Study on explosive nuclear synthesis with low-energy RI beams at CRIB

:

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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.

Tanto piacere!

- Brief introduction of our RI beam separator CRIB (CNS, U-Tokyo)
- Nuclear astrophysics projects at CRIB:

1. Alpha resonant scattering with thick-target method in inverse kinematics (TTIK)

$^{7}Li/^{7}Be+\alpha$, $^{30}S+\alpha$, $^{10}Be+\alpha$, $^{15}O+\alpha$, etc.

2. Trojan Horse experiments with RI beam [skipped]

$^{18}F(p,a)$ in Novae: Silvio Cherubini (INFN-LNS)

$^{7}Be(n,p)/(n,\alpha)$ in BBN: Seiya Hayakawa (CNS, U-Tokyo)

3. ^{26}Al-isomer+p (galactic γ-ray)

H. Shimizu [poster]

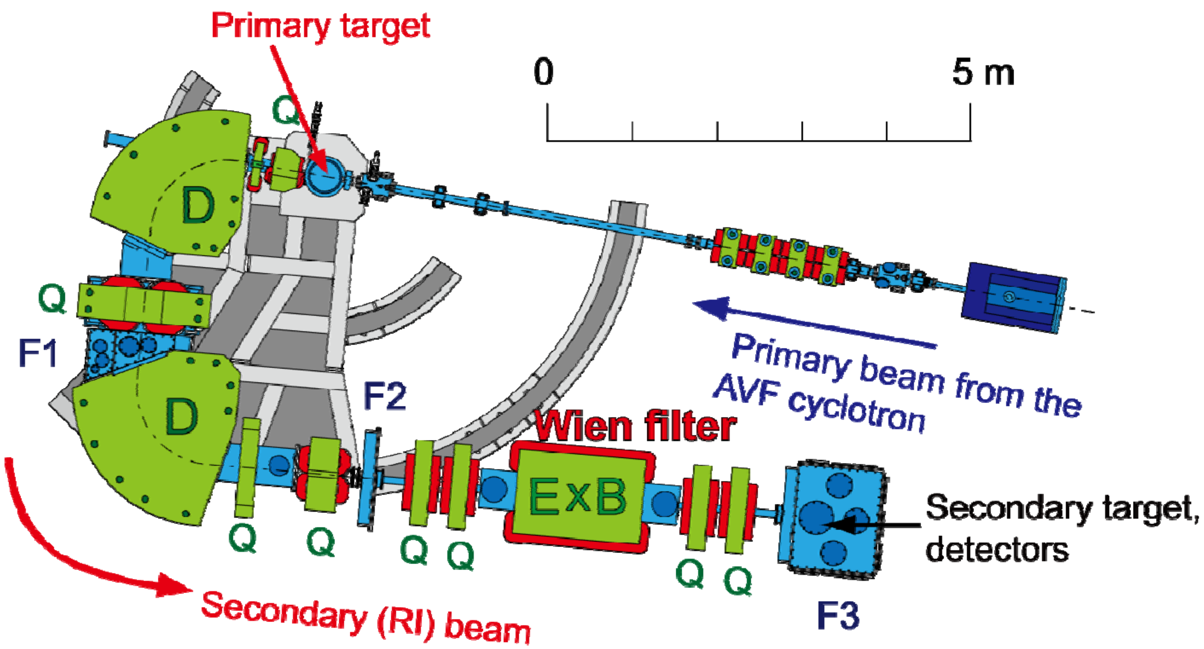
Daid Kahl (CNS → Edinburgh)

4. Reaction study with RI-implanted target

$^{7}Be(d,p)$ with A. Tamii, A. Inoue (RCNP, Osaka)

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.



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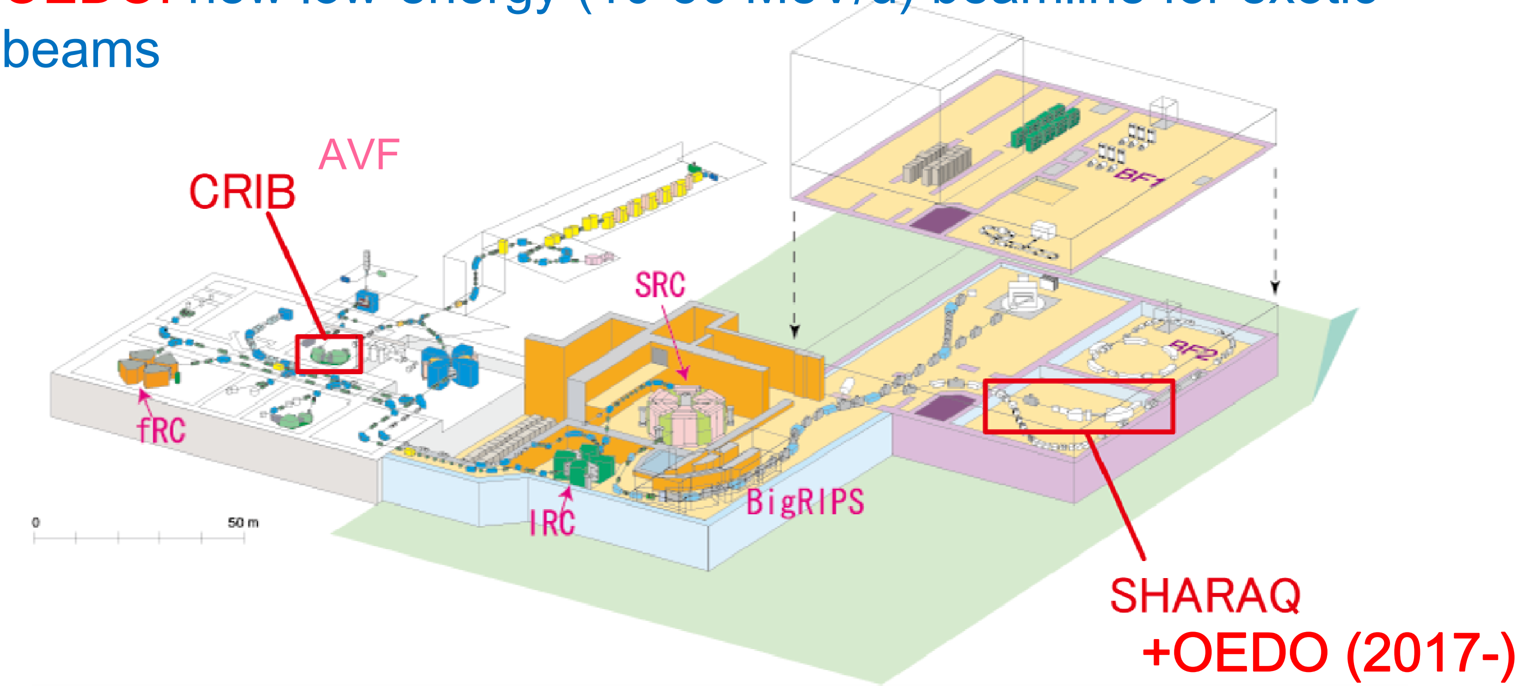
CRIB/OEDO in RIBF

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

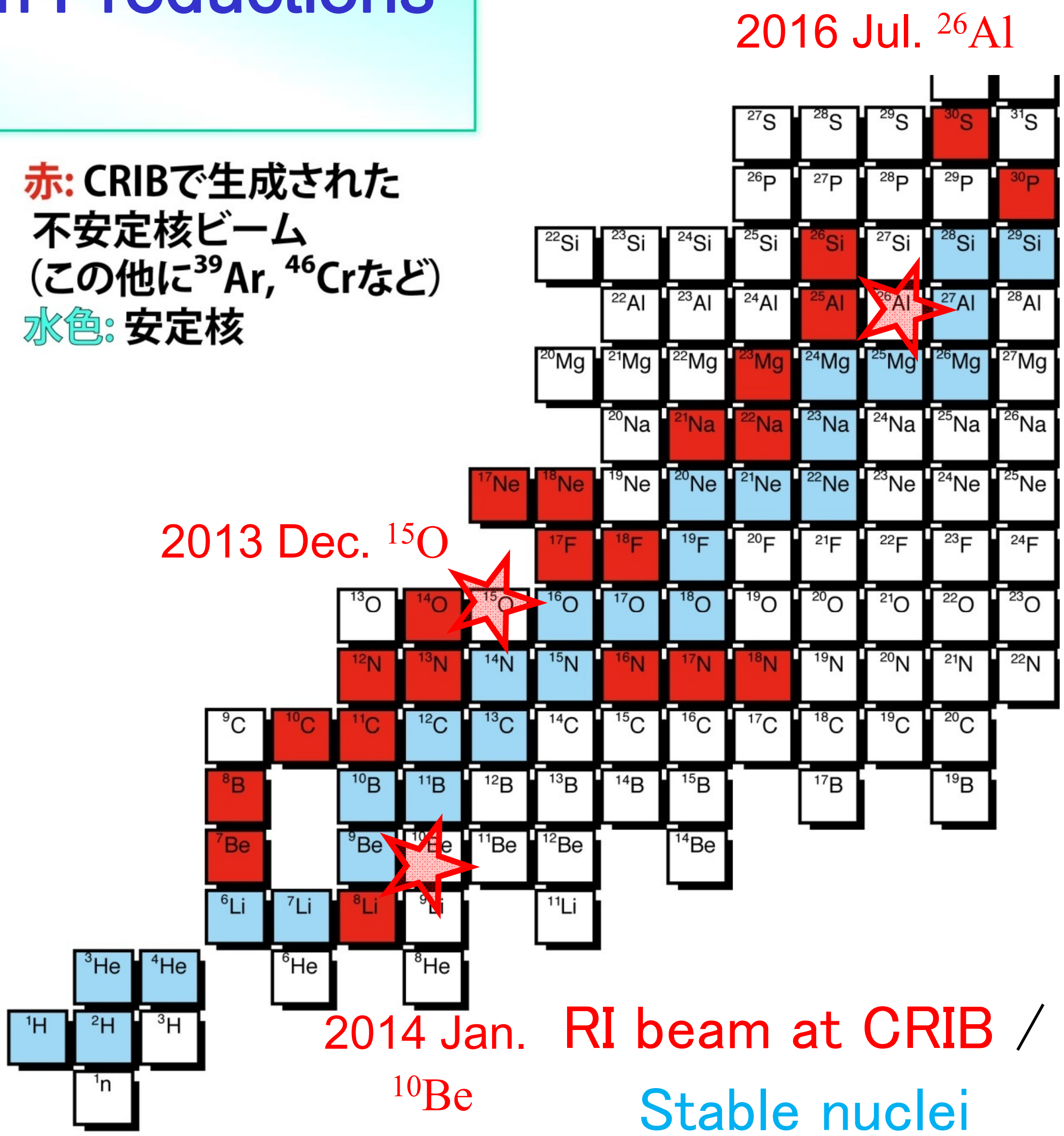


Low-Energy RI beam Productions at CRIB

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

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



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α-resonant scattering … a striking method to study resonant reactions and nuclear clusters

1. ^{7}Li+α (^{11}B), 3-body cluster, neutrino process (H. Yamaguchi et al., Phys. Rev. C (2011).

2. ^{7}Be+α (^{11}C), mirror symmetry between ^{11}B and ^{11}C, supernovae nucleosynthesis H. Yamaguchi et al., Phys. Rev. C (2013).

3. ^{10}Be+α (^{14}C), Linear-chain levels H. Yamaguchi et al., Phys. Lett. B (2017).

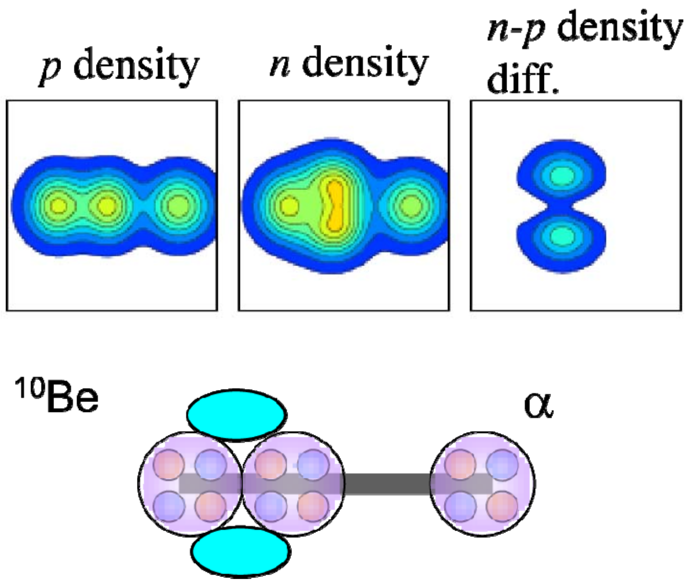
4. ^{30}S+α (^{34}Ar), astrophysical ^{30}S(α, p) reaction D. Kahl et al., Phys. Rev. C (2018).

5. ^{15}O+α (^{19}Ne), Comparison with ^{20}Ne cluster, astrophysical ^{18}F(p, α) reaction Exp. done in 2015, Dahee Kim Ph.D (2018).
6. ^{18}Ne+α (^{22}Mg), Mirror symmetry breaking? ($\Leftrightarrow$^{22}Ne) Exp. Done in 2016.

$^{10}Be+\alpha$

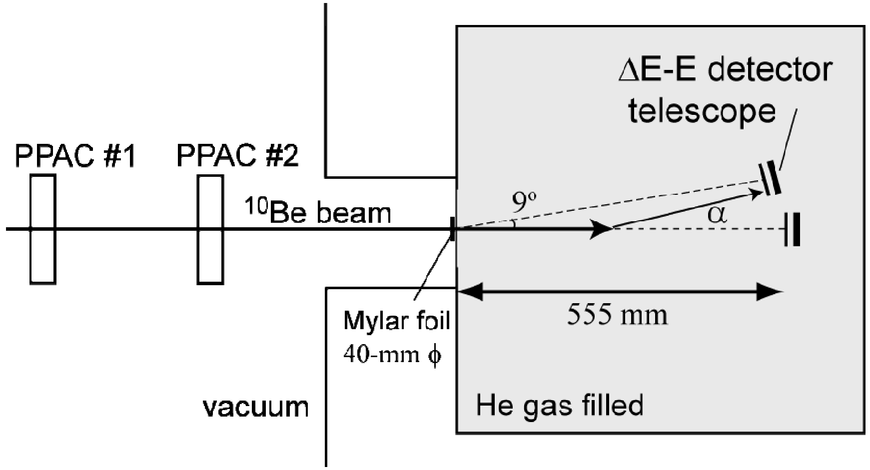
- Linear-chain cluster levels in ^{14}C were predicted in Suhara & En'yo calculation.
- Asymmetric, $^{10}Be+\alpha$ configuration …likely to be observed with $^{10}Be+\alpha$ alpha-resonant scattering.
- May form a band with $J^{\pi}=0^+,2^+,4^+$ a few MeV above α-threshold.
- Scattering of two 0^+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

Suhara & En'yo, PRC 2010 and 2011:



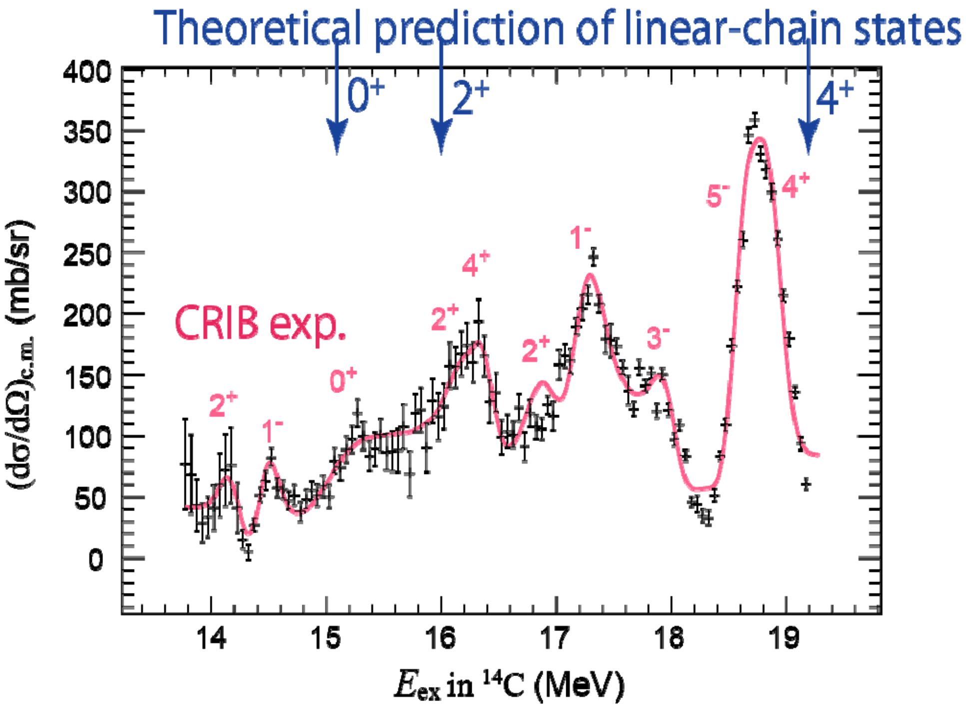
Experimental setup

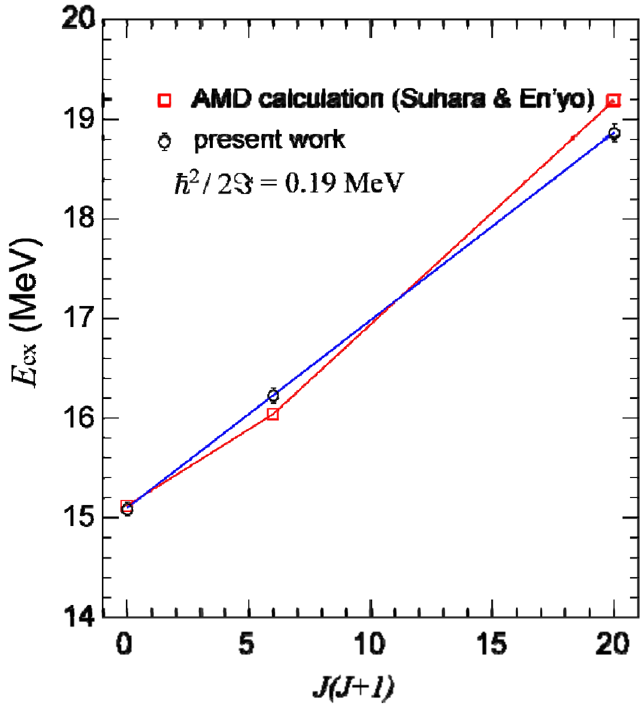
Thick target method in inverse kinematics,
similar to the previous $^{7}Be+\alpha$.



- 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.

Rotational Band identified





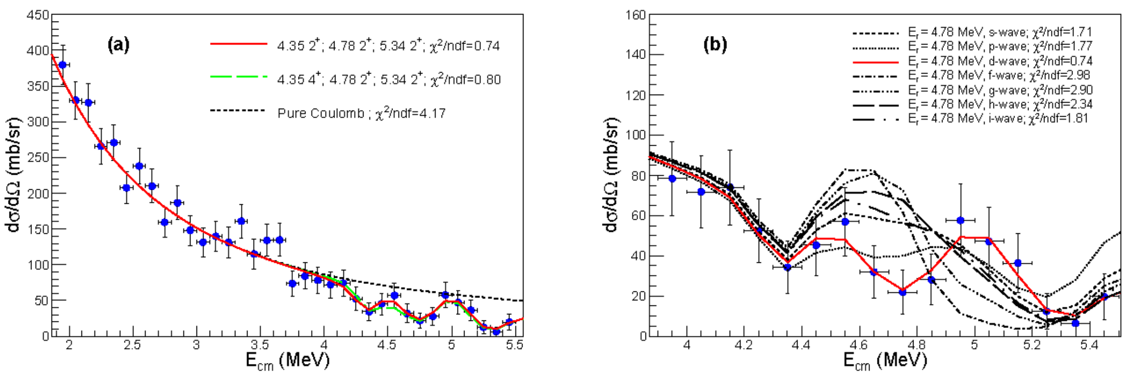
The set of resonances we observed (0^+, 2^+, 4^+) is proportional to *J(J+1)* … consistent with a view of rotational band.

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

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

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

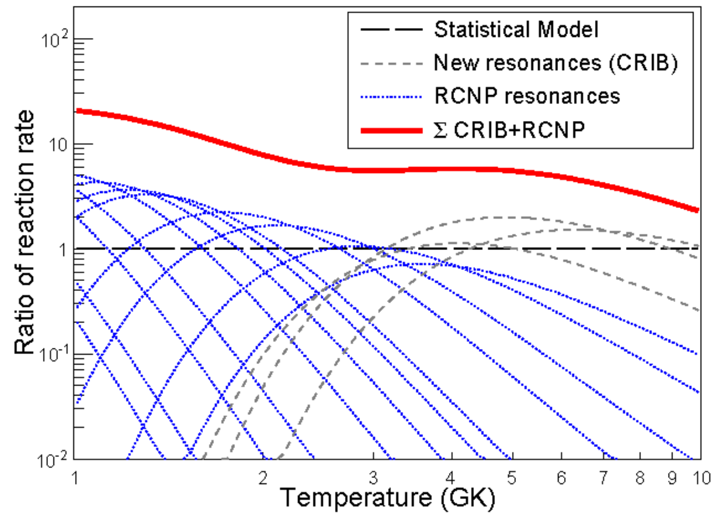
- $^{30}S+\alpha$ resonant scattering with active target… D. Kahl et al., Phys. Rev. C (2018).
- 3 higher-lying resonances were observed:

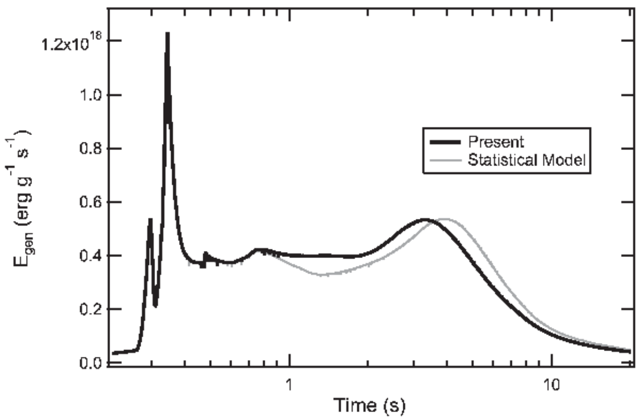


Astrophysical implications

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





⇐X-ray burst energy generation: higher than the statistical model

25% enhancement [even with this single reaction].

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

•See also : Long et al., PRC **97**, 054613 (2018).

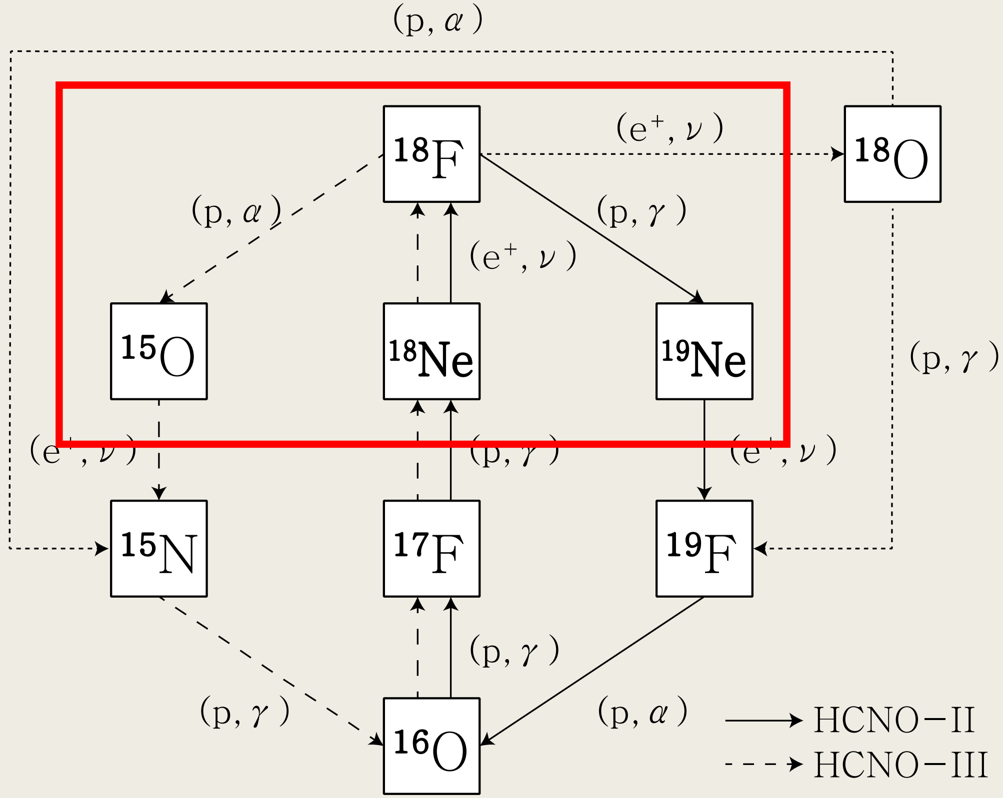
^{15}O+α: in collaboration with Ewha Womans Univ. (Dahee Kim, Aram Kim, K.I. Hahn et al.)

- ^{18}F nucleosynthesis in the classical nova

Destructive reactions of ^{18}F (important for the 511-keV from novae):

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

$$^{18}\mathrm{F}(p,\gamma)^{19}\mathrm{Ne}$$

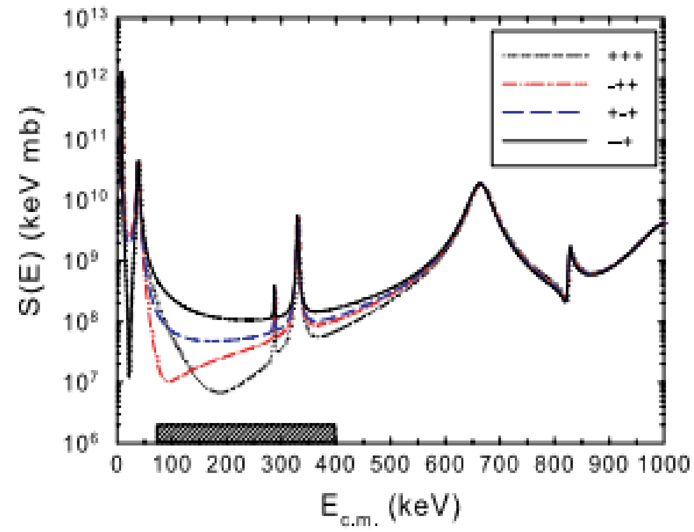


Resonance study

K. Y. Chae et al.
Astrophysical S- factor of the $^{18}F(p,a)^{15}O$ reaction

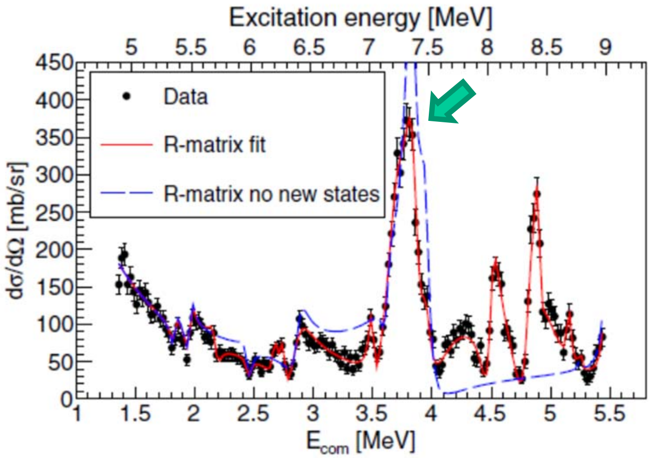
- Resonances near the proton threshold (E_x = 6.411 MeV) are the key for the $^{18}F(p,\alpha)^{15}O$ reaction rate for T_9 = 0.04 - 0.4.
- Many studies, but still uncertain spin-parities and unresolved resonances
- Interference effect

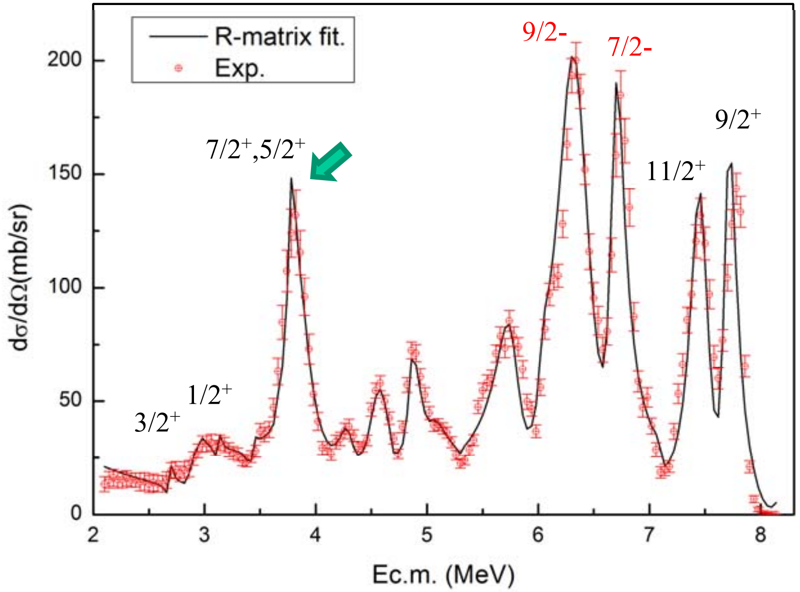
E_r (keV)	J^π	Γ_p (keV)	Γ_α (keV)	Ref.
8	$3/2^+$	2.2×10^{-37}	0.5	[10]
26	$1/2^-$	1.1×10^{-20}	220.0	[10]
38	$3/2^+$	4.0×10^{-15}	4.0	[10]
287	$5/2^+$	1.2×10^{-5}	1.2	[10]
330	$3/2^-$	2.22×10^{-3}	2.7	[11]
450	$7/2^-$	1.6×10^{-5}	3.1	[12]
664.7	$3/2^+$	15.2	24.0	[8]
827	$3/2^+$	0.35	6.0	[12]
842	$1/2^+$	0.2	23.0	[12]
1009	$7/2^+$	27.0	71.0	[12]
1089	$5/2^+$	1.25	0.24	[12]
1122	$5/2^-$	10.0	21.0	[12]

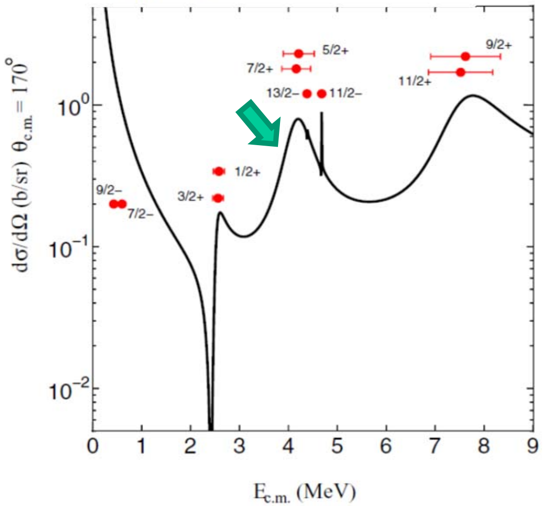


Present work vs Italian group vs Theory

D. Torresi *et al*., Phys. Rev. C 96, 044317(2017)







R. Otani *et al*., Phys. Rev. C 90, 034316(2014)

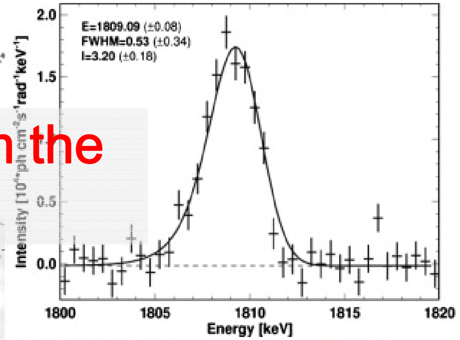
The origin of galactic ^{26}Al gamma rays

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

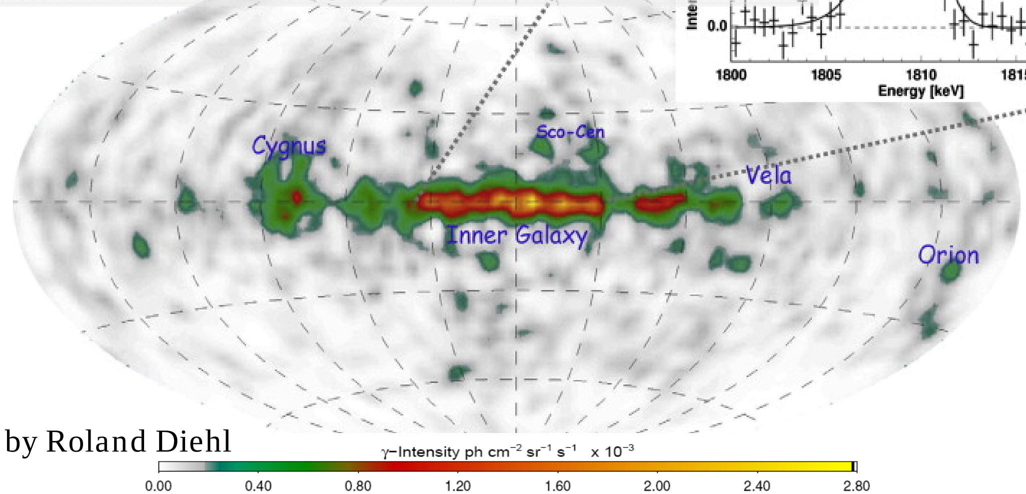
An evidence of the on-going nucleosynthesis.

A 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

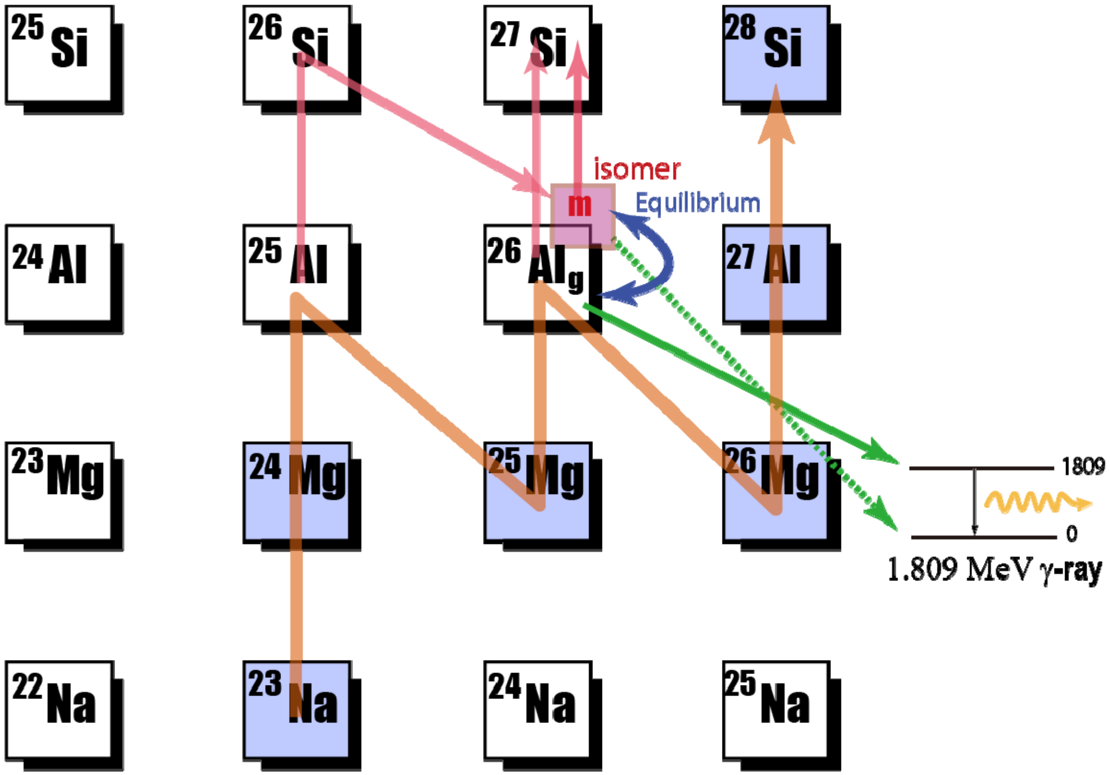
2.0 ± 0.4 $M_\odot$ – Diehl (2016),

but

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

Needs ^{26}Al-destruction process?

Flow around ^{26}Al



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.

^{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

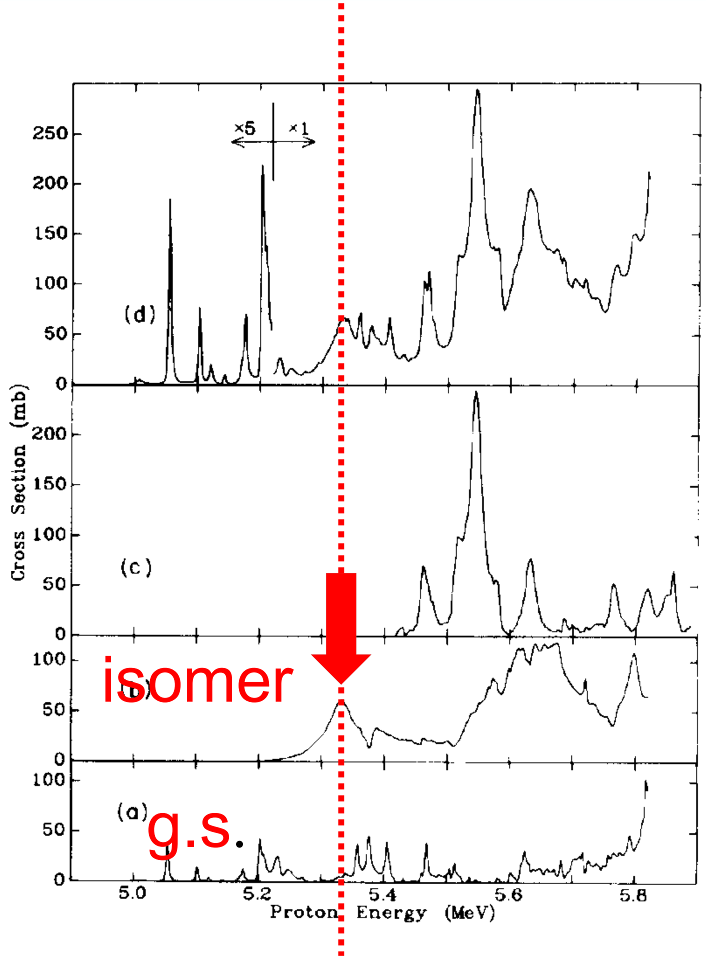
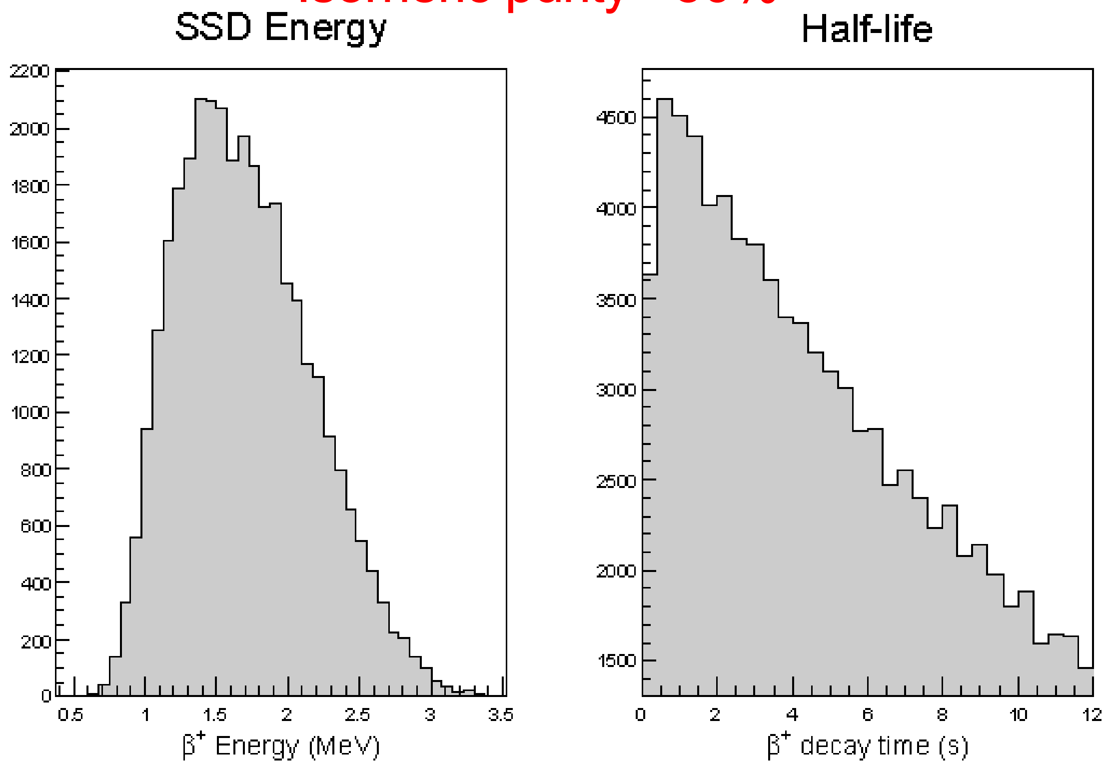


FIG. 4. Excitation functions for (a) ^{26}Mg(p,n_0)^{26}Al, (b) ^{26}Mg(p,n_1)^{26}Al, (c) ^{26}Mg(p,n_2)^{26}Al, and (d) the total neutron yield.

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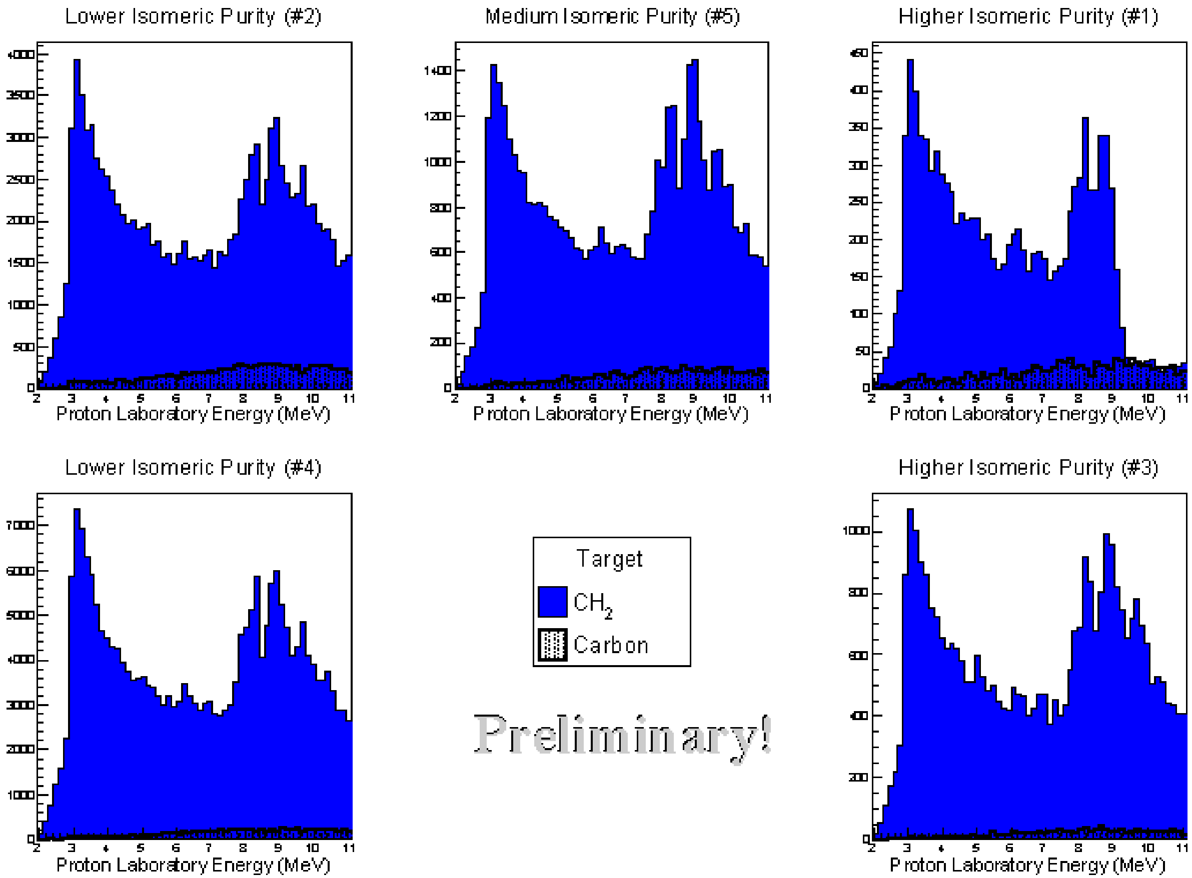
^{26}Al proton spectra – the method worked!



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

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New project:

Reaction measurement with implanted RI target

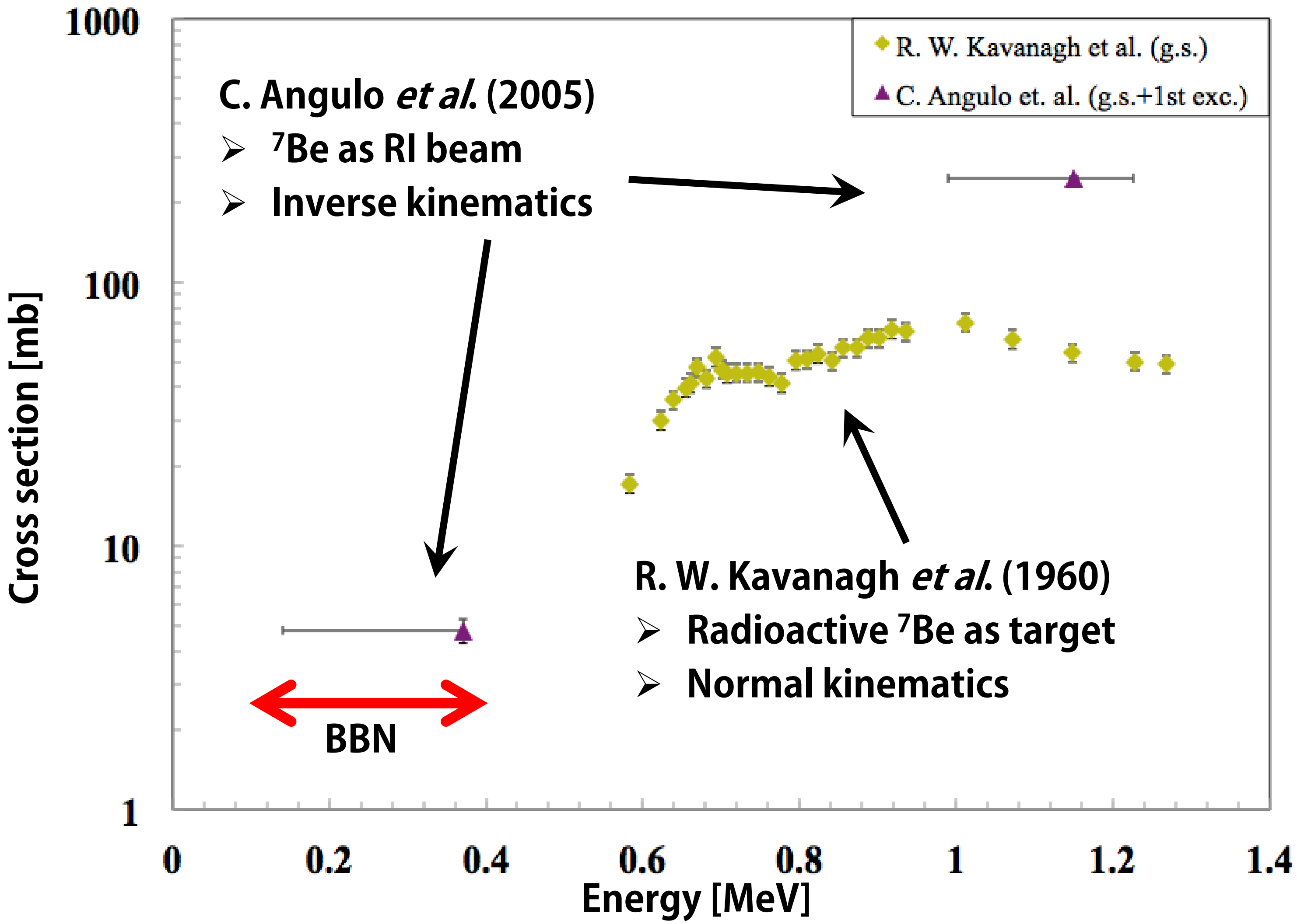
in collaboration with RCNP (A. Tamii, A. Inoue et al.) and JAEA.

-in-flight RI beams: large emittance and low intensity. The RI that did not make a reaction is “disposed” immediately. Can we implant the RI into a small space and reuse them? We can choose an ideal host material for the implantation (Au).

-^{7}Be(d,p) is the first (test)case for us, related to the ^{7}Li abundance problem *[Remember: Talk by I. Wiedenhöver on Monday]*

Stronger motivation is on the technical aspect.

^{7}Be(*d, p*) for the ^{7}Be destruction

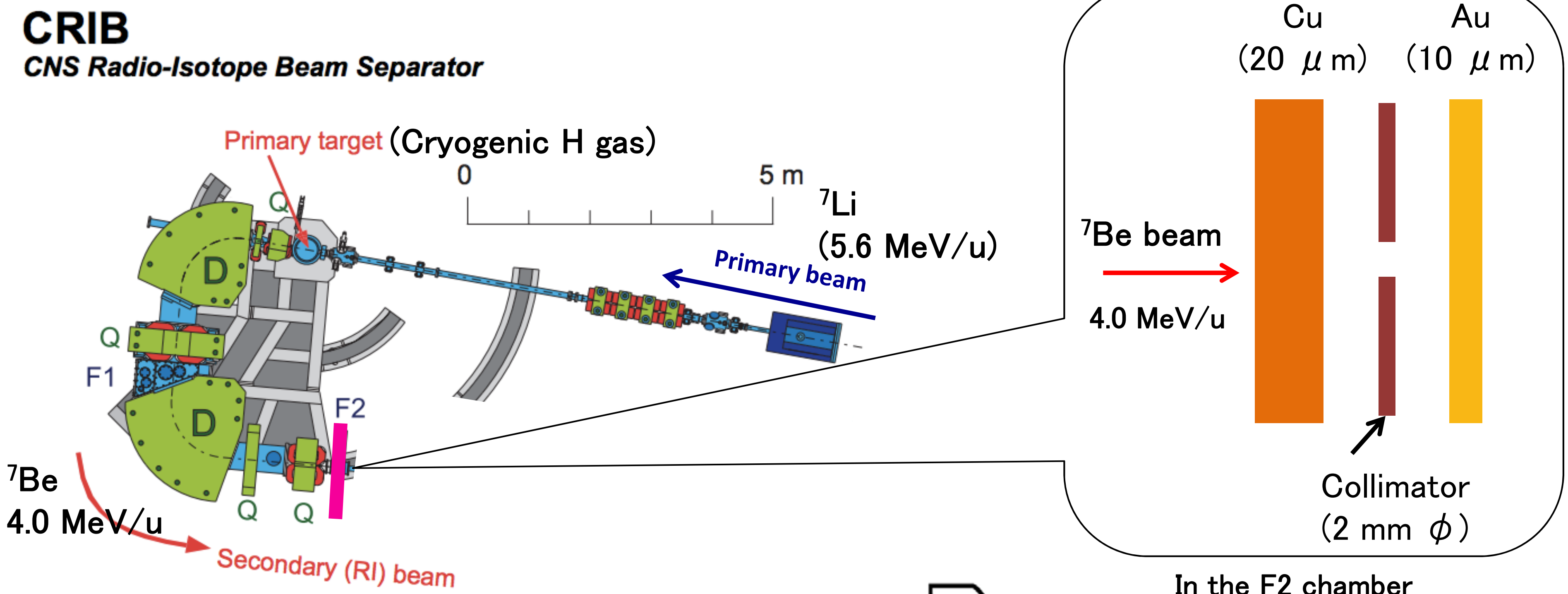


Few data in BBN region

Cross section needs to be increased by a factor of 100 – 1000 to solve the 7Li abundance problem.

^{7}Be(d,p) measurement with an implanted ^{7}Be target

✧ **Step 1: Implant 7Be to make a target at CRIB (April 2018)**

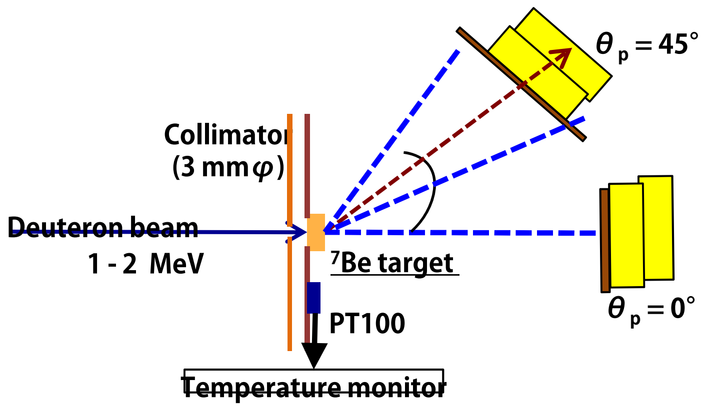


In the F2 chamber

→ 1.2 × 10^{12} ^{7}Be particles in 2mm-ϕ

^{7}Be transported to JAEA (135 km far)

✧ **Step 2: 7Be(d,p) reaction measurement at JAEA**



Measurement completed in June, 2018.
Analysis in progress.

Summary

- CRIB is a low-energy RI beam facility in RIBF operated by CNS, University of Tokyo, providing low-energy (<10MeV/u) RI beams of good intensity and purity.
- Many interests: Cluster structure/alpha-induced astrophysical reactions with alpha resonant scattering, 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/