α-resonance-scattering measurements at CRIB

- ✓ Introduction of CRIB facility
- ✓ Method…Thick target method in inverse kinematics
- ✓ Experiments…^{7}Li+α / ^{7}Be+α
- ✓ Summary

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CRIB members:

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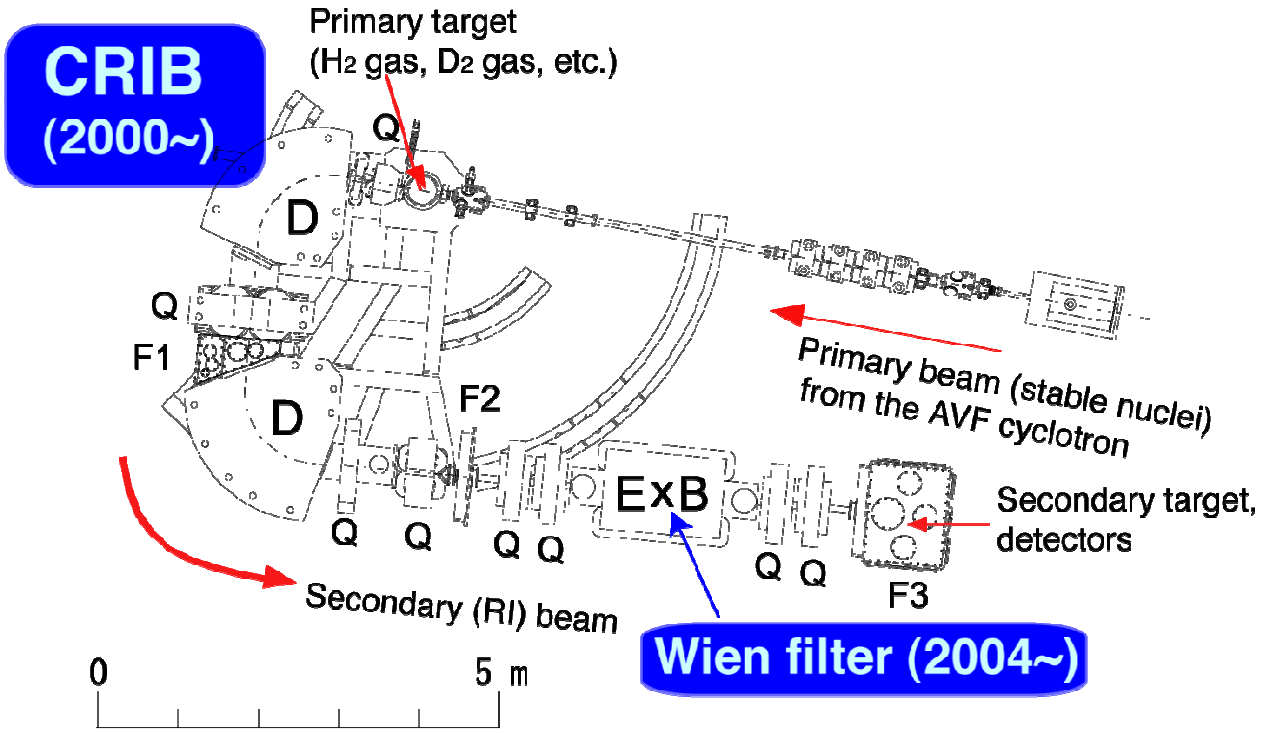
CRIB Introduction

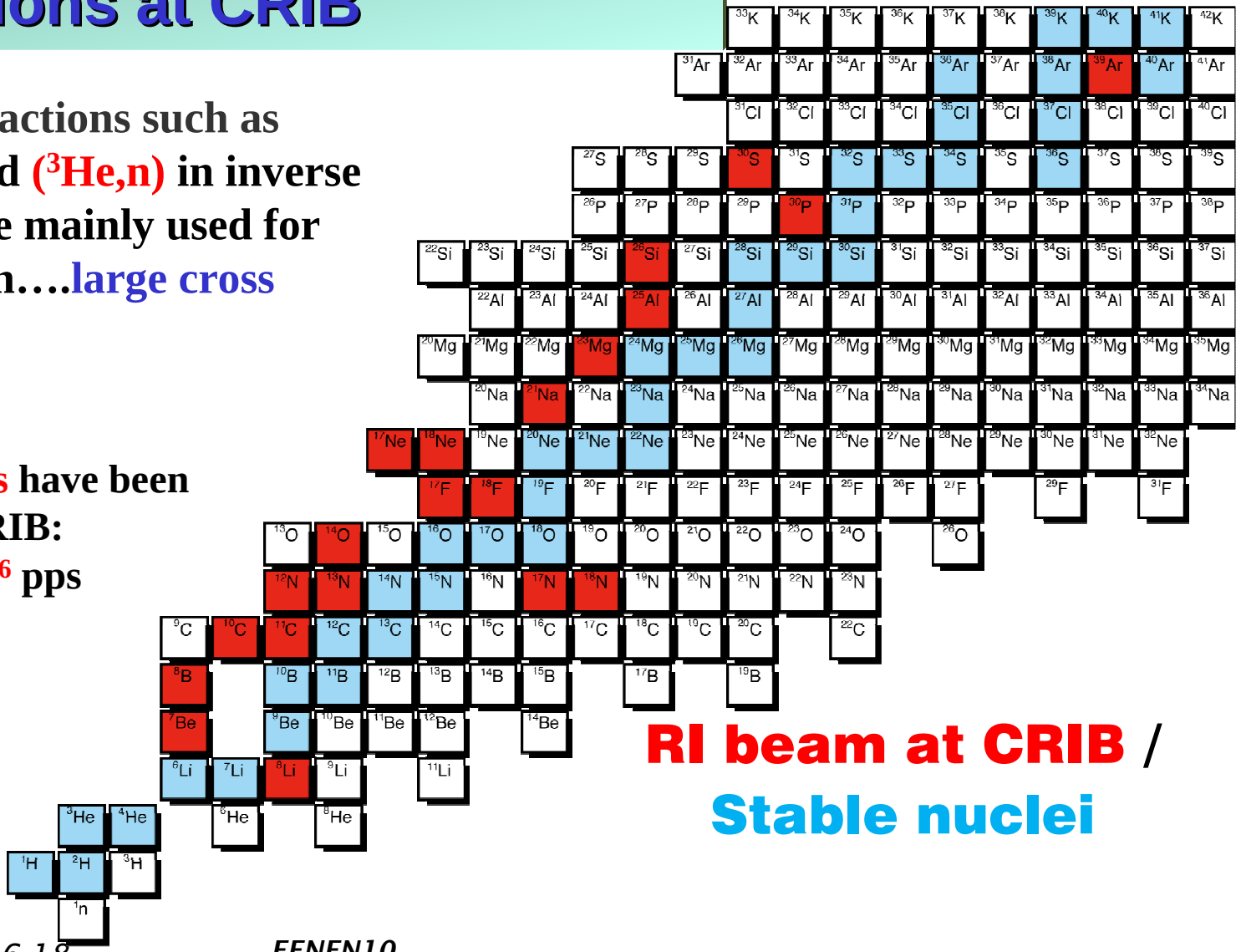
- CNS Radio-Isotope Beam separator , operated by CNS (Univ. of Tokyo), located at RIBF (RIKEN Nishina Center).
  - ✓ Low-energy(<10MeV/u) RI beams by in-flight method.
  - ✓ Primary beam from K=70 AVF cyclotron.
  - ✓ Momentum (Magnetic rigidity) separation by “double achromatic” system, and velocity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



Low-Energy RI beam Productions at CRIB

Direct reactions such as (p,n), (d,p) and (^{3}He,n) in inverse kinematics are mainly used for the production….large cross section

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



Intense secondary beam production using cryogenic gas target

- H_2 gas target of 760 Torr and 80 mm-long worked at 85K stably for a $^{7}Li^{2+}$ beam of 1.3 pμA. (which deposits heat of 7.4W).
- Secondary beam: $^{7}Be^{4+}$ at 4.0 MeV/u, purity 75% (without degrader/ WF).

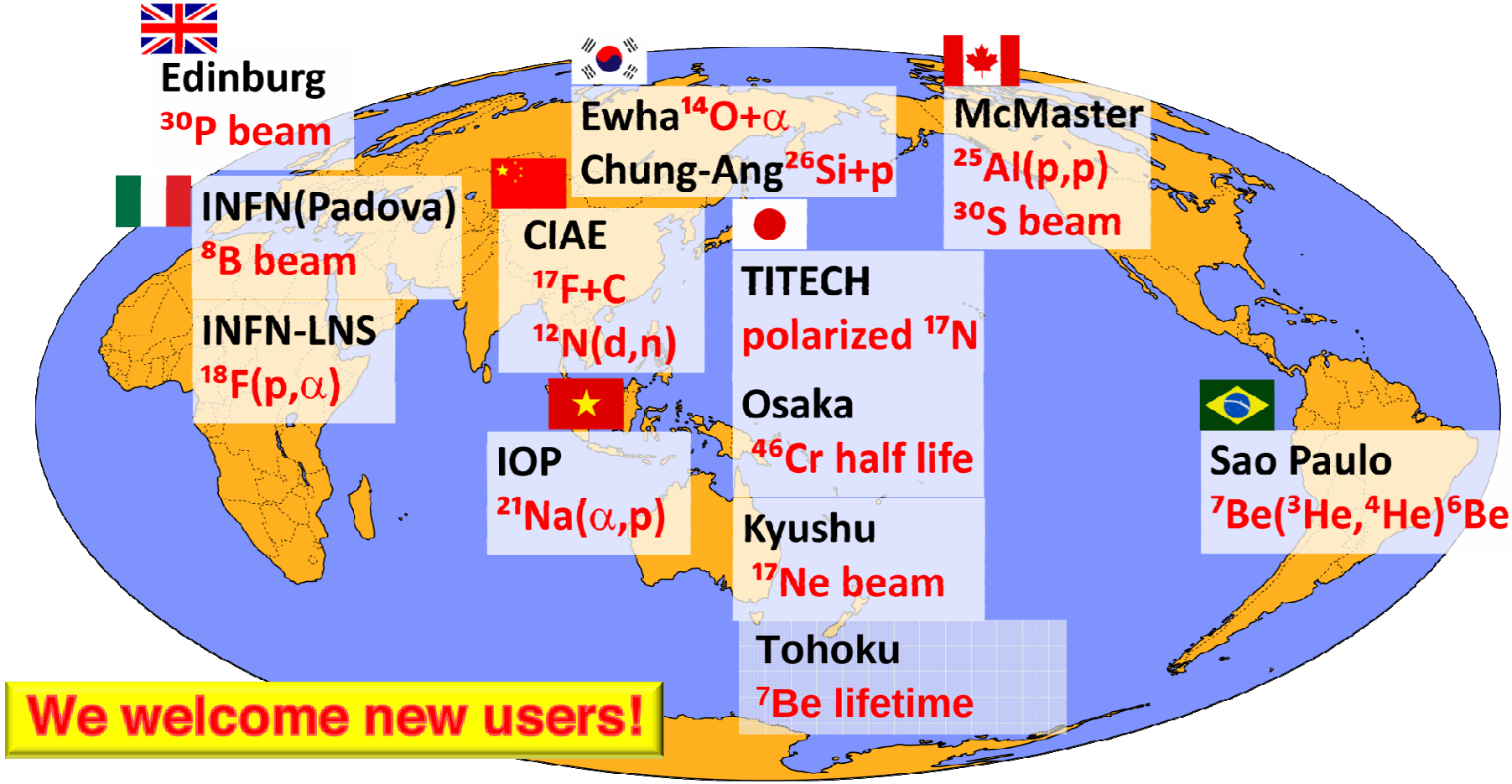
  $2x10^{8}$ pps was achieved.

  H. Yamaguchi et al., NIMA (2008)

Price of ^{3}He gas is quickly rising in these 2 years….a recycling system for ^{3}He gas was built.

International collaborations at CRIB

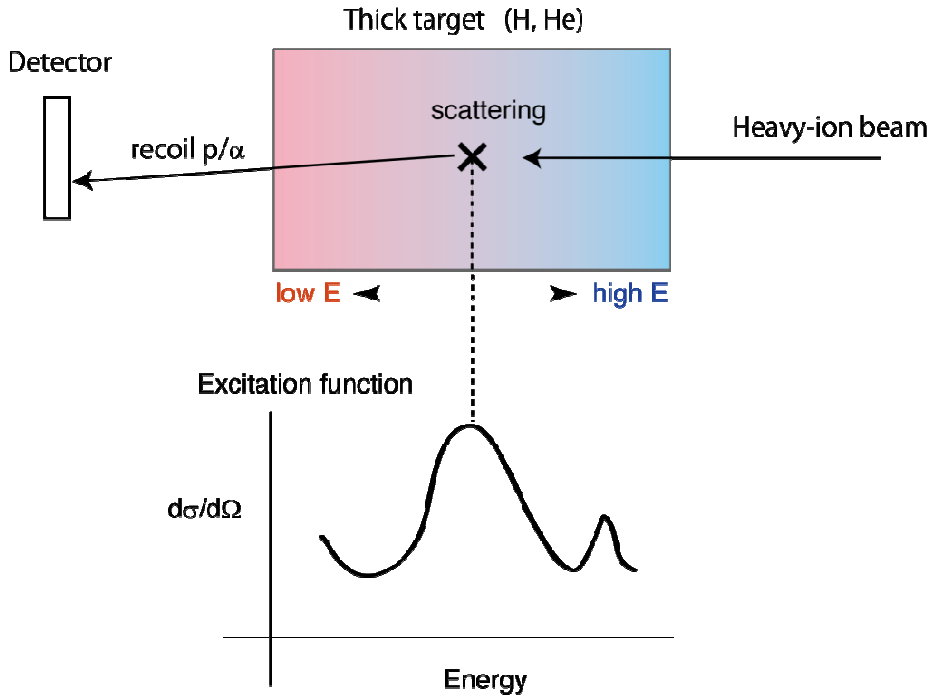
- CRIB experiments performed in 2007-2009,
  by collaborated members of CNS and other institutes:



The “thick-target” method

- Inverse kinematics with a thick target:
  - ✓ Inverse kinematics… measurement is possible for short-lived RI which cannot be used as the target.
  - ✓ Simultaneous measurement of the excitation function for certain energy range.(Small systematic error.)
  - ✓ The beam can be stopped in the target…measurement at $\theta_{cm}=180^{o}$ (where the potential scattering is minimal) is possible.

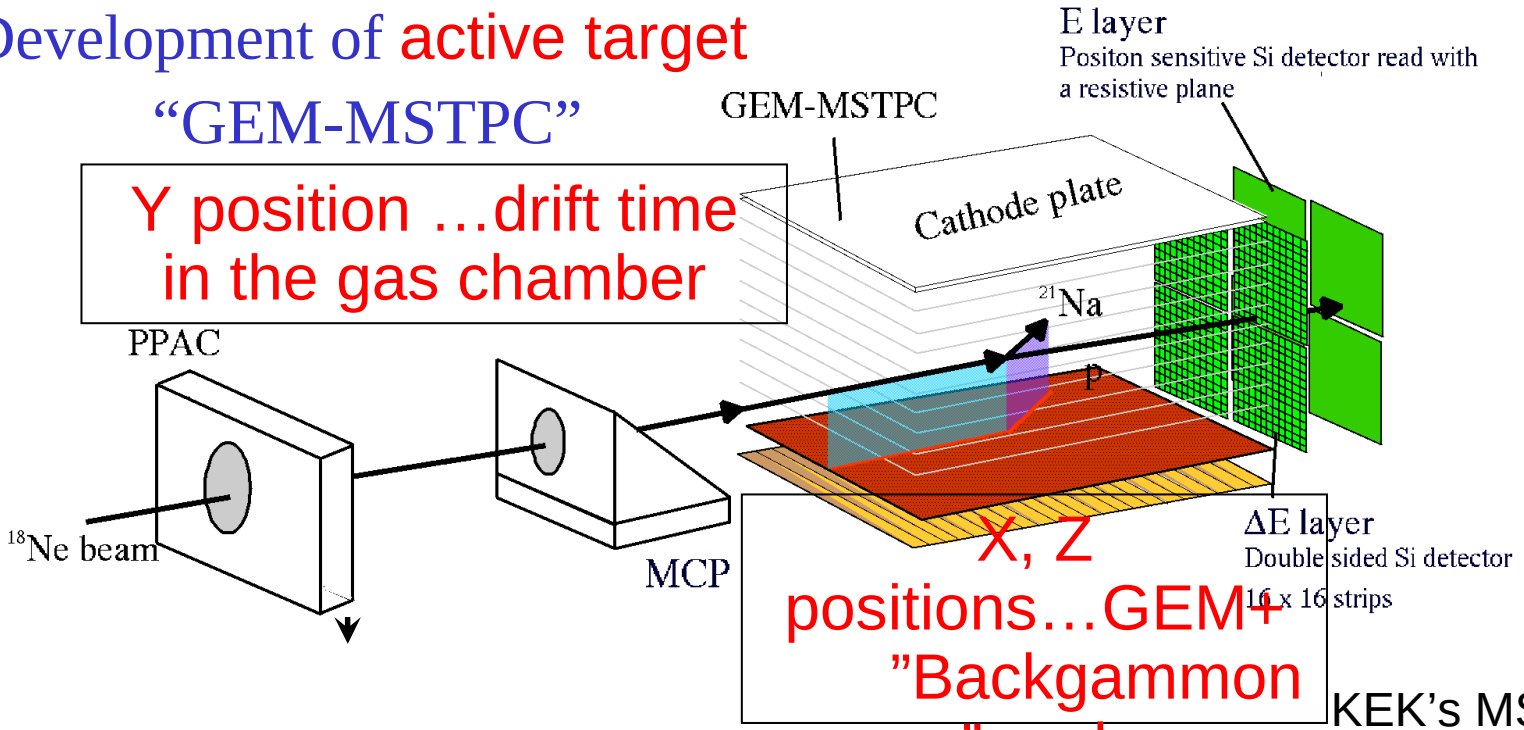
Resonance scattering



Development of active target

"GEM-MSTPC"

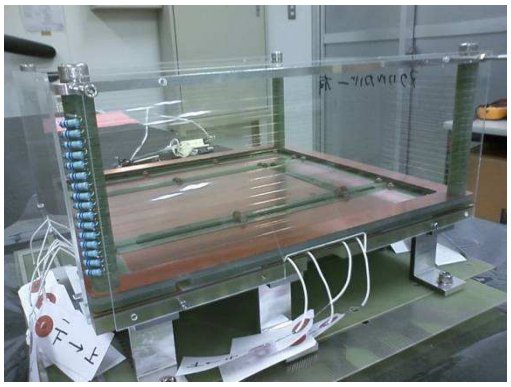
Y position …drift time in the gas chamber



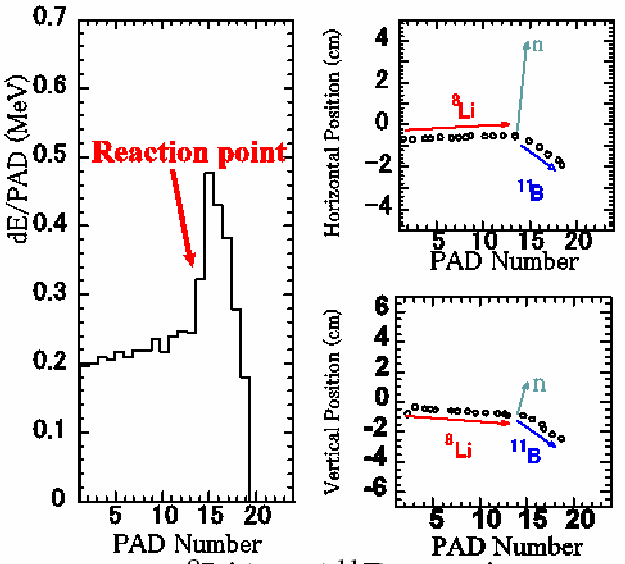
Multiple-Sampling and Tracking Proportional Chamber with Gas Electron Multiplier

- Measurement of 3-dimensional trajectories of the particles at reaction.

- Constructed at CNS.
- Tests with heavy-ion beams performed recently.



KEK's MSTPC result



•^{8}Li(α, n)^{11}B reaction

Proton elastic resonance scattering with the thick target method

Study the resonance states formed by a nucleus and a proton.

Related to hydrogen burning… (p,γ) reaction

Recent results at CRIB :

- ^{13}N+p; T. Teranishi et al., Phys. Lett. B (2007).
- ^{7}Be+p; H. Yamaguchi et al., Phys. Lett. B (2009).
- ^{21}Na+p, ^{22}Mg+p; J.J. He et al, Phys. Rev. C (2007) and Phys. Rev. C (2009).
- ^{25}Al+p; with McMaster Univ. group (A. Chen et al.)
- ^{8}B+p; with Kyushu Univ. (T. Teranishi).
- ^{26}Si+p; with Chung-Ang Univ. (J.Y. Moon et al.).

Study on alpha-induced reactions with thick helium target

Heavy-ion(RI) beam + helium target

- Alpha particle channel… Alpha elastic resonance scattering…related to (α, γ) reactions.
- Proton channel….Direct measurement of (α, p) reactions.

Interests at CRIB:

- ^{16}O+α; tested in 2005.
- ^{7}Li+α; measured in 2009 (mirror of ^{7}Be+α.)
- ^{7}Be+α; measured in Apr, 2010.
- ^{14}O+α; Notani et al. (2004), measured in 2008 with K. Hahn's group (Ewha Womans Univ.). Break-out from CNO.
- ^{21}Na+α; measured in 2008. ^{22}Ne enrichment, galactic γ-ray (Dam N. Binh)
- ^{11}C+α ; measured in 2009, break out from hot-pp (S. Hayakawa)
- ^{30}S+α ; will be measured, XRB (D. Kahl).

^{7}Li+α experiment; Purpose

Stable-stable nuclei elastic scattering, however,

•Feasibility test of the ^{7}Be+α experiment.

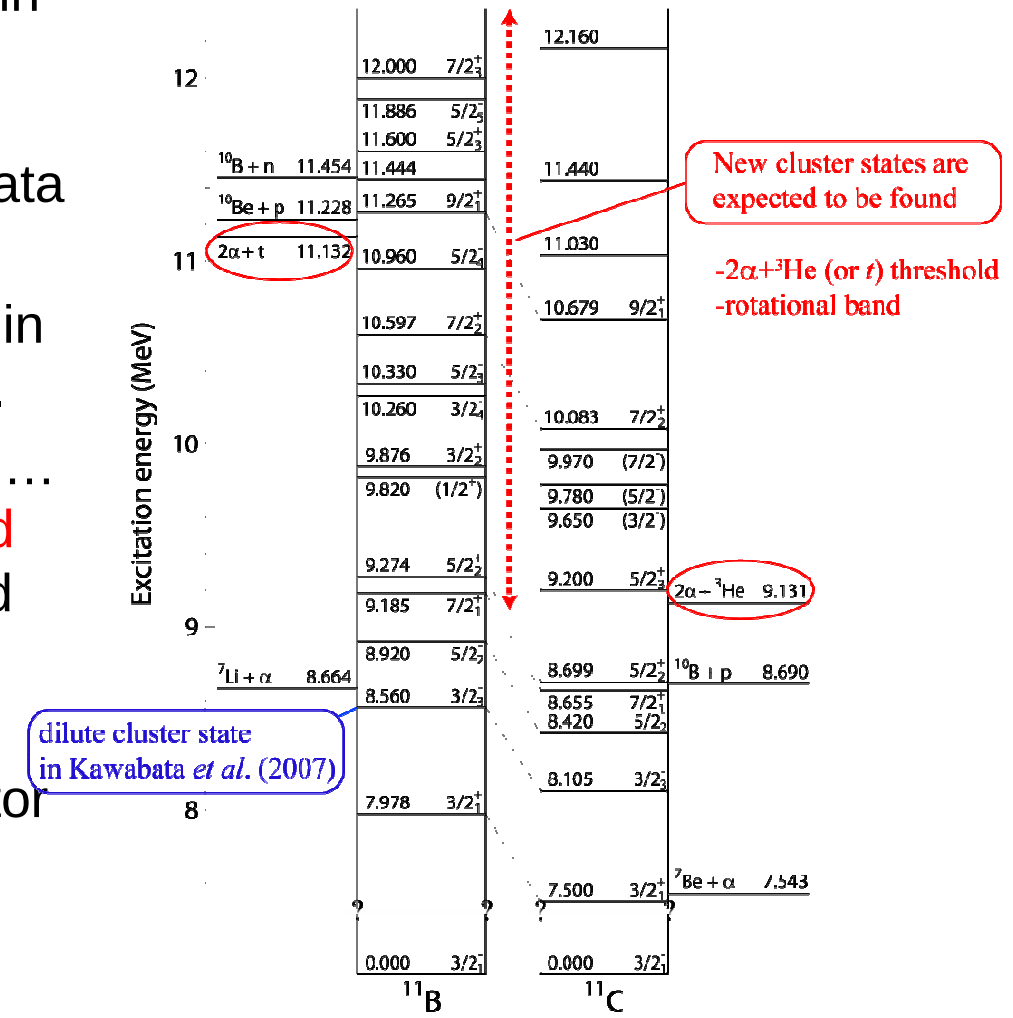
•New measurement of the excitation functions of ^{7}Li+α elastic/inelastic scatterings for Ex=10-13 MeV at 180 deg in the c.m. angle, using thick-target method in inverse kinematics.

•More precise determination of the resonant widths than the previous data [Cusson, Nucl. Phys (1966)].

•Alpha-cluster structure of ^{11}B (α+α+t).

Exotic cluster structure

- $2\alpha+t$ / $2\alpha+^3$He cluster state in ^{11}B/^{11}C, similar to the dilute cluster structure in ^{12}C: Y.K. En'yo (2007), T. Kawabata *et al*. (2007).
- A rotational band is expected in higher excited energy region.
- Near the $2\alpha+^3$He(t) threshold… developed cluster-condensed state with $J^\pi=1/2^+$ is expected (T. Yamada *et al*.), but not found yet.
- α width → spectroscopic factor of α-cluster configuration → evidence of cluster structure



Astrophysical interests

- Related to $^{7}Li(\alpha,\gamma)$, directly measured only at resonances:
  - Paul et al., PR 164 (1967) 1332.
  - Hardie et al., PRC, 29 (1984)1199.
- T<< 1 GK; $^{7}Li(p,\alpha)^{4}He$ (p-p chain).$^{7}Be(\alpha,\gamma)^{11}C(\beta^{+}\nu)^{11}B$ is more important.
- High temperature: triple-α should be fast, but $^{7}Li(\alpha,\gamma)$ may play important roles in some environments:
  - ✓ $^{11}B/^{7}Li$ ratio in supernovae…the ν-process

    ^{11}B is produced mainly through the $^{7}Li(\alpha,\gamma)^{11}B$ reaction.

    The ratio of $^{11}B/^{7}Li$ can be sensitive to the neutrino mixing parameter, θ_{13}.

    (T. Yoshida et al., PRL2006.)
  - ✓ Boron production in inhomogeneous big-bang nucleosynthesis.

PRL 96, 091101 (2006)

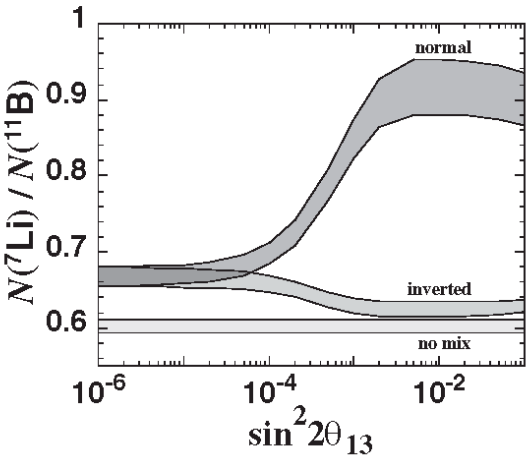
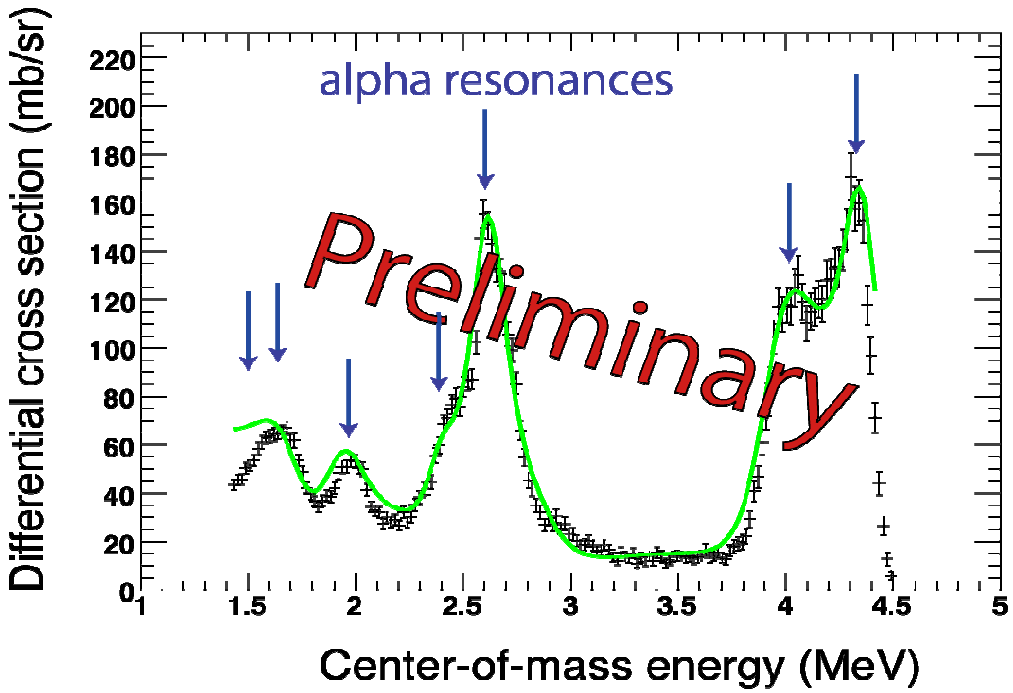


FIG. 3. The number ratio of $^{7}Li/^{11}B$ with the relation of $\sin^2 2\theta_{13}$. The shaded ranges include the uncertainties of neutrino energy spectra deduced from the calculations using three sets of neutrino temperatures and total neutrino energies (see text).

^{7}Li+α elastic scattering exc. function

- Observation consistent with past measurements (Cusson et al., elastic scat. at θ_{CM}=159°and Soic et al, break up).
- New resonance parameters



•Cusson et al,. 1966

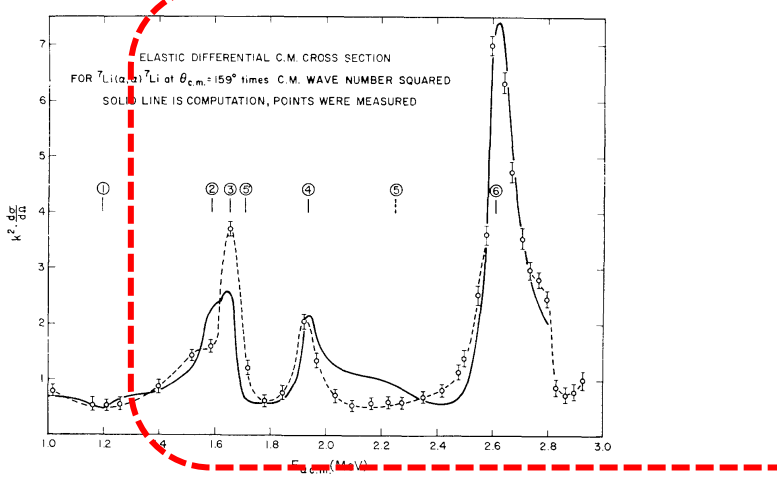
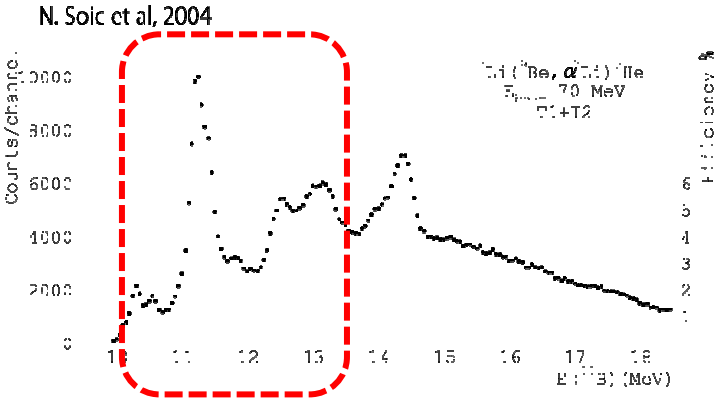


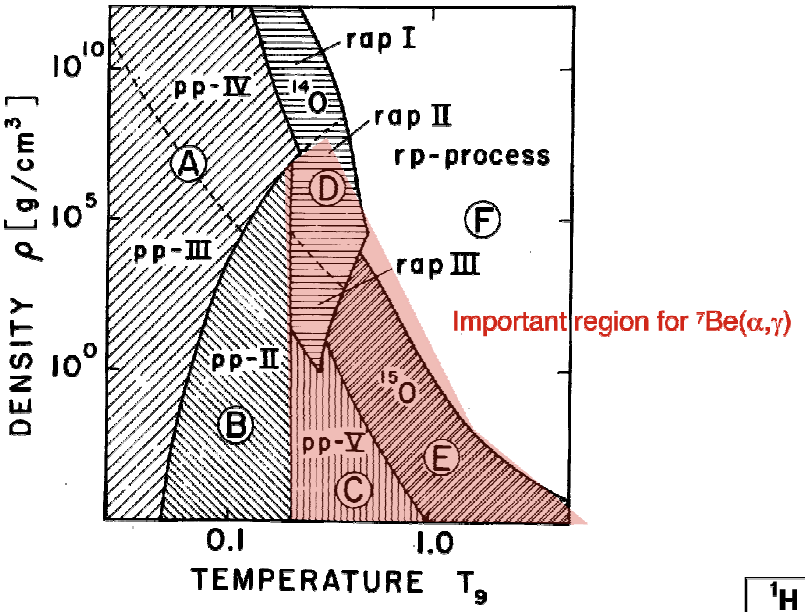
Fig. 14. Comparison of the model-program calculation with experiment for the elastic cross section at $\theta_{c.m.} = 159°$. The solid line is the model program calculation using the parameters listed in table 2. The points are experimental values. The dotted line is a smooth curve drawn through the data points.

N. Soic et al, 2004

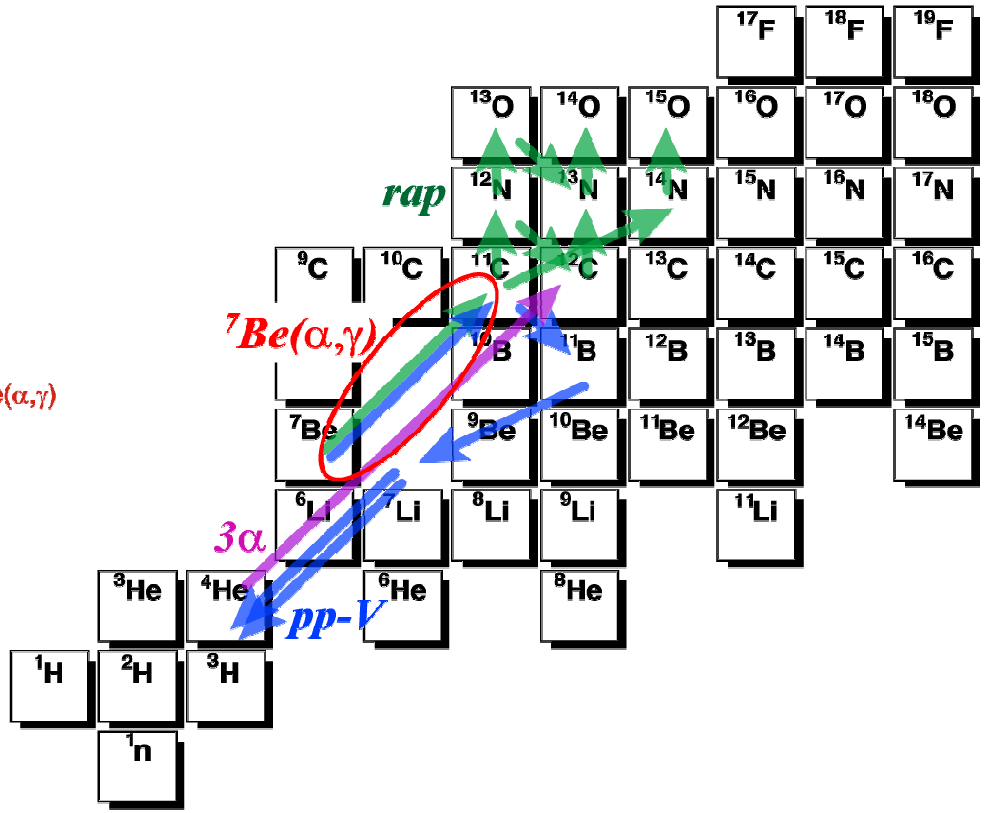


^{7}Be+α study

- ^{7}Be(α,γ)^{11}C …reaction in the hot *p-p* chain
  Important at high temperature (Wiesher *et al*.,1986)
- Supermassive objects, pop-III stars (Fuller *et al*., Mitalas), Novae (Hernanz *et al*.), Big bang nucleosynthesis (Andouze and Reeves),…
- Reaction rate … resonances of ^{11}C must be studied.
- α+α+^{3}He cluster structure.

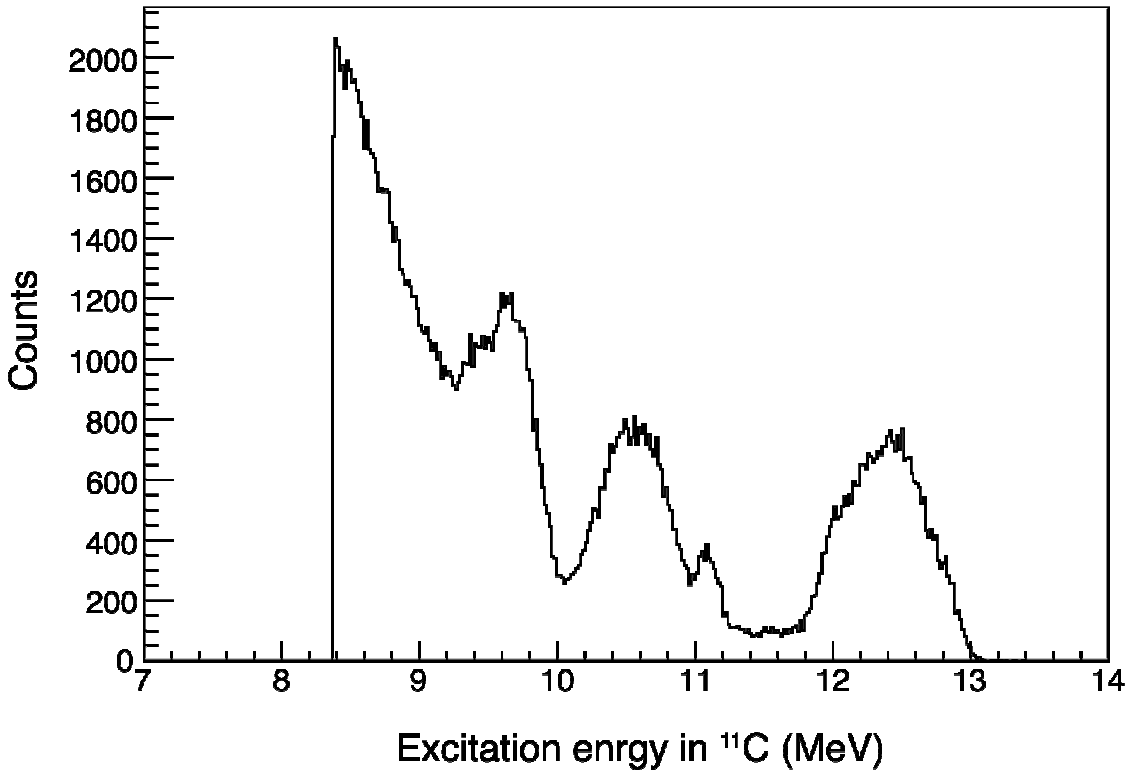


Wiesher *et al*.(1986)



7Be+α

- Measurement performed in April, 2010.



- Several peaks were observed in the excitation function …alpha resonances

Summary

- CRIB is a facility which provides low-energy RI beams with good intensity and purity.

- Developments: cryogenic gas target for intense RI beam, active target etc.

- Experiments mainly on astrophysical interests are performed at CRIB, forming international collaborations. Some of the recent experimental results are presented:

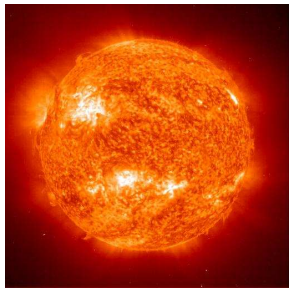
  - ✓ ^{7}Li+α(^{11}B structure, Boron production in high-T environment); resonances were observed, consistent with previous results.
  - ✓ ^{7}Be+α(^{11}C structure, hot p-p chain); measured in April.

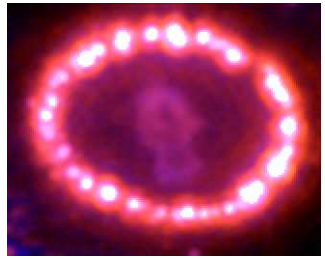
Why low-energy RI beam?

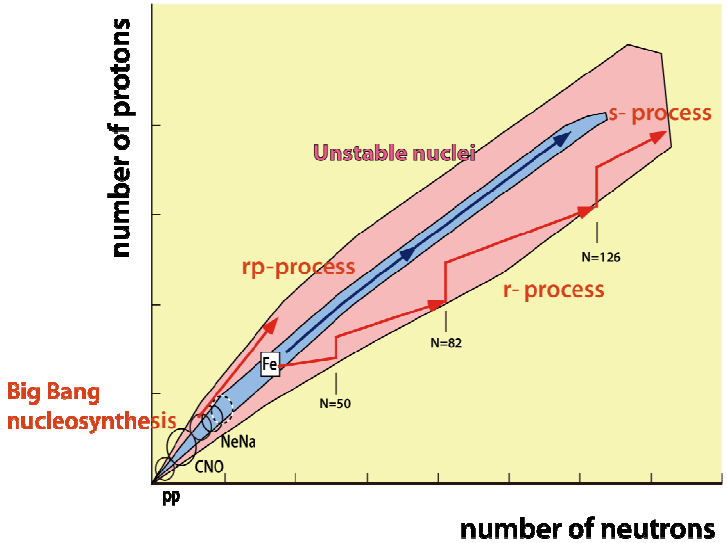
- Astrophysical reactions in stars:

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

  - Low energy beam is suitable.







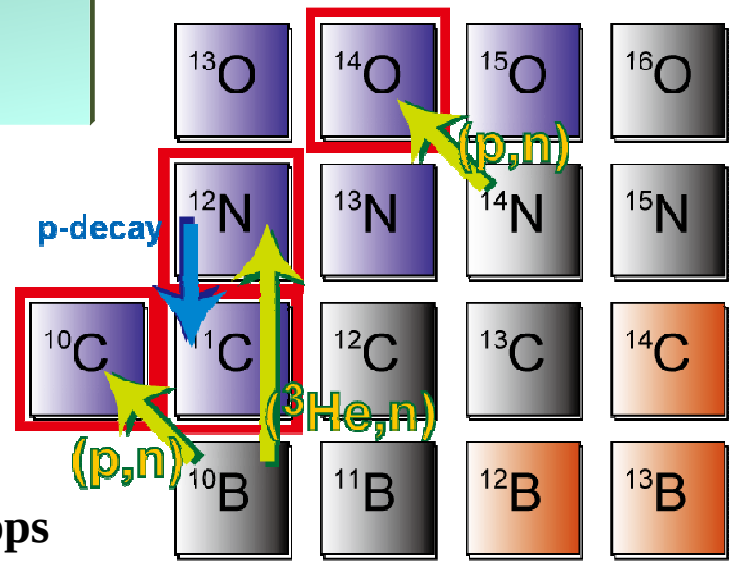
•Nucleosynthesis proceeds through unstable nuclei in some processes(pp chain, CNO cycle, r-, rp-, processes etc.)

Low-Energy RI beam Productions at CRIB

Direct reactions such as (p,n), (d,p) and (^{3}He,n) in inverse kinematics are used for production….large cross section

Many RI beams have been produced at CRIB:

^{7}Be, ^{8}B, ^{8}Li, ^{13}N, ^{17}N, ^{17}F, ^{18}F, ^{18}Ne, ^{21}Na, ^{22}Mg , ^{23}Mg, ^{25}Al, ^{26}Si, ^{39}Ar, … typically 10^4-10^6 pps

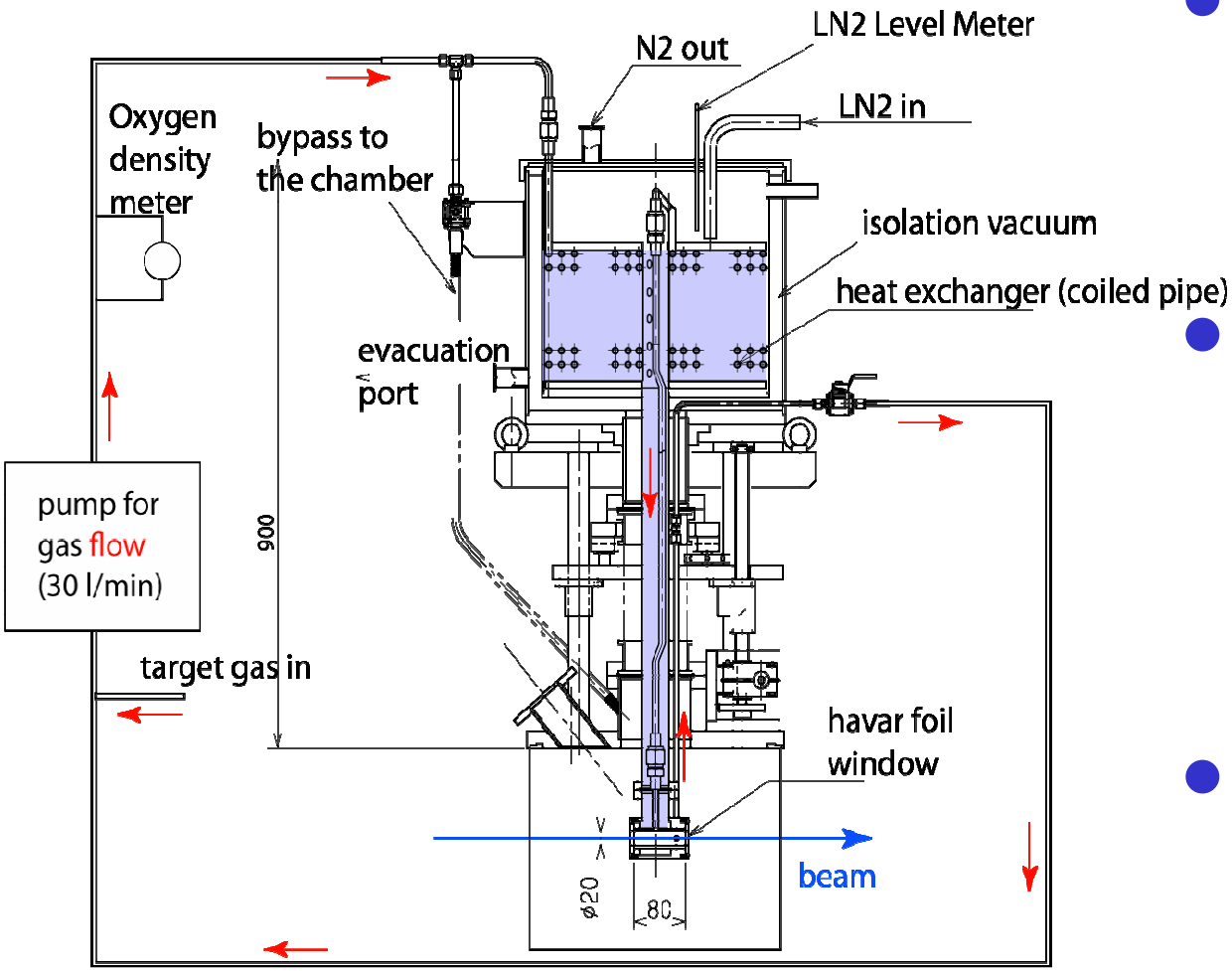


RI beam	Primary beam	Reaction	Cross section	Target	Intensity
^{10}C 6.1 *A* MeV	^{10}B(4+) 7.8 *A* MeV (200 pnA)	p(^{10}B,^{10}C)n	2 mb	CH_4 gas 1.3 mg/cm^2	(**1.6×10^5 pps**)
^{14}O 6.7 *A* MeV	^{14}N(6+) 8.4 *A* MeV (500 pnA)	p(^{14}N,^{14}O)n	8 mb	CH_4 gas 1.3 mg/cm^2	**(1.7×10^6 pps)**
^{12}N 3.9 *A* MeV	^{10}B(4+) 7.8 *A* MeV 200 pnA	^{3}He(^{10}B,^{12}N)n	5 mb	^{3}He gas 0.25 mg/cm^2	**2.5×10^3 pps**
^{11}C 3.4 *A* MeV	^{10}B(4+) 7.8 *A* MeV 200 pnA	^{3}He(^{10}B,^{12}N*)n ^{12}N* → ^{11}C+p	≈20 mb	^{3}He gas 0.25 mg/cm^2	**1.6×10^4 pps**

Developments on going by CNS

- Ion source Development for Hyper ECR and superconducting-magnet ECR.
- AVF cyclotron Beam acceleration in wider energy range. Operation with a larger turn number is being tested. (From 9-10 MeV/u to 11MeV/u.)
- Non-destructive Beam Monitor (S. Watanabe)
- Cryogenic gas target for RI-beam production Working stably for many experiments.
- Wien filter Improvement on the insulator cleaning, for a better stability.
- Detectors for low-energy RI beams
  - ✓ MCP as a beam profile monitor.
  - ✓ Active target (GEM-MSTPC), for measurements of reactions such as ^{18}Ne(α,p). (T. Hashimoto).

Cryogenic gas target: design

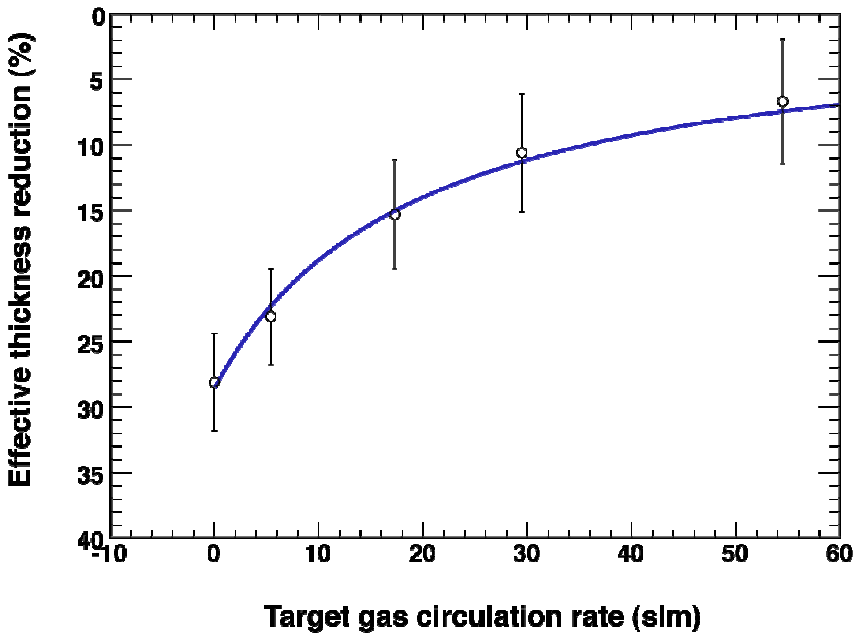


Features:

- Lq. N_2 cooling (automatic refill) for the better cooling power (~100 W) and thicker target.
- Forced target gas flow (>30 l/min) to have a better cooling, and to avoid target density reduction by the high-current beam.
- Oxygen density monitoring

Target density reduction by heat

- High heat deposition (>5 mW/mm) at a gas target is known to reduce the gas density around the beam track (J. Görres et al., 1980).
- In our measurement, the target density was reduced by ~30% due to the high heat deposition of 7.4W (65 mW/mm in the gas).
- We succeeded in minimizing the reduction to ~5% by making a forced circulation of the target gas.



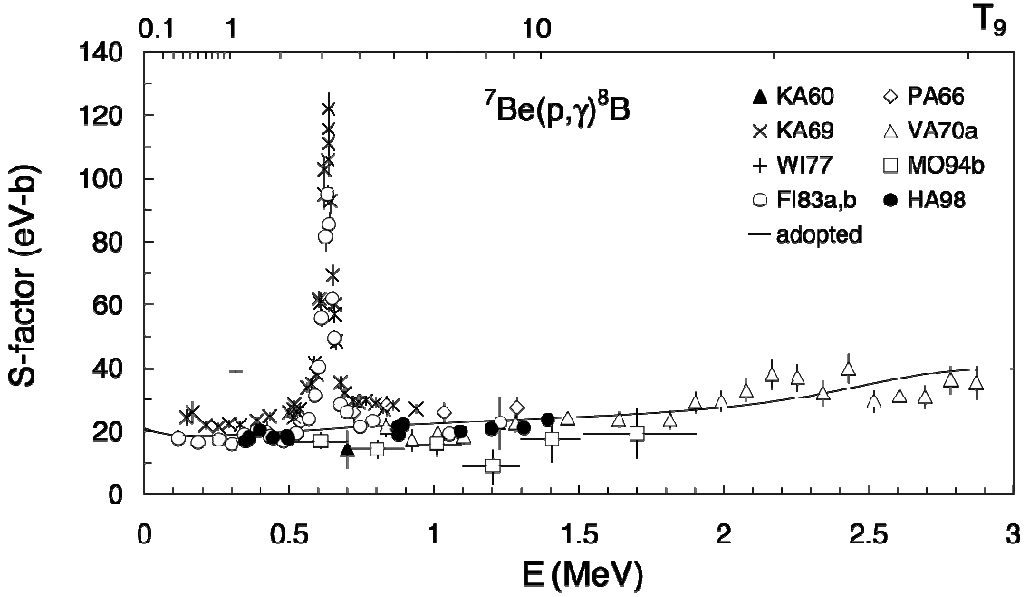
H. Yamaguchi *et al*., Nucl. Instr. Meth. A **805** (2008) 546.

Astrophysics study at CRIB: ^{7}Be(p,γ)^{8}B

- Astrophysically important reaction: ^{7}Be(p,γ)^{8}B
  - ✓ ^{8}B neutrino … important for the solar model.
  - ✓ Nucleosynthesis in some enviroments (hot p-p chain etc.)
- Astrophysical S-factor $S_{17}(0)$…determined by ^{7}Be(p,γ)^{8}B cross section.

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

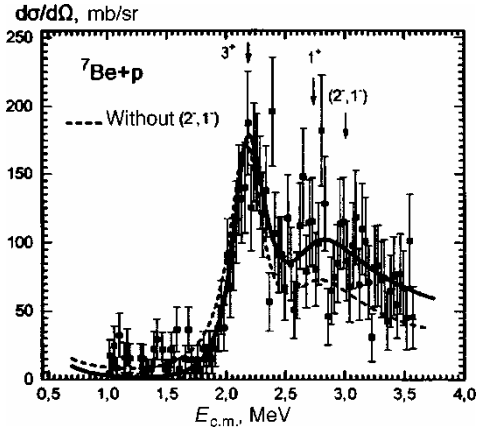
- For a precise determination of S_{17},
  - ✓ resonances in ^{8}B may affect the S-factor ⇒ the resonance structure must be studied.

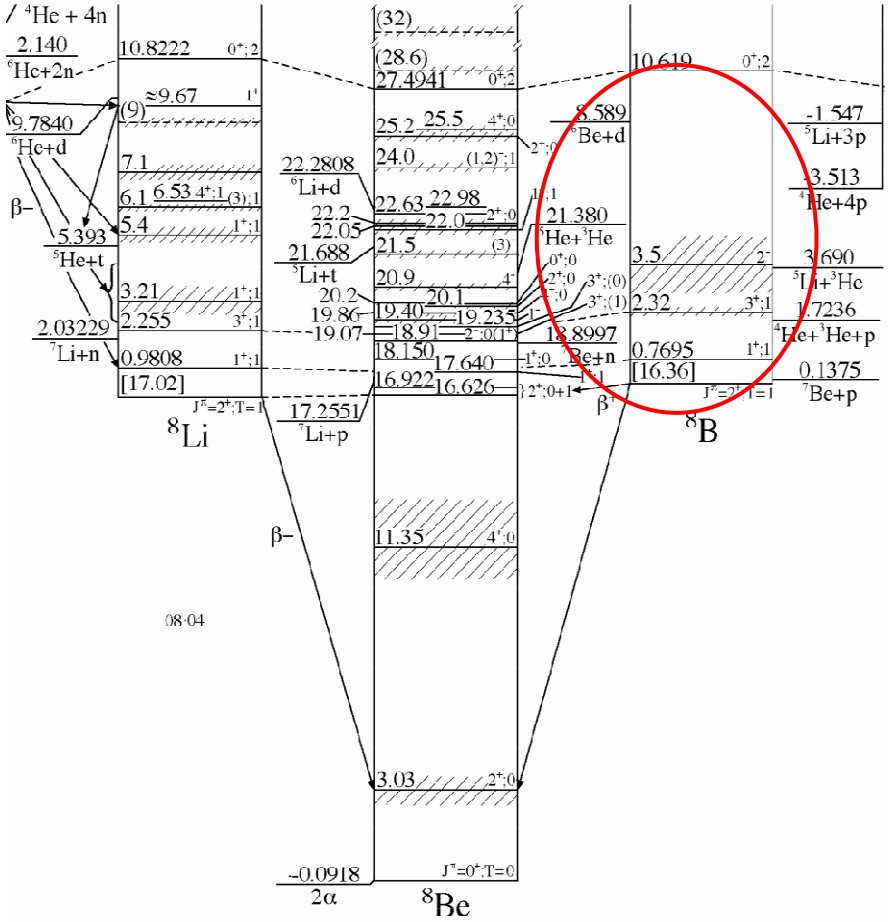


- Now we know $S_{17}(0)$ with the uncertainty of 6-8%.
  - ✓ Junghans *et al*, PRC (2003),
  - ✓ Cyburt *et al.*, PRC (2004),
  - ✓ Schümann *et al.*, PRC (2006).

^{7}Be+p elastic resonance scattering

- Study the structure of ^{8}B
  - ✓ States at 0.77 MeV and 2.32 MeV are well known, but no clear knowledge above 3.5 MeV.
  - ✓ A broad (>4 MeV) state at 3.5 MeV …2^{-} was reported; low-lying 2s state? The resonance may contribute to the ^{7}Be(p,γ) cross section even around the solar energy.

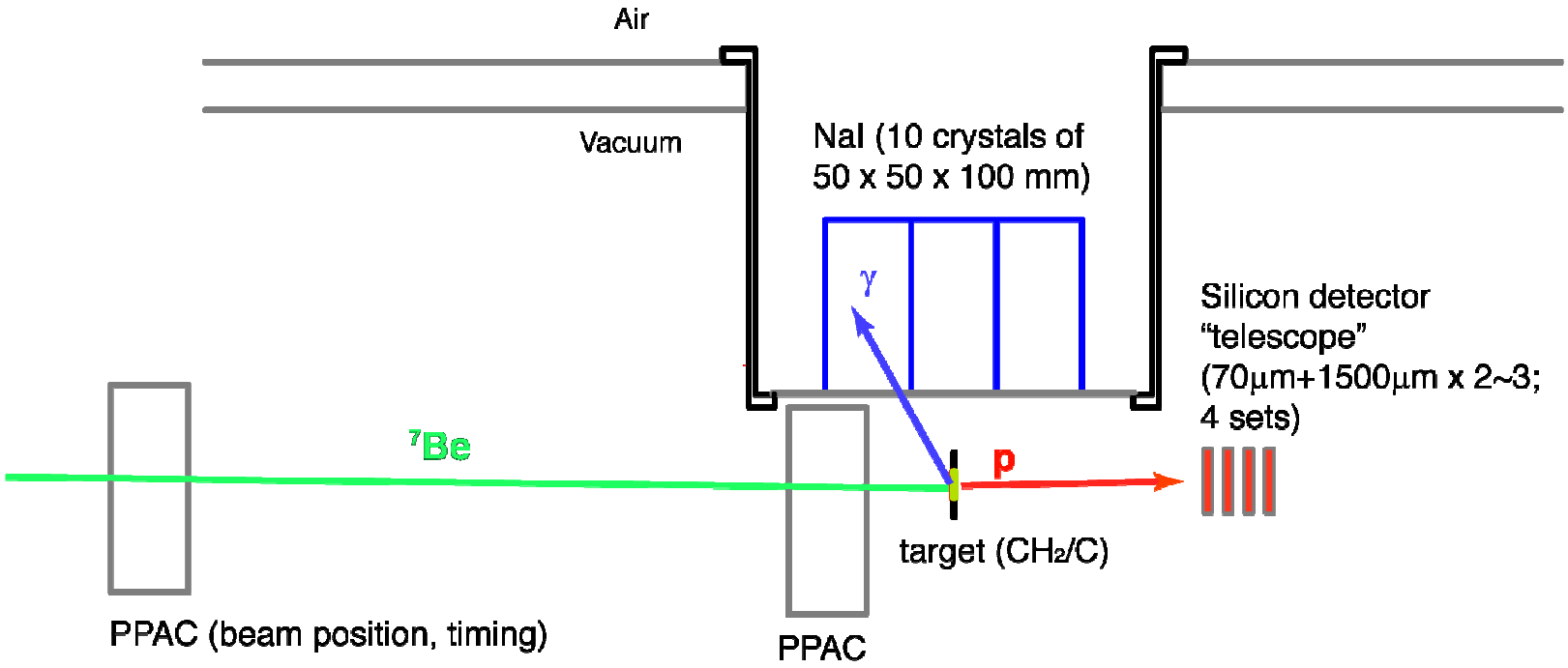




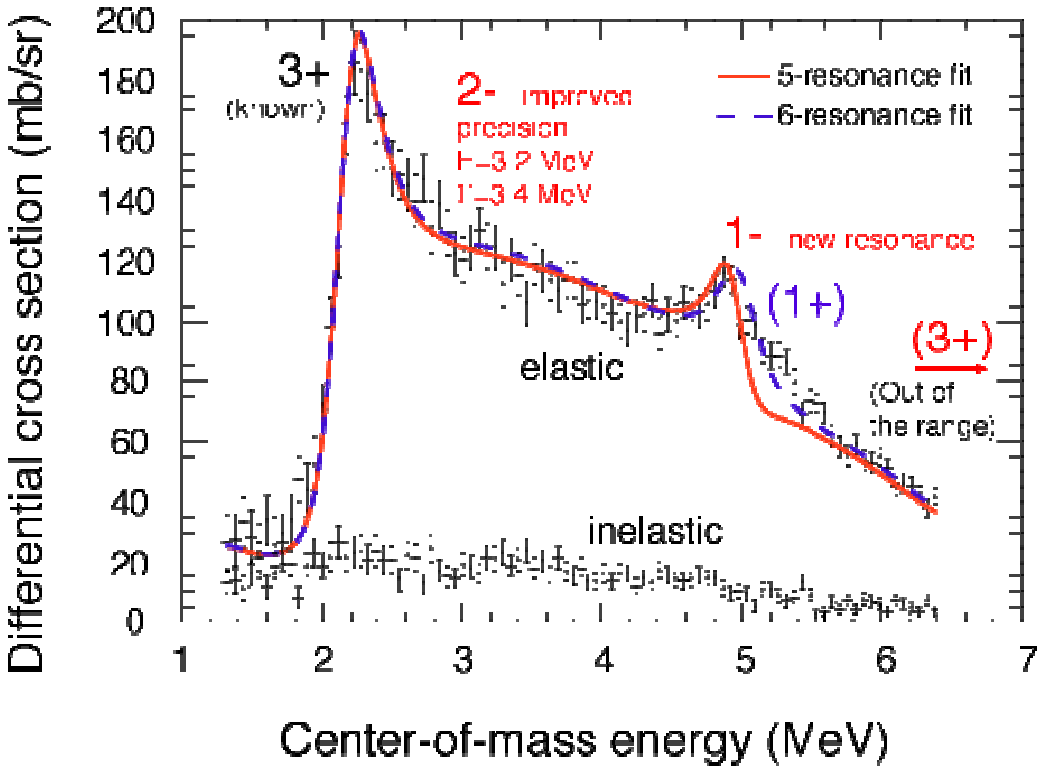
V.Z. Gol'dberg *et al*, JETP Lett. (1998), another measurement in G.V. Rogachev *et al*, Phys. Rev. C (2001).

Method (Experimental setup)

- Thick target method in inverse kinematics: all the ^{7}Be were stopped in the CH_2 target, and recoil protons (E_{max}=23 MeV) were detected by silicon detectors (60 msr x 4 sets, covering up to 45 degree).
- $E_{proton} \rightarrow E_{cm} \rightarrow E_{ex}$



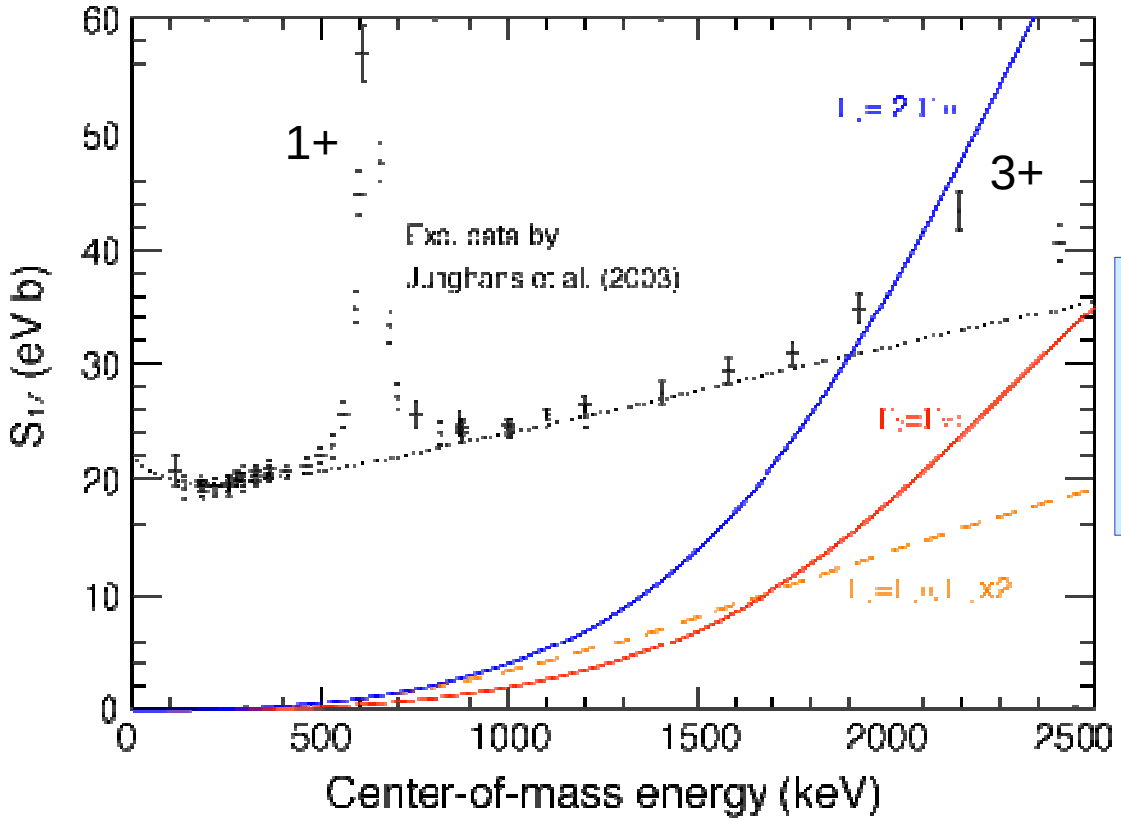
Excitation function of ^{7}Be+p



- R-matrix fit was performed for the measured excitation function. The overall shape was roughly reproduced by introducing two new states, 1^{-} and 3^{+} , and parameters of the 2^{-} state were determined with improved precisions.

$S_{17}(0)$ with 2- resonance

- Resonant contribution by the 2- resonance… evaluated by the Breit-Wigner formula (for 3 parameter sets). Negligible at the solar energy.

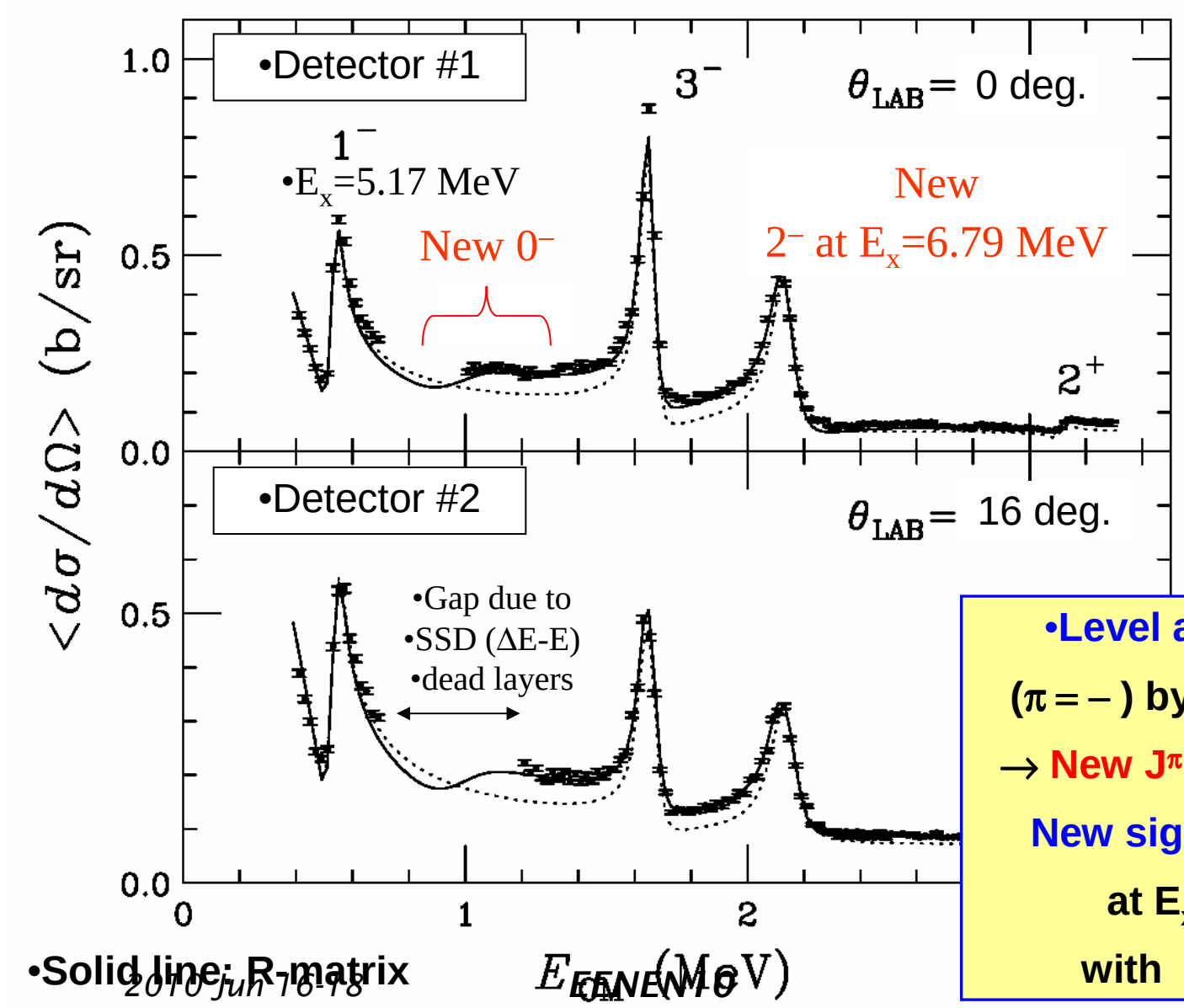


Results for 2 different $\Gamma\gamma$ are shown.

Orange curve…Γp was twiced from our best value.

- Nonresonant contribution …discussed in Barker et al.(2000), They assumed consistent energy and width for the 2- state with ours.

^{13}N+p; ^{14}O resonances relevant to X-ray burst/SN



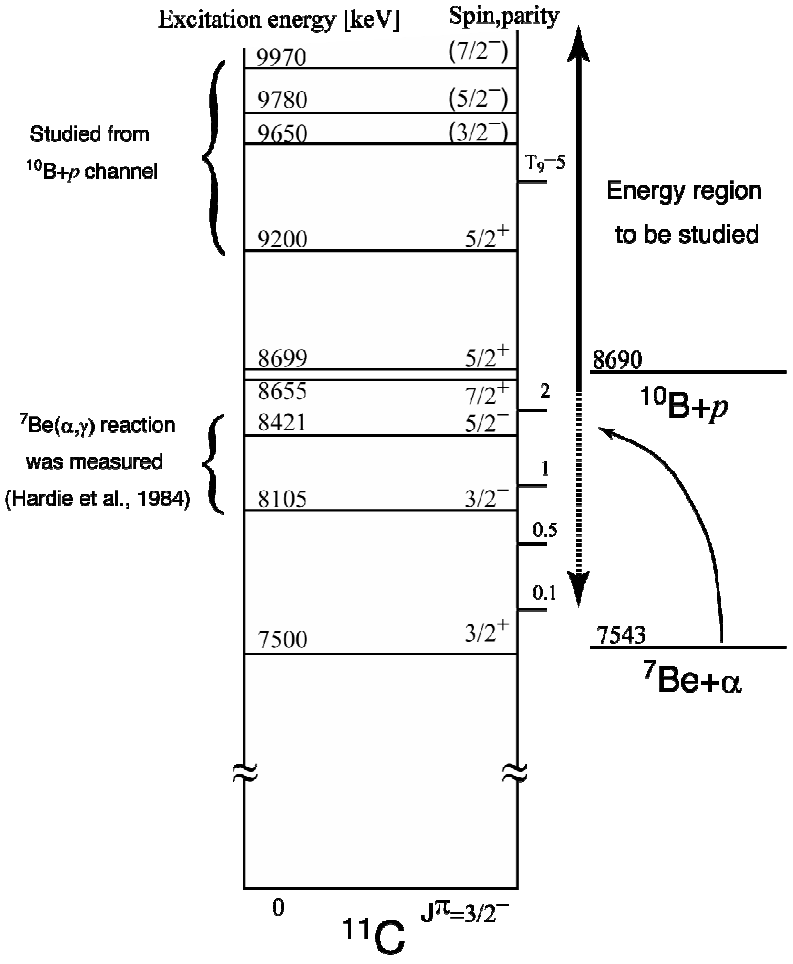
•Solid line: R-matrix

•Energy resolution
• ~20 keV (FWHM)

•Level at E_x = 6.79 MeV
($\pi = -$) by ^{14}N(^{3}He,t) reaction
→ New J^π assignment $J^\pi = 2^-$
New signature of 0^- level
at E_x = 5.71(2) MeV
with Γ = 400(100) keV

Previous measurements for ^{11}C structure

- Structure studies from the ^{10}B+*p* channel… Hunt *et al.* (1956), Overlay and Whaling (1962), Jenkin *et al.* (1964), etc.
- ^{7}Be(α,γ) direct reaction measurement Hardie *et al.* (1984)… 15μA α beam bomberded 5x10^{16} atoms/cm^2 ^{7}Be target, only at the energies of two resonances (8.1 & 8.4 MeV).
- Resonance parameters of high excited states are not fully determined.
- We are going to perform a measurement of ^{7}Be(α,α) for the structure study.

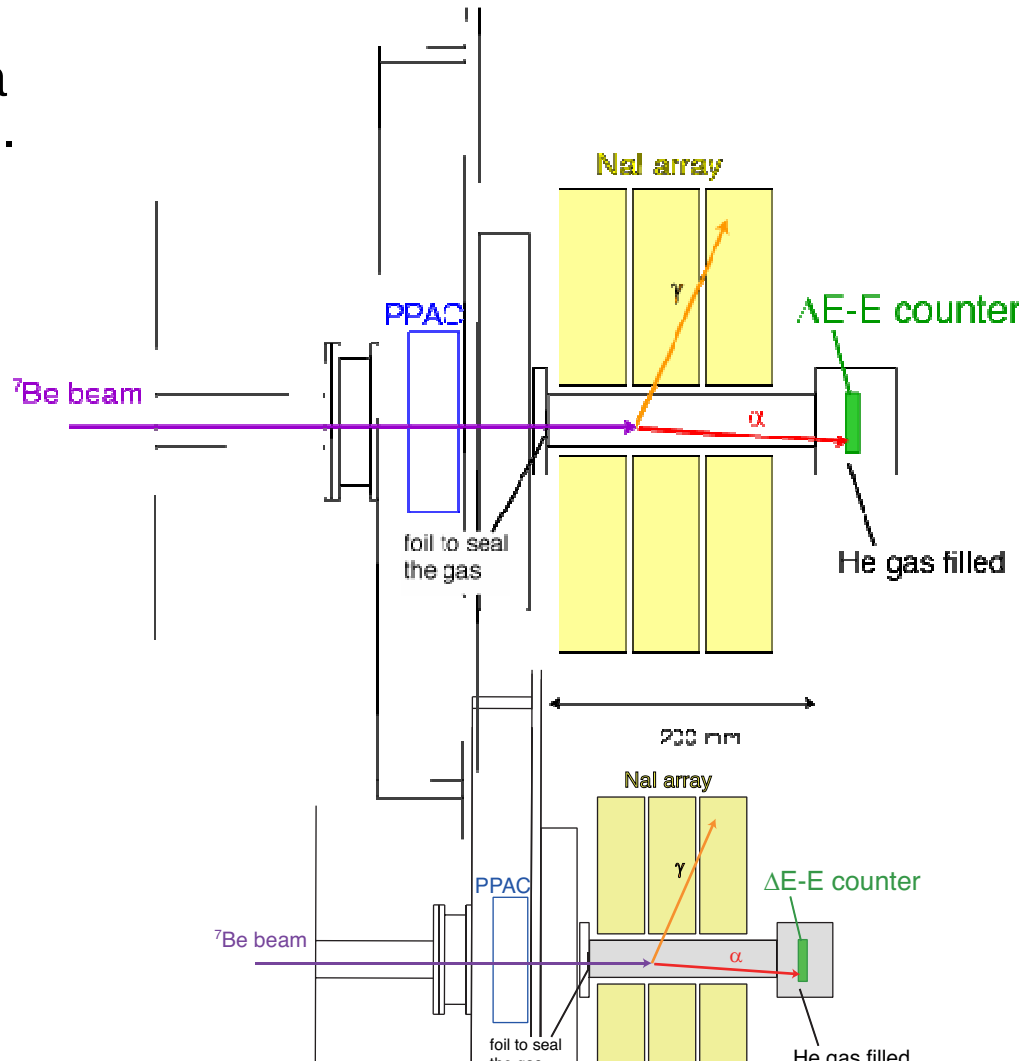


Method; measurement

- 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.
- Energy range to be scanned:

  E_{cm}: 1 - 5.5 MeV,

  E_{α}: 3 - 14 MeV.

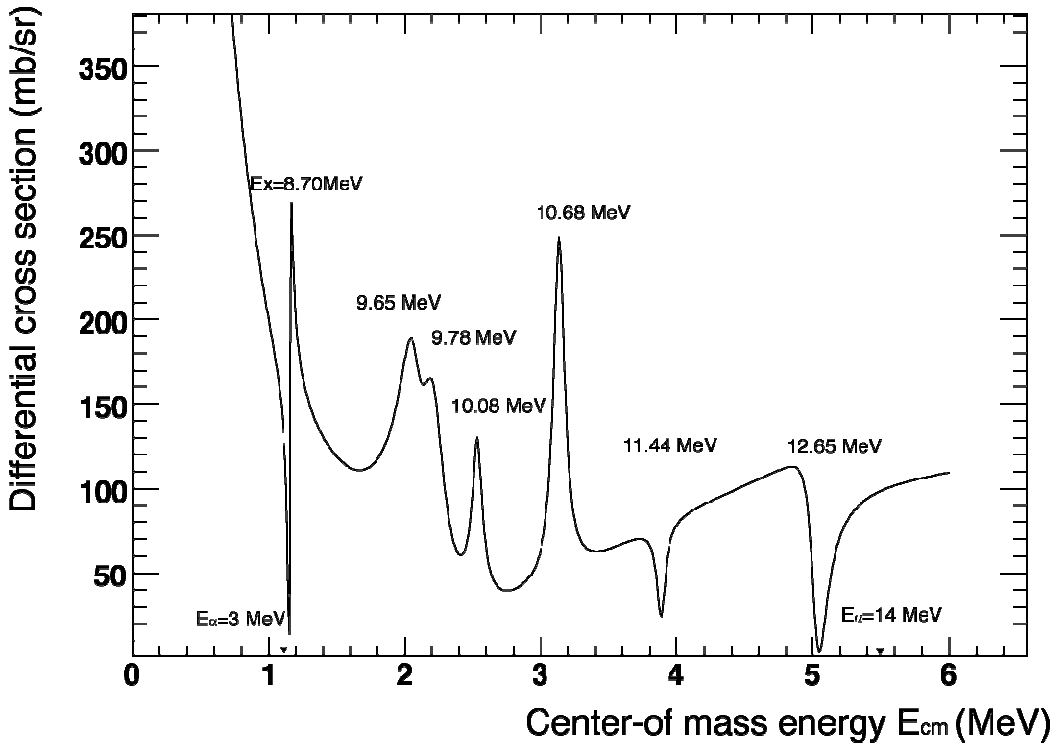


Excitation function

- Measured energy of α □ E_{cm}

  □ Excitation function will be obtained.

- Expected spectrum calculated with R-matrix formalism:



^{7}Li+α experiment; Purpose

•Feasibility test of the 7Be+α experiment.

•New measurement of the excitation functions of ^{7}Li+α elastic/inelastic scattering at 180 deg in c.m. angle, using thick target method in inverse kinematics. Better energy resolution (30 keV) than the Cusson et al. data [Nucl. Phys (1966)] (50 keV?).

•Astrophysical interests?:

Related to ^{7}Li(α,γ), measured only at resonances:

- •Paul et al., PR 164 (1967) 1332.
- •Hardie et al., PRC, 29 (1984)1199. <- this is the only known measurement of ^{7}Be(α,γ) as well.

T<0.1GK; ^{7}Li(p,α)^{4}He (p-p chain).^{7}Be(α,γ)^{11}C($\beta^{+}\nu$)^{11}B is more important.

Higher temperature: triple-α should be fast, but may play important role in some environments; "ν-process" in core-collapse supernovae, big-bang nucleosynthesis.

^{7}Li+α Levels and References

Table 11.6: Structure in ^{7}Li(α, α)^{7}Li and ^{7}Li(α, α')^{7}Li[a]

E_α[b] (keV)	E_α[c] (keV)	$\Gamma_{c.m.}$ (keV)	E_x (MeV ± keV)	J^π
1900 ± 10		130 ± 30	9.873 ± 10	$\frac{3}{2}^+$
2480 ± 50		150 ± 40	10.24 ± 50	$\frac{3}{2}^{(-)}$, $\frac{1}{2}$
	2630 ± 30	80 ± 30	10.34 ± 30	$\frac{5}{2}^-$, $\frac{7}{2}$
3040 ± 10	3040	70 ± 10	10.599 ± 10	$\frac{7}{2}^+$
3600 ± 50		4500	10.96 ± 50	$\frac{5}{2}^-$
	4120 ± 30	90 ± 50	11.29 ± 30	$\frac{9}{2}^+$
4430 ± 50	4430		11.49 ± 50	
4600 ± 50		150 ± 50	11.59 ± 50	
5050 ± 30		150 ± 50	11.88 ± 30	
	5300 ± 200	≈ 1000	12.0 ± 200	
	5500 ± 100	60 ± 50	(12.17 ± 100)[d]	
6100 ± 30		150 ± 50	12.55 ± 30	
6850 ± 60		270 ± 50	13.03 ± 60	
(7200 ± 50)[e]		50 ± 50	(13.25 ± 50)[d]	
	7800 ± 100	500 ± 200	(13.63 ± 100)[d]	
(8450 ± 200)[f]		500 ± 200	(14.0 ± 200)	
(9450 ± 200)[f]		≤ 250	(14.7 ± 200)	
	9950 ± 20	500 ± 200	(15.00 ± 20)[d]	
(11200 ± 200)[f]			(15.8 ± 200)	

To be studied at CRIB

[a] Mostly from (1966CU02). For other parameters see Table 11.9 in (1975AJ02). See also Table 11.8 in (1985AJ01).
[b] ^{7}Li(α, $\alpha'\gamma$)^{7}Li: σ (total).
[c] ^{7}Li(α, α_0)^{7}Li.
[d] ^{7}Li(α, n)^{10}B threshold.
[e] Anomaly in angular distribution.
[f] Observed at $\theta = 60°$.

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^{7}Li+α elastic scattering:

- Cusson, Nucl. Phys. **86** (1966) 481-508… ^{7}Li+α , E_α=1.6-12 MeV.
- Paul *et al.*, Phys. Rev. **164** (1967) 1332… ^{7}Li+α, 1.3-3.2 MeV
- Bingham *et al.*, Nucl. Phys. A **175** (1971) 374-384… ^{7}Li/^{6}Li+α , 12.0-18.5 MeV.
- Bohlen *et al.*, Nucl. Phys. A **179** (1972) 504… ^{7}Li+α, 2.5-4.5 MeV
- Kelleter *et al.*, Nucl. Phys. A **210** (1973) 502-508… ^{7}Li+α , 8.6-22.5 MeV.

The data are:

"Mostly from 1966CU02"

J^π is determined only in the low-energy region by ^{7}Li(α,α).