse kinematics at scattering/reaction measurement…discussed later.

The method…TTIK

- W.W. Daenick and R. Sherr (1963) “thick target method” $^{12}C(p,p)$.
- K.P. Artemov et al., (1990)

Thick-Target with Inverse Kinematics

^{12}C beam into thick helium (α) target

Effective method of study of α-cluster states

K. P. Artemov, O. P. Belyanin, A. L. Vetoshkin, R. Wolskj, M. S. Golovkov, V. Z. Gol’dberg, M. Madeja, V. V. Pankratov, I. N. Serikov, V. A. Timofeev, V. N. Shadrin, and J. Szmider

I. V. Kurchatov Institute of Atomic Energy

(Submitted 15 February 1990)
Yad. Fiz. **52**, 634–639 (September 1990)

For study of states with a large reduced α width the method of measurement of the excitation function of elastic scattering of α particles is proposed, but in a geometry which is the reverse of the traditional experimental arrangement. The targets are helium gas which is simultaneously a moderator for the primary beam of heavy ions and an absorber which shields the detector from the direct beam. The advantages of the method are obvious in those cases in which in the usual experimental arrangement the need arises of using gas targets or targets of rare isotopes or of measurements at an angle 180°. To check the method we have carried out a comparison with the known $\alpha + {}^{12}C$ interaction. New results are obtained in the interaction $^{15}N + \alpha$.

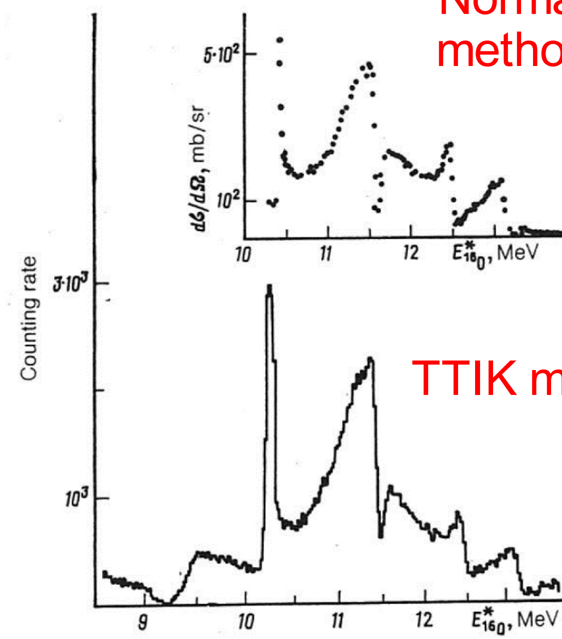
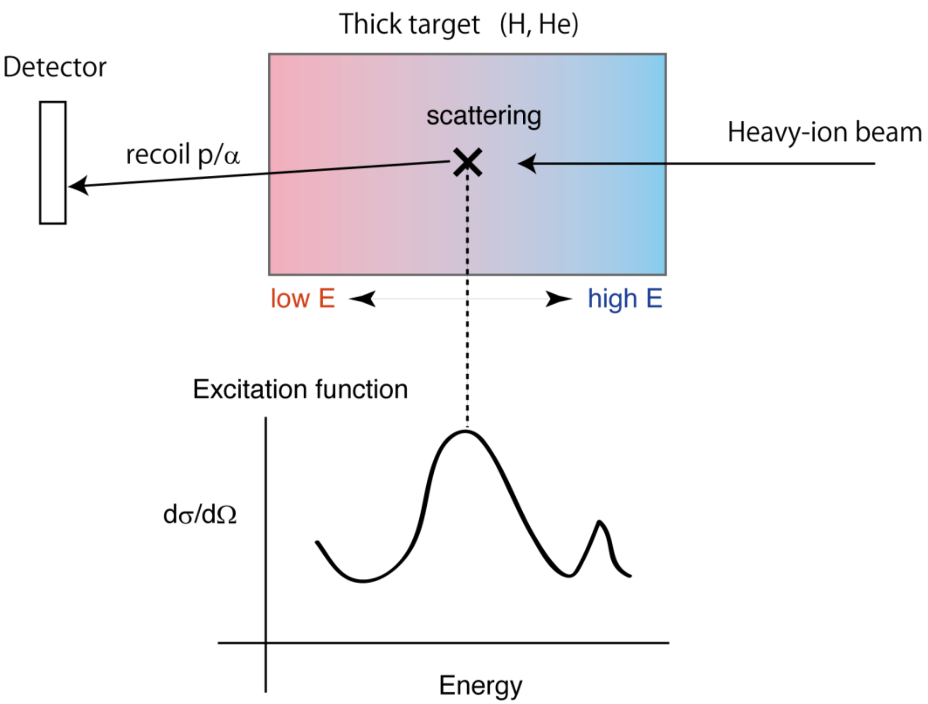


FIG. 1. Spectrum of α particles obtained in interaction of ^{12}C ions with initial energy 28 MeV with helium. The detection angle is 0°. In the insert we have given the excitation function for elastic scattering of α particles by carbon from Ref. 4. The detection angle is 158.8°.

The thick-target method in inverse kinematics

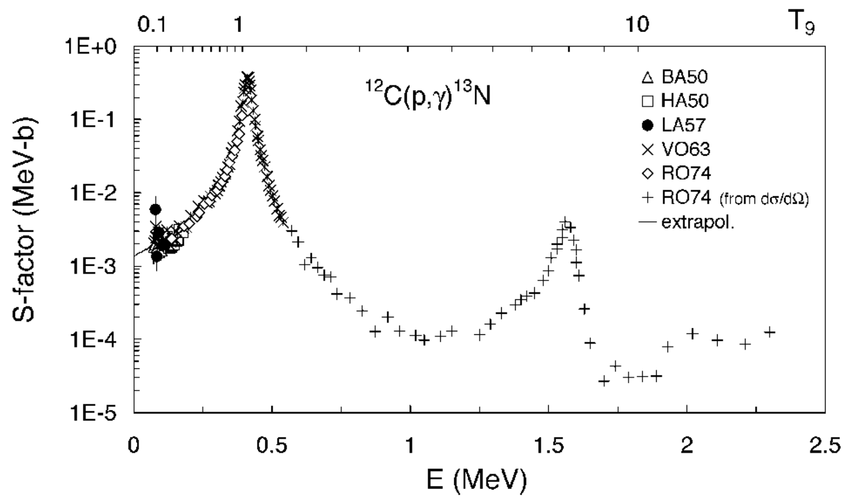
Measurement of resonance scattering



- Measurement is possible for short-lived RI which cannot be used as the target.
- $E_{cm}=E_{beam} * A_t/(A_p+A_t) \ll E_{beam}$ Measurement can be at low energy with high resolution.
- Simultaneous measurement for a certain energy range.(No need to change beam energy.)
- The beam can be stopped in the target…measurement at $\theta_{cm}=180^o$ is possible.

Resonant reaction

- Sometimes the reaction is dominated by resonant reactions.
- We only need to know resonance parameters (E, Γ, J^{π}) and apply the resonant reaction formula:



$$\sigma(E) = \pi \lambda\!\!\!^{-2} \frac{2J+1}{(2J_1+1)(2J_2+1)}(1+\delta_{12})\frac{\Gamma_a \Gamma_b}{(E-E_0)^2+(\Gamma/2)^2}$$

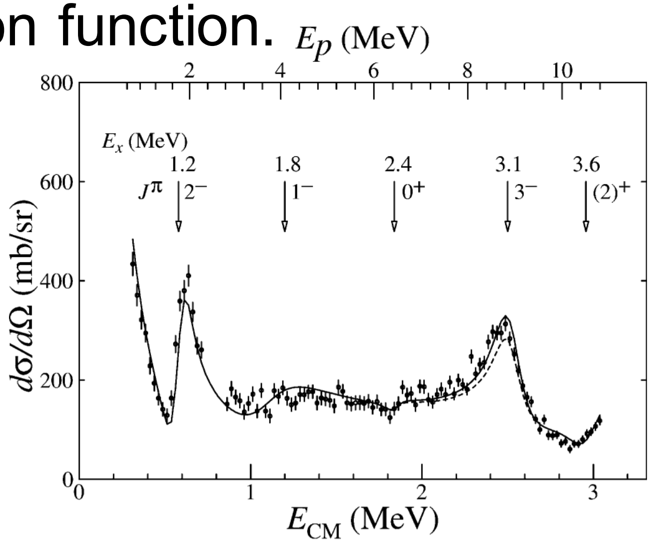
$$\sigma(E=E_0) \propto \frac{\Gamma_a \Gamma_b}{\Gamma^2} \text{(max.c.s.)}, \ \int_0^{\infty} \sigma(E)dE \propto \frac{\Gamma_a \Gamma_b}{\Gamma} \text{(integrated c.s.)}.$$

If $\Gamma_a << \Gamma_b$, the integrated c.s. $\propto \Gamma_a \Gamma_b/(\Gamma_a + \Gamma_b) \sim \Gamma_a$

($\Gamma_\gamma << \Gamma_p$ for low-energy (p,γ) reactions.)

Resonant elastic scattering

- Elastic scattering
  - At energies far below Coulomb barrier…Simply Rutherford scattering. Cross section is higher at low energies and angles.
  - At higher energies… interference of Coulomb and nuclear potential … "resonances" can be observed in the excitation function.



T. Teranishi et al. / Physics Letters B 556 (2003) 27–32

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Breit-Wigner formula

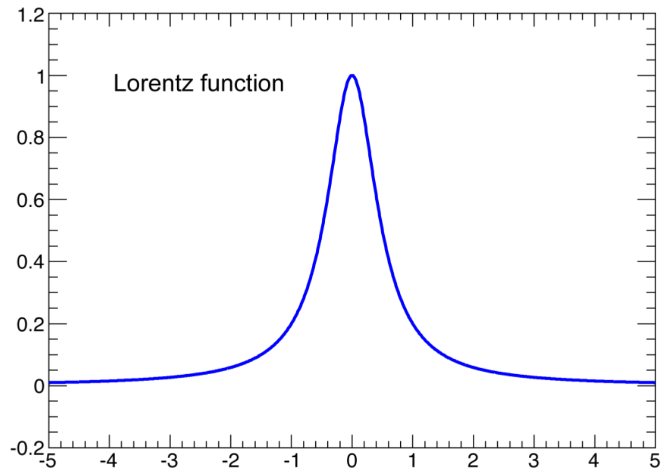
- Atomic Breit-Wigner:

  Lorentz function

$$I(E) \propto \frac{1}{(E-E_0)^2 + (\Gamma/2)^2}$$

E_0 : transition energy

Γ : natural width ($2\pi\Gamma = \tau^{-1}$)



- Breit-Wigner for nuclear resonant reaction:

$$\sigma(E) = \pi ƛ^2 \frac{2J+1}{(2J_1+1)(2J_2+1)}(1+\delta_{12})\frac{\Gamma_a \Gamma_b}{(E-E_0)^2 + (\Gamma/2)^2}$$

$ƛ$: de Broglie wavelength

J_1, J_2, J : spins of projectile, target, excited state in the compound nucleus

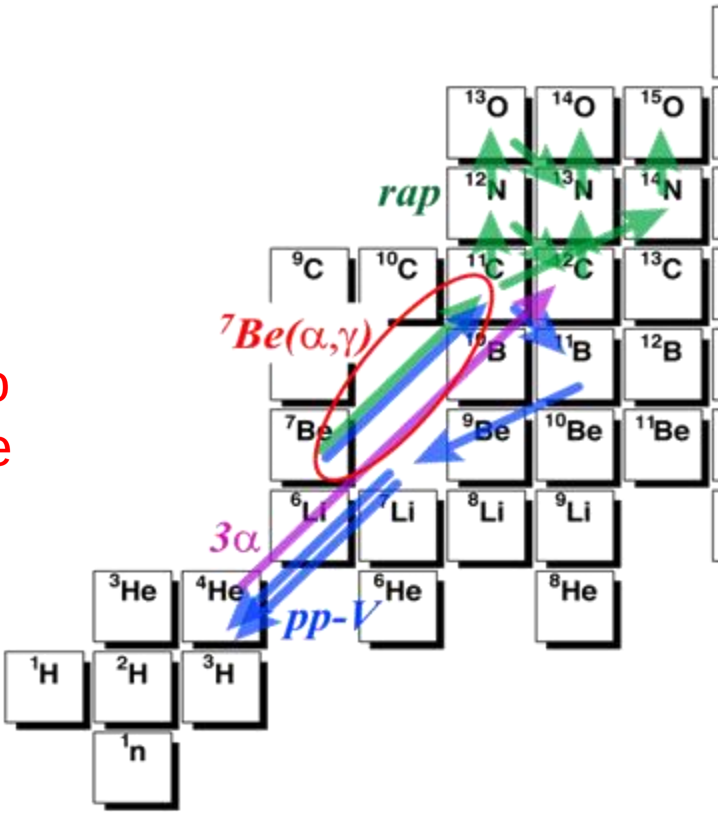
δ_{12} : 1 for identical particles, 0 otherwise

Γ_a, Γ_b : Widths of entrance and exit channels

^{7}Li+α/ ^{7}Be+α study

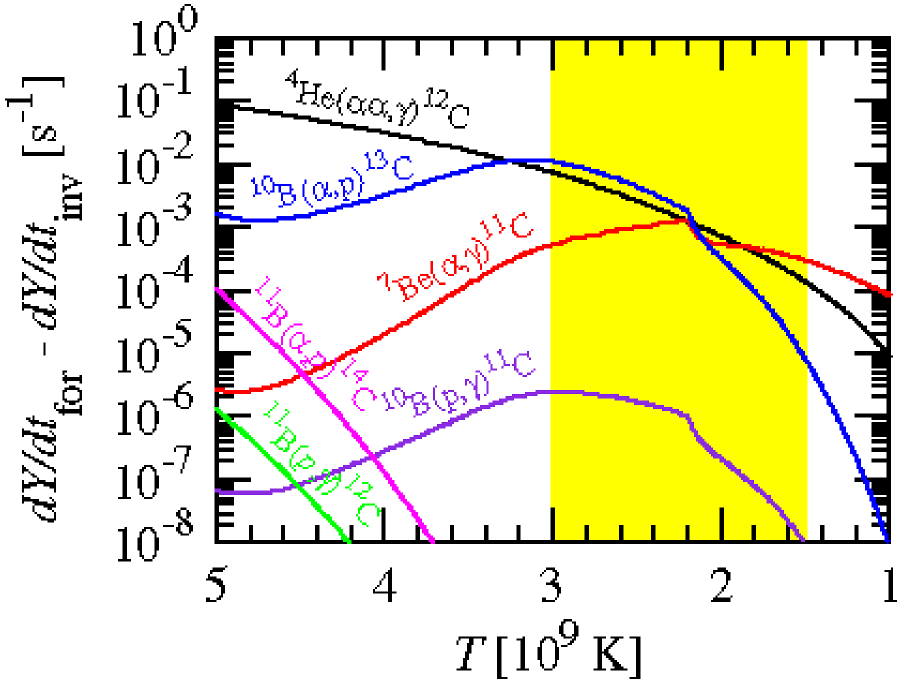
- ^{7}Li(α,γ)^{11}B …important at high-T, as a production reaction of ^{11}B (the ν-process in core-collapse supernovae).
- ^{7}Be(α,γ)^{11}B … one of the reaction in hot *p-p* chain, relevant at high-T.

- α-cluster structure in ^{11}B/^{11}C :
  - 2α+*t* / 2α+^{3}He cluster states are known to exist (similar to the dilute cluster structure in ^{12}C.)
  - Several "bands" which have α-cluster structure could be formed. We can study the band and cluster structure more in detail.



^{7}Be(α,γ) in supernovae

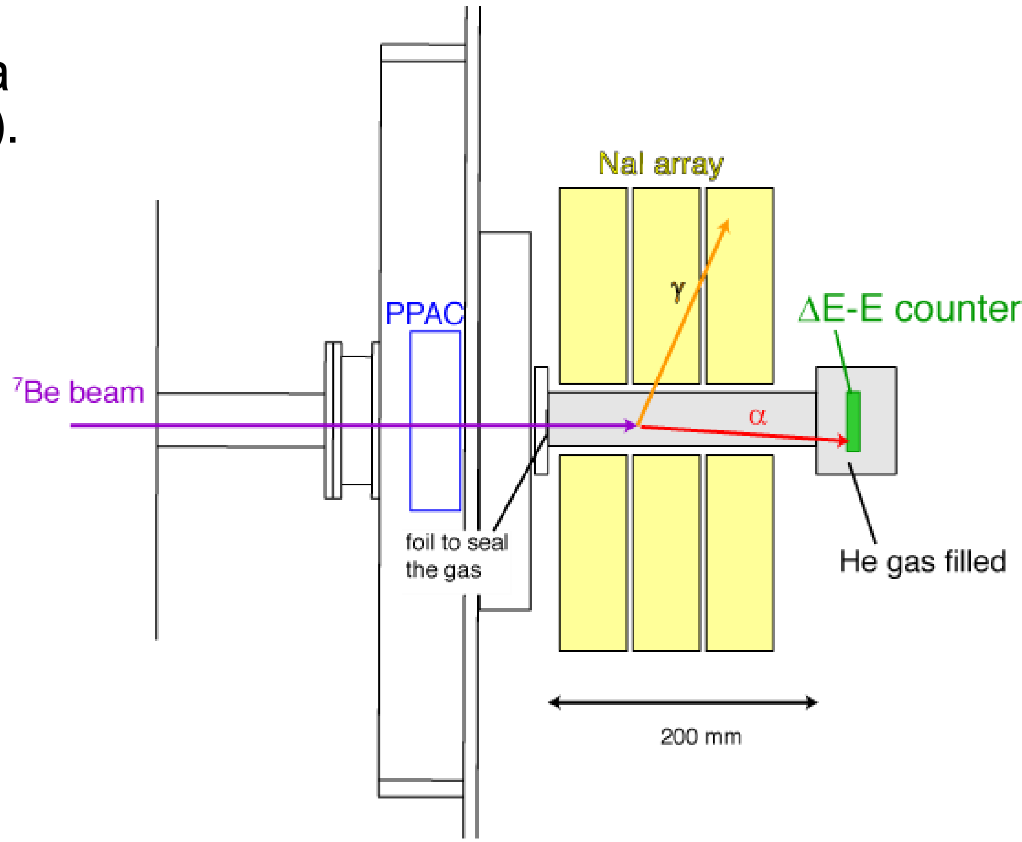
νp-process calculation ($T_9>1$) shows considerable contribution by ^{10}B(α,p)^{13}C and ^{7}Be(α,γ)^{11}C as much as the triple-alpha process.



S. Wanajo et al., Astrophys. J (2010)

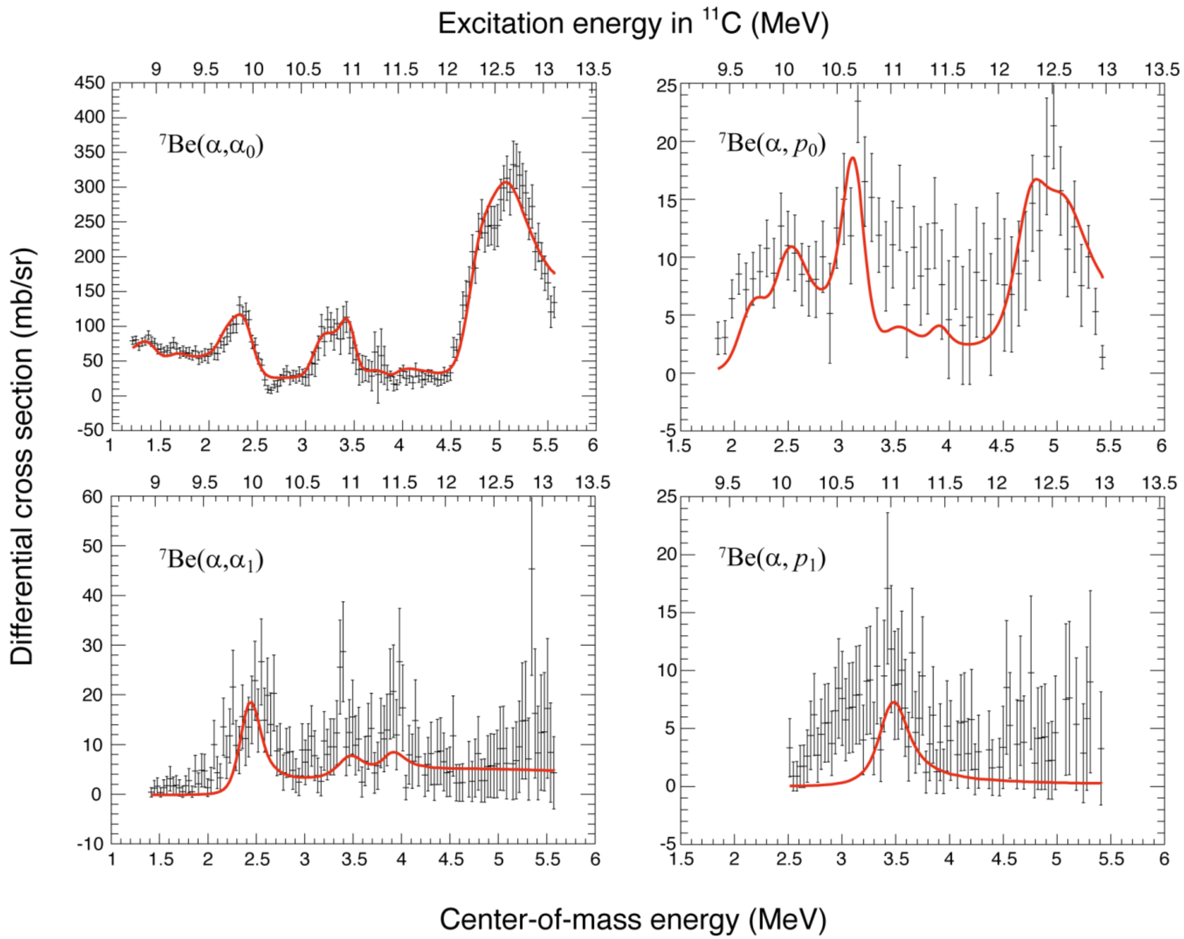
Setup for ^{7}Li/^{7}Be+α

- Thick target method with inverse kinematics …An efficient method to measure excitation function.
  - ^{7}Be beam is monitored by a PPAC (or an MCP detector).
  - ^{7}Be beam stops in a **thick helium gas target** (200 mm-long, 1.6 atm).
  - Recoiled α particles are detected by ΔE-E counter (10 μm and 500 μm Si detectors) at forward angle.
  - NaI array for γ-ray measurement (to identify inelastic events).



$^{7}Be+\alpha$ Excitation functions

- 4 excitation functions… new information on resonant widths, spin, and parity. *H. Yamaguchi et al., PRC (2013).*



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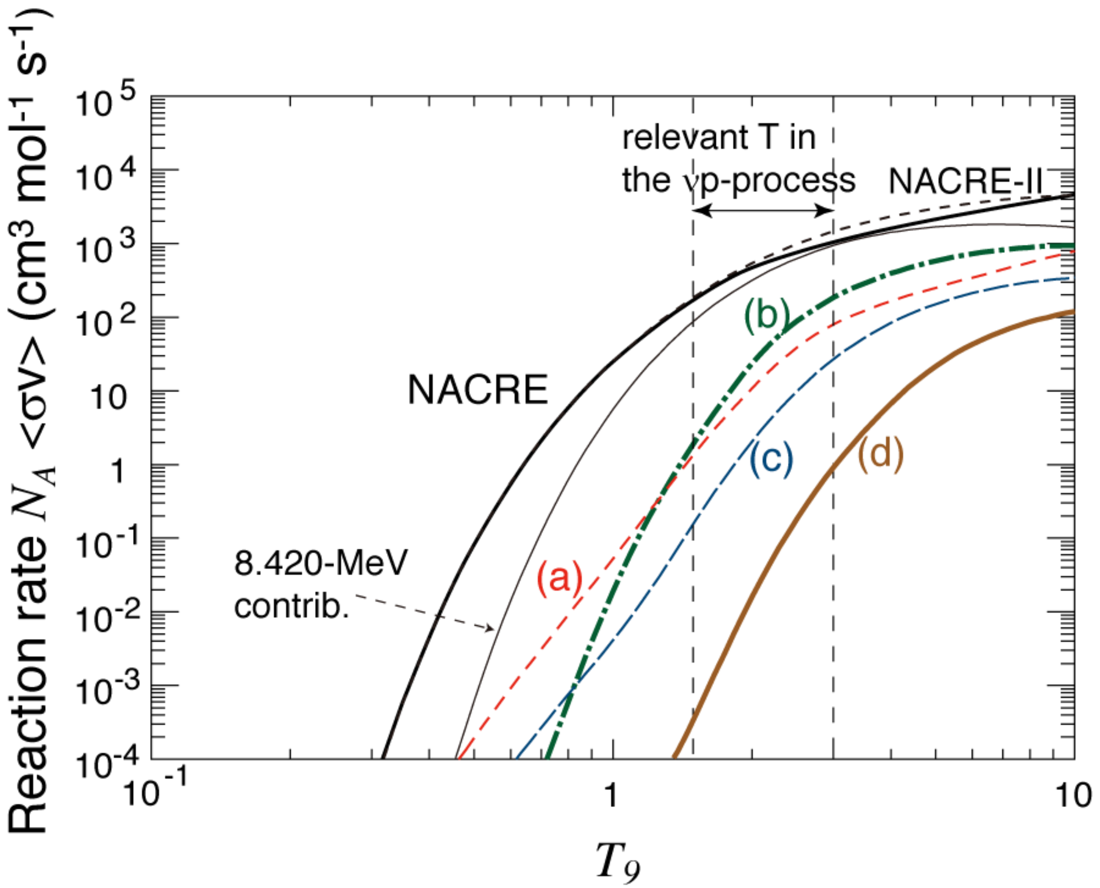
Resonant contribution to $^{7}Be(\alpha,\gamma)$

- Small but not negligible contribution compared to lower-lying states (~10%).



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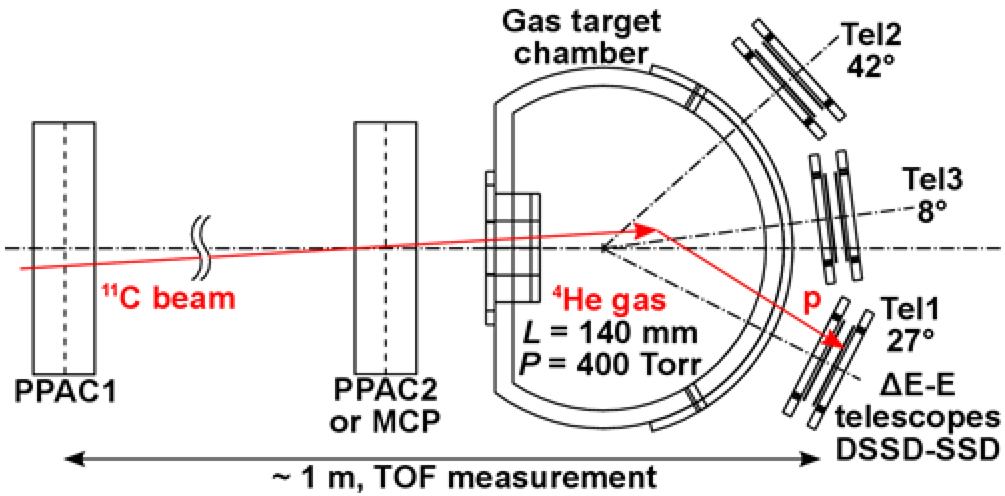
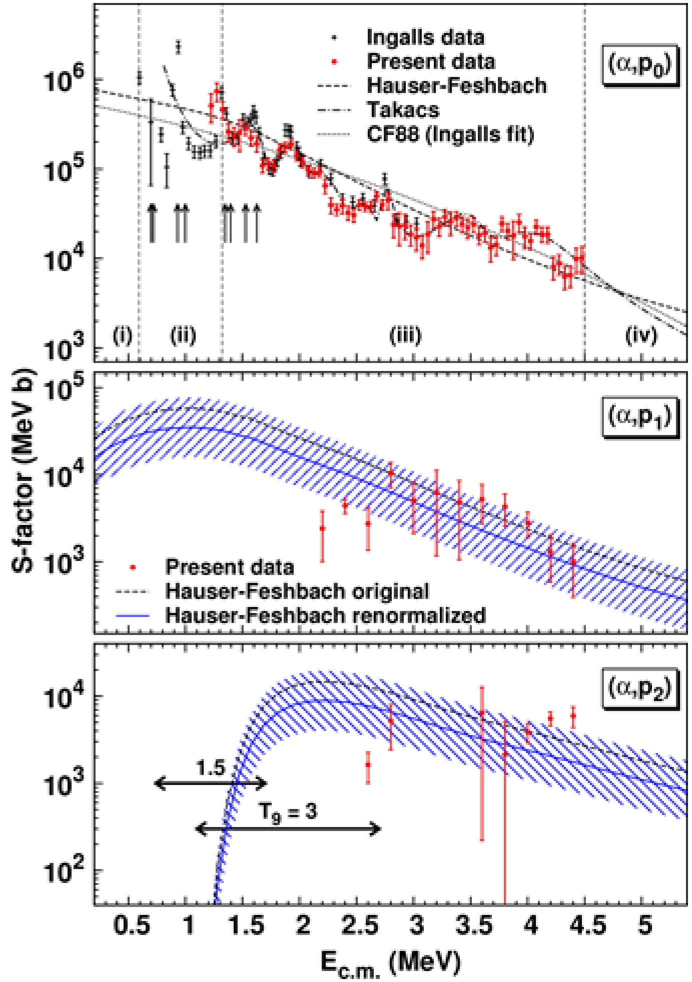
Direct measurement of (α, p) reactions

- $^{11}C(\alpha,p)^{14}N$@CRIB [S. Hayakawa et al., PRC **93**, 065802, (2016)]

An important alpha-induced reaction as a bypass of the 3α process in explosive hydrogen-burning processes.

Reactions to excited levels identified by TOF information





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Limitation of the TTIK for astrophysical reaction studies

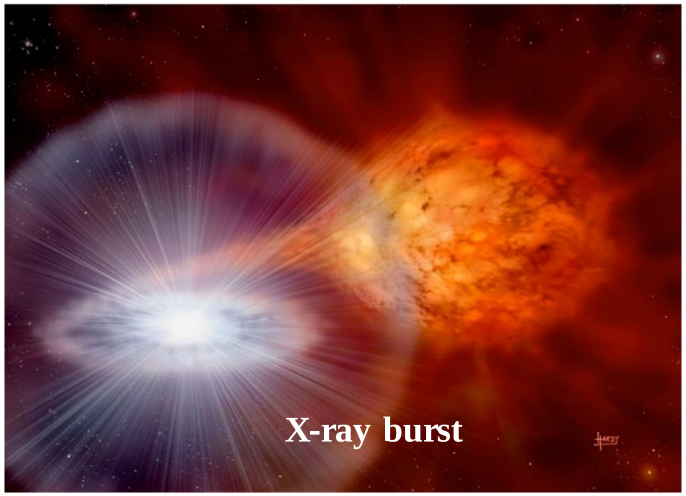
- Resonant scattering: Very striking experimental method available even with kHz-order RI beams (thanks to the large cross section) and suitable for resonance search, however,…
  - ◆ We cannot access the low energy close to the threshold where the Coulomb scattering dominates.
  - ◆ Γ_α or Γ_p can be determined (if they are large), but we need another partial width (such as Γ_γ) to determine reaction cross section.
- Direct reaction:
  - ◆ Still the yield may not sufficient for capture reactions at low-T, but we can study (α, p) reactions at explosive stellar environments, for example.
- As a common problem, the reaction/scattering channel we observe must be the dominant one. (i.e. we may have backgrounds by reactions producing the same particle, such as inelastic scattering, break up reaction, and fusion evapolation)…this problem can be solved with an active target.

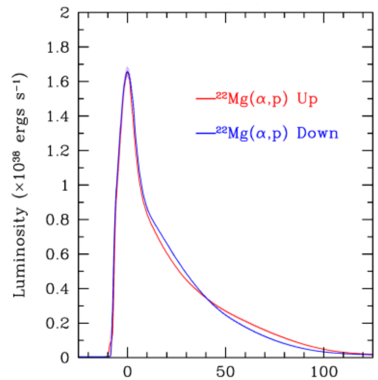
Measurement of ^{25}Al+p elastic scattering relevant to the ^{22}Mg(α,p)^{25}Al reaction

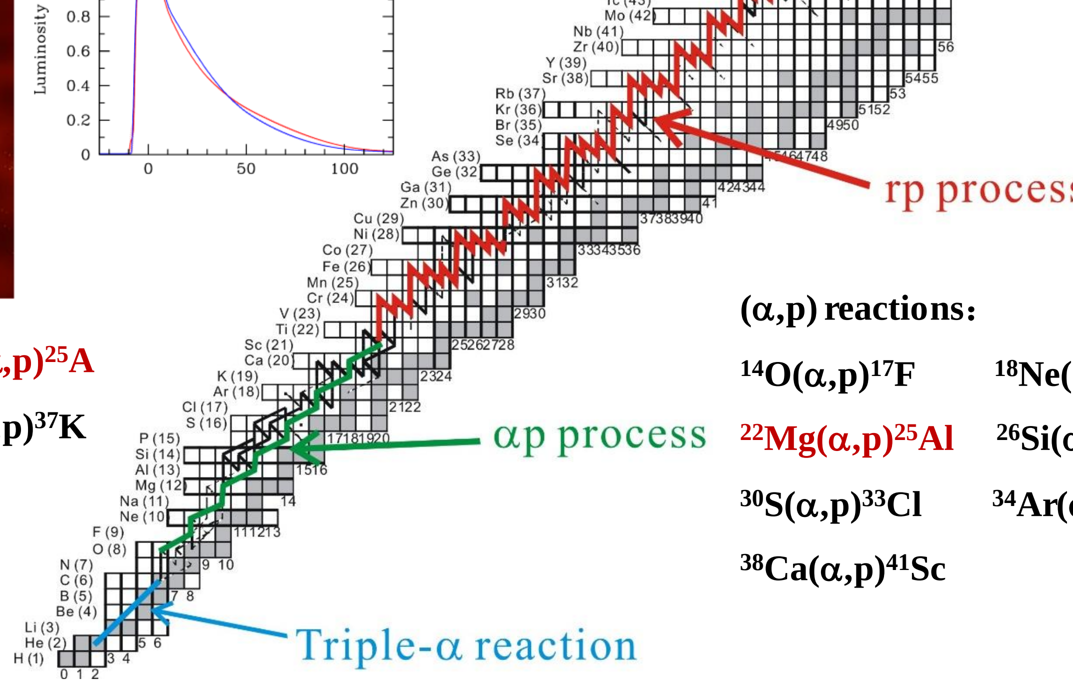
Jun Hu, X.D. Tang, S.W. Xu, L.Y. Zhang, S.B Ma, N.T. Zhang, J.J. He, H. Yamaguchi. K. Abe, S. Hayakawa, L. Yang, H. Shimizu, D. Kahl, T. Teranishi, J. Su. H.W. Wang, B. Guo et al.,

Institute of Modern Physics, Chinese Academy of Sciences,
CNS. The University of Tokyo,
National Astronomical Observatories,
The University of Edinburah.
CIAE, SINAP

1.1 αp-process in Type I X-ray bursts







^{14}**O(α,p)**^{17}**F**(p,γ)^{18}**Ne(α,p)**^{21}**Na**(p,γ)^{22}**Mg(α,p)**^{25}**Al**(p,γ)^{26}**Si(α,p)**^{29}**P**(p,γ)^{30}**S(α,p)**^{33}**Cl**(p,γ)^{34}**Ar(α,p)**^{37}**K**(p, γ)^{38}**Ca(α,p)**^{41}**Sc**

(α,p) reactions:

^{14}**O(α,p)**^{17}**F** ^{18}**Ne(α,p)**^{21}**Na**

^{22}**Mg(α,p)**^{25}**Al** ^{26}**Si(α,p)** ^{29}**P**

^{30}**S(α,p)**^{33}**Cl** ^{34}**Ar(α,p)**^{37}**K**

^{38}**Ca(α,p)**^{41}**Sc**

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1.2 Sensitivity study to the light curve of X-ray burst

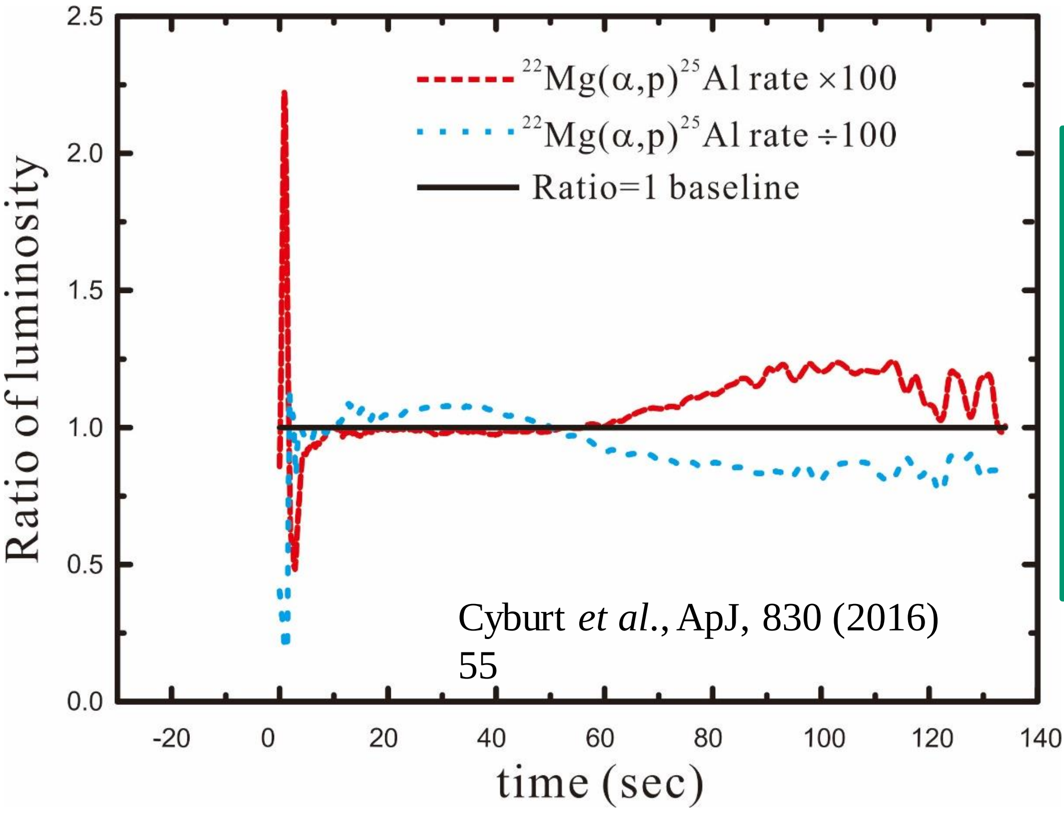
(α, p) reactions that impact the burst light curve in the multi-zone x-ray burst model.

Rank	αp-process reaction	Source of reaction rates adopted by multi-zone model
1.	$^{22}Mg(\alpha,p)^{25}Al$	Non-SMOKER
2.	$^{14}O(\alpha,p)^{17}F$	Hu *et al.* PRC 90 (2014) 025803
3.	$^{18}Ne(\alpha,p)^{21}Na$	He *et al.* PRC 88 (2013) 012801
4.	$^{26}Si(\alpha,p)^{29}P$	Non-SMOKER
5.	$^{30}S(\alpha,p)^{33}Cl$	D. Kahl *et al.* PRC 97 (2018)
6.	$^{34}Ar(\alpha,p)^{37}K$	Non-SMOKER
7.	$^{38}Ca(\alpha,p)^{41}Sc$	Non-SMOKER

Ref: Cyburt *et al.*, ApJ, 830 (2016) 55

$^{22}Mg(\alpha,p)^{25}Al$ could be the most sensitive reaction in the αp-process and may have a prominent impact on the burst light curve.

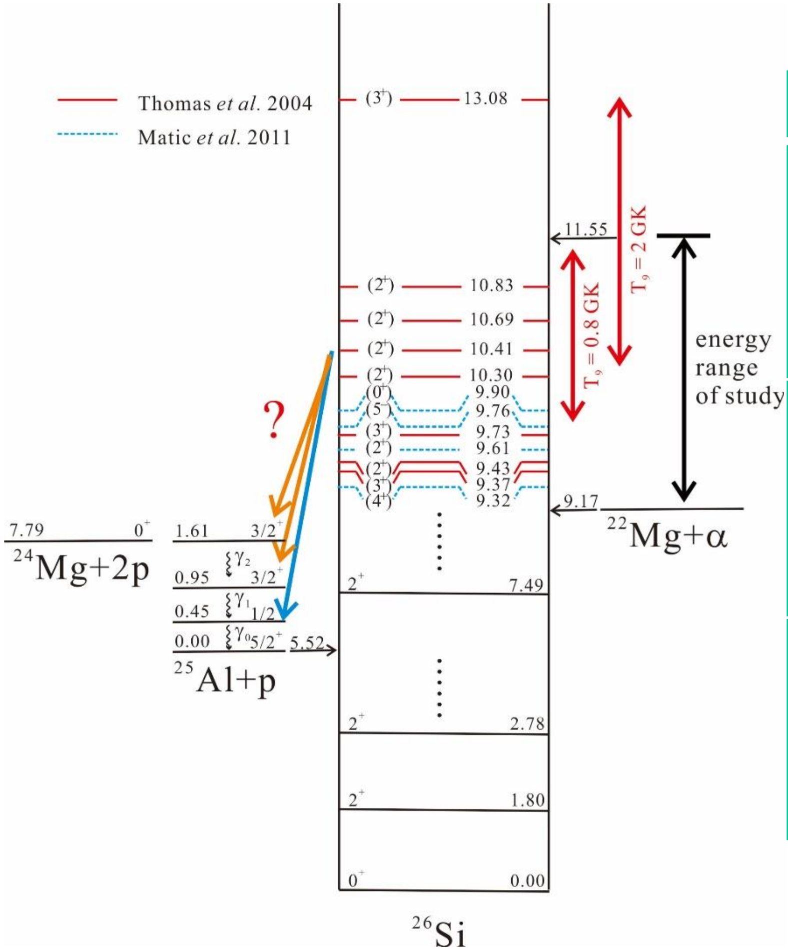
1.3 The effect of $^{22}Mg(\alpha,p)^{25}Al$ on the X-ray burst light curve



The $^{22}Mg(\alpha,p)^{25}Al$ reaction has a sizeable impact on the abundance of ^{22}Na, as well as the isotopic anomalies of $^{20}Ne/^{22}Ne$ ratio found in meteorites.

Change in multi-zone model X-ray burst light curves induced by variation of the $^{22}Mg(\alpha,p)^{25}Al$ reaction up (Up rate ×100) and down (Dn rate ÷100)

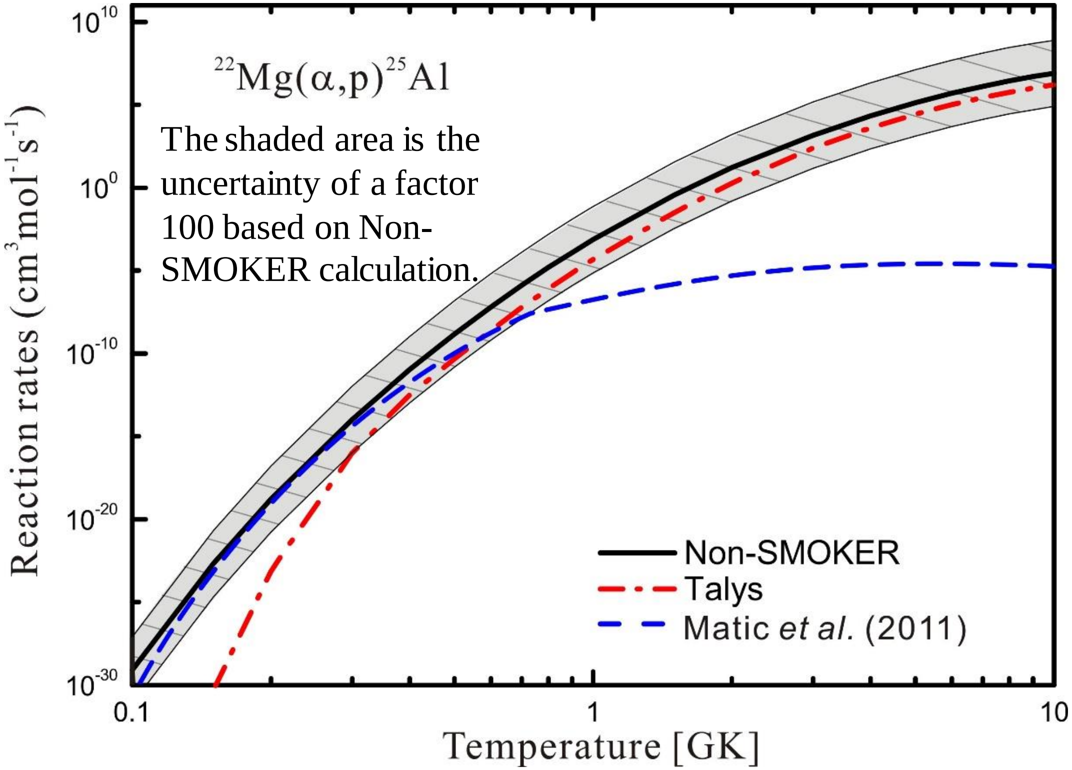
2.2 Status of level properties in ^{26}Si



Experimental technique	E_{res}	J^{π}	Γ_{p0}	$\Gamma_{p'}$	Γ_{α}
β-delayed proton measurement of ^{26}P Thomas et al. 2004	√ Ex>10 MeV	– Shell model calculation	–	–	–
$^{28}Si(p,t)^{26}Si$ Matic et al. 2011	√ Ex<10 MeV	– Analog state assignment	–	–	–
^{25}Al+p scattering measurement above the α threshold of ^{26}Si (will be done)	√ Excitation function measurement	√ R-Matrix fitting	√ $^{25}Al(p,p)^{25}Al$	√ $^{25}Al(p,p')^{25}Al$	–

All the previous measurements didn't touch the astrophysical interested energy region.

2.3 Status of $^{22}Mg(\alpha,p)^{25}Al$ astrophysical reaction rate

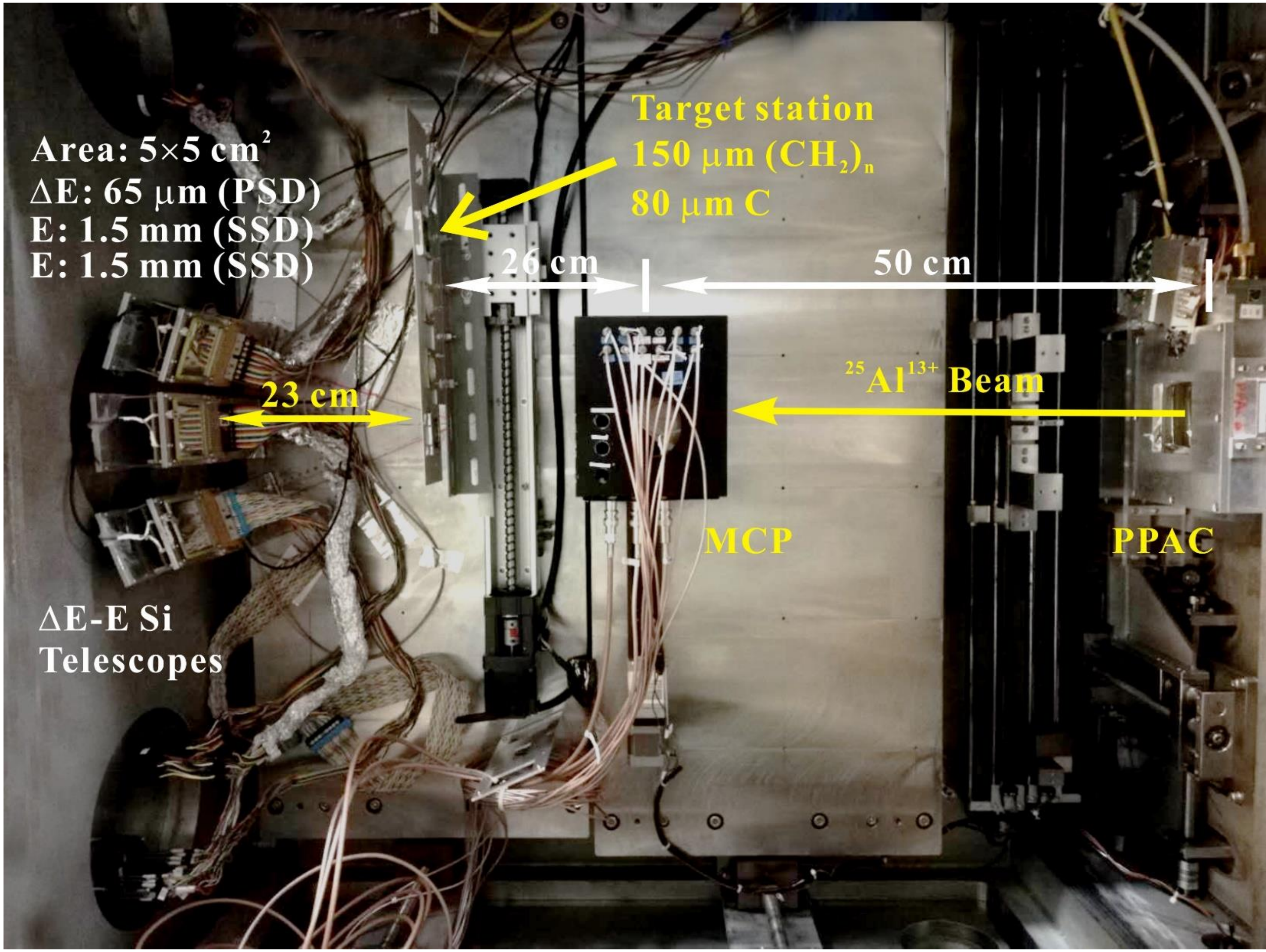


Large difference between the experiment and theoretical calculation.

The $^{22}Mg(\alpha,p)^{25}Al$ reaction rate as a function of the temperature for the Hauser-Feshbach predictions TALYS and non-SMOKER

Experimental Setup at F3 focal plane

^{25}Al beam:
2 x 10^5 pps, 80% purity



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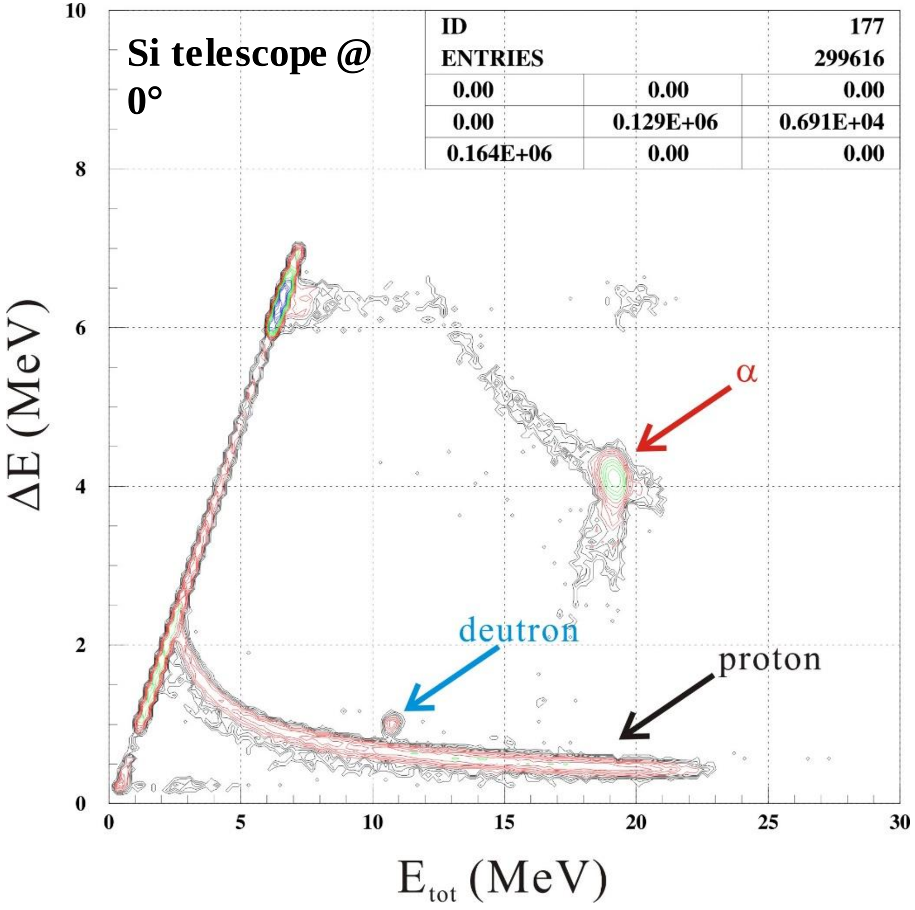
Particle Identification for the Recoiling Particles



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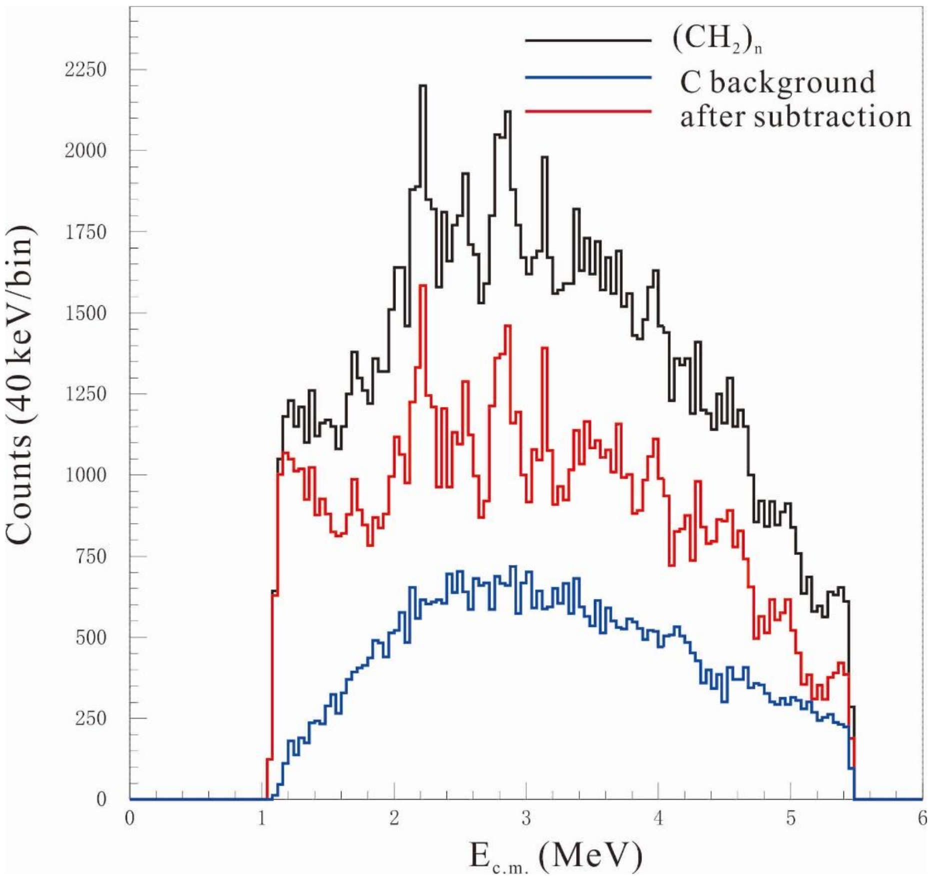
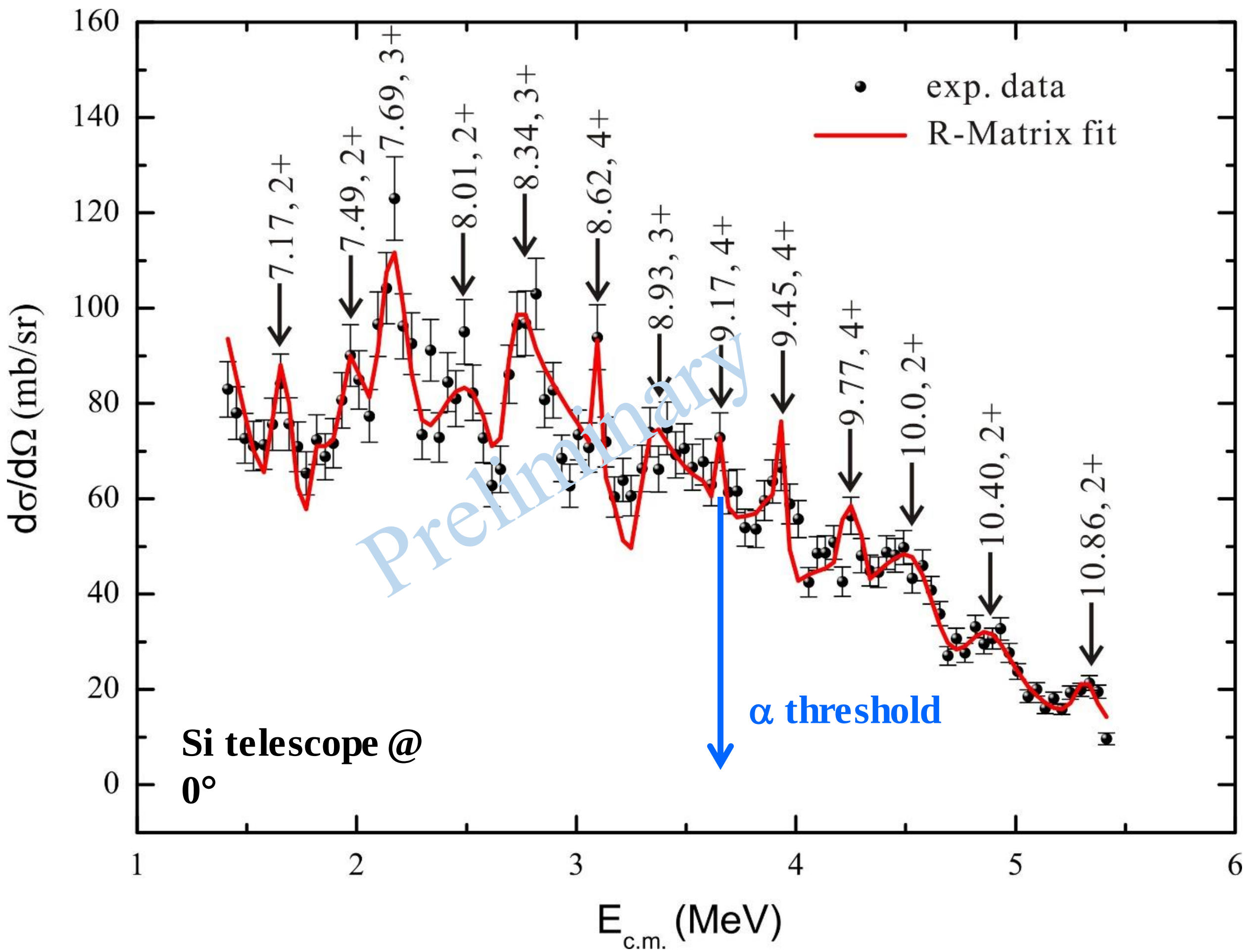
$^{1}H(^{25}Al, p)^{25}Al$ Excitation Function @ 0°



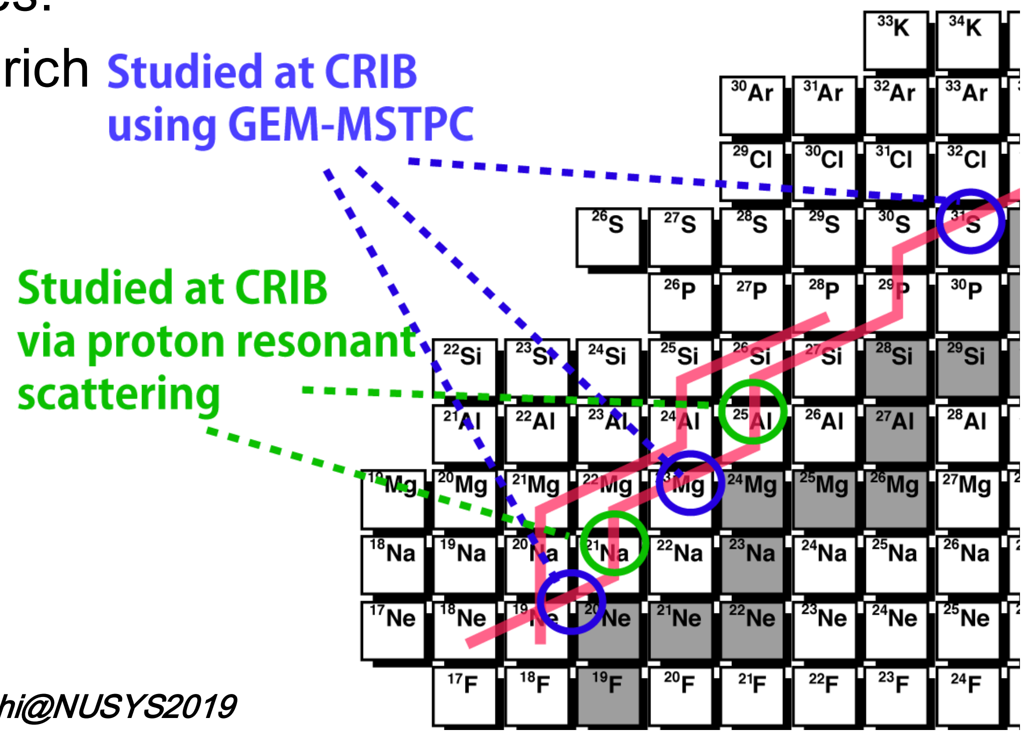
Preliminary R-Matrix Fit Result

1. We observed 13 resonant states in ^{26}Si.
2. The spin parities of 5 states above the α threshold were determined for the first time (in the present tentative analysis).



The αp-process

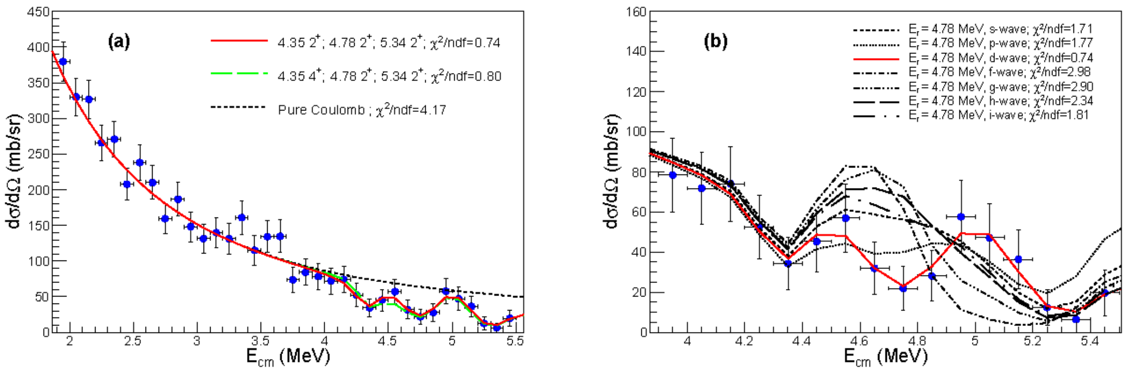
- αp-process: (α,p),(p,γ) reactions occur faster than β-decay at high temperature. Accelerates the rp-process (Wallace and Woosley, 1981).
- Suitable objective for CRIB
  - ◆ Not many direct measurements of (α,p) reactions have been performed in other facilities.
  - ◆ Involves A=18-30, proton rich unstable nuclei.
  - ◆ T=1.5GK, close to the beam energy at CRIB.



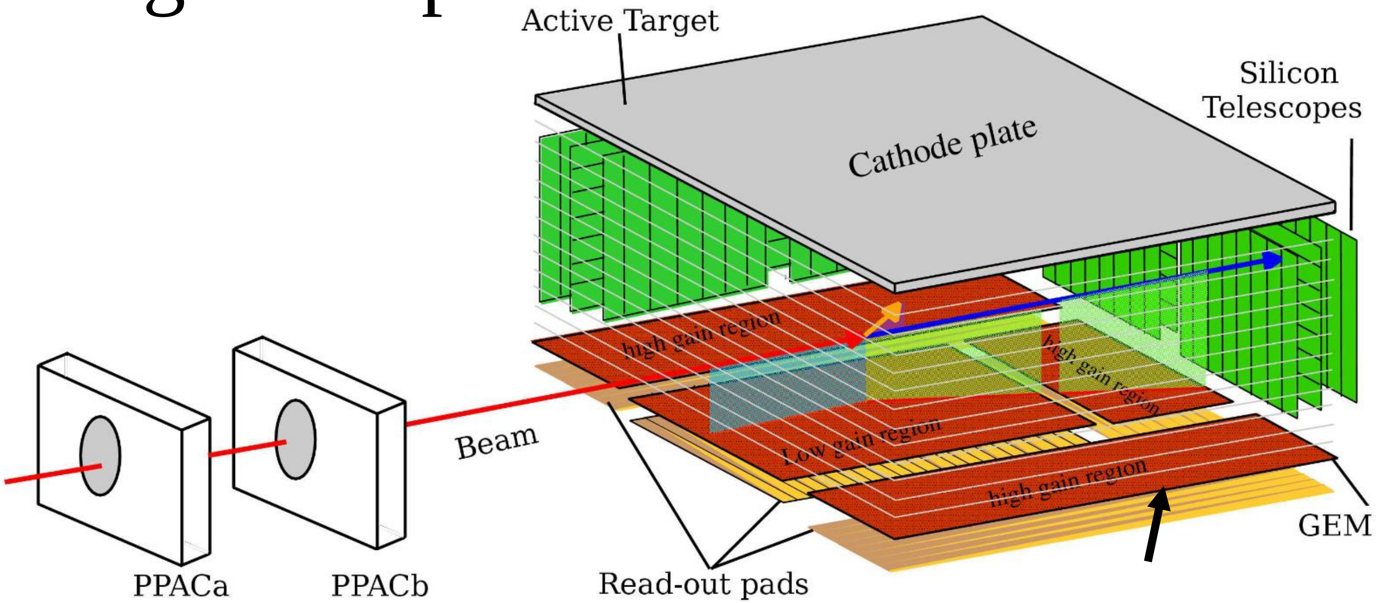
$^{30}S(\alpha,p)$

- $^{30}S(\alpha,p)$ … one of the key reaction in X-ray bursts.
- Scarce ^{34}Ar resonance information, reaction rate evaluation was by statistical model.

- $^{30}S+\alpha$ resonant scattering with active target (D. Kahl et al., submitted to Phys. Rev. C).
- 3 higher-lying resonance observed: 1



Active target Setup



He (90%) +CO_2 (10%) mixture gas(160 torr)

- Acts as a He target and a detector (TPC) simultaneously
- GEM with “backgammon” type readout pad.
- 3-dimentional trajectory and energy loss can be measured ⇒ Accurate event identification.

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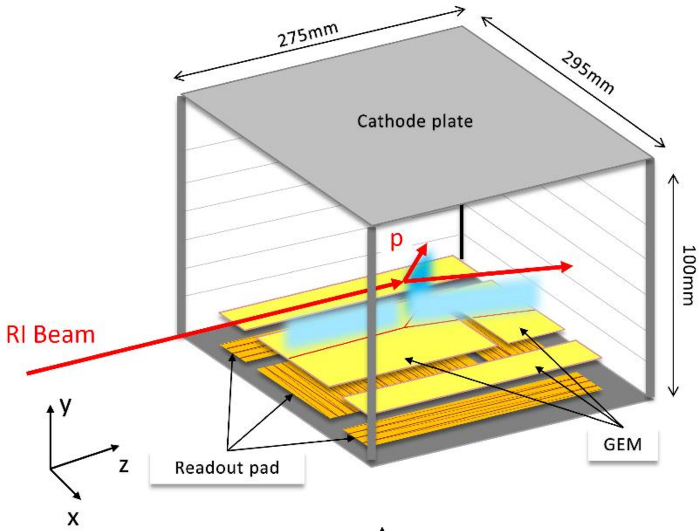
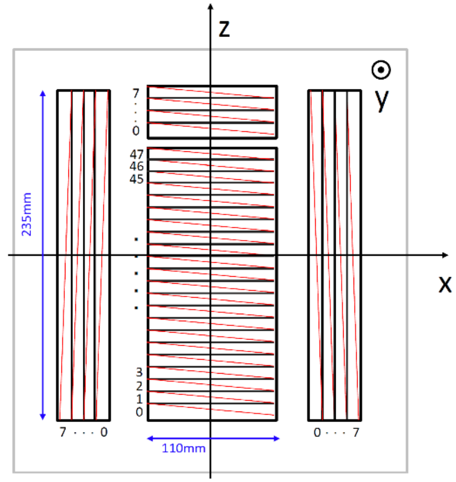
How to obtain the 3D-trajectory?

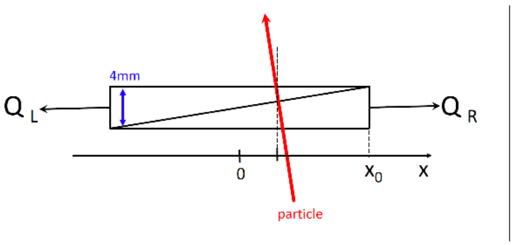


X: L⇔R ratio of the "Backgammon" pad.

Y: Electron drift time in the TPC.

Z: pad #.





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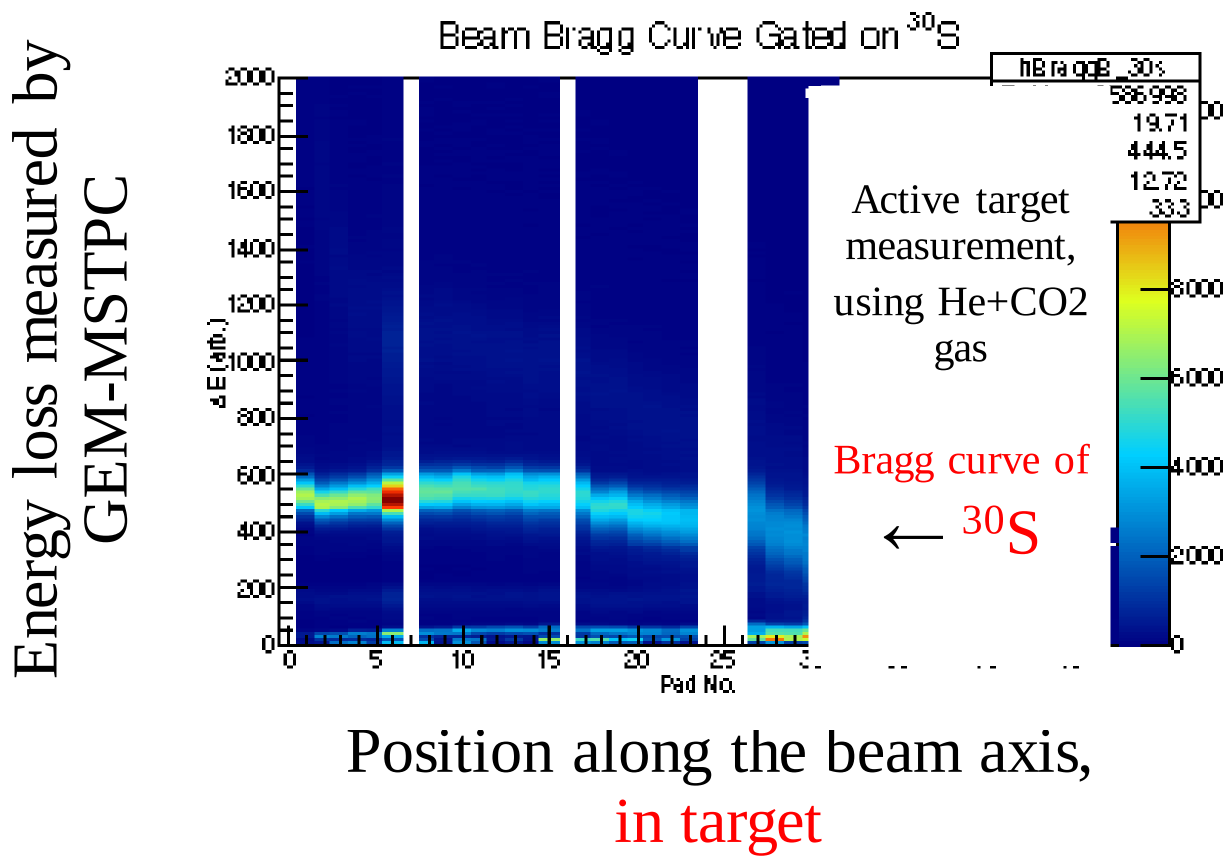
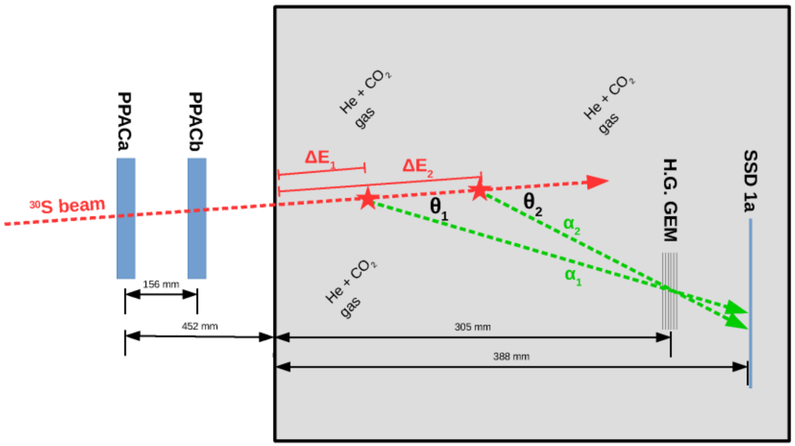
Bragg curve

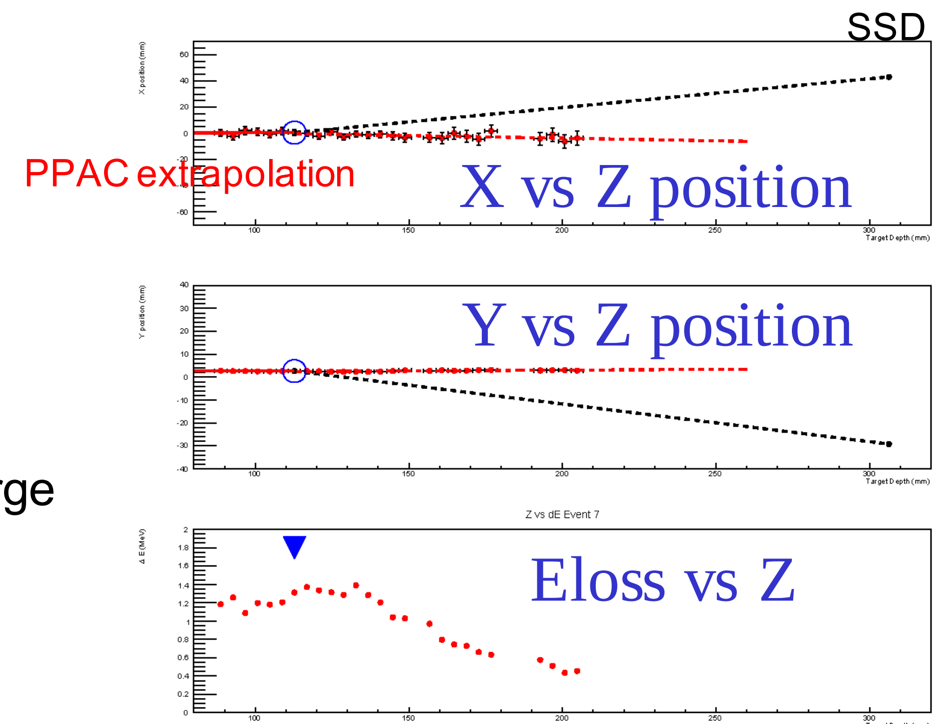
- The energy loss profile in the target (the Bragg curve) can be measured with the active target, which should be known precisely for the TTIK experiments.



Kinematic reconstruction analysis



← 2 PPACs + GEM-MSTPC (low-gain/high gain GEM regions) + SSD



Kinematics reconstruction with

-Beam trajectory with PPAC

-Energy loss profile with GEM

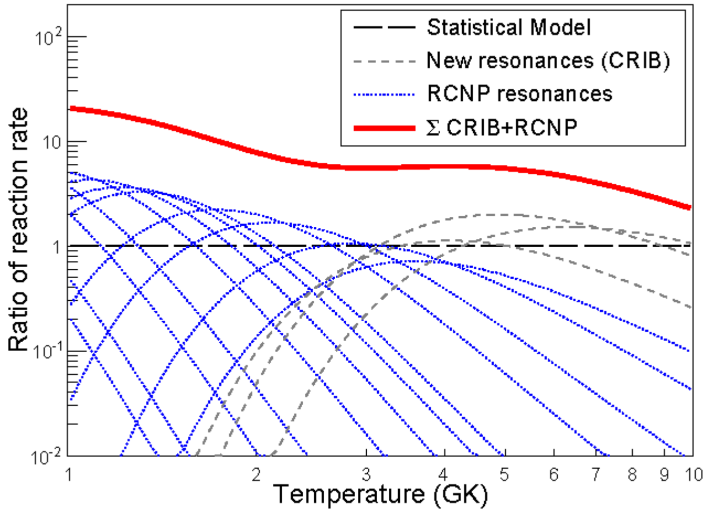
-Particle energy with SSD

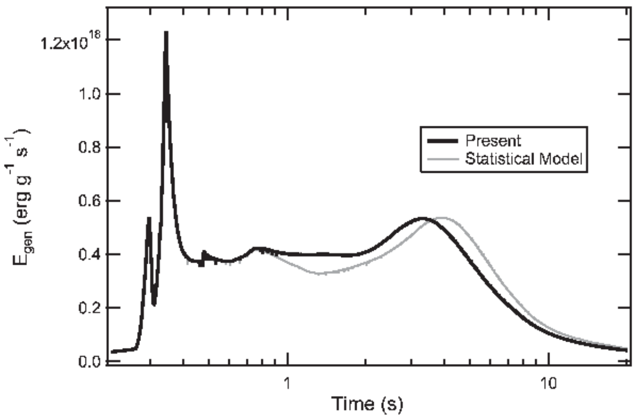
In reality, the uncertainty was quite large due to the energy resolution (10%).

Astrophysical implications

Reaction rate evaluation with RCNP(Osaka) $^{36}Ar(p,t)^{34}Ar$ transfer reaction data + CRIB(Tokyo) resonant scattering data

⇒Higher than the stat. model rate calculation





⇐Energy generation higher than the statistical model

25% enhancement [with a single reaction].

-Max. 30% of abundance change for A=20-80 nuclei.

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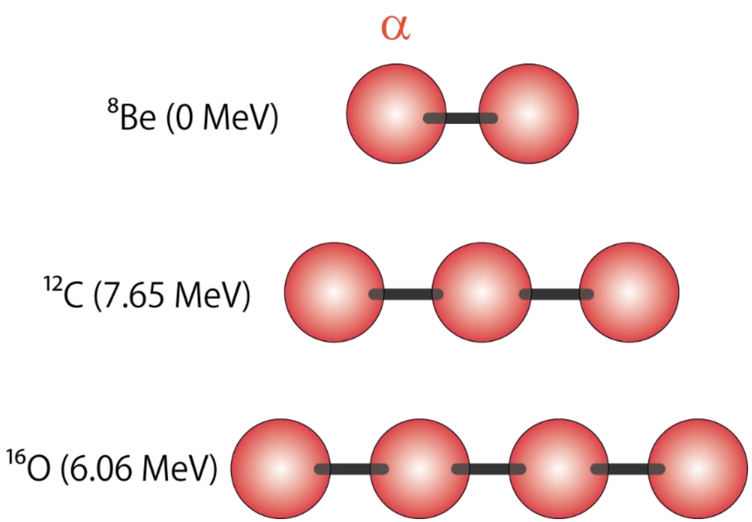
Morinaga (1956) and linear chain

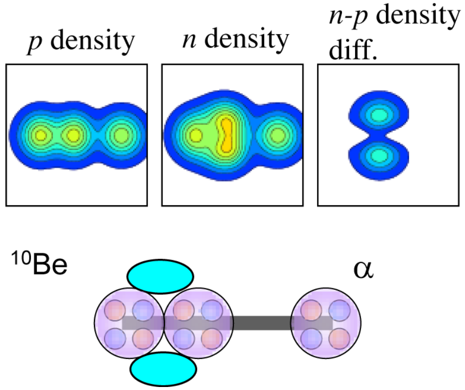
- Discussed on 4n-nuclei based on the alpha particle model
- Predicted linear-chains in ^{12}C, ^{16}O, etc., from their high momenta of inertia.

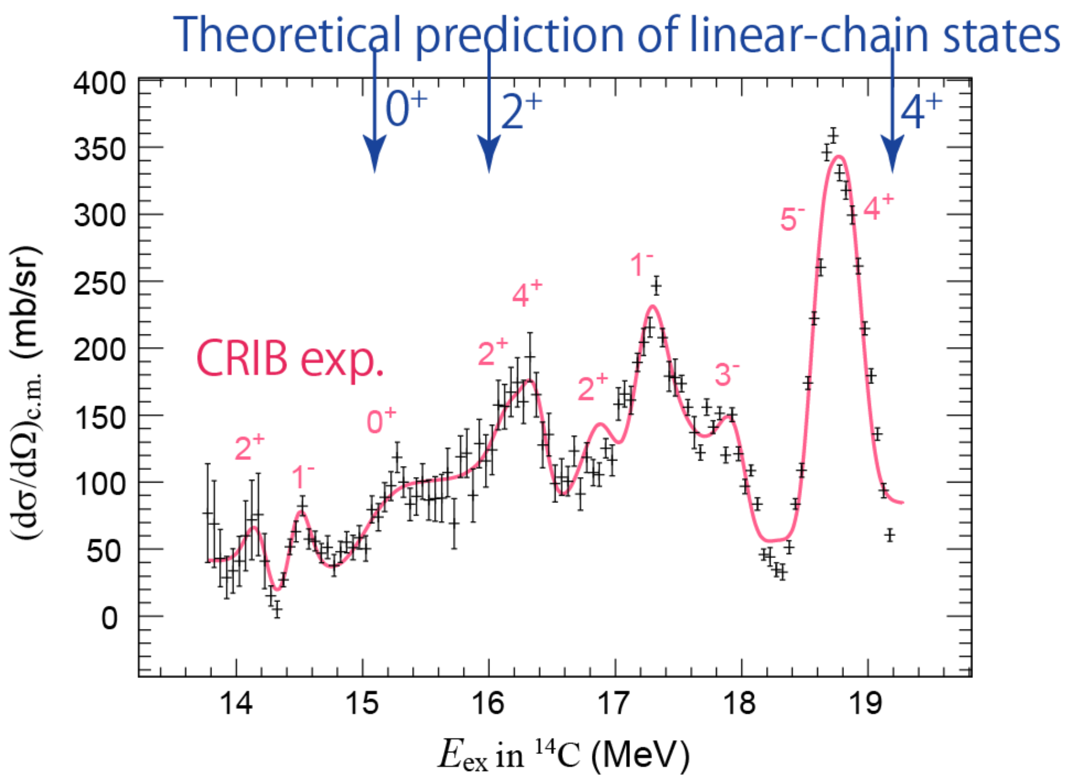


- It was shown in later studies that the Hoyle state is NOT a linear-chain state.

Linear-chain levels

Suhara & En'yo, PRC 2010 and 2011:



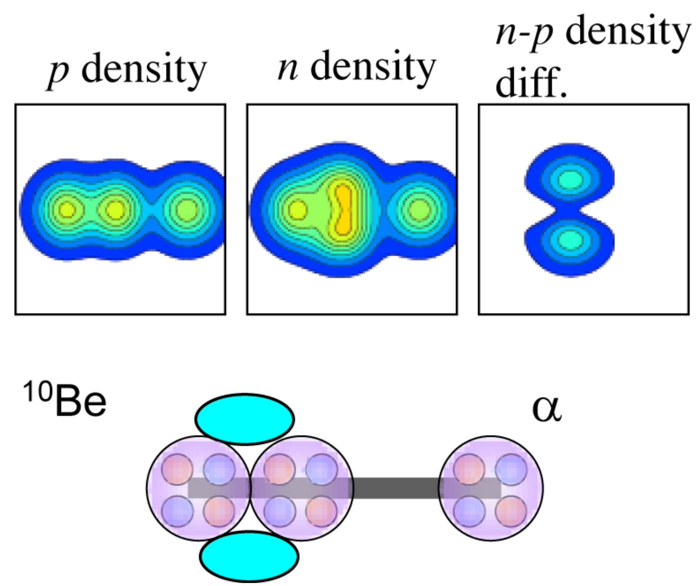


Excellent agreement between exp. and theory for the (0+, 2+, 4+) states.

^{10}Be+α

- Linear-chain cluster levels in ^{14}C were predicted in Suhara & En'yo papers.
- Asymmetric, ^{10}Be+α configuration …likely to be observed with ^{10}Be+α alpha-resonant scattering.
- May form a band with $J^{\pi}=0^+,2^+,4^+$ a few MeV above α-threshold.
- Scattering of two 0^+ particles…only l-dependent resonant profile.

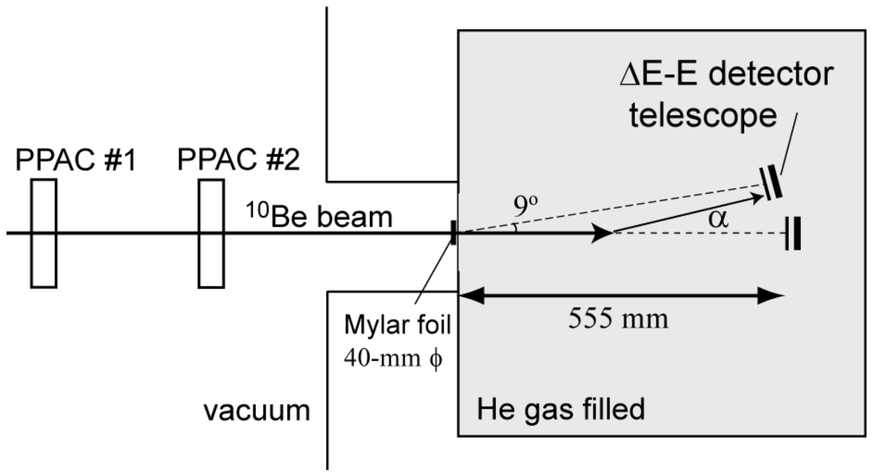
Suhara & En'yo, PRC 2010 and 2011:



Similar experiments independently conducted by Birmingham group and MSU group, published already.

Experimental setup

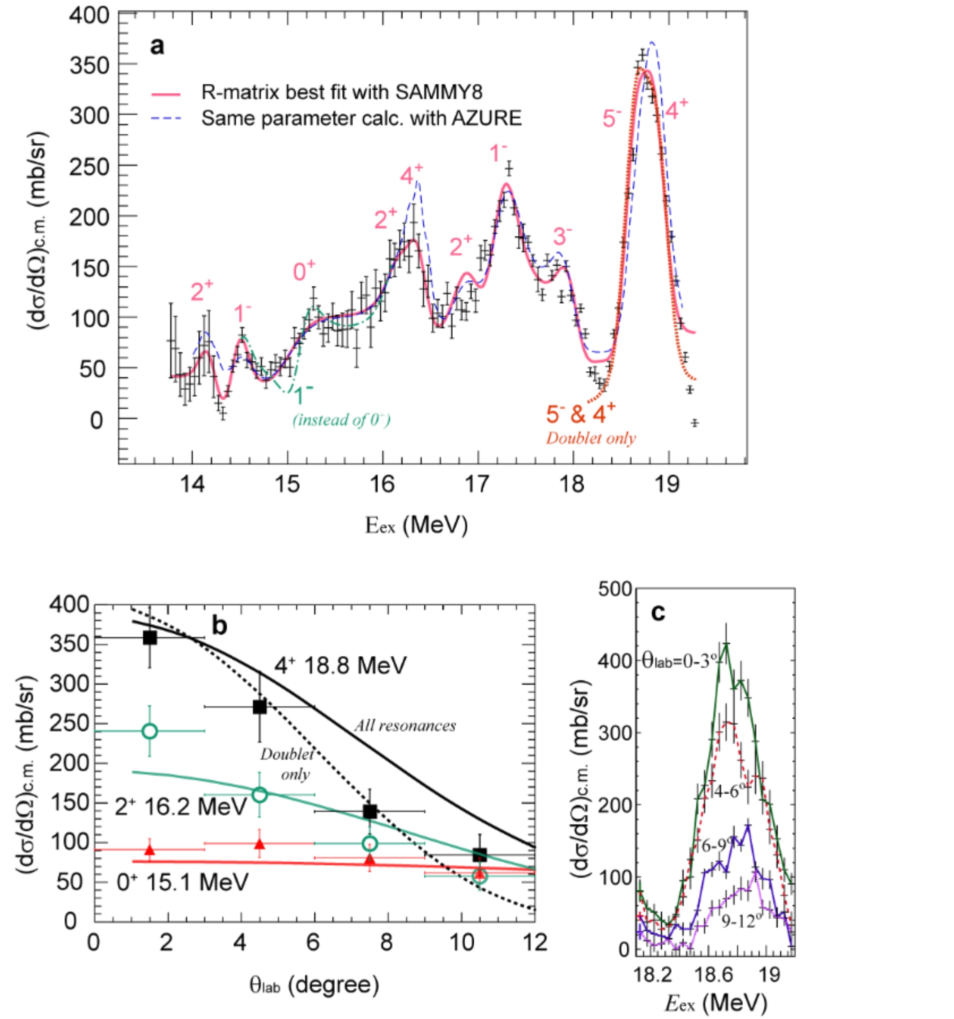
Thick target method in inverse kinematics, similar to the previous ^{7}Be+α.



- Two PPACs for the beam PI, trajectory, number of particles.
- Two silicon detector telescopes for recoiling α partciles.
- E_{cm} and θ obtained by event-by-event kinematic reconstruction.

Excitation function

- The excitation function we obtained for 13.8-19.2 MeV exhibits many resonances.
- R-matrix analysis performed, and some of the resonance parameters (E, J^{π}, Γ_{α}) were determined.



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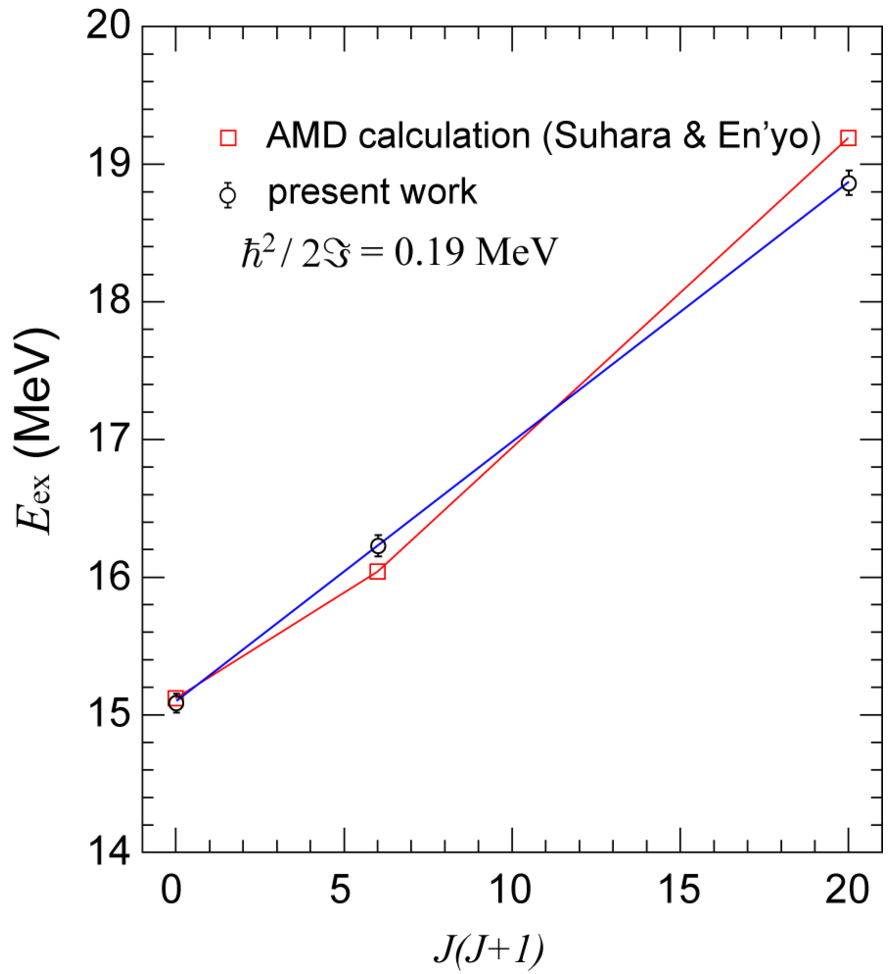
Rotational Band

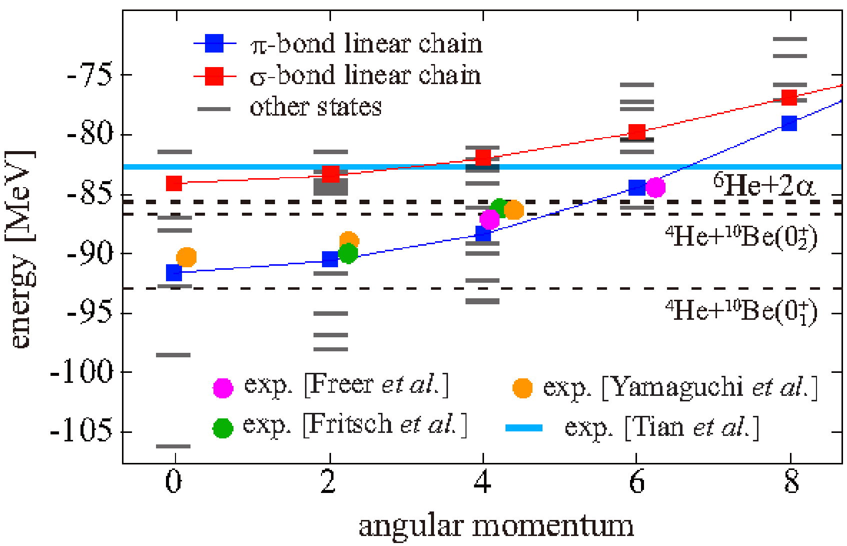
The set of resonances we observed (0+, 2+, 4+) is proportional to *J(J+1)* … consistent with a view of rotational band.

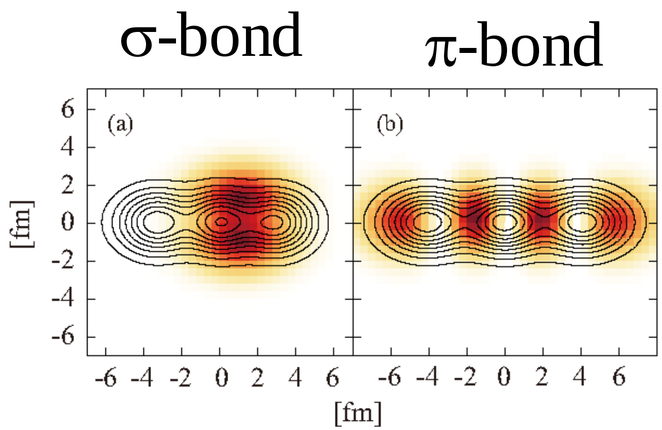
Also perfectly consistent with the theoretical prediction.



Baba and Kimura (2016 & 2017)

PHYSICAL REVIEW C **95**, 064318 (2017)





Another AMD calculation,

"σ-bond" linear chain band, consistent with 3 experiments

"π-bond" linear chain band at higher energy (studied by Peking Univ. group).

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How certain are the linear-chain states?

- Identification of the 0^+ state…1^- was excluded with 3σ significance, but the error can be systematic.
  - ◆Limited statistics and angular range
  - ◆Background subtraction
  - ◆Inelastic scattering?

- We planned the 4th experiment at INFN-LNS (Catania, Italy):
  - ◆With offline-production ^{10}Be beam
  - ◆Inelastic scattering separation with TOF.

⇒Performed in Oct., 2018.

The “CHAIN” experiment at INFN-LNS (Catania, Italy)

^{10}Be+α with more intense beam, higher energy and angular resolution: ~2 weeks beamtime.

Investigation of α-chain structures in ^{14}C.

H. Yamaguchi [1], A. Di Pietro[2], R. Dressler[3], J. P. Fernández-García[4], P. Figuera[2], S. Hayakawa[1], S. Heinitz[3], D. Lattuada[5], M. Lattuada[2,6], E. Maugeri[3], M. Milin[7], H. Shimizu[1], A. C. Shotter[8], D. Shumann[3], N. Soic[9], D. Torresi[2], L. Yang[1] M. Zadro[9],

[1] *Center for Nuclear Study (CNS), University of Tokyo, RIKEN, Wako, Japan*
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Abstract

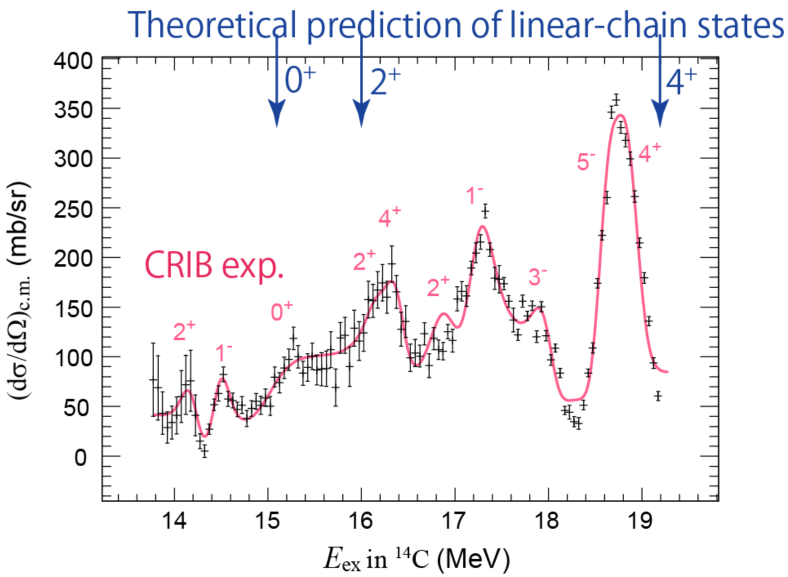
We propose to measure the excitation function for the elastic scattering process ^{10}Be+^{4}He, in order to shed some light upon the existence of linear-chain cluster states in the n-rich ^{14}C nucleus. These states are expected to have a configuration in which ^{10}Be and α are spatially separated, and thus they can be observed by the ^{10}Be+α resonant elastic scattering. In order

Result (very preliminary)

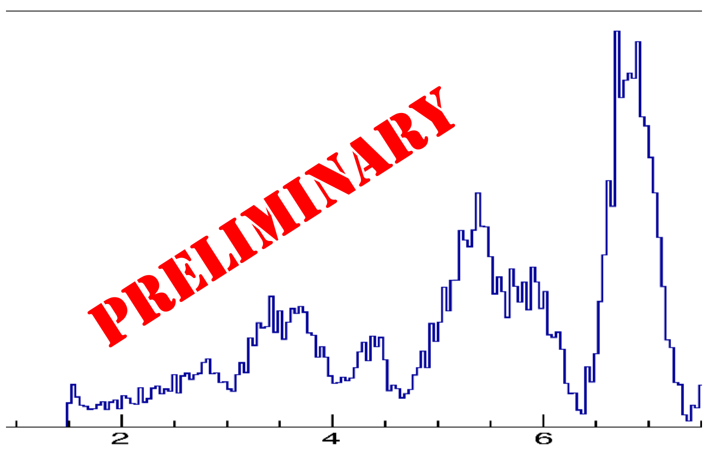
CRIB vs LNS(Tandem)

Including 0-8 deg events

Theoretical prediction of linear-chain states



@5 deg, No normalization for the effective target thickness/absolute cross section yet

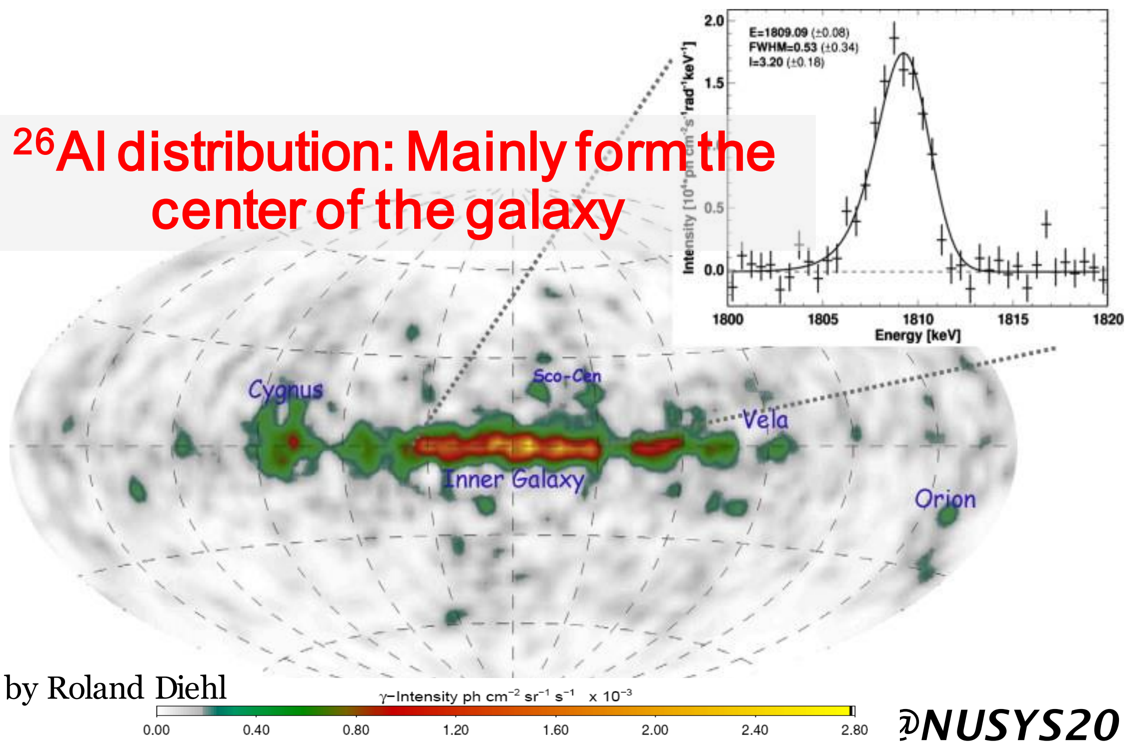


The origin of galactic ^{26}Al gamma rays

^{26}Al γ-ray : The first observed cosmic γ-ray from specific nuclide
(1.809 MeV)

Evidence of on-going nucleosynthesis.
Key for understanding the evolution of the galaxy (^{26}Al^{gs}, $t_{1/2}$ = 0.7 million years)
Production source: still uncertain. Massive stars? Supernovae? Novae?

^{26}Al distribution: Mainly form the center of the galaxy



by Roland Diehl

Too much ^{26}Al

2.0 ± 0.4 $M_\odot$ – Diehl (2016),

but

> 3$M_\odot$ expected from ccSN, WR, AGB and SAGB simulation.

Needs ^{26}Al-destruction process?

Amount of ^{26}Al in galaxy

"RADIOACTIVE ^{26}Al IN THE GALAXY: OBSERVATION VERSUS THEORY" − Prantzos & Diehl (1996)

Summarizing the theory and observation at that time,

$1.5 \sim 3\ M_\odot$

Estimation by a recent observation 26Al

$2.0 \pm 0.4\ M_\odot$ − Diehl (2016)

Stellar production by calculation

Nova: $\sim 0.8\ M_\odot$ − Bennet et al. (2013)

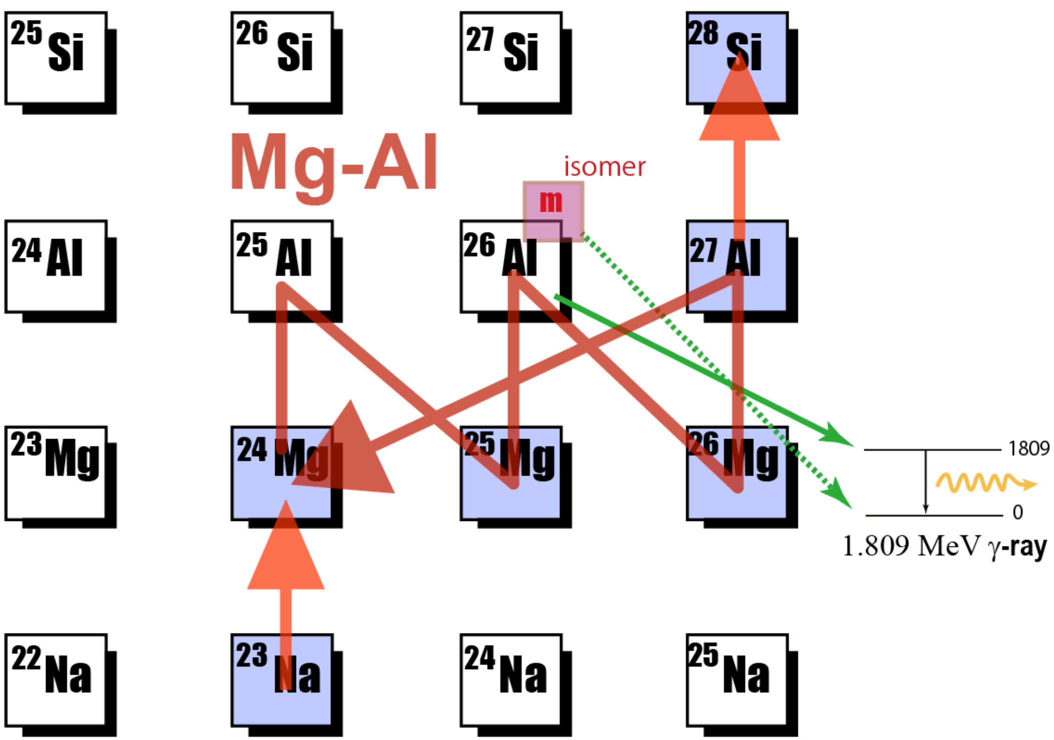
ccSN&WR(11-120 Ms): $1.8 \sim 2\ M_\odot$ − Limongi & Chieffi (2006)

AGB: $\sim 0.4\ M_\odot$ − Mowlavi & Meynet (2000)

SAGB: $\sim 0.3\ M_\odot$ − Siess & Arnould (2008)

Total production of ^{26}Al exceeds the amount estimated by observation! (Needs destruction process?)

^{26}Al



Low-T (<<0.4 GK)

- *Simple scheme: ^{26}Al is on the Mg-Al cycle, decay into ^{26}Mg.*
- *Both ^{26g}Al (ground state) and ^{26m}Al (isomer, τ=6.3s) are produced. Only ^{26g}Al decay into the excited state of ^{26}Mg and emit 1.809-MeV γ-rays.*

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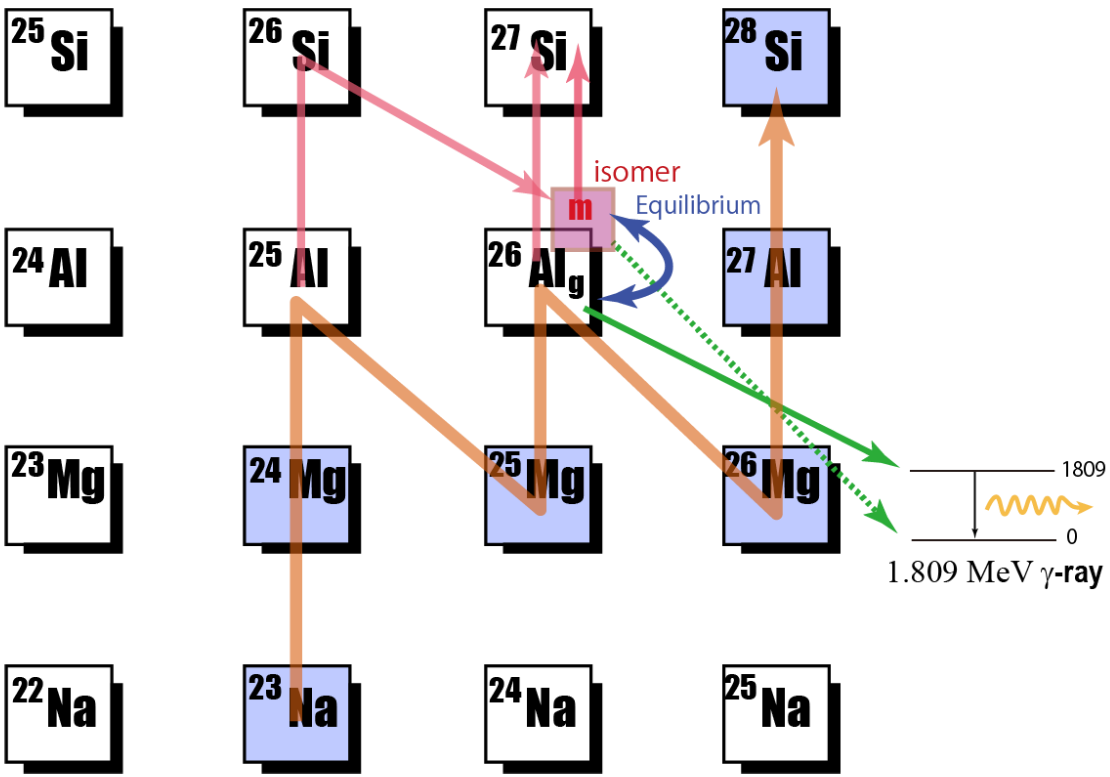
26Al



High-T (>> 0.4GK)

Isomeric ^{26}Al does not produce γ-rays, however,

- ^{26m}Al production by ^{25}Mg(p,γ) and also from ^{25}Al⇒^{26}Si decay.
- Thermal equilibrium between ^{26g}Al and ^{26m}Al.
- ^{26}Al(p,γ)^{27}Si reaction destroys ^{26}Al.

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^{26}Al isomer beam

- ^{26}Mg(p,n)^{26}Al reaction: At the energy of CRIB, the maximum angular momentum brought by the beam is limited, and the production of ^{26}Al ground state(5^+) is highly suppressed. ⇒High purity ^{26}Al isomer beam production is possible.
- This seemed to be a unique idea in 2014, but…

^{26}Al^m beam @Argonne:

S. Almaraz-Calderon et al., Phys. Rev. Lett 119, 072701 (2017), B.W. Asher et al., NIM A (2018).

At CRIB:

2016 First ^{26m}Al beam production

2017 ^{26m}Al+p resonant scattering measured

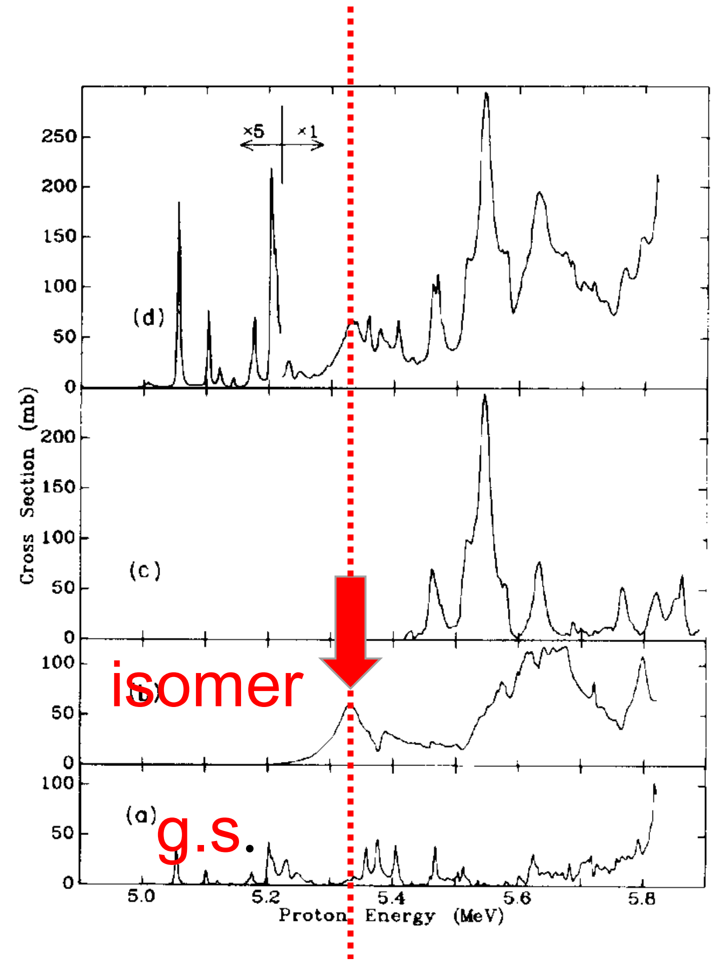

FIG. 4. Excitation functions for (a) ^{26}Mg(p,n_0)^{26}Al, (b) ^{26}Mg(p,n_1)^{26}Al, (c) ^{26}Mg(p,n_2)^{26}Al, and (d) the total neutron yield.

Cocktail beam at the RI optimization focal plane

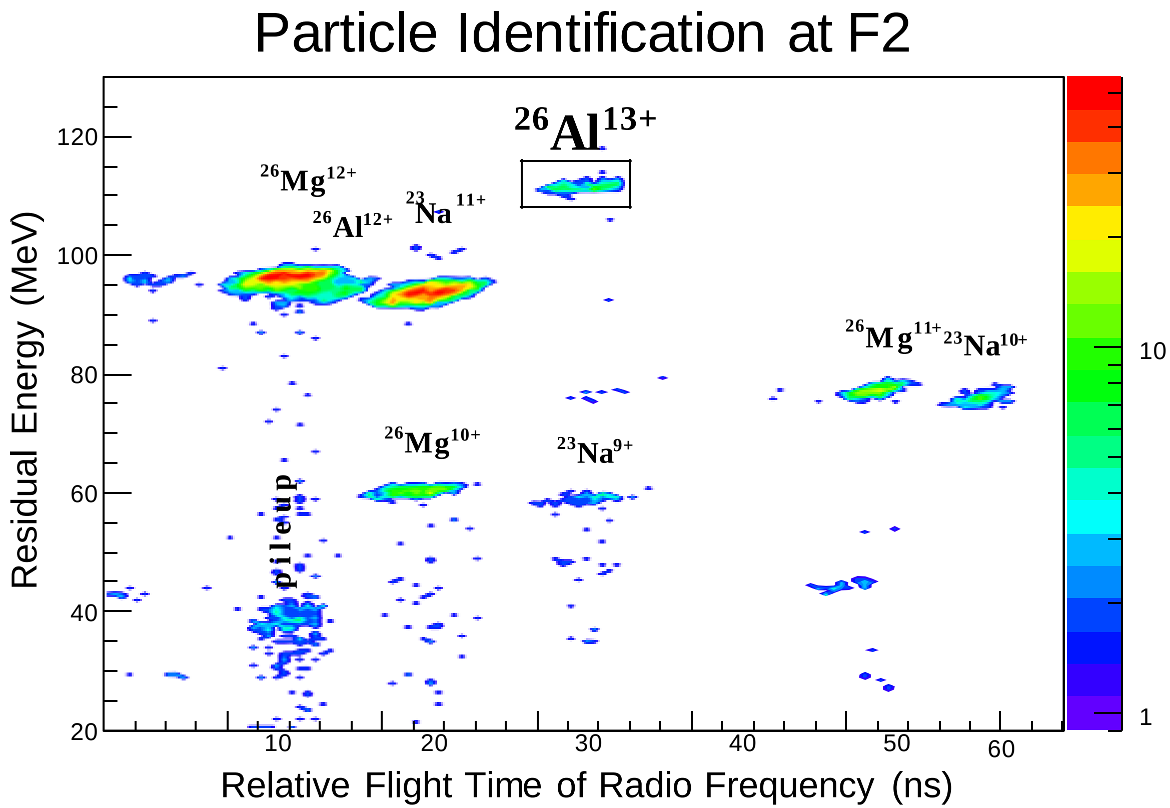

Figure: Flight time vs. residual energy. $^{26}Al^{13+}$ is clearly separated. Main contaminant ^{23}Na. This is illustrative (not optimized).

Intensity ~2 x 10^5 pps at F3.

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Experimental setup for ^{26m}Al(p, p) measurement

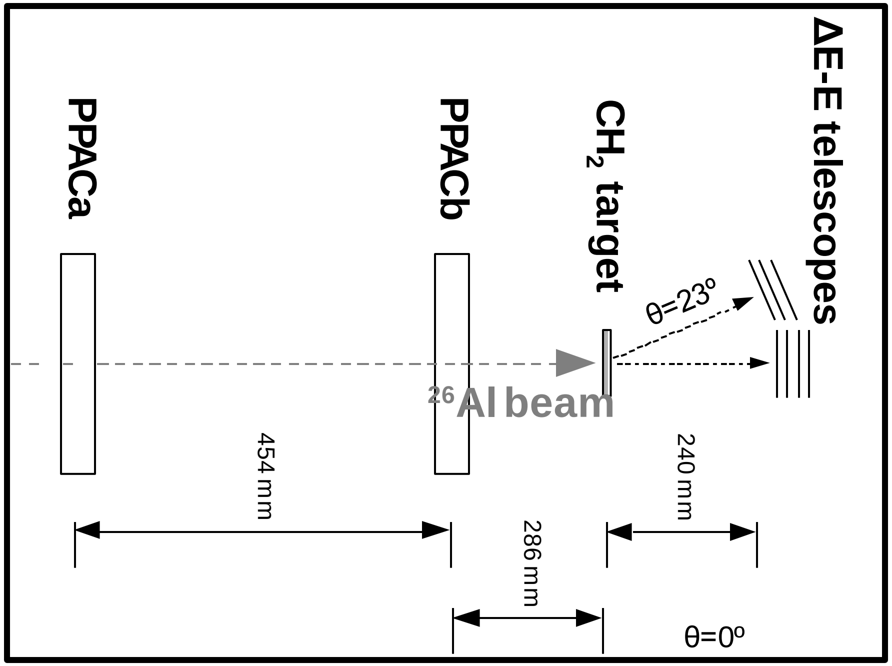

Figure: Beam is tracked by PPACs before impinging on and stopping in one of the targets. Scattered protons were detected by ΔE-E Si telescopes, the first layer is 75 μm with 16×16 strips and the other detectors 1.5 mm. An array of 10 NaI detectors was placed above the target to measure γ-rays (not depicted).

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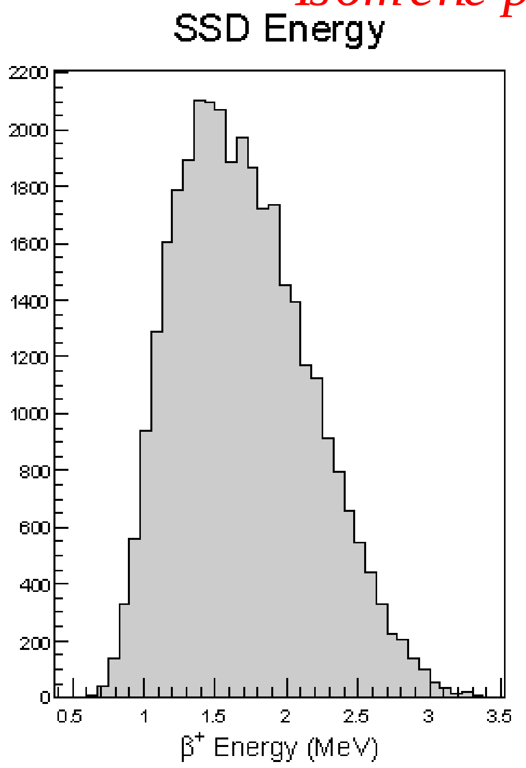
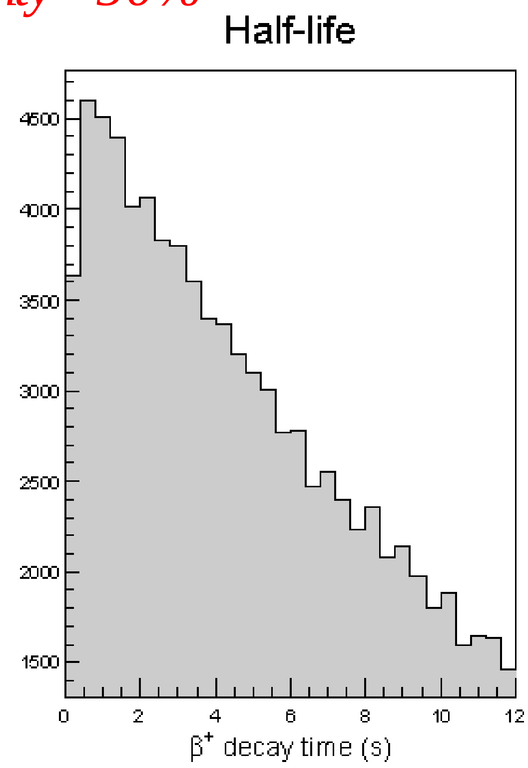
Proof we made ^{26m}Al

- *Pulsed the beam in regular tests, 12 s on — 12 s off*
  - *Measured the β^+'s with the Si telescope*
    - *(Also measured 511-keV γ's with NaI)*
      - *Isomeric purity ~50%*





β^+ decay measurements: (a) Energy spectrum and (b) Decay timing. Both are consistent with ^{26m}Al.

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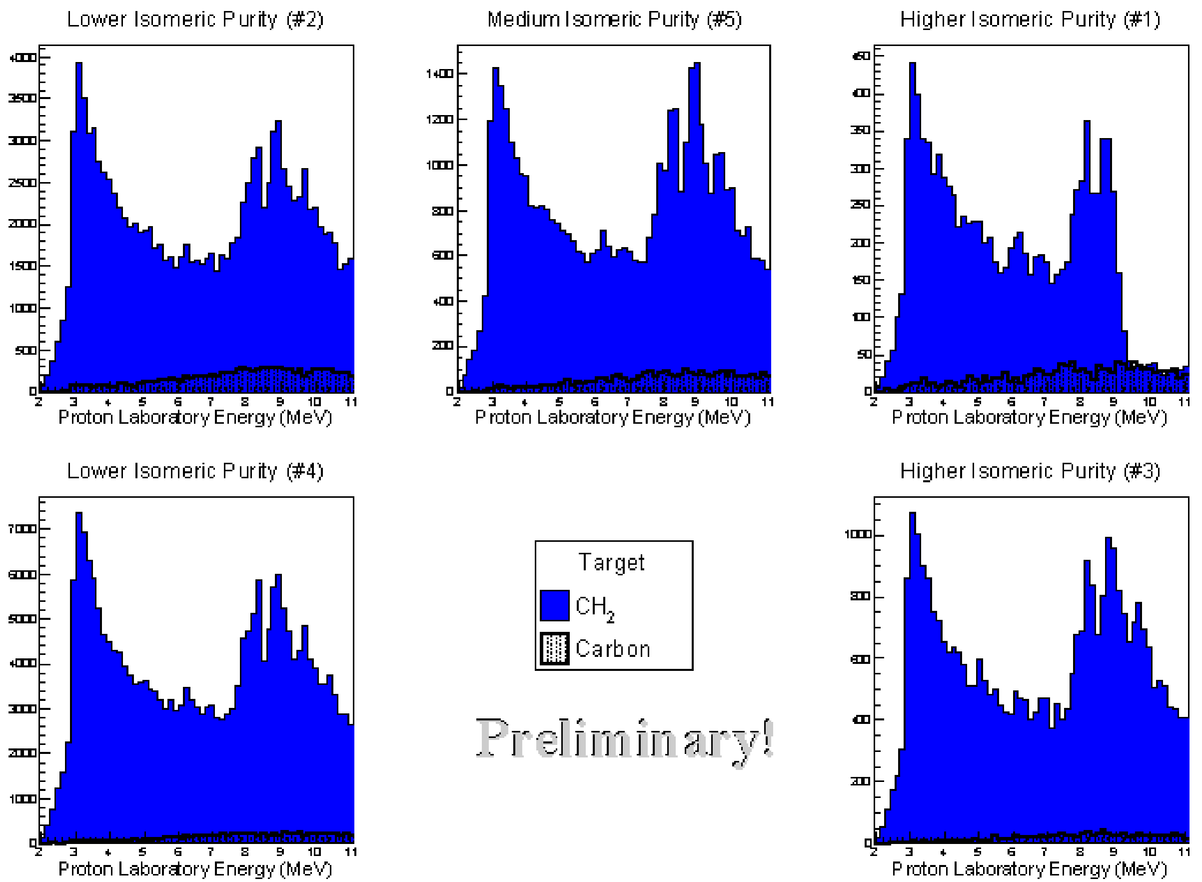
^{26}Al proton spectra — the method worked!



Rough normalization (factor 2 error). Clear evidence of structure arising from ^{26m}Al and not ^{26g}Al.

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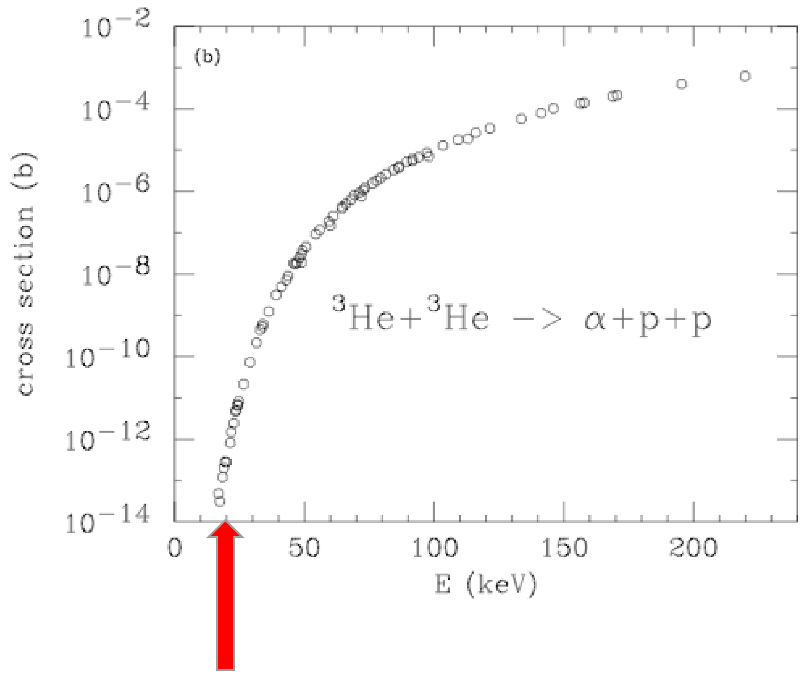
Need of indirect method

Stellar reaction cross section often has a strong dependence on energy (or temperature), changing by orders of magnitude.

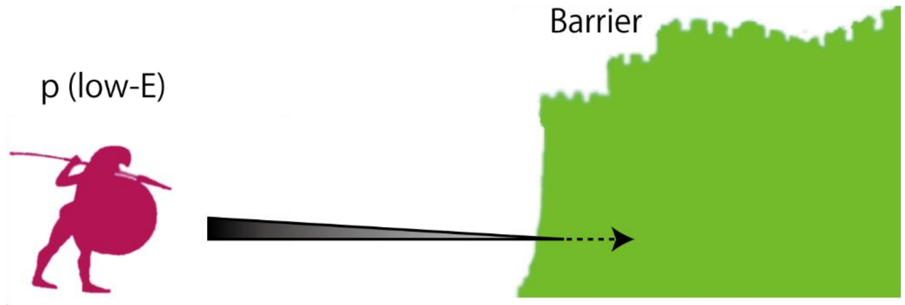
…This is because of the tunneling probability of the Coulomb barrier.

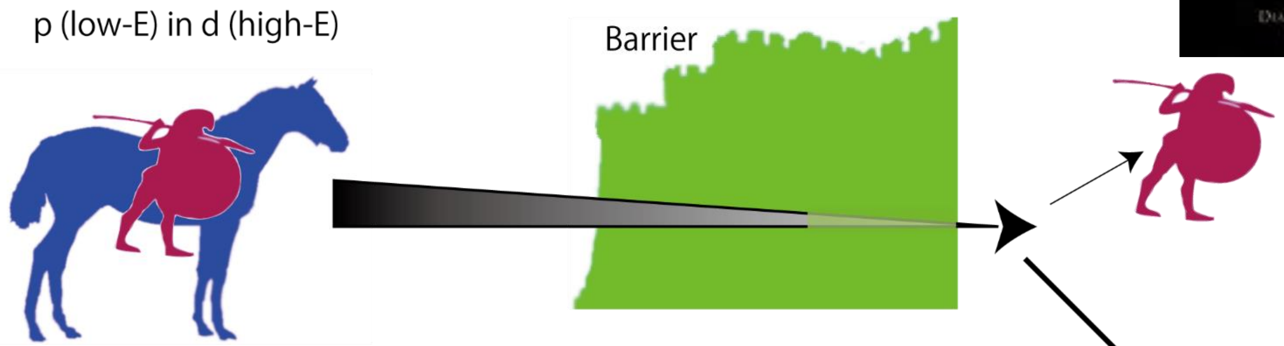
Experimentally, this causes much trouble. We need a clever way.

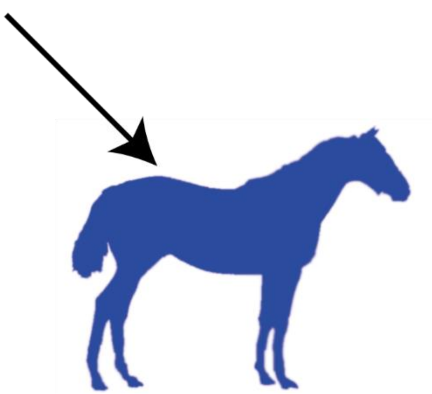


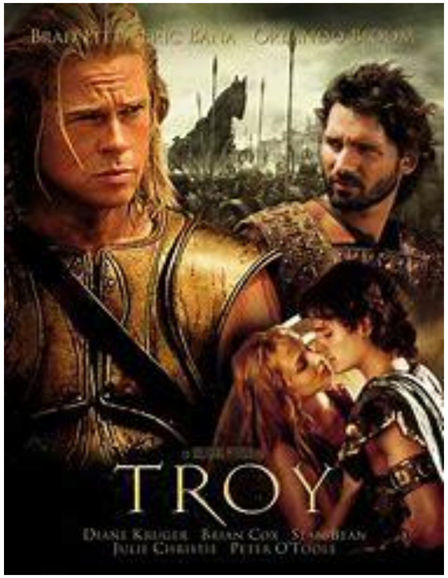
Solar T

The Trojan Horse Method(THM)









When the horse (neutron) does nothing significant in the castle (nucleus), the reaction can be called as a "quasi-free" reaction.

The $^{18}F(p,\alpha)$ project (with THM)

- $^{18}F(p,\alpha)$… an astrophysical reaction important in novae, and other high-T environments.

- Measurement with the Trojan Horse Method performed in 2008

…**The first THM+RI beam experiment in the world.**

- The RI Beam at CRIB (after development):

Primary beam: $^{18}O^{8+}$, 4.5-5 MeVA

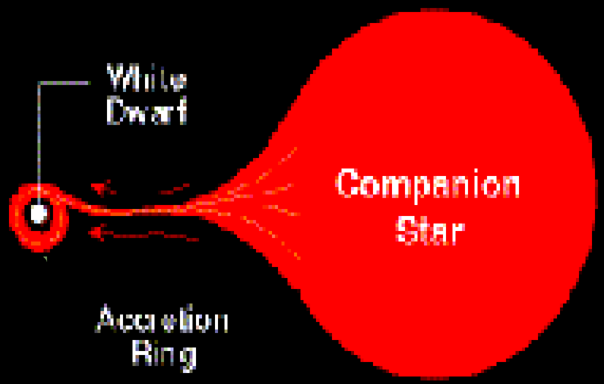
Production target: H_2

Production reaction: $^{18}O(p,n)^{18}F$

◆ Purity nearly 100%

◆ Intensity > 5 x 10^5 pps

A NOVA MICKEY MOUSE PICTURE AND $^{18}F(p,\alpha)^{15}O$



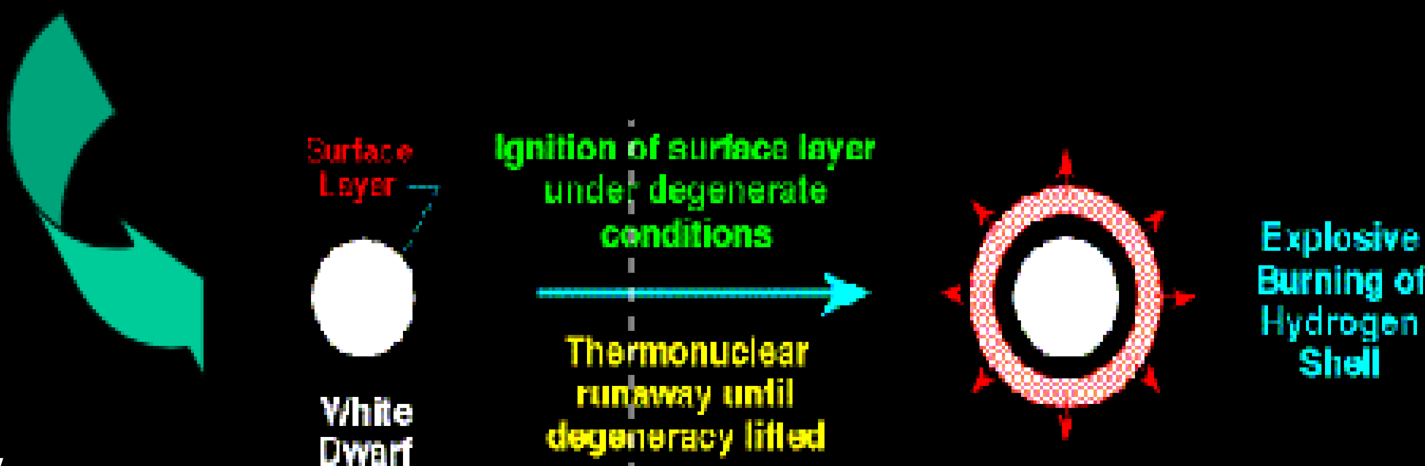
Thin hydrogen surface layer accumulated on white dwarf through accretion ring

Observed γ- rays come from e^+e^-

e^+ come from ^{18}F decay mostly

At novae temperatures (100 - 500 keV) ^{18}F can be mainly destroyed by

$^{18}F(p,\alpha)^{15}O$

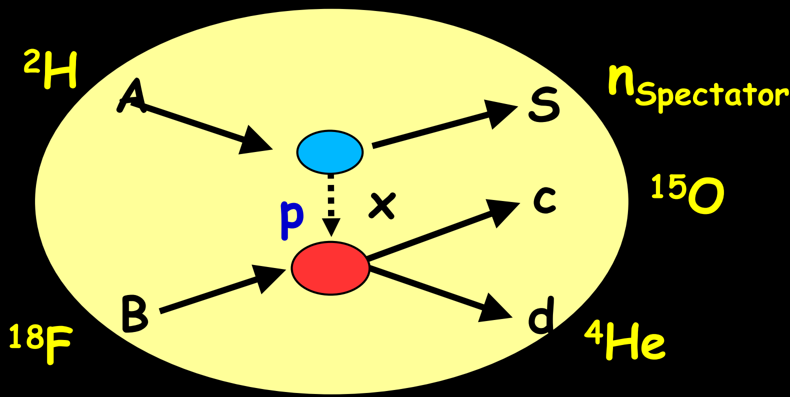


For the star energetics this is peanuts!

Slides by S. Cherubini

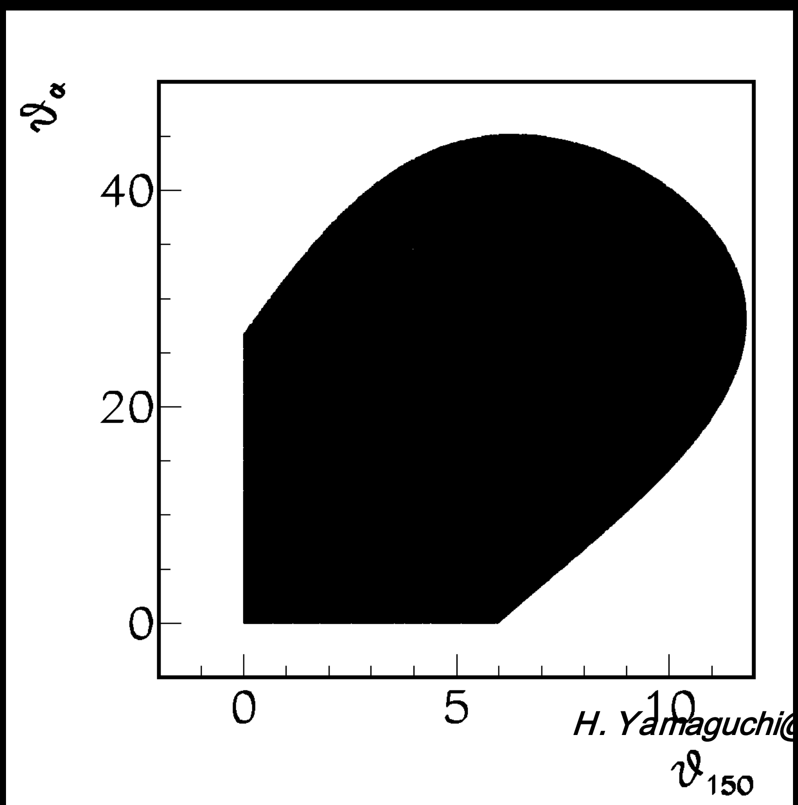
THM measurement: $^{18}F(p,\alpha)^{15}O$ via $^{2}H(^{18}F,\alpha\,^{15}O)n$

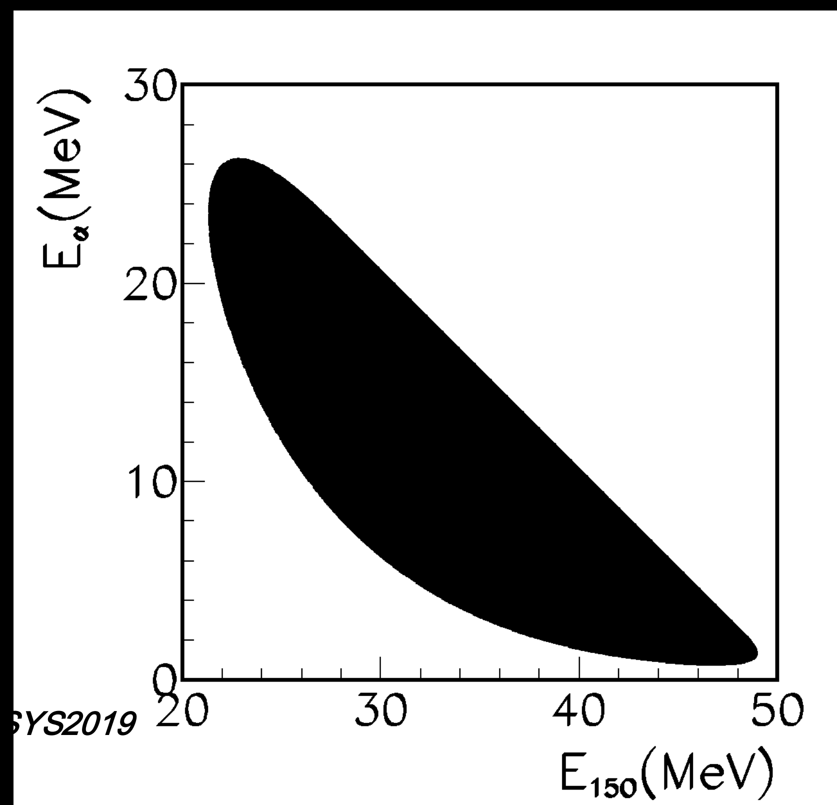
Kinematics



$^{2}H(^{18}F,\alpha\,^{15}O)n$

$E(^{18}F)$ = 50 MeV





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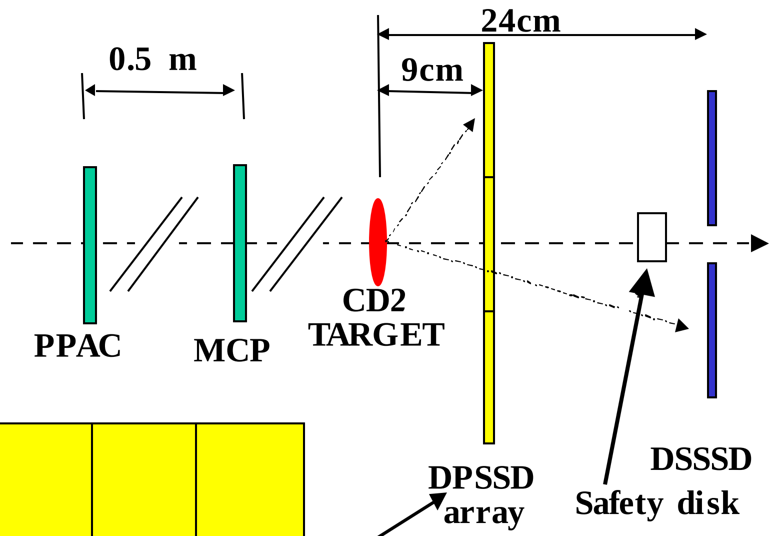
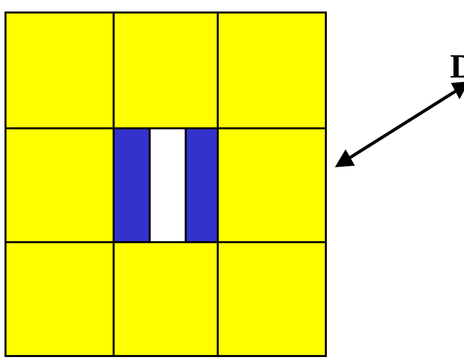
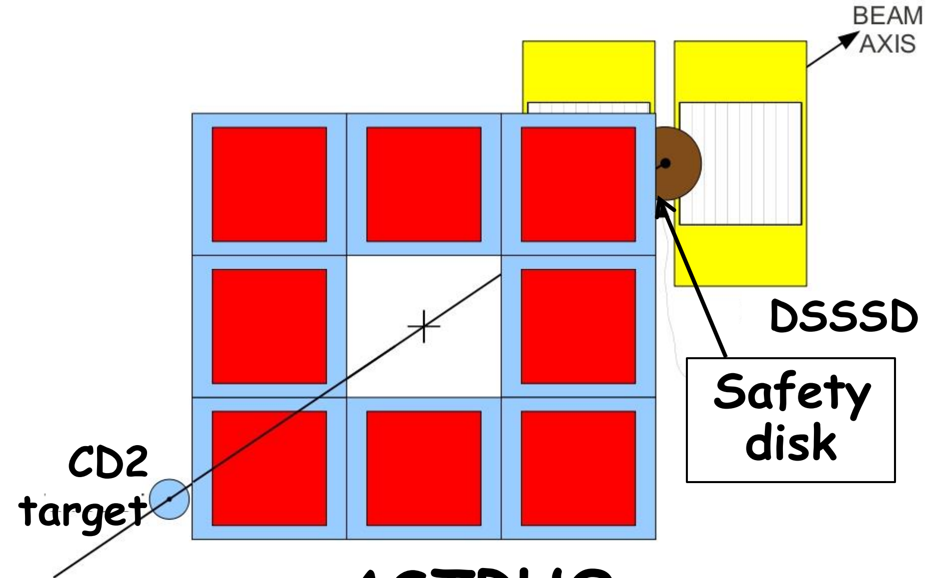
EXPERIMENTAL SETUP

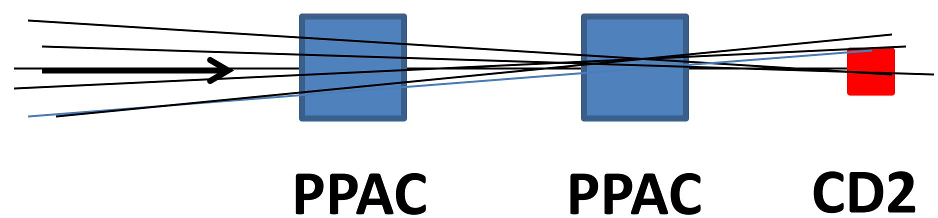




ASTRHO:
Array of Silicons for
TRojan HOrse



ASTRHO



Beam track reconstruction

EVENT SELECTION

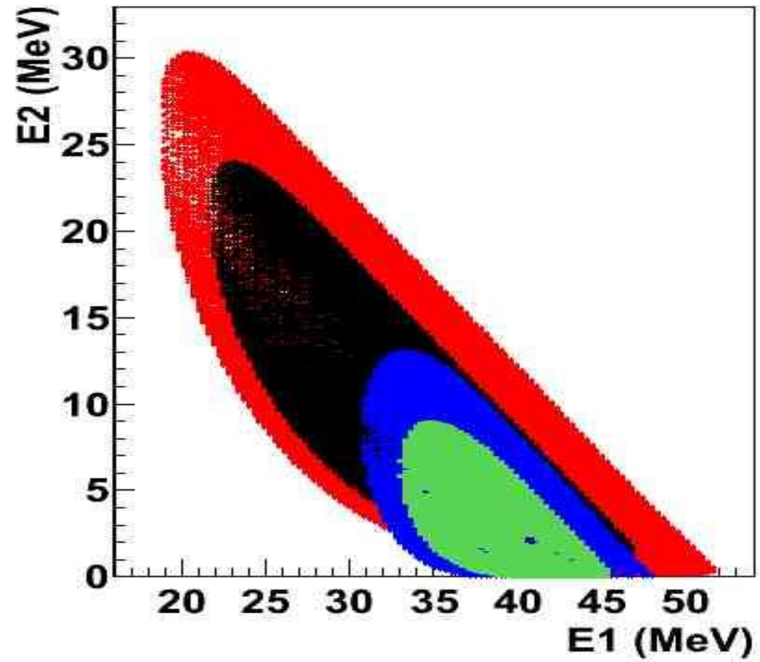
Red: $^{18}F + d \rightarrow {}^{15}N + \alpha + p$

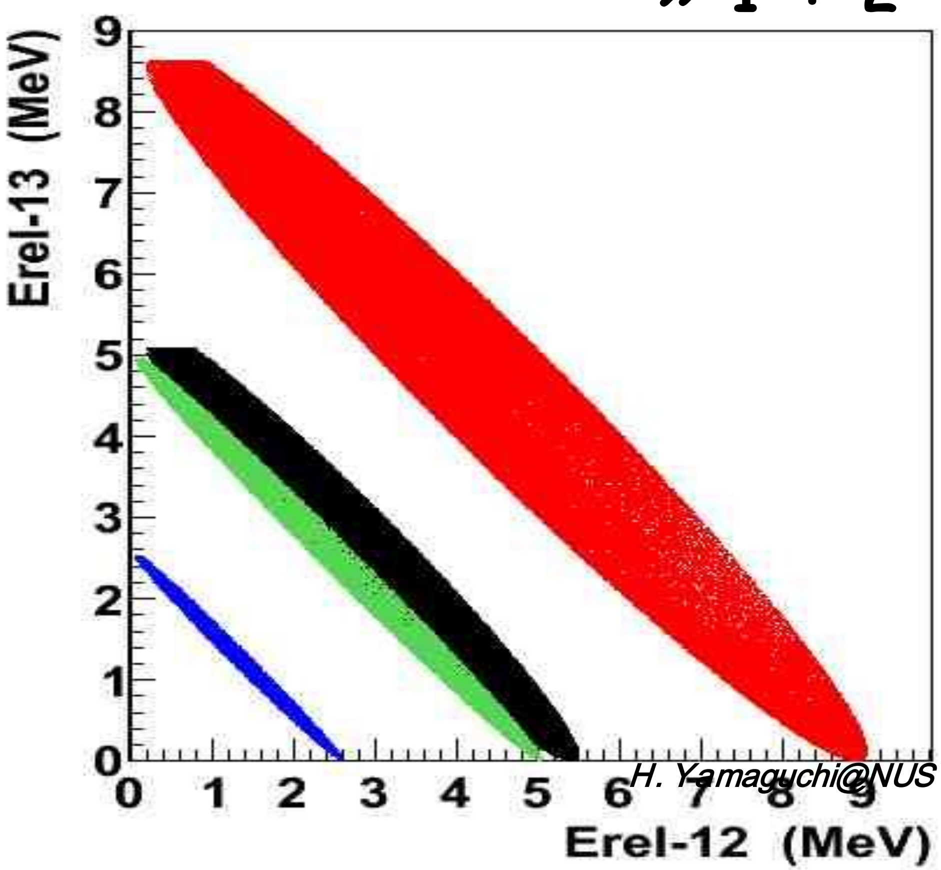
Black: $^{18}F + d \rightarrow {}^{15}O + \alpha + n$

Blue: $^{18}F + d \rightarrow {}^{18}F + p + n$

Green: $^{18}F + d \rightarrow {}^{18}O + p + p$

» 1 + 2 + 3





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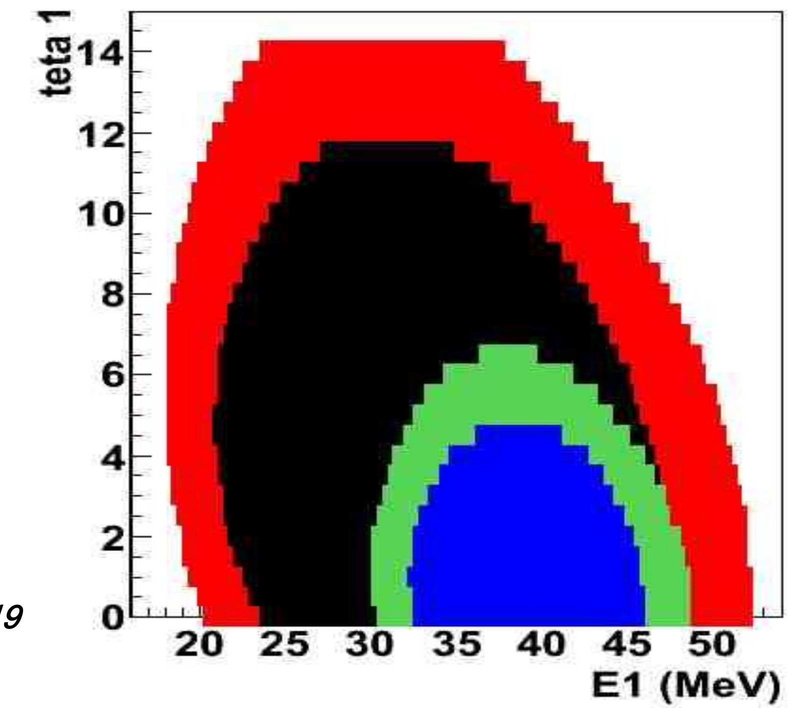
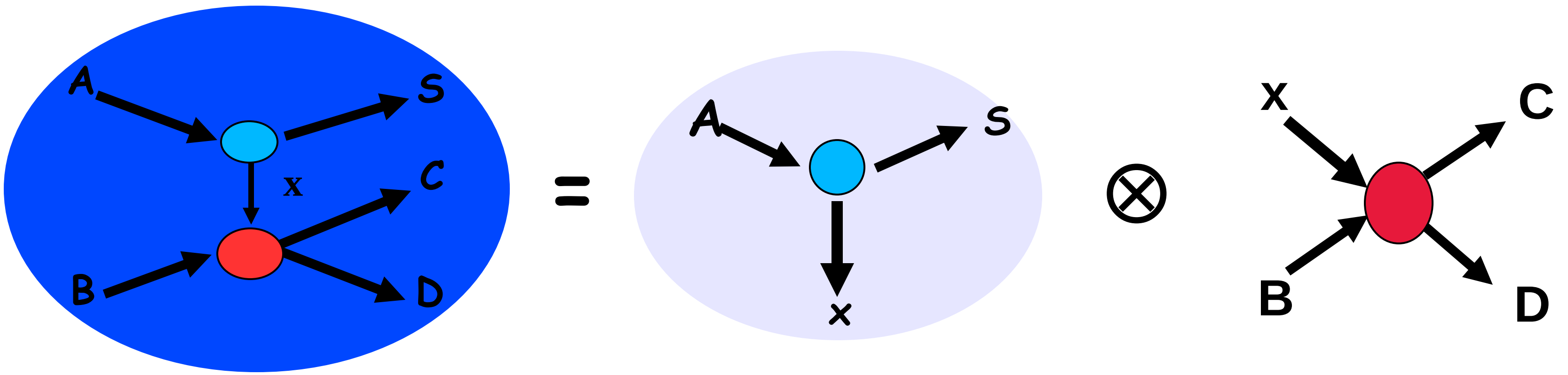


Assuming that a Quasi-free mechanism is dominant one can use the (PW)IA:



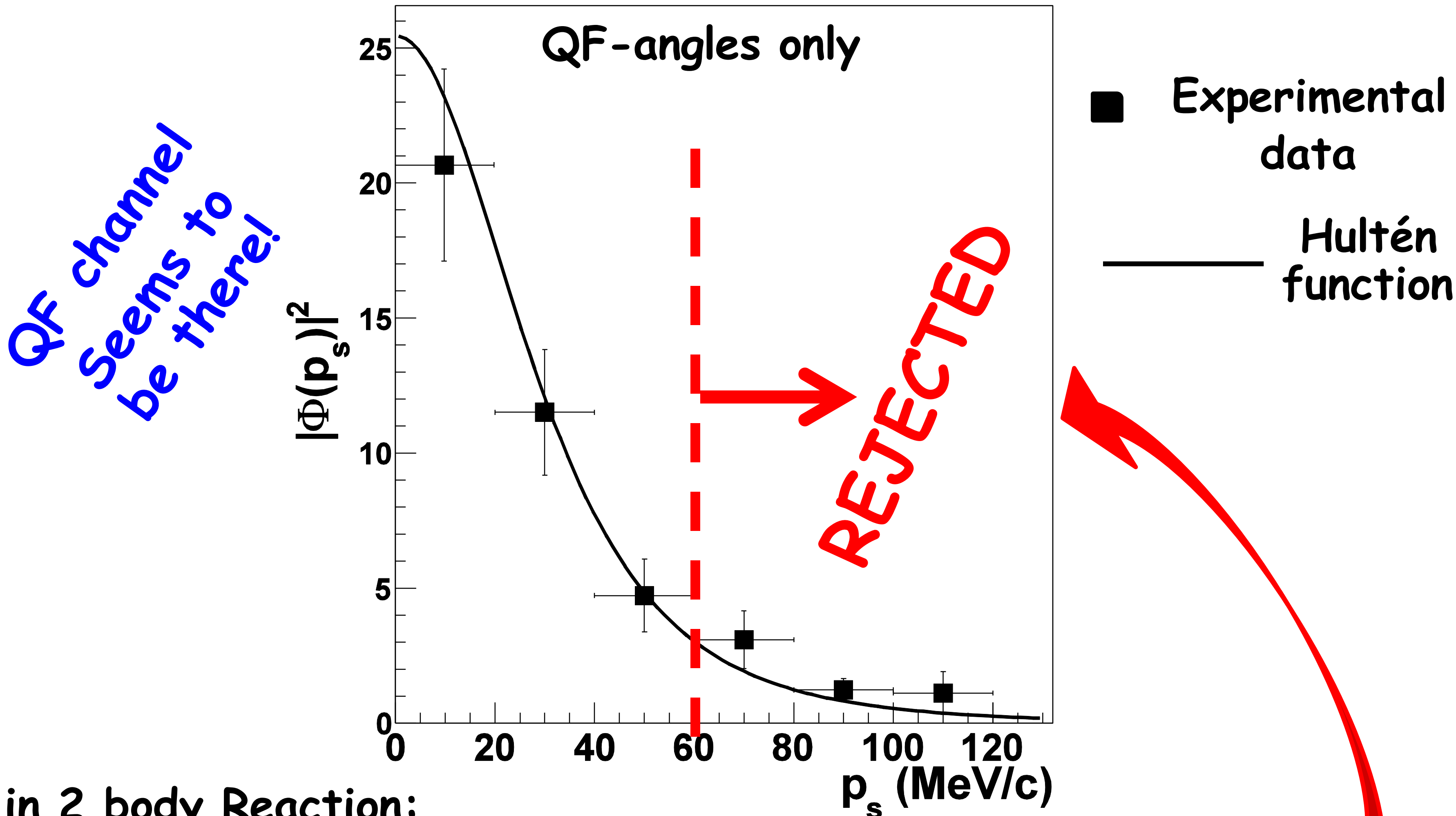
3-body Reaction = Virtual Decay ⊗ **Virtual reaction** (astrophysical process)

$$\frac{d^3\sigma}{d\Omega_C\, d\Omega_D\, dE_{cm}} \Big/ KF \cdot |\Phi(P_s)|^2 \propto \frac{d\sigma^N}{d\Omega}$$

<u>Measured at high energy</u> / <u>Calculated e.g. Montecarlo</u> ∝ <u>Indirectly Measured</u>

$E_{Bx} = E_{CD} - Q_{2b}$

EXPERIMENTAL IMPULSE DISTRIBUTION

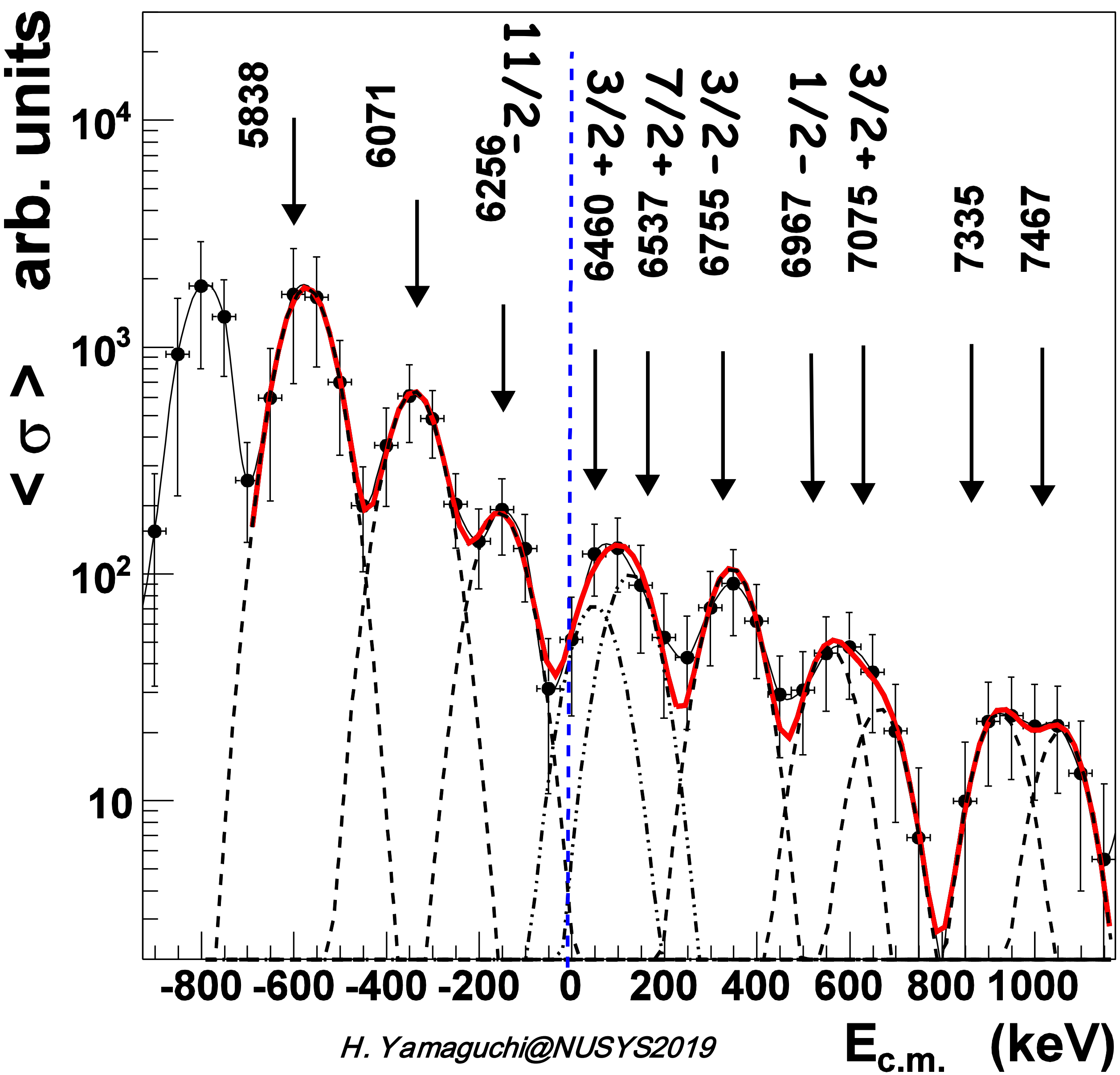


If in 2 body Reaction:

Ecm= const

Θcm =const → $d2\sigma/d\Omega$ = const → $d3\sigma/d\Omega \propto |\Phi(P_s)|^2$

THM(=barriers free) CROSS SECTION



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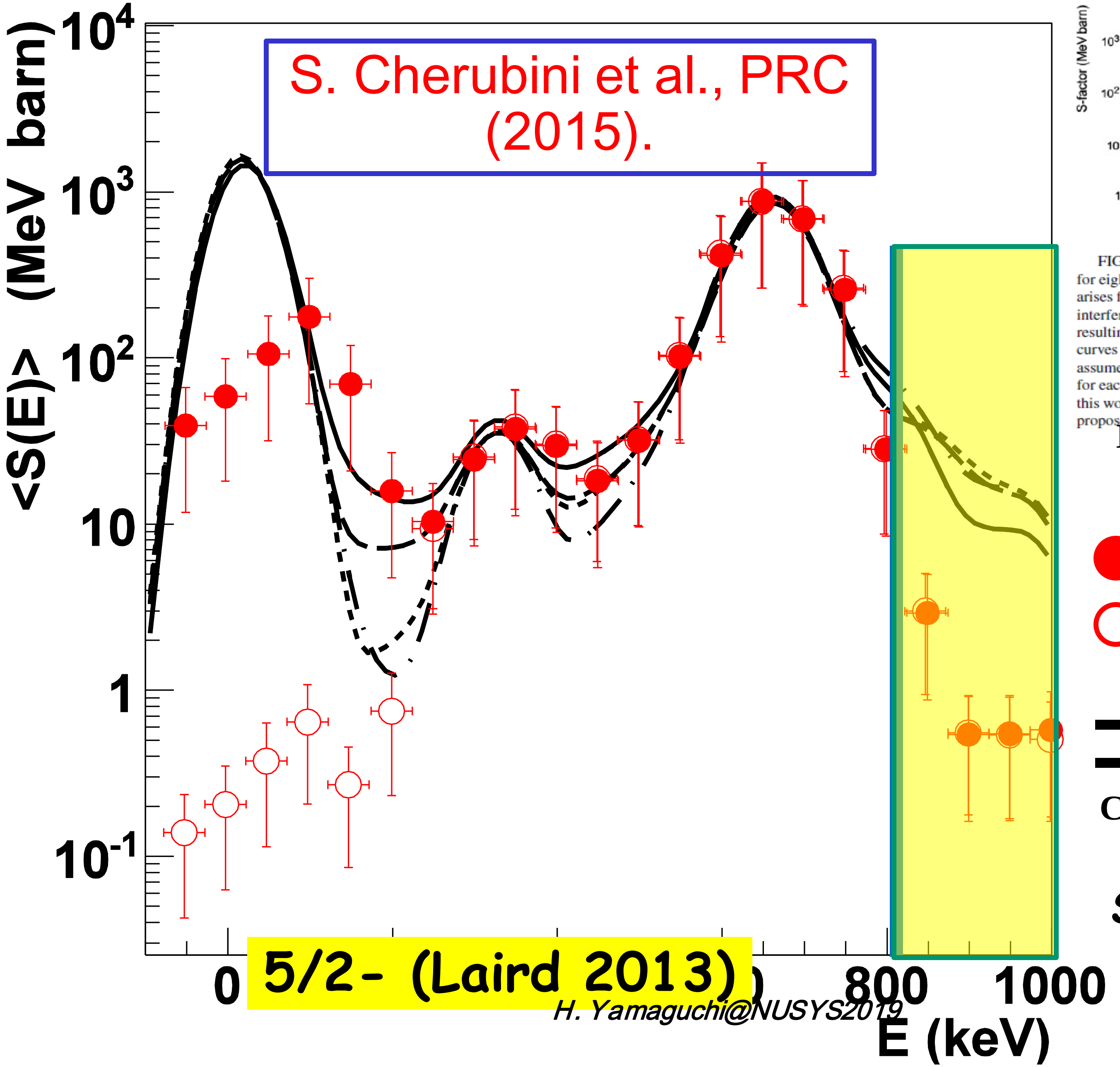
S(E) from THM 8 keV 3/2+



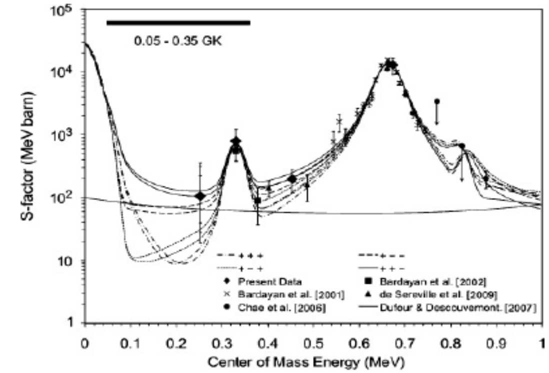


FIG. 3. The $^{18}F(p,\alpha)^{15}O$ S factors, calculated using the R matrix, for eight possible interference terms. The range in possible S factors arises from the interference between the $J^{\pi} = 3/2^{+}$ resonances. The interference between resonances dominates in the region of interest, resulting in four groups of S-factor curves. The upper and lower curves of each group are shown in the figure. The legend gives the assumed phase, for the 8-, 38-, and 665 keV resonances, respectively, for each pair of curves. Also plotted are the measured S factors from this work, those from previously published data [4,10,12,19], and the proposed contribution from $1/2^{+}$ states predicted in Ref. [6].

Direct data...C.E. Beer, et al.

THM data

C.E. Beer, Phys. Rev. C 83, 042801(R) (2011)

Smeared to THM resolution

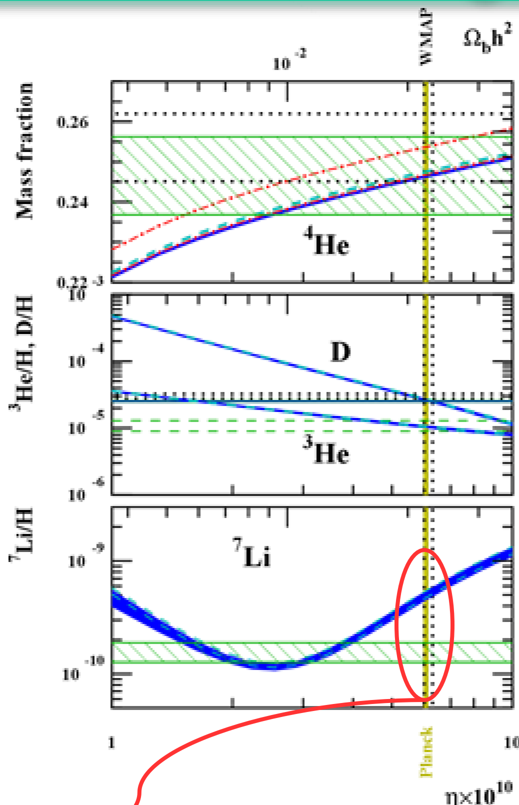
^{7}Be(n,p)^{7}Li and the ^{7}Be(n,α)^{4}He reactions with THM for cosmological lithium problem

S. Hayakawa[1], M. La Cognata[2], L. Lamia[2], H. Shimizu[1], L. Yang[1], H. Yamaguchi[1], K. Abe[1], O. Beliuskina[1], S. M. Cha[4], K. Y. Chae[4], S. Cherubini[2,3], P. Figuera[2,3], Z. Ge[5], M. Gulino[2,6], J. Hu[7], A. Inoue[8], N. Iwasa[9], D. Kahl[10],
A. Kim[11], D. H. Kim[11], G. Kiss[5], S. Kubono[1,5,7], M. La Commara[12,13], M. Lattuada[2,3], E. J. Lee[4], J. Y. Moon[14],
S. Palmerini[15,16], C. Parascandolo[13], S. Y. Park[11], D. Pierroutsakou[13], R. G. Pizzone[2,3], G. G. Rapisarda[2],
S. Romano[2,3], C. Spitaleri[2,3], X. D. Tang[7], O. Trippella[15,16], A. Tumino[2,6], P. Vi[5] and N. T. Zhang[7]

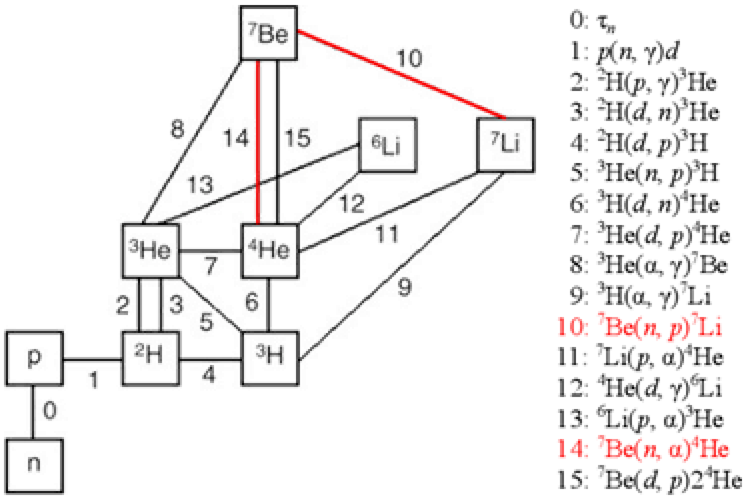
[1]Center for Nuclear Study (CNS), University of Tokyo, [2]INFN - Laboratori Nazionali del Sud,
[3]University of Catania, [4]Sungkyunkwan University, [5]RIKEN Nishina Center, [6]Kore University of Enna,
[7]Institute of Modern Physics, Chinese Academy of Sciences, [8]Research Center for Nuclear Physics (RCNP), Osaka University, [9]Tohoku University, [10]University of Edinburgh, [11]Ewha Womans University,
[12]University of Naples Federico II, [13]INFN – Naples, [14]Institute for Basic Science (IBS),
• [15]INFN - Perugia, [16]University of Perugia

Center for Nuclear Study + INFN LNS, Università degli Studi di Catania, Sungkyunkwan University + many others

Cosmological ^{7}Li problem



A. Coc et al. J. Cos. Astropart. Phys. 2014

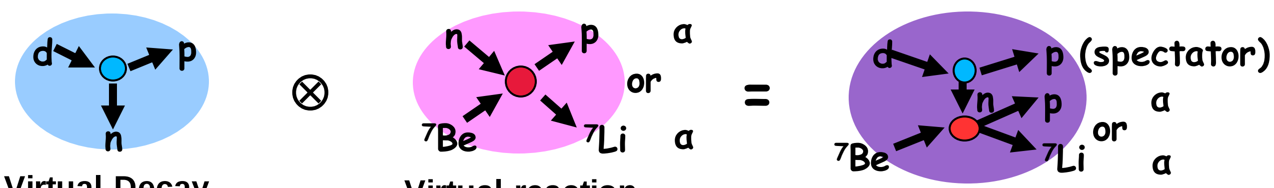


Iocco et al. Phys. Rep. 2009

- ^{7}Li problem... disagreement between theory and observation by a factor of 3−4
  - Due to CMB obs.? Low-metallicity stars obs.? Standard BBN model? Nuclear Physics?
  - ^{7}Be abundance in the end of BBN determines ^{7}Li predominantly
  - $p(n,\gamma)d$, ^{3}He$(d,p)^4$He, ^{7}Be$(n,p)^7$Li, ^{7}Be$(n,\alpha)^4$He, ^{7}Be$(d,p)2\alpha$, etc.
- Temperature ~ $10^{10} - 3\times10^8$ K, Energy: 1 MeV − 25 keV

Trojan Horse Method for RI + neutron

- Trojan Horse method: (Spitaleri+ Phys. Atom. Nucl. 2011)
- $^{7}Be(n,p)^{7}Li$, $^{7}Be(n,\alpha)^{4}He$ via $^{2}H(^{7}Be,^{7}Li\,p)^{1}H$, $^{2}H(^{7}Be,\alpha\alpha)^{1}H$
- PWIA applicable when Quasi-free mechanism is dominant



Virtual Decay — Virtual reaction — 3-body Reaction

$$\text{(Kinematic Factor)}\cdot|\Phi\,(P_s)|^2 \times \frac{d\sigma^{HOES}}{d\Omega} \propto \frac{d^3\sigma}{d\Omega_p\, d\Omega_{7Li}\, dE_{cm}}$$

Calculated by Monte Carlo simulation

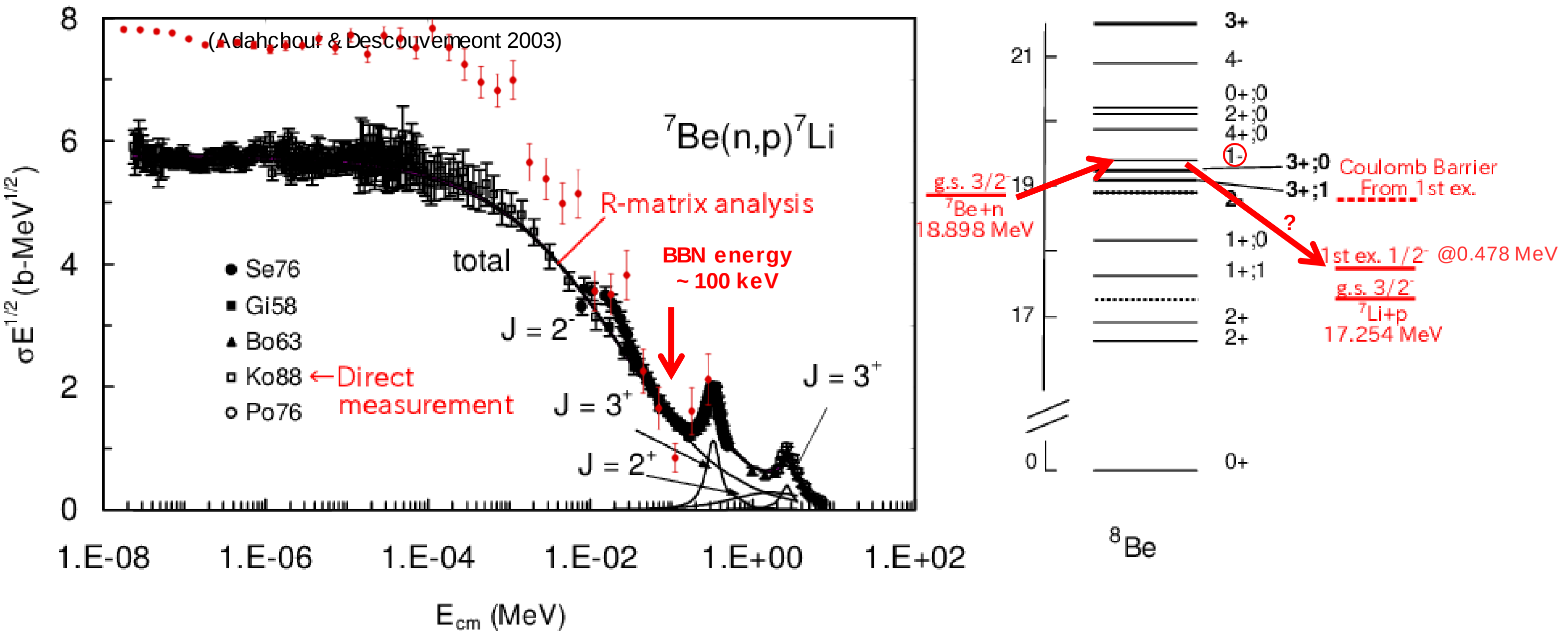
Half-off energy-shell 2-body cross section

Measured at $E_{d\text{-}7Be}$ > Coulomb barrier

↑

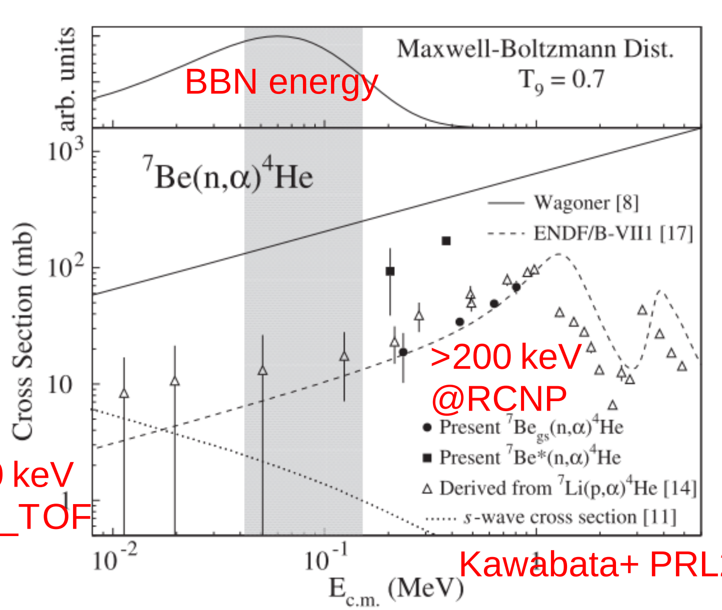
σ^{OES} = Normalization $\times\ \sigma^{HOES} \times$ Penetrability

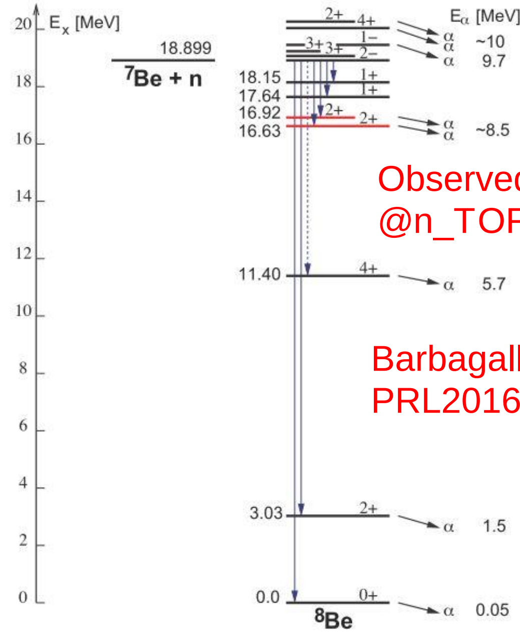
$^{7}Be(n, p)^{7}Li$ (Q = 1.644 MeV)



- Sensitivity: $\partial \log Y_{7Li} / \partial \log \langle \sigma v \rangle_{7Be} = -0.71$ (Coc & Vangioni 2010, Cyburt+ 2016, etc.)
  If 5 × higher rate ➡ ^{7}Li problem solved
- Direct measurement up to 13.5 keV, time-reversal reactions at higher energies.
- R-matrix analysis: Adahchour & Descouvemont 2003.
- New n_TOF measurement: enhancement below BBN energies (Damone+ PRL 2018)

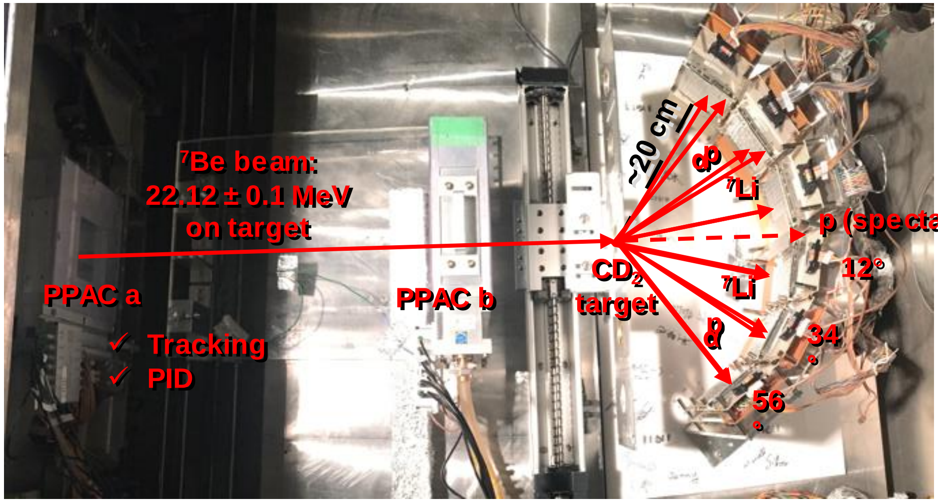
$^{7}Be(n,\alpha)^{4}He$ (Q = 18.990 MeV)





- Hou et al. PRC 2015: evaluation from $^{4}He(\alpha,p)^{7}Li$
- Barbagallo et al. PRL 2016: s-wave measurement @ nTOF
- Kawabata et al. PRL 2017: p-wave measurement @RCNP
- Lamia et al. APJ 2017: evaluation of $^{7}Li(p,\alpha)$ data measured by THM.
- Recent works consistent... Yet no direct data in the BBN range.

Experimental setup



- 6 ΔE-E position sensitive silicon telescopes
- ^{7}Li-p and α-α coincidence measurements

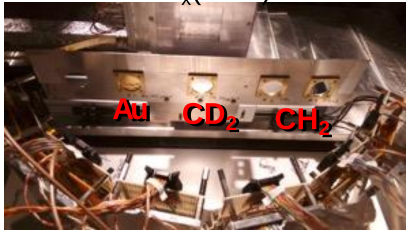
… spectator not measured

- CD_2: 64 μg/cm^2

➡ ΔE_{beam} ~ 150 keV

➡ To resolve $E_x(^7\mathrm{Li}^{1st})$ = 478 keV

- Hamamatsu Charge-division PSD: position resolution ~ 0.5 mm

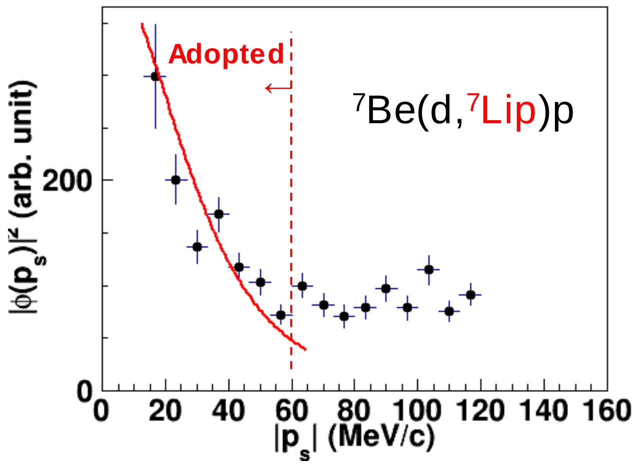


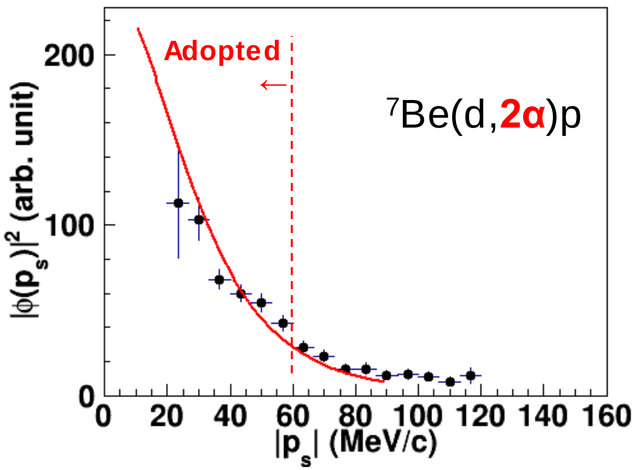
➡ Total angular resolution (PPACs & PSDs & alignment) ∽ 0.5° ➡ ΔE_{cm} ~ 60 keV

Momentum distributions of the spectator *p*

$Y_{exp}/Y_{sim} \propto d^3\sigma/(d\Omega_p d\Omega_{7Li} dE_{cm})$ / KF $\propto |\Phi(p_s)|^2 d\sigma/d\Omega$

$\sim |\Phi(p_s)|^2$ at a fixed $E_{c.m.}$ and $\theta_{c.m.}$ ($\Leftrightarrow$ 2-body cross section is const.)

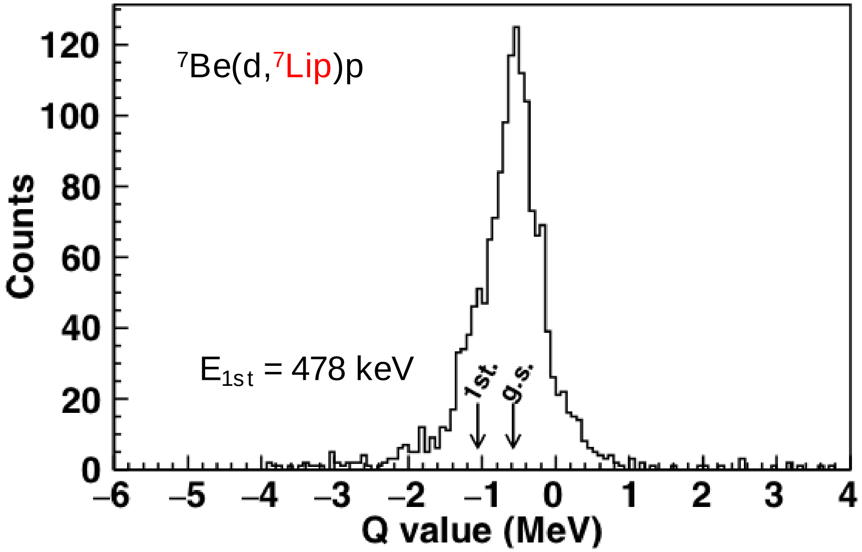


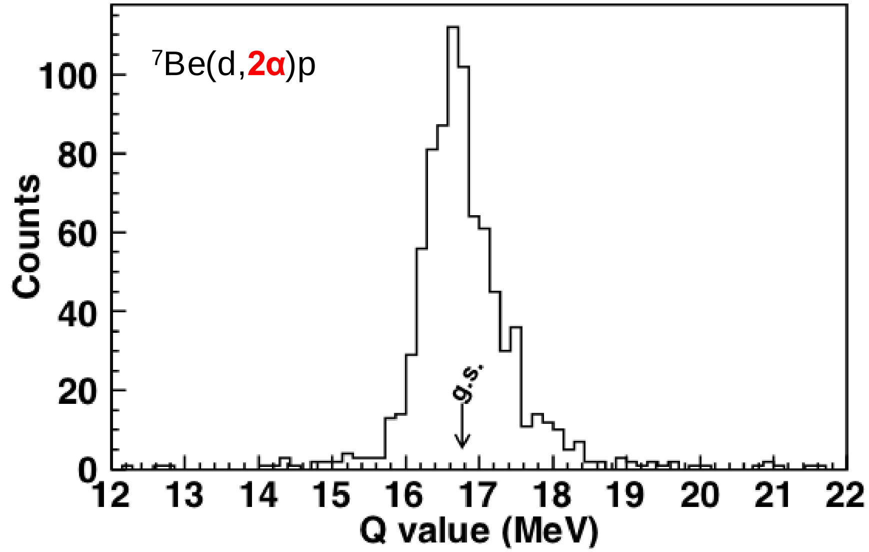


Hulthén function in momentum space
for p-n intercluster motion (PWIA app.)

Good agreement up to 60 MeV/c
Evidence that quasi-free contribution is dominant.→ THM is valid!

Q-value spectra of the 3-body channels





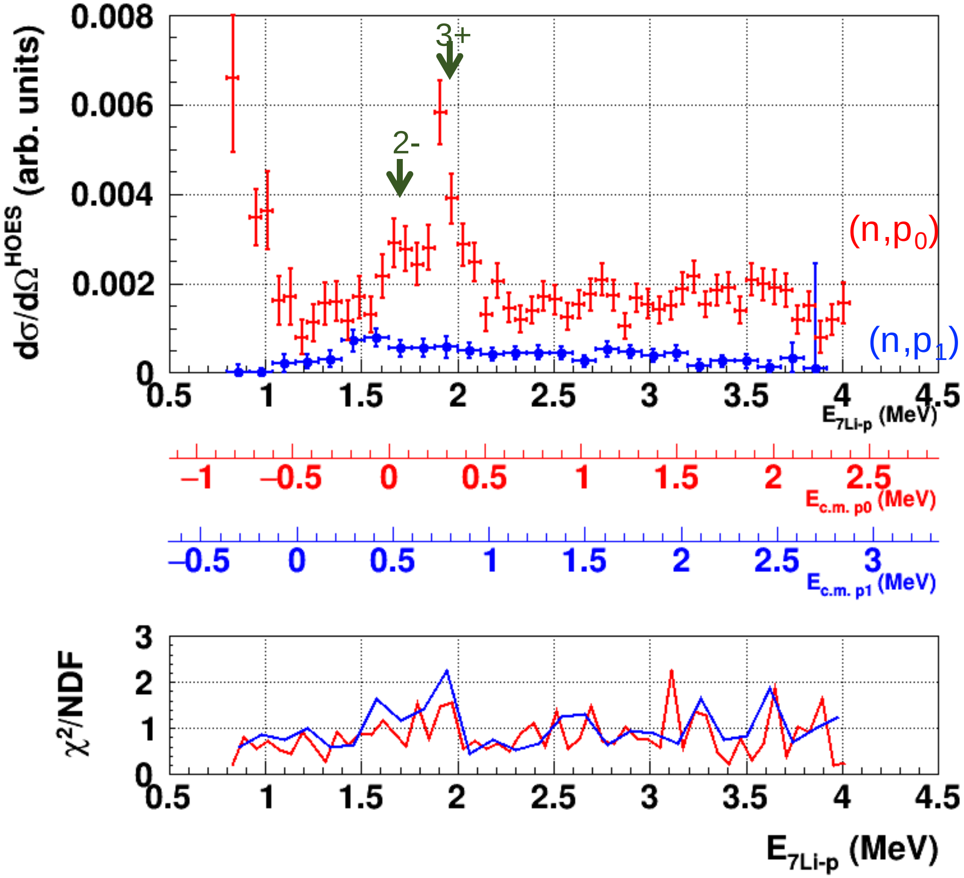
Reaction	*Q*-value (MeV)
p+2α	16.766
^{7}Li+2*p*	-0.589
^{7}Be+*n*+*p*	-2.225
^{5}He+*p*+^{3}He	-4.547

$Q_{3body} = E_1 + E_2 + E_3 - E_{beam}$

$\Delta Q_{3body} \sim \sqrt{(\Delta E_1^2 + \Delta E_2^2 + \Delta E_3^2 + \Delta E_{beam}^2)}$

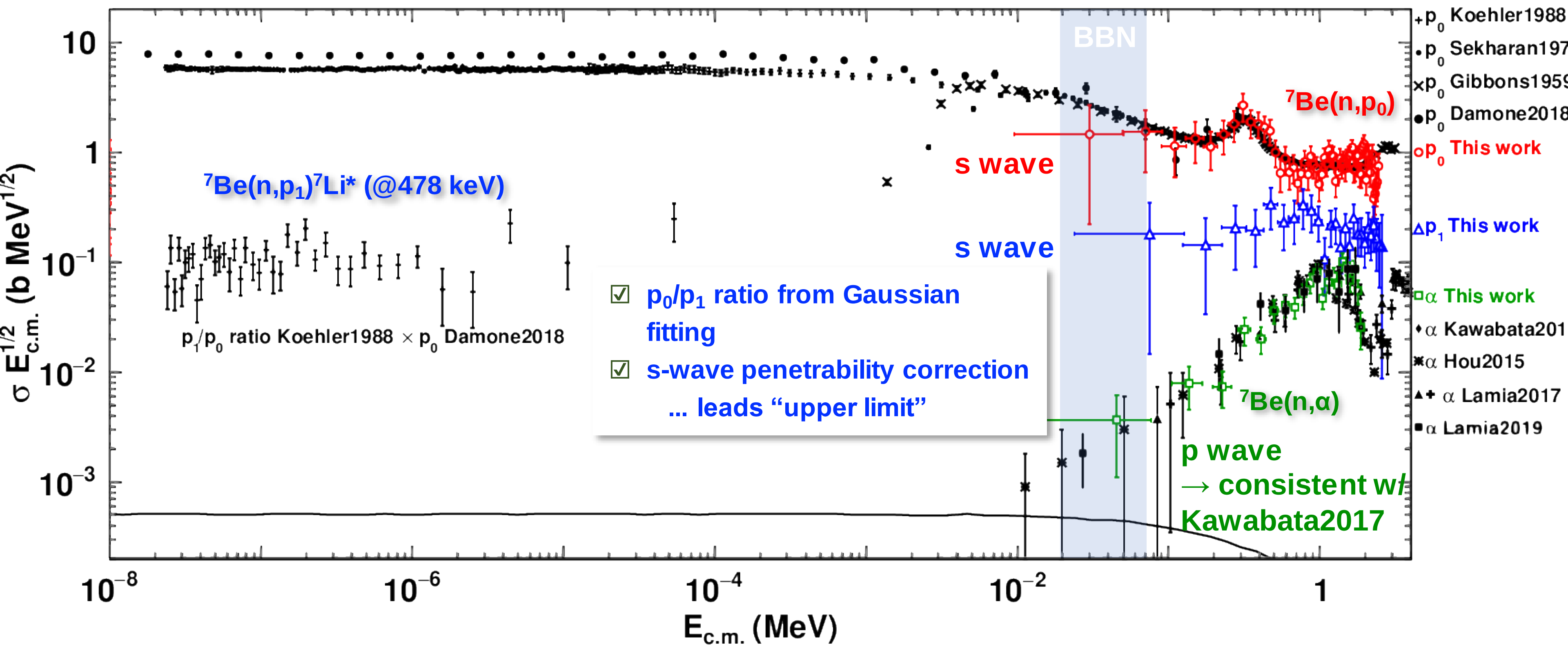
~ 200 keV expected with 64 μg/cm^2 CD_2

Gaussian fitting to Q-value spectra

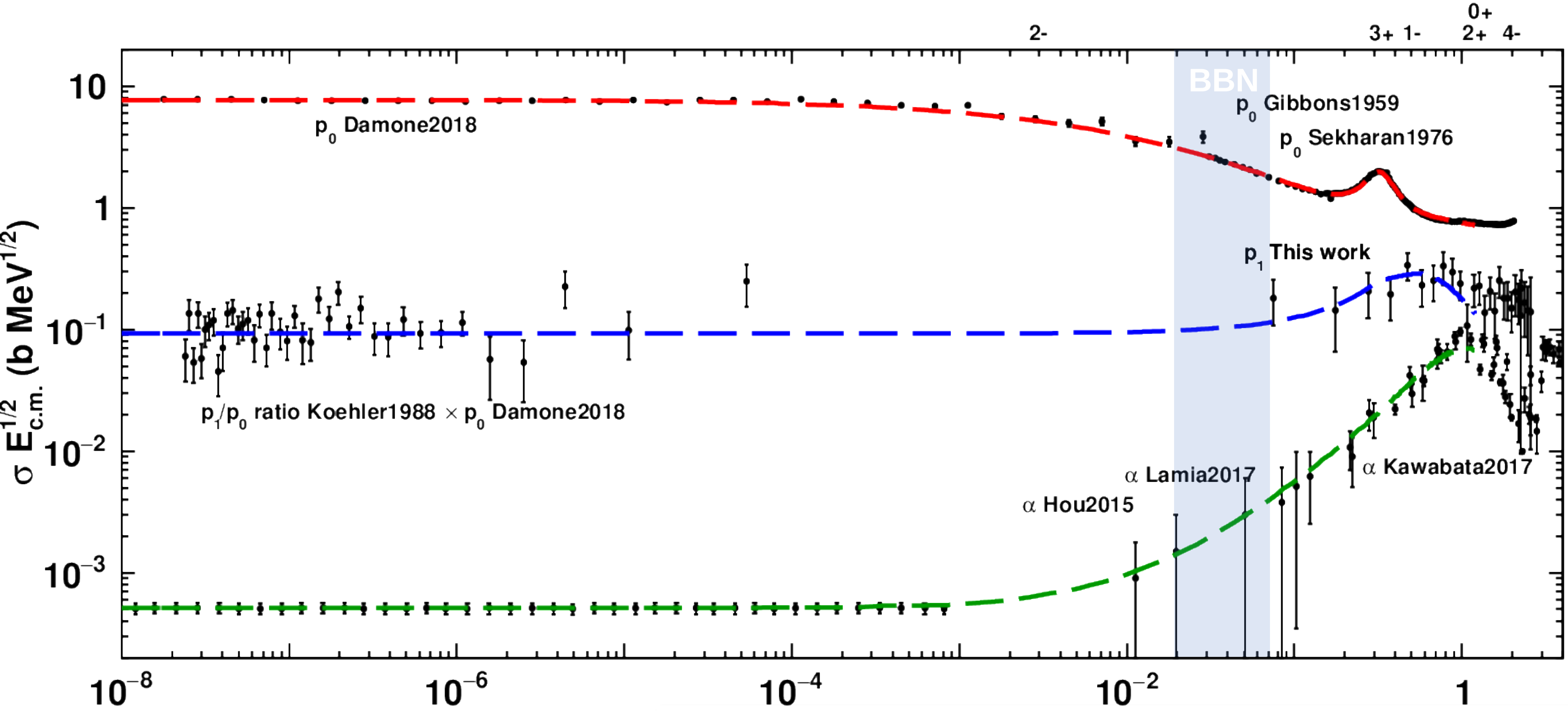


- Isotropy assumed (as no strong angular dependence seen)
- Checked systematic change of widths & peaks
  ➡ Reduces errors

$^7Be(n,p_0)$, (n,p_1) & (n,α_0) cross sections by CRIB



(Preliminary) R-matrix fitting by AZURE2



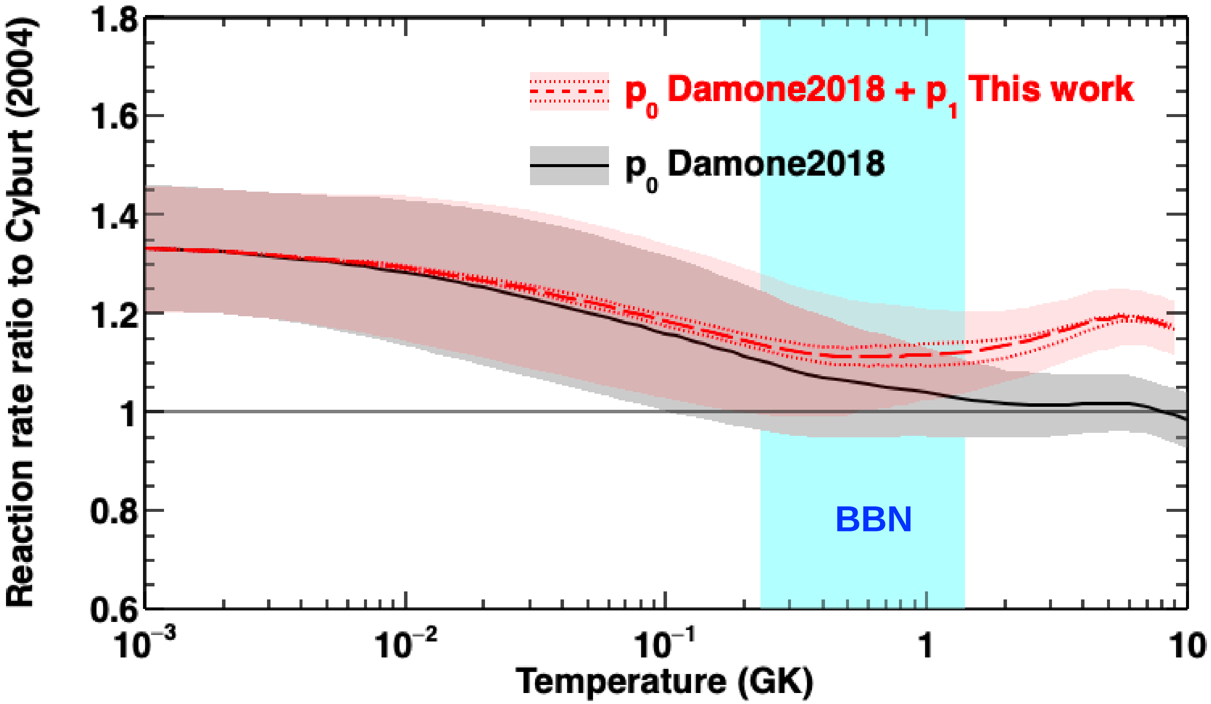
Condition (starting from simple assumptions):

- ☑ Fix known J^{π} and $E_{resonance}$ (except 1-)
- ☑ Adopt $l \leqq 3$
- ☑ Exclude no neutron emission states
- ☑ Fit Only $E_{c.m.} < 1.2$ MeV

Procedure:

- ☑ Start from (n,p_0) channel with Ada.&Desc.2003 parameters.
- ☑ Fit only (n,p_1) and (n,α) channels.
- ☑ Fit (n,p_0) channels again.
- ☑ Fix converged parameters and iterate.
- ☑ χ^2 converged (preliminary): $\chi^2_{p0}/NDF = 1.59$, $\chi^2_{p1}/NDF = 1.33$, $\chi^2_{\alpha}/NDF = 0.68$

Revised ^{7}Be(n,p) Reaction rate



n_TOF result (Damone+ PRL2018):
~ 5% higher rate in BBN range
➡ 96% ^{7}Li abundance

This work:
~ 15±15% higher rate (preliminary)
➡ ~ 90% ^{7}Li abundance (preliminary)
(with the sensitivity $\partial \log Y_{7Li} / \partial \log\langle\sigma v\rangle_{7Be} = -0.71$)

Recent ^{7}Be+d work @ FSU
(Rijal+ PRL122, 182701 (2019)):
Resonance of (d,α) channel just in BBN Gamow window
➡ ~ 87% ^{7}Li abundance

Considering (n_TOF + CRIB) x FSU
➡ ~ 80% ^{7}Li abundance

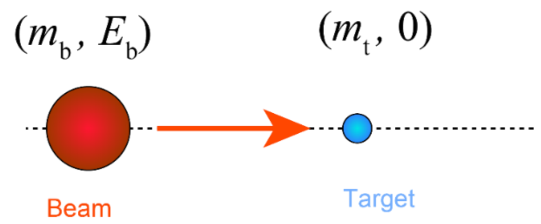
Summary

- Study on astrophysical reactions with (low-energy) RI beams:
  - Not easy, but possible for some cases
  1. Direct measurement with Intense RI beam, or efficient measurement by TTIK.
  2. Resonant scattering to study resonances
  3. Indirect methods
  - Active target…new experimental technique to make a complete thick-target experiment/low-energy reaction study
  - CRIB at CNS, the University of Tokyo, providing unique low-energy (<10MeV/u) RI beams…we welcome new collaborators and new ideas.

http://www.cns.s.u-tokyo.ac.jp/crib/crib-new/

Homework (In-flight RI beam)

[1] A ^{7}Be beam is created by the in-flight method, using a ^{7}Li beam (mass: M_b) at an energy of E_b and a hydrogen (Mass M_t) target. How much is the maximum angle deviation of the produced ^{7}Be particle from the original ^{7}Li beam trajectory?



For simplicity, you can assume

-The maximum angle deviation occurs when $\theta_{c.m.}$ is close to $90°$.

-Q-value in the production reaction (p,n) is negligible. (^{7}Li/^{7}Be masses are the same.)

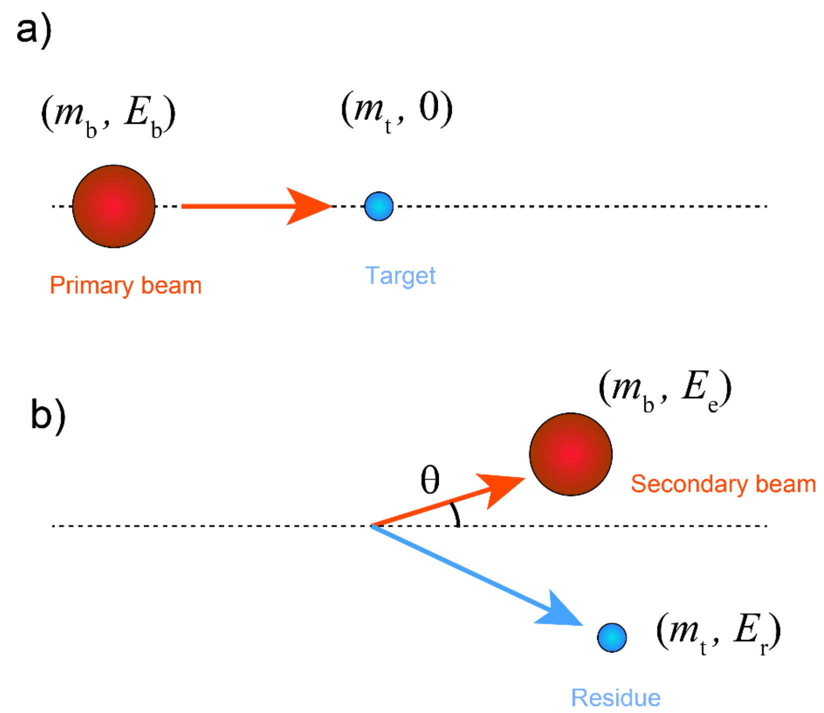
-The energy loss in the target is ignorable.

Hint) You can use the formula, $\cos\theta_{lab} = \frac{x+\cos\theta_{c.m.}}{\sqrt{1+x^2+2x\cos\theta_{c.m}}^2}$, $x = \frac{M_b}{M_t}$

Homework

[2] When the ^{7}Li beam energy is E_b = 10MeV/u (~70 MeV) and ^{7}Be produced with the angle $\theta_{lab} < 3°$ is accepted, how much is the energy spread $\Delta E_e / E_e$? Here we define ΔE_e as the energy difference of the ^{7}Be beam particle at $0°$ and $3°$.

Hint) Consider energy -momentum conservation.



Answer

[1] Use the formula $\cos\theta_{\text{lab}} = \frac{x + \cos\theta_{\text{c.m.}}}{\sqrt{1 + x^2 + 2x\cos\theta_{\text{c.m}}}^2}$, $x = \frac{M_{\text{b}}}{M_{\text{t}}}$.

At $\theta_{\text{c.m.}} \sim 90°$,

$$\cos\theta_{\text{max}} = \frac{x}{\sqrt{1+x^2}} = \frac{1}{\sqrt{1+1/x^2}}$$

As $1/x^2 \ll 1$,

$$\cos\theta_{\text{max}} \simeq 1 - \frac{1}{2x^2}$$

On the other hand, for small angles,

$$\cos\theta \simeq 1 - \frac{1}{2}\theta^2$$

Therefore,

$$\theta_{\text{max}} \simeq \frac{1}{x} = \frac{1}{7}(\text{rad}) = 8.2°$$

Answer

[2] Energy conservation: $E_b = E_e + E_r$ ... (1)

Momentum conservation:

$p_b = p_e \cos\theta + p_r \cos\varphi$ ... (2)

$0 = p_e \sin\theta - p_r \sin\varphi$ ... (3)

φ is the (laboratory) scattering angle of the residual particle (neutron).

Using (2) and (3),

$$p_r^2 (\cos^2\varphi + \sin^2\varphi) = p_e^2 + p_b^2 - 2 p_b p_e \cos\theta$$

From (1),

$$p_r^2 = 2M_t E_r = 2M_t(E_b - E_e) = (1/x)(p_b^2 - p_e^2) \qquad (x \equiv \frac{M_b}{M_t})$$

Combining these, we obtain a quadratic equation as,

$$(1 + \frac{1}{x})p_e^2 - 2p_b p_r \cos\theta + (1 - \frac{1}{x})p_b^2 = 0$$

The solution is,

$$p_e = \frac{\cos\theta \pm \sqrt{\cos^2\theta - (1 - \frac{1}{x^2})}}{1 + \frac{1}{x}} p_b$$

Answer

Take the positive sign solution of $p_e = \dfrac{\cos\theta \pm \sqrt{\cos^2\theta - (1-\frac{1}{x^2})}}{1+\frac{1}{x}} p_b$

- For $\theta = 0°$

$$p_e = \frac{1+\sqrt{1-(1-\frac{1}{x^2})}}{1+\frac{1}{x}} p_b = p_b$$

This means the momentum (or energy) of the secondary beam is the same as the primary beam (under present approximation).

- For $\theta = 3°$, and $x = 7$

$$p_e = \frac{\cos\theta + \sqrt{\cos^2\theta - (1-\frac{1}{x^2})}}{1+\frac{1}{x}} p_b = \frac{0.99863+\sqrt{0.99863^2-(1-\frac{1}{7^2})}}{1+\frac{1}{7}} p_b = 0.9901\ p_b$$

$$\Delta p_e/p_e = 1 - 0.9901 \sim 1\%$$

$$\Delta E_e/E_e \sim 2\%$$

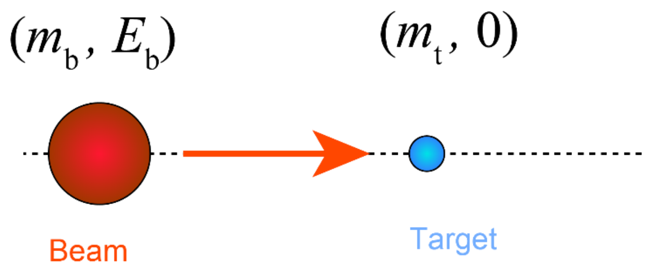
Implication

- The result shows the produced ^{7}Be particles mostly go to the forward angle (< 8°). Taking the most forward angles, the ^{7}Be particles have similar energies (within 2%). This is why it can be regarded as a secondary beam.
- For higher mass particle beam, the secondary beam is even more focused to the forward angle (while the stopping power is huge).
- The energy (10MeV/u) was not used…the solution is independent of the energy (but remember it's an approximation).
- The negative solution in [2] also makes a beam with another energy. The positive (negative) solution corresponds to events in which the residual is scattered to very backward (forward) angle.

Homework (TTIK)

[1] Suppose we make a scattering experiment by irradiating a beam (kinetic energy E_b, mass M_b) onto a target (Mass M_t). Show that the center-of-mass energy $E_{c.m.}$ (energy of the system in the center-of-mass frame) at the scattering is given by the following formula for non-relativistic energy:

$$E_{c.m.} = \frac{M_t}{(M_b + M_t)} E_b$$



Hint) In c.m. frame, the sum of the momentum vectors will be zero.

Note) This result implies that the $E_{c.m.}$ resolution can be better than the uncertainty of the beam energy in the inverse kinematics condition, $M_b > M_t$.

Homework

[2] In the resonant scattering experiments in inverse kinematics, we measure the energy and the angle of the recoiling ion, E_r and θ. First we consider a thin-target case, where the energy loss in the target is negligible.

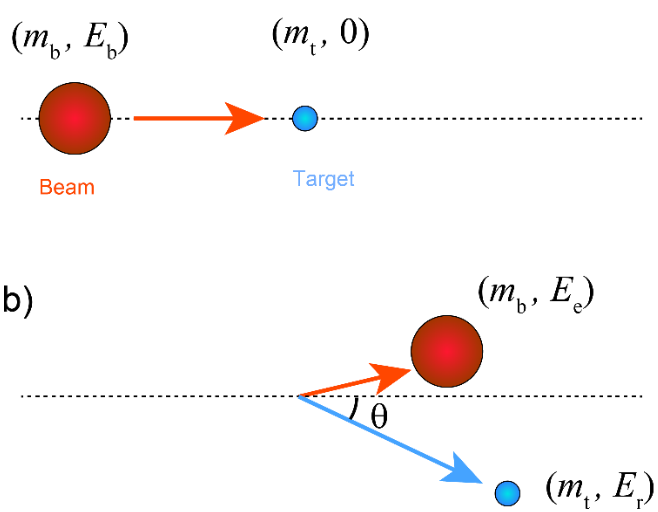
Assuming the particle masses and the beam energy E_b are known, how do you obtain the $E_{c.m.}$ of the scattering events from the measured quantities?

a) Before scattering

b) After scattering

a)

b)



Homework

[3] How the formula can be modified when we use a thick-target in which the beam energy is significantly degraded. (Can we still obtain $E_{\mathrm{c.m.}}$ from the measured E_{r} and θ?)

[4] What are the advantages and disadvantages of the TTIK (thick-target in inverse kinematics) method, as compared to the traditional, normal kinematics method?

Answer

[1] There are several ways to calculate it.

One way is to calculate the invariant mass, ${M_{\mathrm{INV}}}^2 = E^2 - \vec{p}^2$ for each frame. (Here we use a unit with $c = 1$, and $E^2 = m^2 + p^2$ is the squared relativistic energy.)

Momentum of b: $p_{\mathrm{b}} = \sqrt{2 M_{\mathrm{b}} E_{\mathrm{b}}}$

Total energy of b: $E = \sqrt{{M_{\mathrm{b}}}^2 + {p_{\mathrm{b}}}^2} \sim M_{\mathrm{b}} + E_{\mathrm{b}}$ (non-relativistic case)

Lab frame: ${M_{\mathrm{INV}}}^2 = ((M_{\mathrm{b}} + E_{\mathrm{b}}) + M_{\mathrm{t}})^2 - {p_{\mathrm{b}}}^2$

$= ((M_{\mathrm{b}} + M_{\mathrm{t}}) + E_{\mathrm{b}})^2 - 2 M_{\mathrm{b}} E_{\mathrm{b}}$

$\sim (M_{\mathrm{b}} + M_{\mathrm{t}})^2 + 2 E_{\mathrm{b}} (M_{\mathrm{b}} + M_{\mathrm{t}}) - 2 M_{\mathrm{b}} E_{\mathrm{b}}$

$= (M_{\mathrm{b}} + M_{\mathrm{t}})^2 + 2 E_{\mathrm{b}} M_{\mathrm{t}}$

CM frame: consider a combined system with a mass $(M_{\mathrm{b}} + M_{\mathrm{t}})$, and momentum vectors are cancelled out.

$${M_{\mathrm{INV}}}^2 = (M_{\mathrm{b}} + M_{\mathrm{t}})^2 + 2 (M_{\mathrm{b}} + M_{\mathrm{t}}) E_{\mathrm{c.m.}}$$

These must be equal,

$2 (M_{\mathrm{b}} + M_{\mathrm{t}}) E_{\mathrm{c.m.}} = 2 E_{\mathrm{b}} M_{\mathrm{t}}$

$E_{\mathrm{c.m.}} = E_{\mathrm{b}} \, M_{\mathrm{t}} / (M_{\mathrm{b}} + M_{\mathrm{t}})$

Answer

[2] Energy conservation: $E_b = E_e + E_r$ ... (1)

Momentum conservation:

$p_b = p_e \cos\varphi + p_r \cos\theta$ ... (2)

$0 = p_e \sin\varphi - p_r \sin\theta$ ... (3)

φ is the (laboratory) scattering angle of the ejectile.

From (2) and (3),

$p_e^2 (\cos^2\varphi + \sin^2\varphi) = p_r^2 + p_b^2 - 2 p_b p_r \cos\theta$

Rewritten with energies:

$2M_b E_e = 2M_t E_r + 2M_b E_b - 2 p_b p_r \cos\theta$

Using (1),

$(M_b + M_t) E_r = p_b p_r \cos\theta$

Square both sides,

$(M_b + M_t)^2 E_r^2 = p_b^2 p_r^2 \cos^2\theta = 4 M_t E_r M_b E_b \cos^2\theta$

$$E_r = \frac{4 M_t M_b \cos^2\theta}{(M_b + M_t)^2} E_b = \frac{4 M_b \cos^2\theta}{(M_b + M_t)} E_{c.m.}$$

Answer

[3] In the thick-target method condition, the formula we obtained in [2],

$$E_r = \frac{4M_t M_b \cos^2\theta}{(M_b + M_t)^2} E_b = \frac{4M_b \cos^2\theta}{(M_b + M_t)} E_{c.m.}$$

is only valid at the scattering point.

E_b is obtained from the original beam energy E_{b0}, if the energy loss of the beam particle is known (we assume that is known by experiment or theory):

$$E_b = E_{b0} - E_{loss,b}(L),$$

where L is the distance from the target entrance to the reaction position.

The recoiling particle energy we measure (E_{meas}) is also modified by

$$E_r = E_{detec} - E_{loss,b}(L_2)$$

L_2 is the length that the recoiling particle runs in the target, known from L and the scattering angle θ.

Therefore, if only L is known, we can get $E_{c.m.}$ from the above relationship.

Answer

[3] (continued) L cannot be known immediately, but can be obtained, such as, in the following way:

(I) Assume a certain value of L, such that the reaction position will be inside the target.

(II) Calculate E_b, E_r , E_{detec}, using this L and measured θ.

(III) If calculated E_{detec} is larger than the real measurement, it means the reaction actually occurred more downstream (and vice versa).

(IV) Shift L to the correct direction and repeat (II)-(III), until true E_{detec} is found.

By performing this iterative calculation, we can obtain $E_{c.m.}$ event by event.

Answer

[4] (The following does not cover everything)

Advantages:

-Simultaneous measurement of a certain range of energy → Good statistics with no systematic error for the beam intensity at each energy.

-No need to change the energy step by step (Nice feature for RI beams/cyclotron beams).

-When the beam is stopped in the target, measurement at $\theta_{c.m.}=180^o$ is possible. (Coulomb scattering is minimal.)

Disadvantages:

-No identification between two or more processes emitting the same kind of ion (if we do not use an "active target"), e.g., elastic and inelastic proton scatterings.

-Resolution limited by the energy straggling of the beam.

-Precise energy loss function is needed (otherwise we easily get shift, skew, and wrong normalization of the spectrum.)