Recent activities at CRIB (CNS, the University of Tokyo)

Nuclear astrophysics group (CRIB supporting members) in Center for Nuclear Study, Univ. of Tokyo:

Hidetoshi Yamaguchi 山口英斉 (Group leader/Lecturer),
Seiya Hayakawa, Lei Yang (Postdoc.),
Hideki Shimizu (Grad. Student)

Technical Staff:

CRIB/Wien Filter: Y. Kotaka, K. Yoshimura, M.Katayanagi,
Hyper ECR ion source: Y. Ohshiro

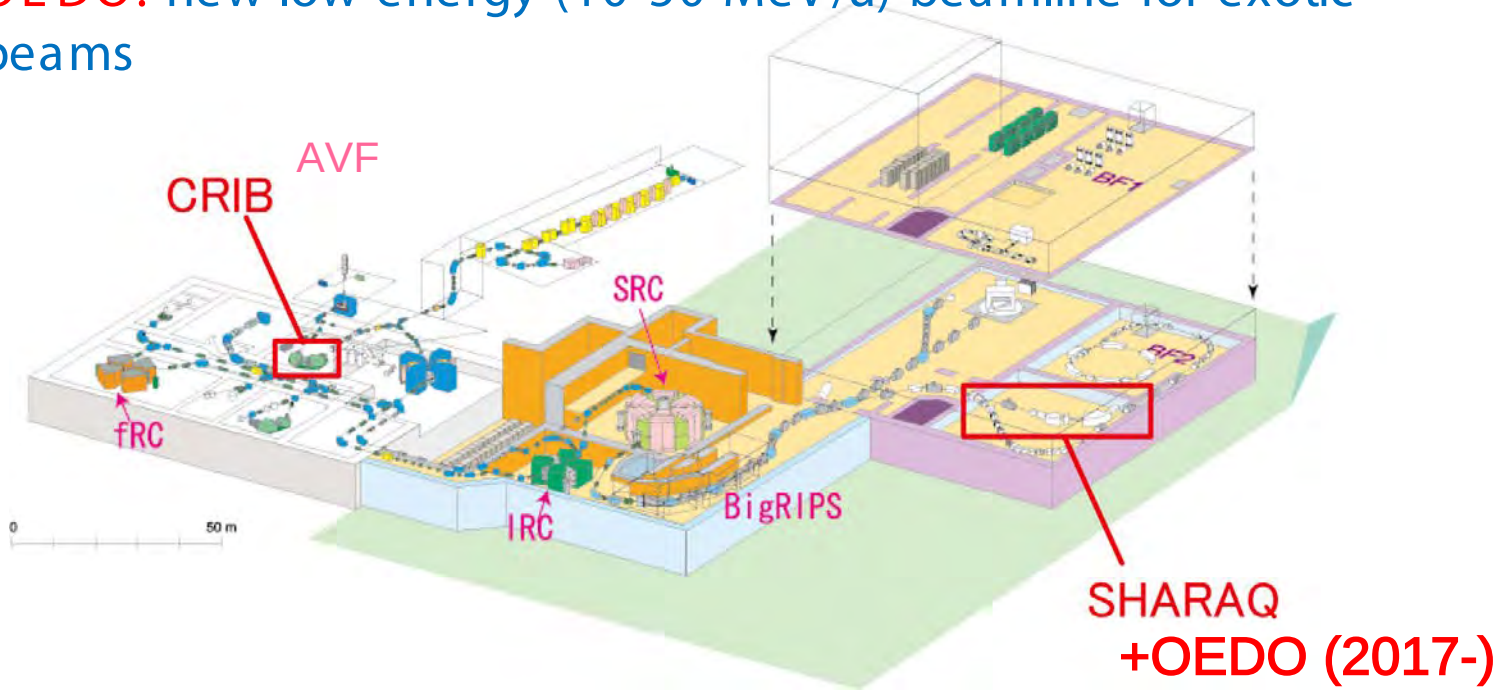
in Collaboration with:

RIKEN, KEK, Kyushu, Tsukuba, Tohoku, Osaka (Japan), McMaster (Canada), CIAE, IMP, Beihang (China), Chung-Ang, IBS, Ehwa, SKKU (Korea), INFN Padova/Catania (Italy), IOP(Vietnam) and others.

CRIB/OEDO in RIBF

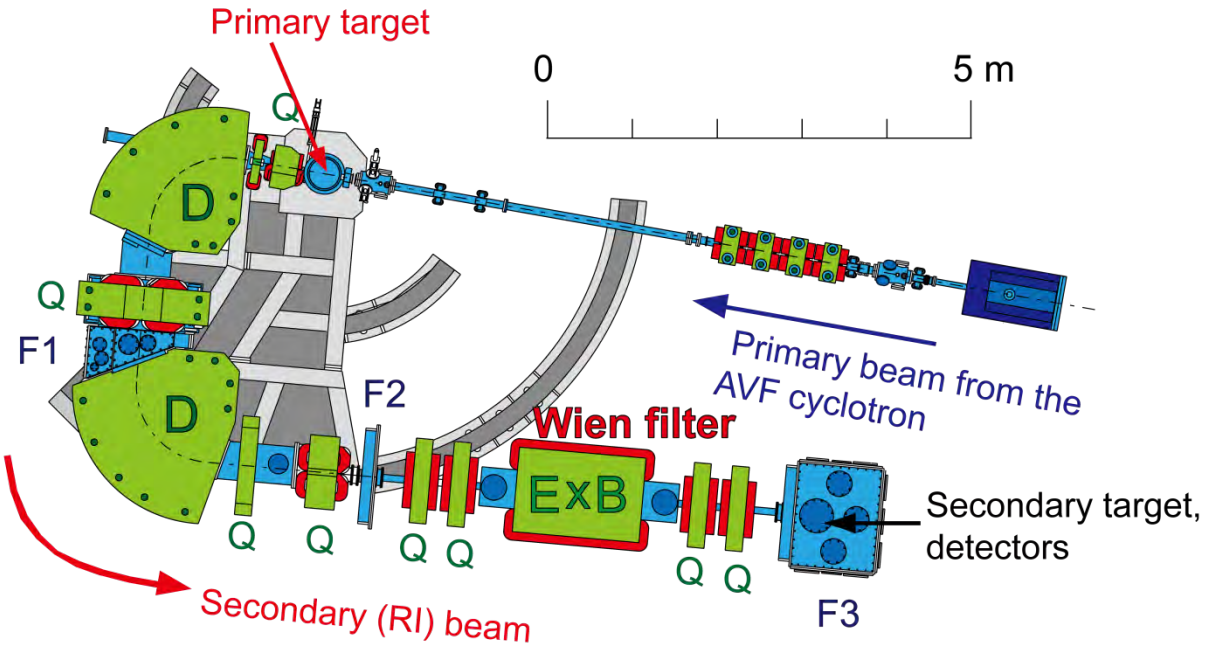
Facilities operated by CNS, the University of Tokyo in RIBF (RIKEN Nishina center)

- CRIB: RI beam separator for low-mass, low-energy (<10 MeV/u) RI beams
- SHARAQ: high resolution spectrometer
- OEDO: new low-energy (10-50 MeV/u) beamline for exotic beams



CRIB

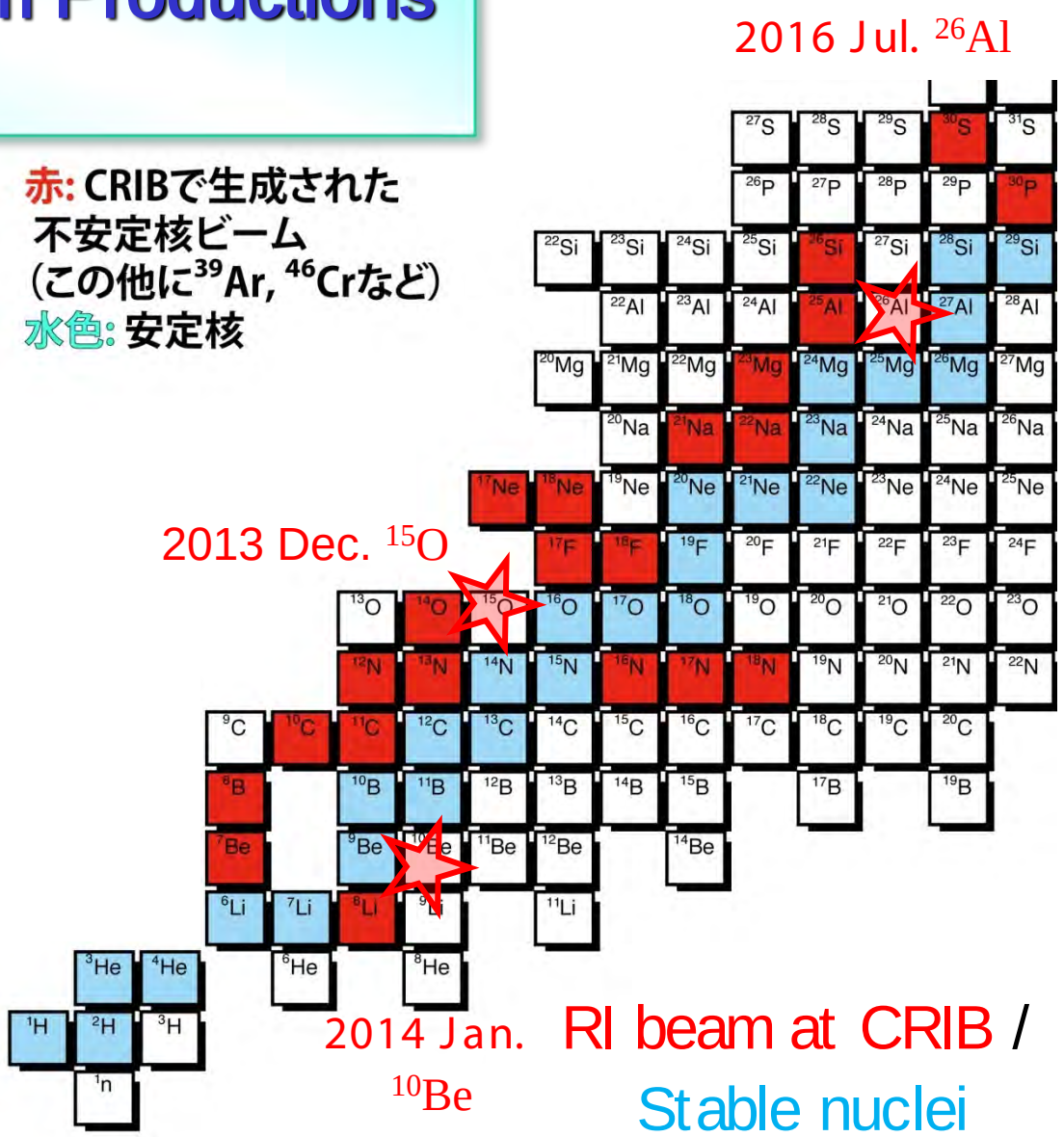
- CNS Radio-Isotope Beam separator , constructed and operated by CNS, Univ. of Tokyo, located at RIBF (RIKEN Nishina Center).
  - Low-energy(<10MeV/u) RI beams by in-flight method.
  - Primary beam from K=70 AVF cyclotron.
  - Momentum (Magnetic rigidity) separation by "double achromatic" system, and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



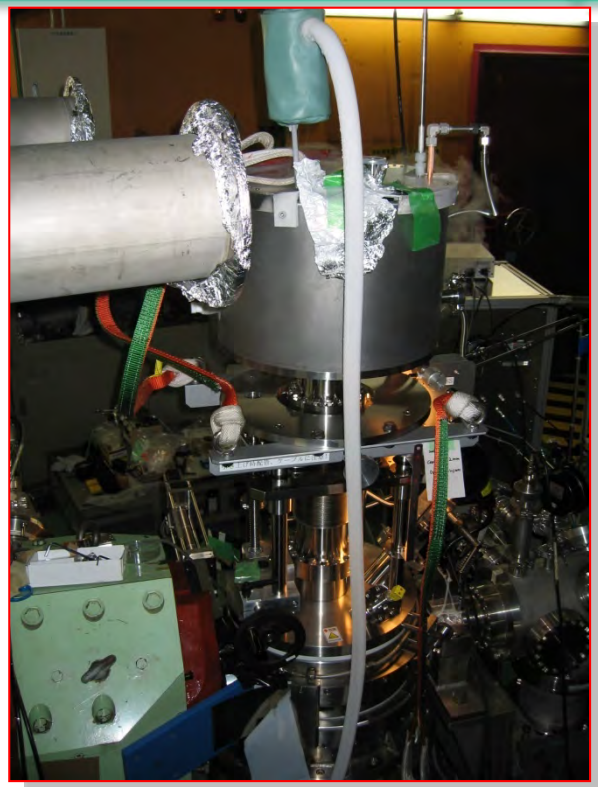
Low-Energy RI beam Productions at CRIB

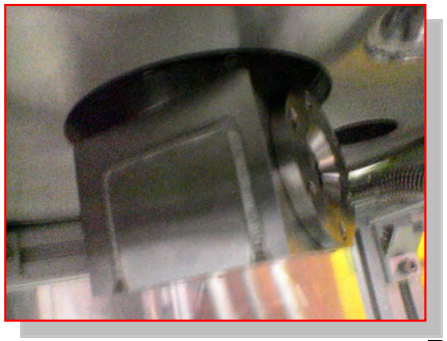
2-body reactions such as (p,n), (d,p) and (^{3}He,n) in inverse kinematics are mainly used for the production….large cross section

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



Intense secondary beam production using cryogenic gas target





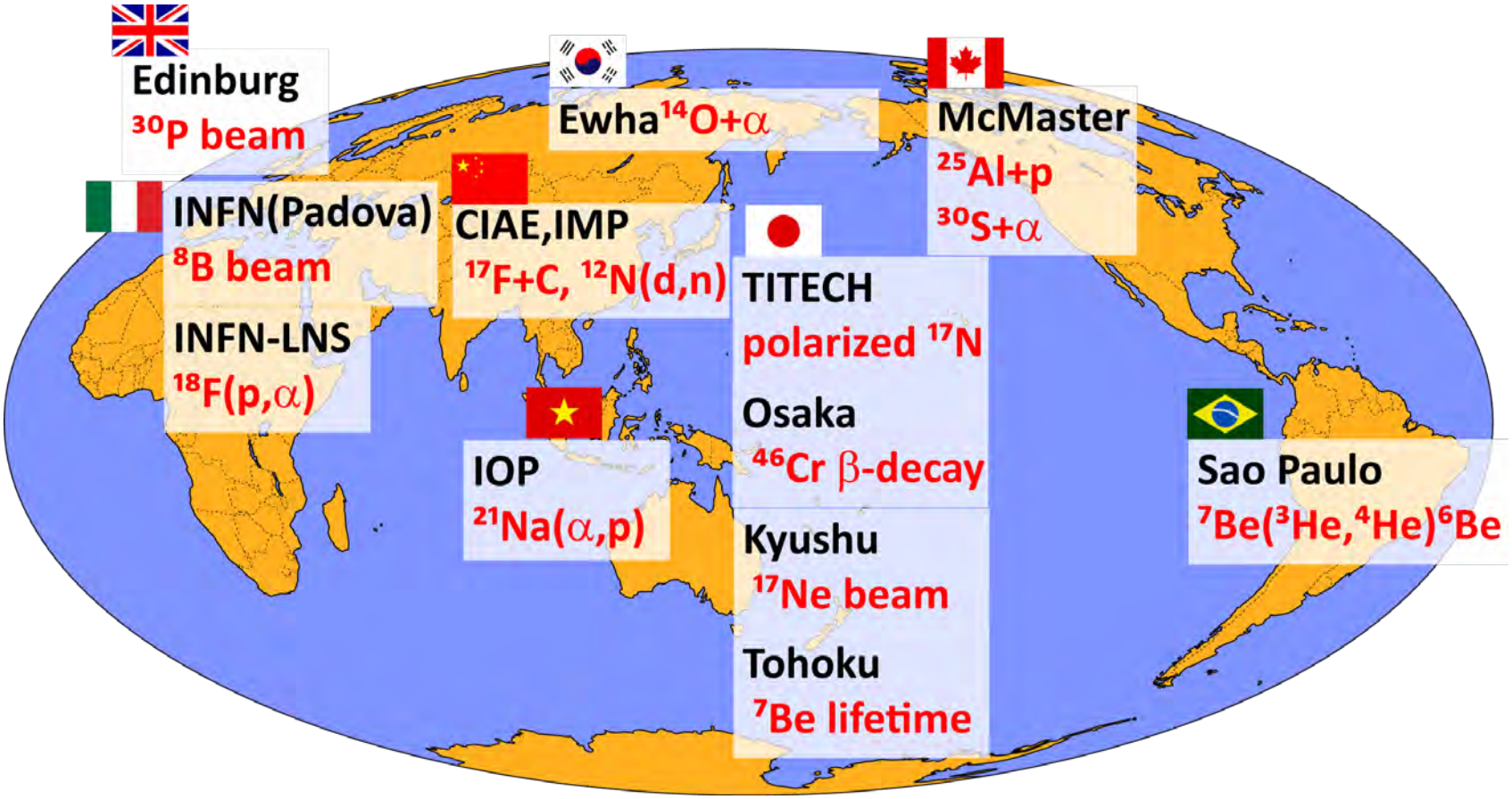
- H_2 gas target of 760 Torr and 80 mm-long worked at 85K stably for a $^{7}Li^{2+}$ beam of 1.3 pμA. (which deposits heat of 7.4W).
- Secondary beam: $^{7}Be^{4+}$ at 4.0 MeV/u, purity 75% (without degrader/ WF),

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

  H. Yamaguchi et al., NIMA (2008)

CRIB is collaborative

- CRIB experiments during 2007-2010 proposed by external groups:



CRIB is collaborative

- CRIB experiments after 2010 proposed by external groups:

CRIB is productive …publications in the last 5 years

Proton resonant scattering; astrophysical reactions, galactic γ-ray from ^{26}Al.

^{26}Si+p; H.S. Jung et al., Phys. Rev. C (2012).

^{25}Al+p; Jun Chen et al., Phys. Rev. C(2012), H.S. Jung et al., Phys. Rev. C (2014).

^{21}Na+p; J.J. He et al., Phys. Rev. C (2013), L.Y. Zhang et al., Phys. Rev. C (2014).

^{22}Na+p; S. Jin et al., Phys. Rev. C (2012).

^{17}F+p; J. Hu et al., Phys. Rev. C (2014).

α-resonant scattering; α clustering and (α,γ) reactions

^{7}Li+α/^{7}Be+α; H. Yamaguchi et al., Phys. Rev. C (2011 and 2013).

^{30}S+α; D. Kahl, Dr. thesis at Univ. of Tokyo (2015), Phys. Rev. C (2018).

^{10}Be+α; H. Yamaguchi et al., Phys. Lett. B (2017).

(α,p) direct reaction measurement

^{11}C(α,p); S. Hayakawa, Dr. thesis at Univ. of Tokyo (2012), Phys. Rev. C (2016).

^{14}O+α; A. Kim et al., Phys. Rev. C (2015).

Indirect astrophysical reaction measurement

^{18}F(p,α); Trojan Horse Method with RI beam S. Cherubini et al., Phys. Rev. C (2015).

^{12}N(p,γ) by ANC B. Guo et al., Phys. Rev. C (2013).

Reaction mechanism

^{17}F+^{12}C; Quasi-elastic scattering G.L. Zhang et al., Eur. Phys. J. A (2012).

Beamtime at **CRIB**, 2016-2017

- Measurement of the 7Be(d,p) Reaction with Implanted 7Be target and the Primordial 7Li Production in the Big Bang A. Tamii (RCNP)/H. Yamaguchi (CNS)

Beamtime used: 2 days (3 days remaining). The first production of implanted ^{7}Be target at CRIB in Jun. 2016. (d,p) measurement at JAEA Tandem followed, using the implanted target. To be completed in 2018.

- ^{26m}Al proton resonant elastic scattering with CRIB D. Kahl (Edinburgh)

2+12 days. The first ^{26}Al (ground state+isomer) beam production at CRIB in Jul, 2016. ^{26m}Al+p resonant scattering at CRIB in Mar. 2017, isomeric purity ~50%.

- Study of alpha cluster structure in ^{22}Mg K.Y. Chae (SKKU)

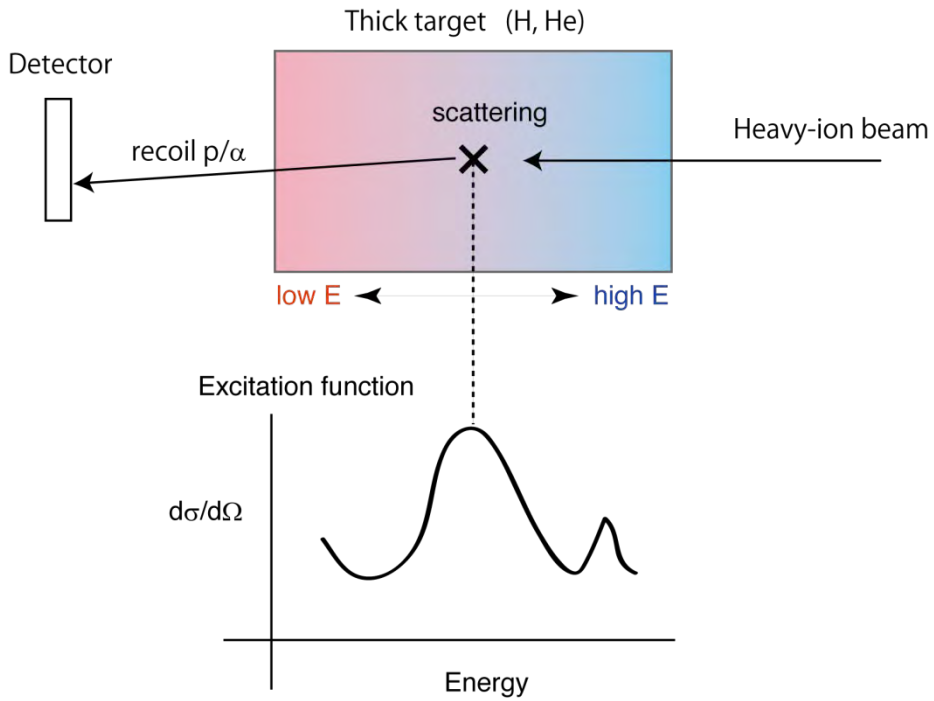
10 days in Sep. 2016. New resonances in ^{22}Mg are observed by a broad range scan.

- Indirect study of the Big Bang Nucleosynthesis reactions ^{7}Be(n,p)^{7}Li and ^{7}Be(n,α)^{4}He by the Trojan Horse Method S. Hayakawa (CNS)

14 days in Nov. 2016. The second Trojan Horse experiment performed at CRIB.

The thick-target method in inverse kinematics

Measurement of resonance scattering



- 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, no need to change beam energy.)
- The beam can be stopped in the target…measurement at θ_{cm}=180 deg. (where the potential scattering is minimal) is possible.

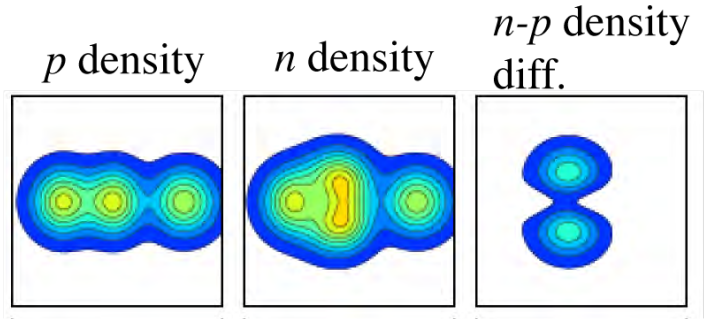
^{10}Be+α

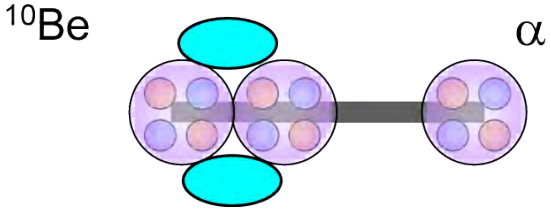
- Linear-chain cluster state:

has not been found since its first prediction by Morinaga in 1956.

- Linear-chain cluster states in ^{14}C were predicted in Suhara & En'yo calculation.
- 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.

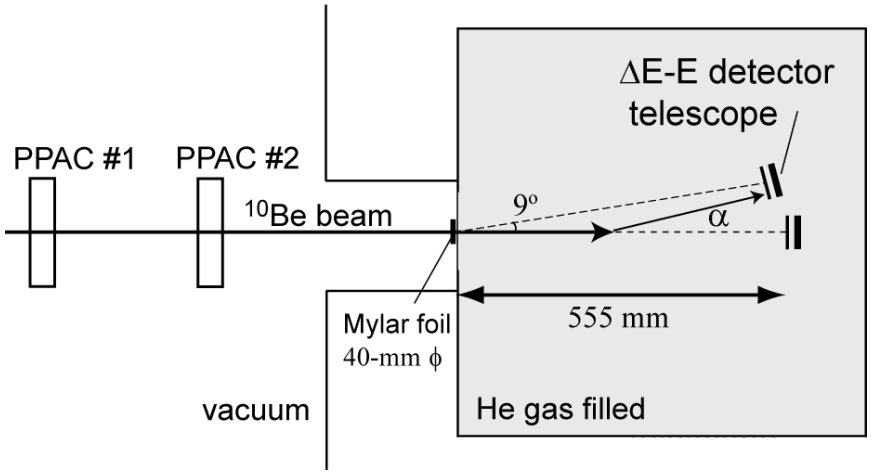
Suhara & En'yo, PRC 2010 and 2011:





Experimental setup

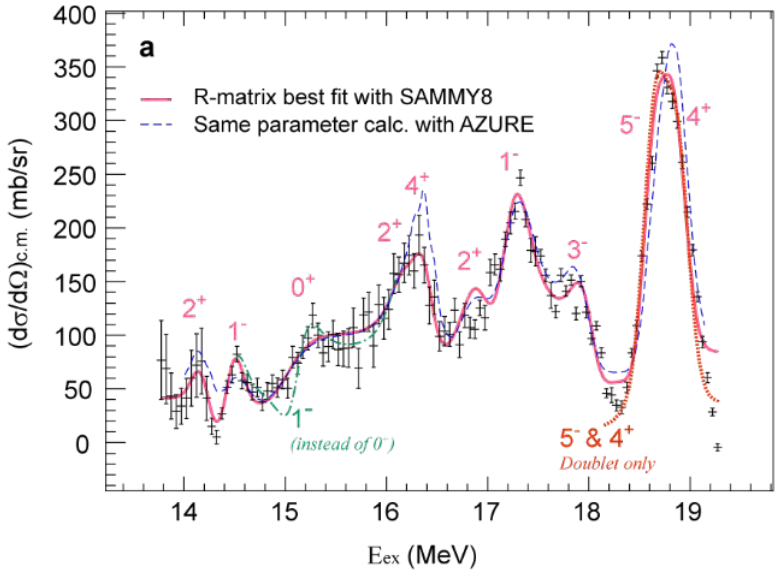
Thick target method in inverse kinematics,
similar to the previous ^{7}Be+α.

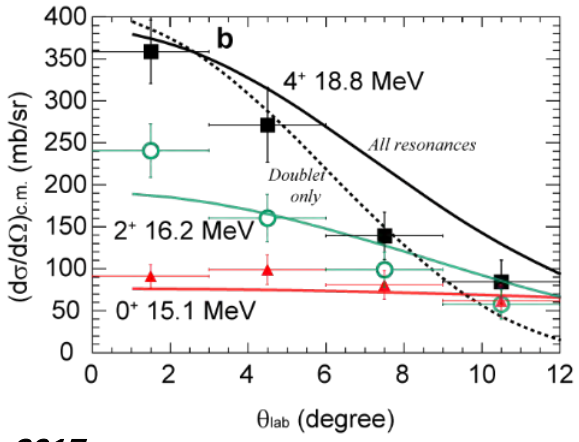


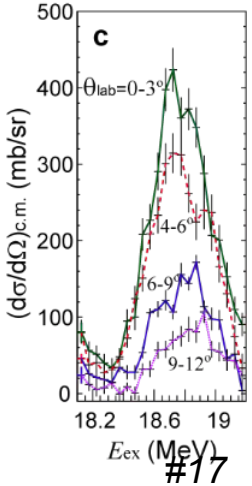
- Two PPACs for the beam PI, trajectory, number of particles.
- Two silicon detector telescopes for recoiling α partciles.
- E_{cm} and θ obtained by event-by-event kinematic reconstruction.

Excitation function

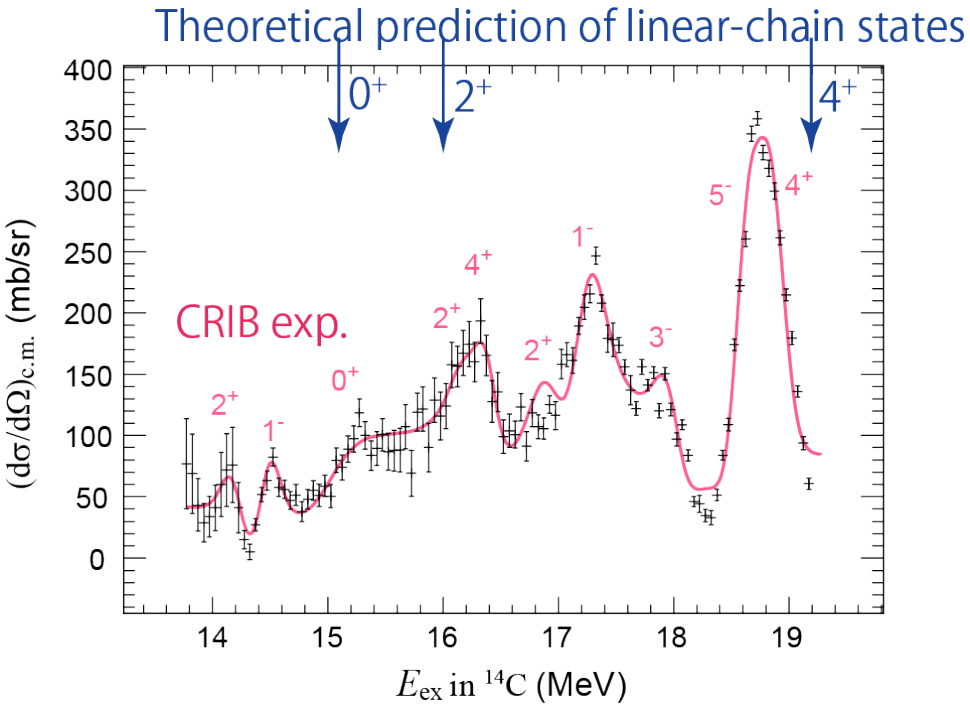
- The excitation function we obtained for 13.8-19.2 MeV exhibits many resonances.
- R-matrix analysis was performed to determine resonance parameters (E, J^{π}, Γ_{α}).

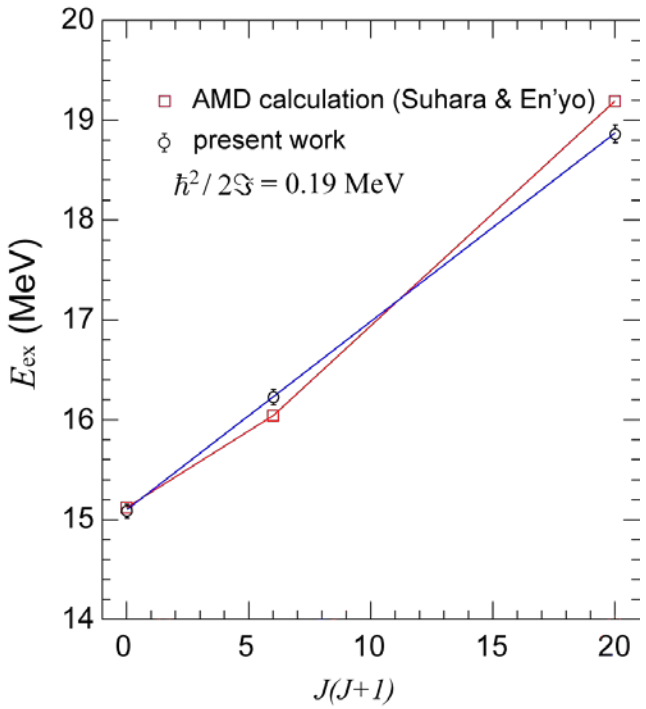






Rotational Band





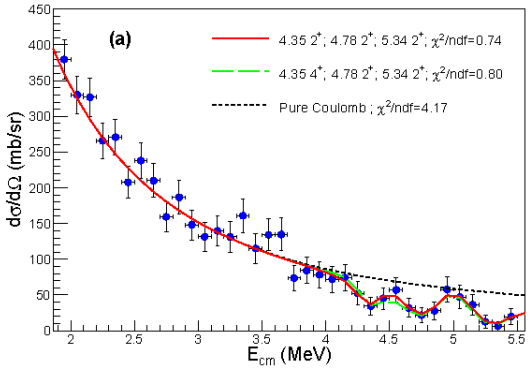
The set of resonances we observed (0^+, 2^+, 4^+) is proportional to $J(J+1)$ … consistent with a view of rotational band.

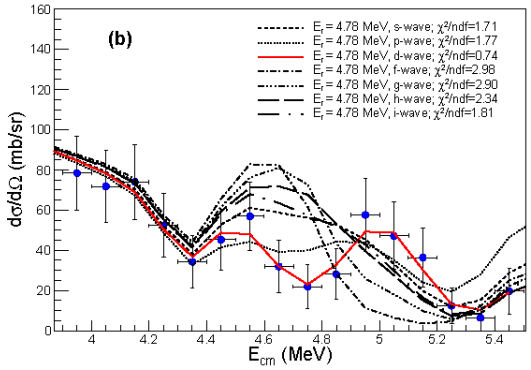
In a good agreement with the theoretical predictions;
Suhara-En'yo (2010)/ Baba-Kimura (2016).

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

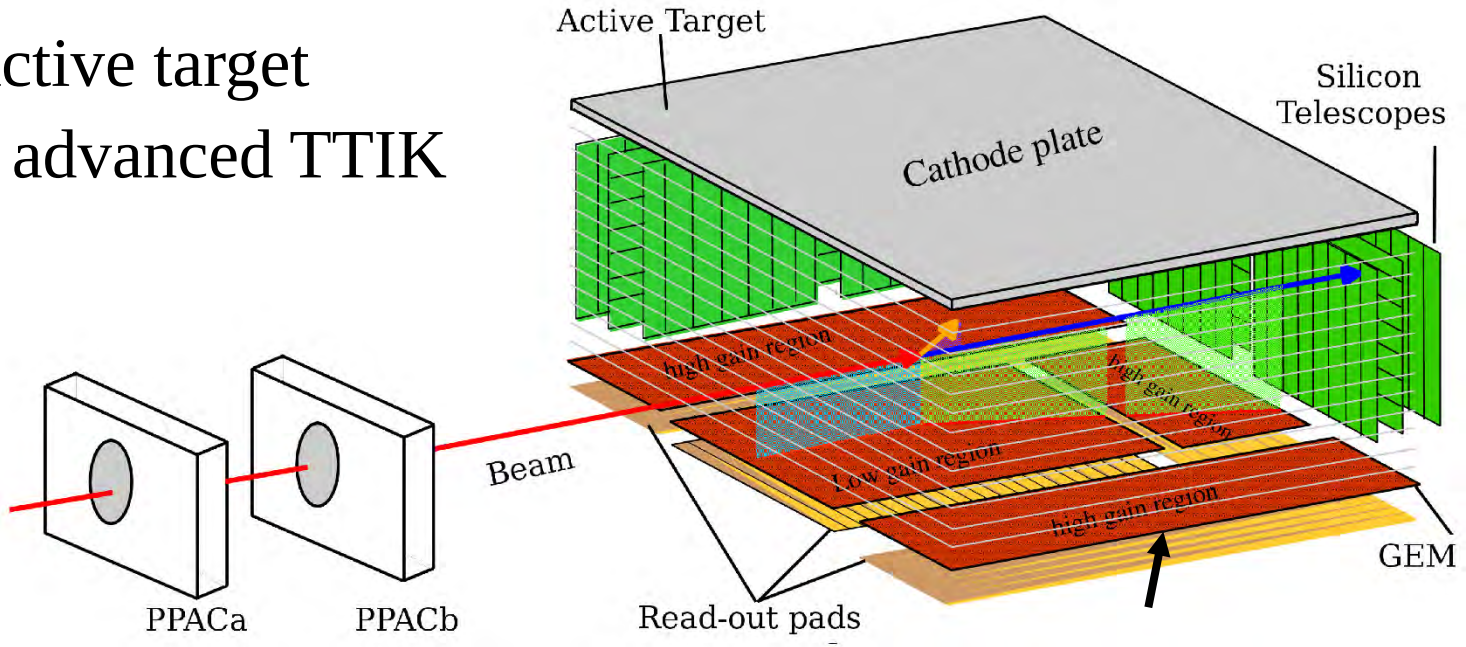
- $^{30}S(\alpha,p)$ … one of the key reaction in X-ray bursts.
- Scarce ^{34}Ar resonance information, reaction rate evaluation was only by statistical model.

- $^{30}S+\alpha$ resonant scattering with active target (D. Kahl et al., Phys Rev. C, accepted yesterday).
- 3 higher-lying resonances were observed:





Active target for an advanced TTIK



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

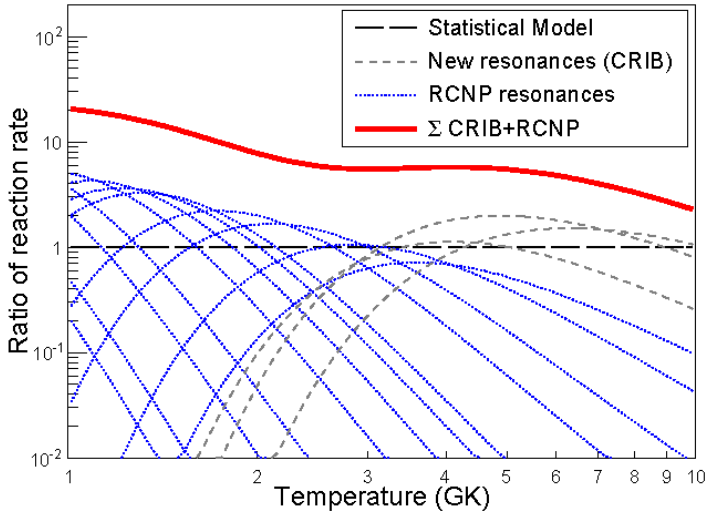
- Acts as a He target and a detector (TPC) simultaneously
- GEM with “backgammon” type readout pad.
- 3-dimentional trajectory and energy loss can be measured

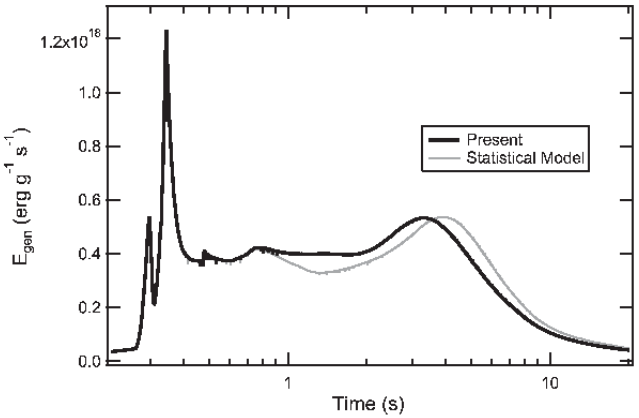
⇒ Accurate event identification.

Astrophysical implications

Reaction rate (upper limit) 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



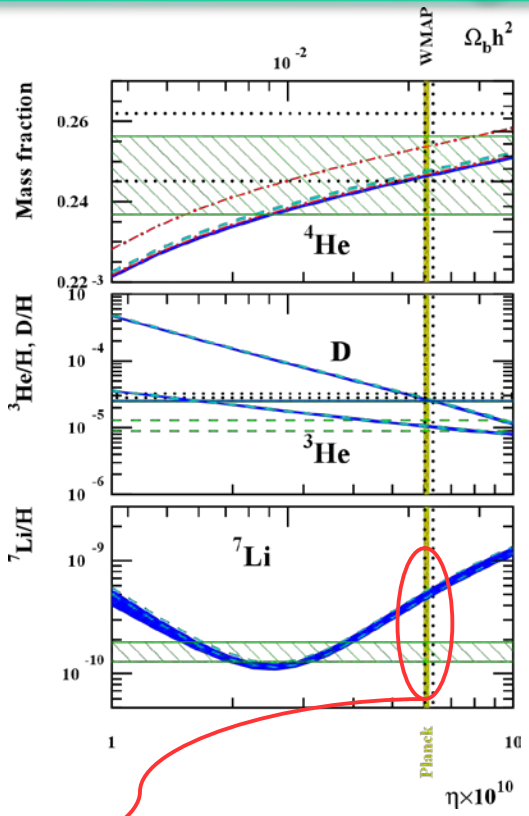


⇐Energy generation higher than the statistical model

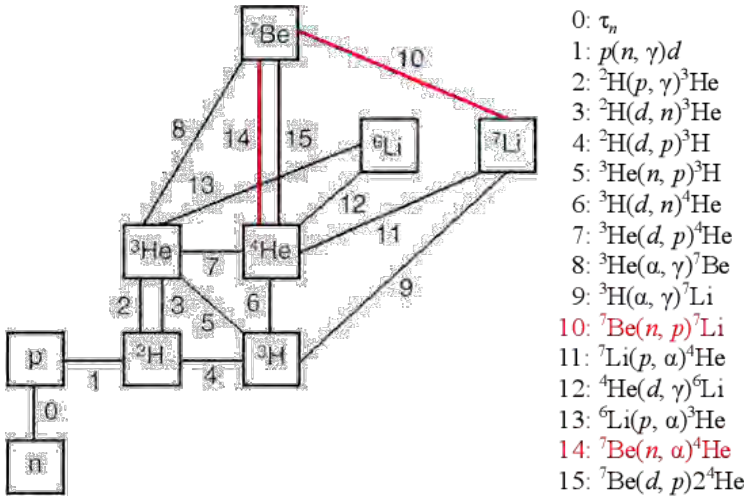
25% enhancement [even with this single reaction].

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

Cosmological ^{7}Li problem



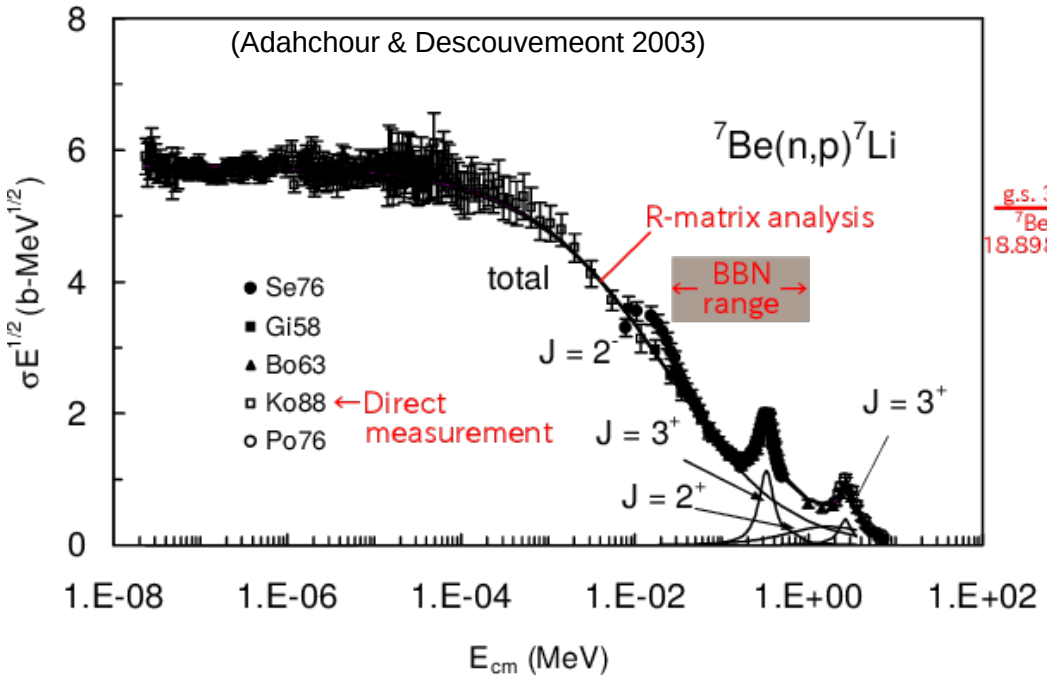
A. Coc et al. J. Cos. Astropart. Phys. 2014

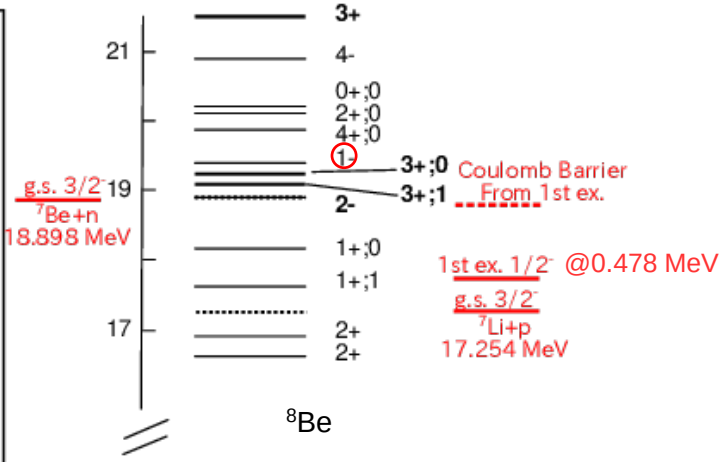


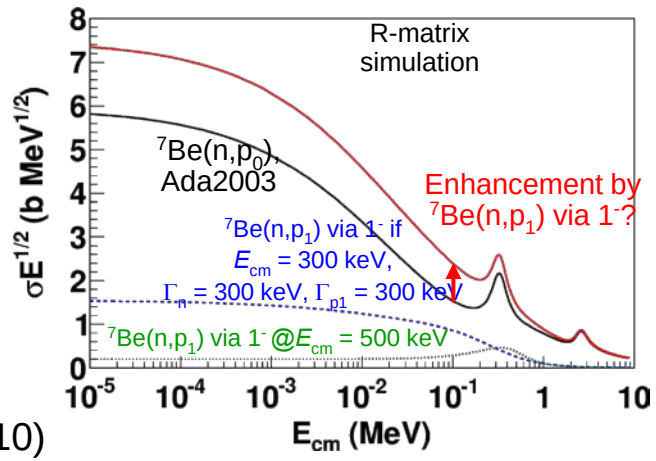
Iocco et al. Phys. Rep. 2009

- ^{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.

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







Main ^{7}Be destruction process (>90%)

Sensitivity: $\partial \log Y_{^7Li} / \partial \log \langle \sigma v \rangle_{^7Be} = -0.71$

⇒ If $\langle \sigma v \rangle_{^7Be} \times 2$, $Y_{^7Li} \times 0.6$ (Coc & Vangioni, 2010)

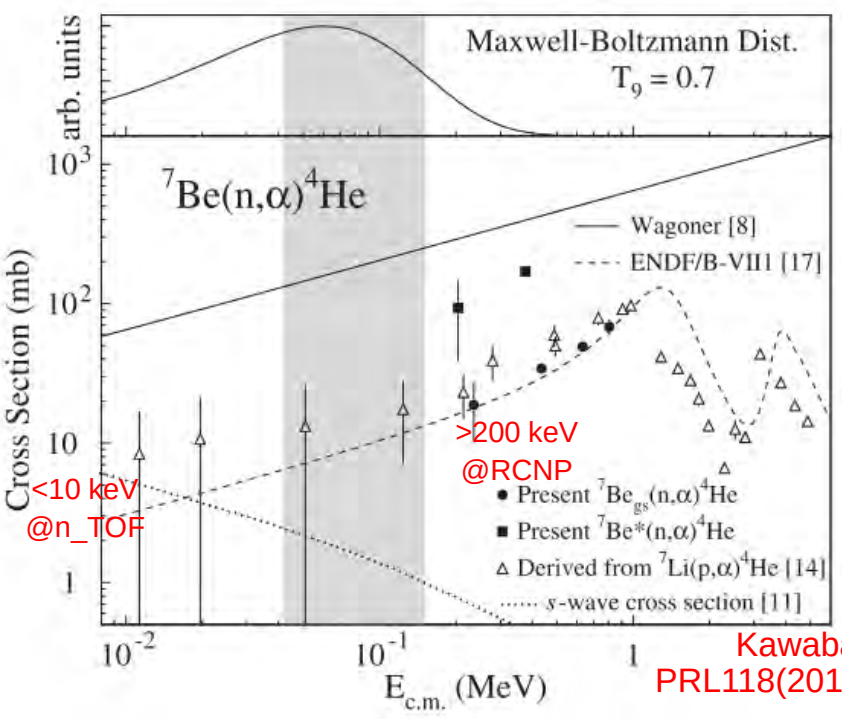
Direct measurement up to 13.5 keV, time-reversal reactions at higher energies.

R-matrix analysis: Adahchour & Descouvemeont 2003

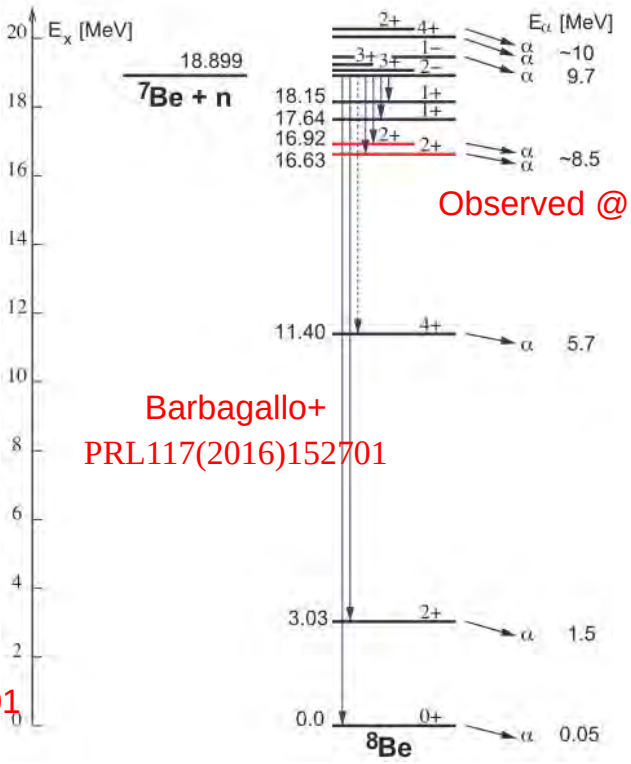
One 2- close to the threshold, two 3$^+$ resonances, one non-resonant broad 2$^+$

Accuracy: 1σ confidence level ~ 1%

^{7}Be(n,α)^{4}He (Q = 18.990 MeV)



Kawabata+
PRL118(2017)052701



Barbagallo+
PRL117(2016)152701

Revised reaction rate from mirror reaction by Hou+ (2015)

Direct measurement up to 10 keV by Barbagallo+ at n_TOF (2016)

Measured only α decays after γ-ray emission from ^{8}Be excited states

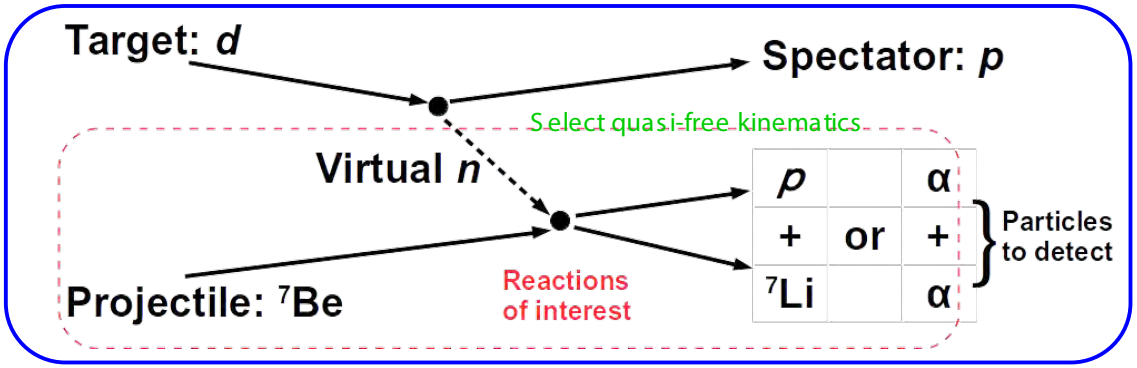
S-wave only → 1/v low

Time-reversal reaction measurement down to 200 keV by Kawabata+ at RCNP (2017)

Measured p-wave neutrons → dominant at BBN energies

Trojan Horse Method for RI + *n*

^{7}Be(*n*,*p*)^{7}Li, ^{7}Be(*n*,α)^{4}He via ^{2}H(^{7}Be,^{7}Li*p*)^{1}H, ^{2}H(^{7}Be,αα)^{1}H



$$\frac{d^3\sigma}{d\Omega_p d\Omega_{Li} dE_p} \propto (Kinematic\,factor) \cdot \left|\phi(p_{spec})\right|^2 \cdot \frac{d\sigma(E)^{HOES}}{d\Omega}$$

Three-body reaction cross section

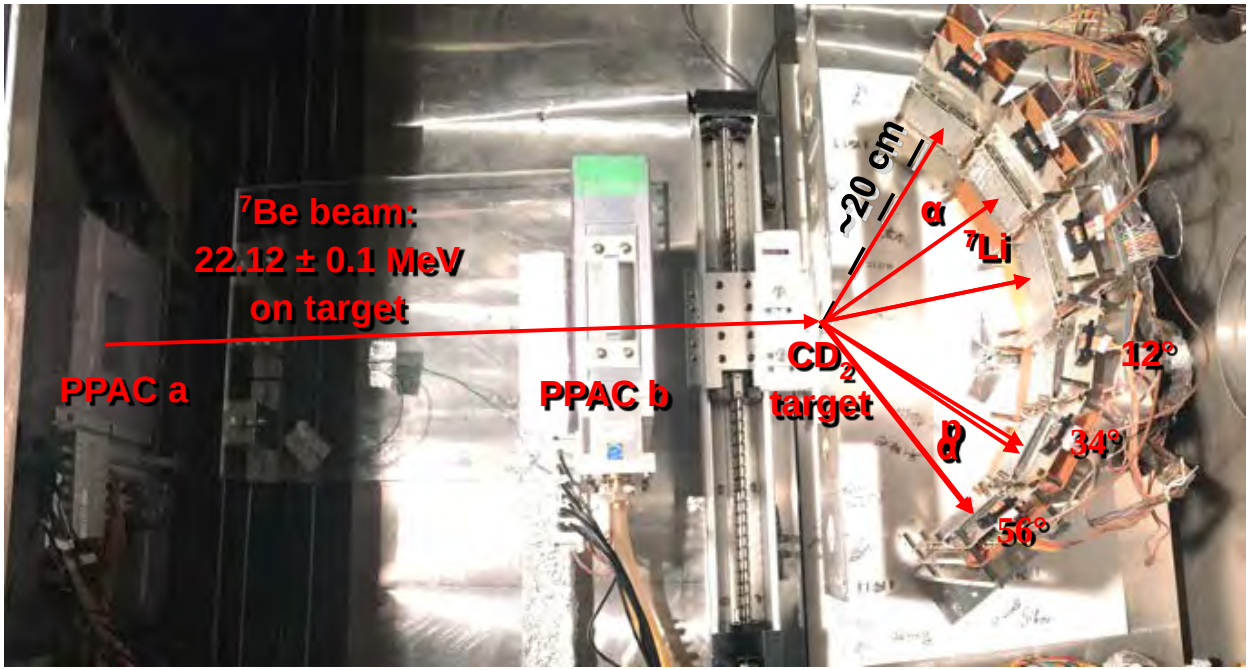
Calculated by Monte Carlo simulation

Momentum distribution of *n*-*p* in *d*: well-known

Half-off-energy-shell two-body reaction cross section

- Powerful method to approach astrophysical energies.
- One of the first applications of THM to RI + n reactions.
- Normalization to external data at higher energies.

Experimental setup



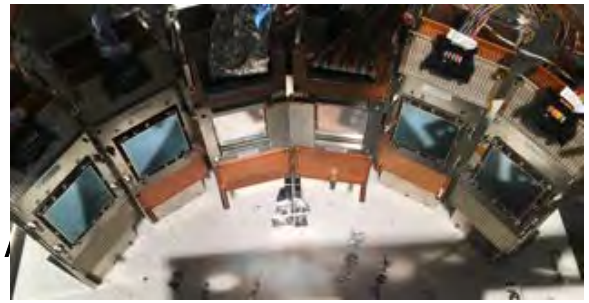
6 ΔE-E position sensitive silicon telescopes

Total angular resolution

~ 0.5° ⇒ ΔE_{cm} ~ 60 keV

CD$_2$: 64 μg/cm^2
→ ΔE_{beam} ~ 150 keV

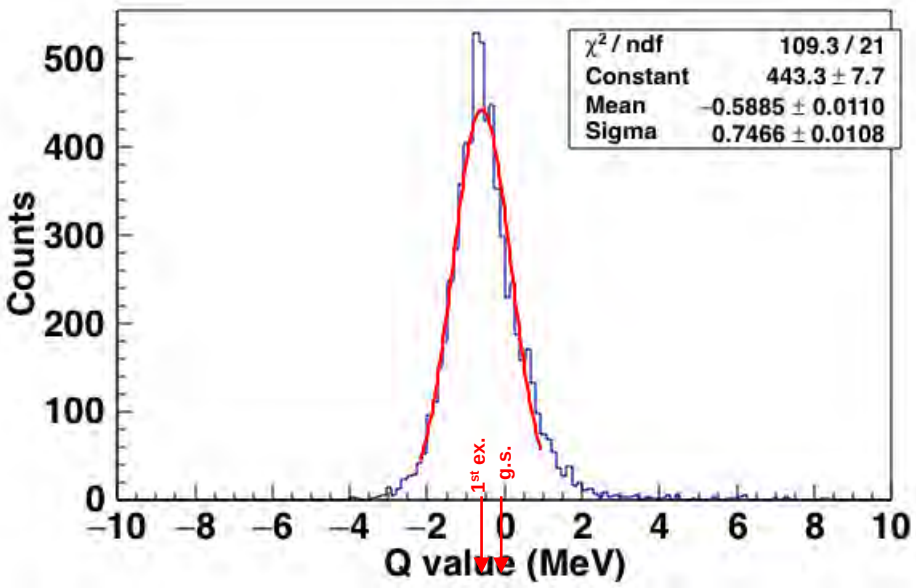
Hamamatsu Charge-division PSD: position resolution ~ 0.5 mm



Observed ~ 3000 Quasi-free events in 14-day beam time

Q-value spectra of the 3-body channels

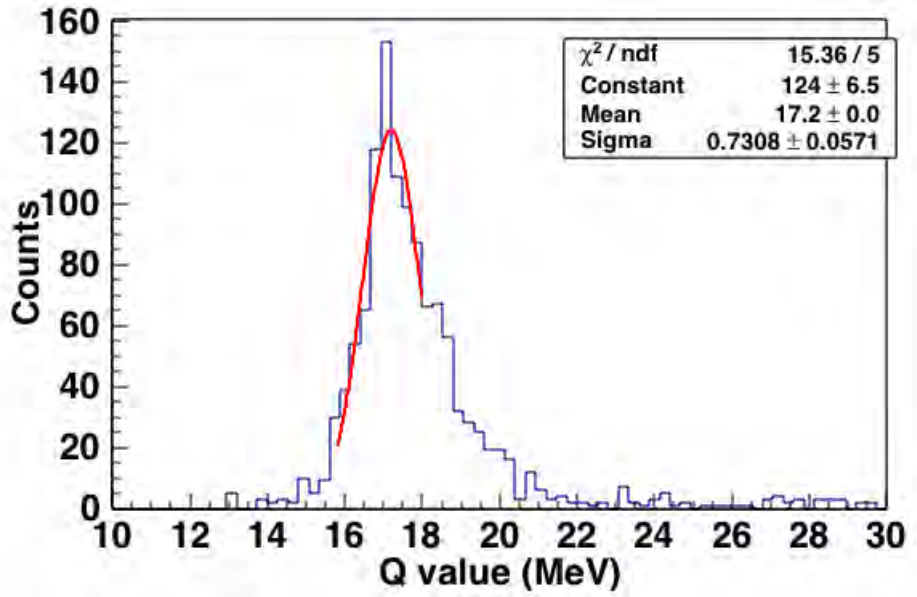
^{7}Be(d,^{7}Lip)p



Known value:
Q(g.s.) = -0.589 MeV
Q(1st) = -1.058 Mev

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

^{7}Be(d,2α)p



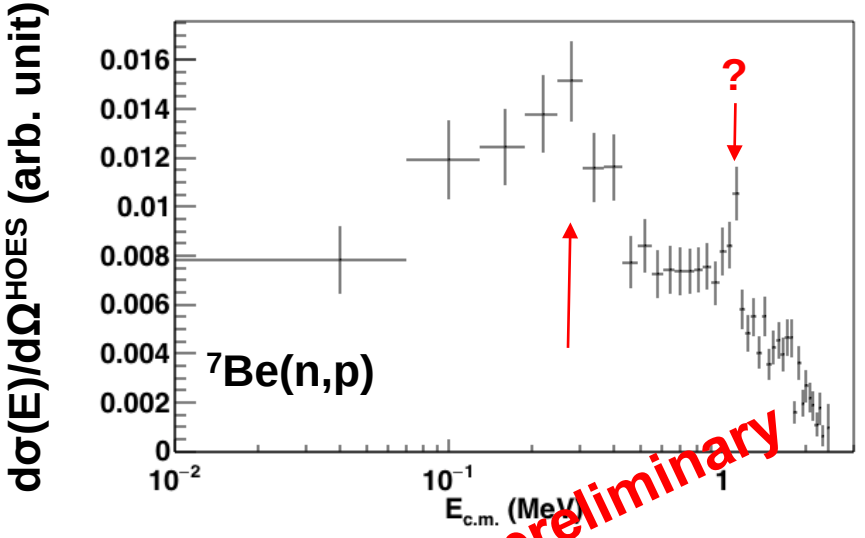
Known value:
Q(g.s.) = 16.766 MeV

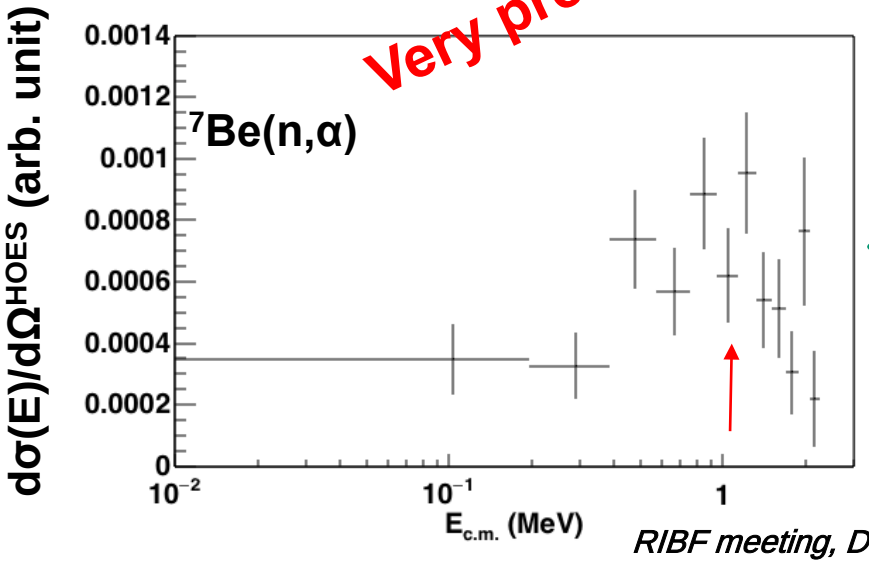
$$Q_{3body} = E_1 + E_2 + E_3 - E_{beam}$$

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

~ 200 keV expected with 64 μg/cm^2 CD_2 *#41*

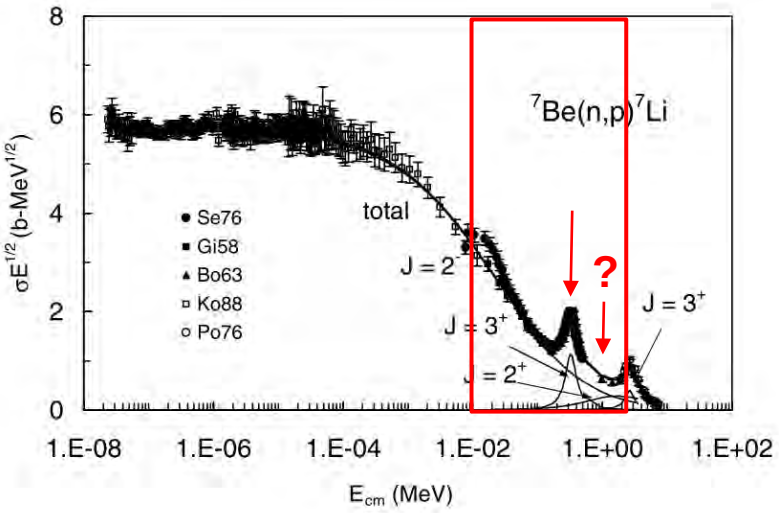
HOES cross sections for $|p_s| < 40$ MeV/c

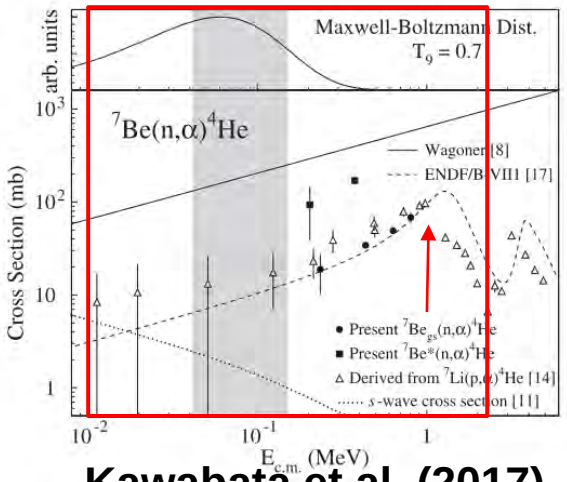




Very preliminary

Adahchour & Descouvemont (2003)





Kawabata et al. (2017)

RIBF meeting, Dec. 2017

Summary

- CRIB is a low-energy RI beam facility in RIBF operated by CNS, University of Tokyo, providing low-energy (<10MeV/u) RI beams with high intensity and purity.
- Many interests: Cluster structure with alpha resonant scattering, astrophysical (α,p) reaction measurement, reaction mechanism study, indirect measurements (THM and ANC), Al-26 isomeric beam for the cosmic gamma-rays, implanted RI target.
- We welcome new collaborators and new ideas. Please contact with me if you have any idea.
- The proposals are judged at the NP-PAC meeting (now once in a year in December), same as other RIBF facilities.
- Visit CRIB webpage for more information. http://www.cns.s.u-tokyo.ac.jp/crib/crib-new/