

Studying nuclear reactions with the low-energy RI beam separator CRIB

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



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with an Aid of Technical Staff:

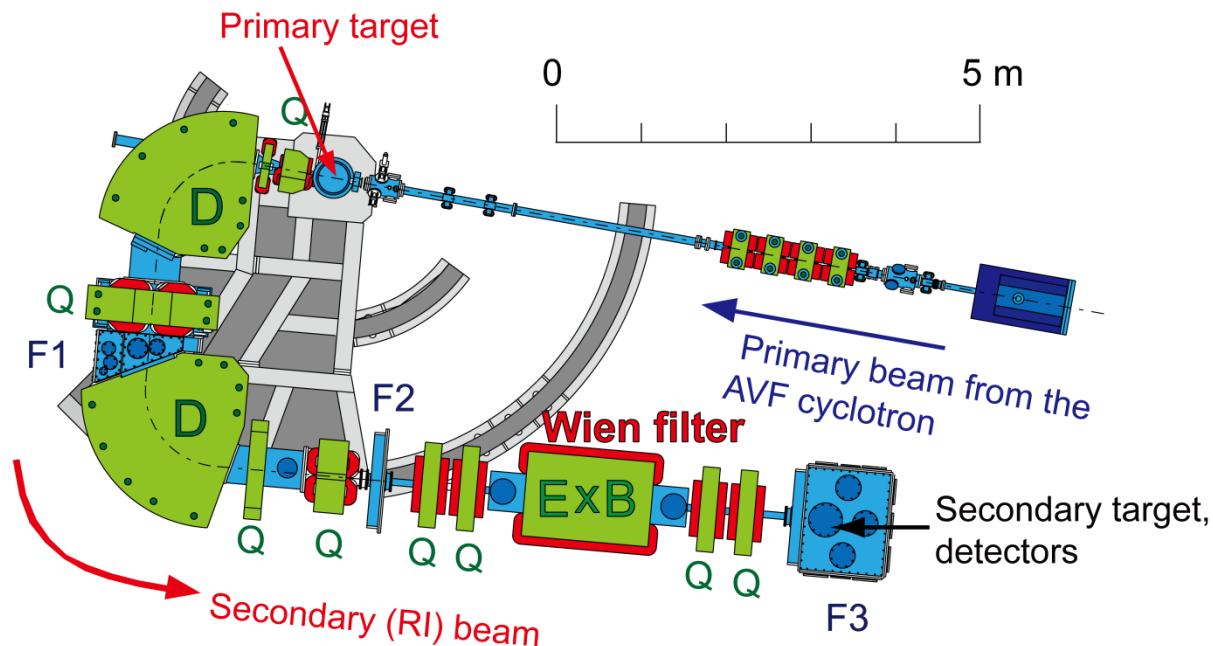
N. Yamazaki (CRIB/Wien Filter), K. Yoshimura, T. Senoo,
Y. Ohshiro (Hyper ECR ion source), S. Yamaka

in Collaboration with:

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

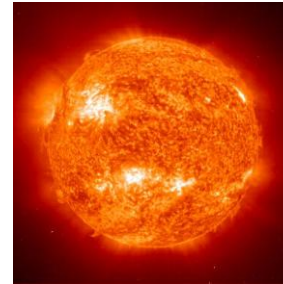
CRIB

- **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.

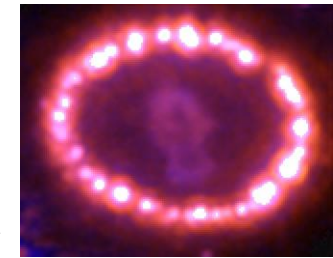


Why low-energy RI beam?

- Stellar astrophysical reactions :
T ~ 10^6 - 10^9 K (typically **keV to a few MeV**).
⇒ **Low** energy is not **bad** energy!
It is an **advantage** for nuclear astrophysics and structure study.



The Sun

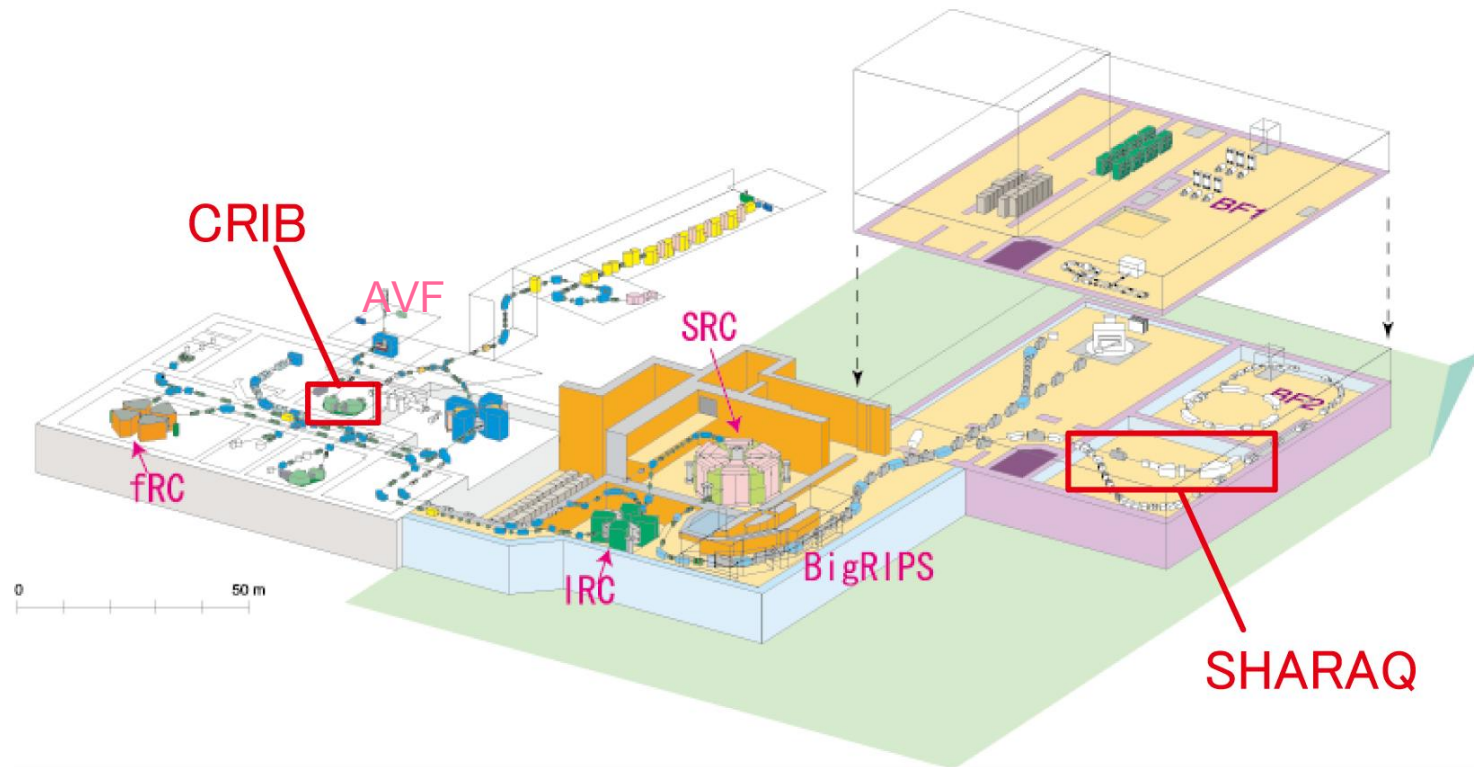


SN1987A

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

CRIB in RIBF

- AVF alone, operation cost $\sim 1/10$ of BigRIPS.
- Ion source / AVF/ CRIB...have been developed under CNS-RIKEN collaboration (joint venture).

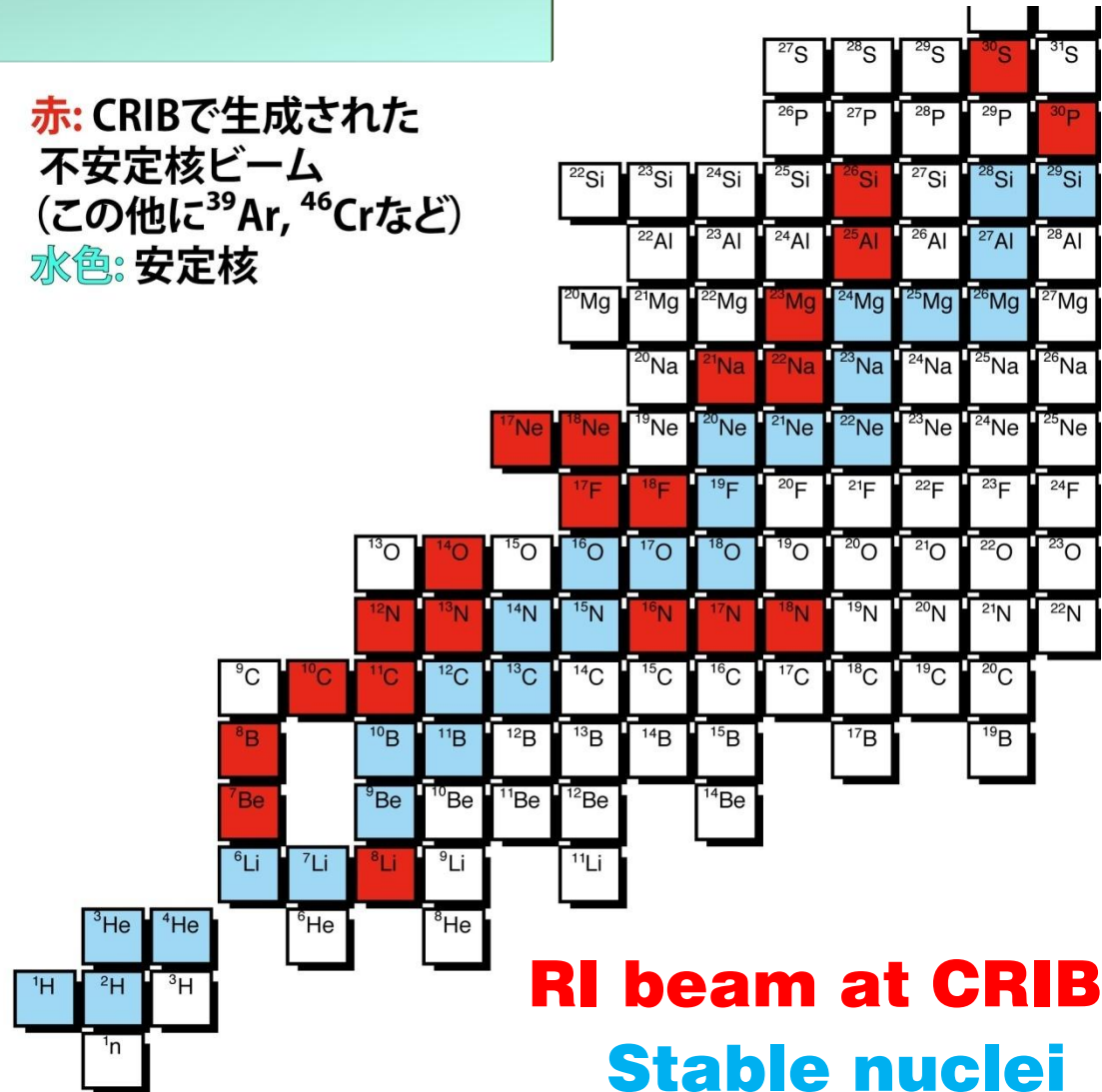


Low-Energy RI beam Productions at CRIB

Direct reactions such as (p,n), (d,p) and (^3He ,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

赤: CRIBで生成された不安定核ビーム
(この他に ^{39}Ar , ^{46}Cr など)
水色: 安定核



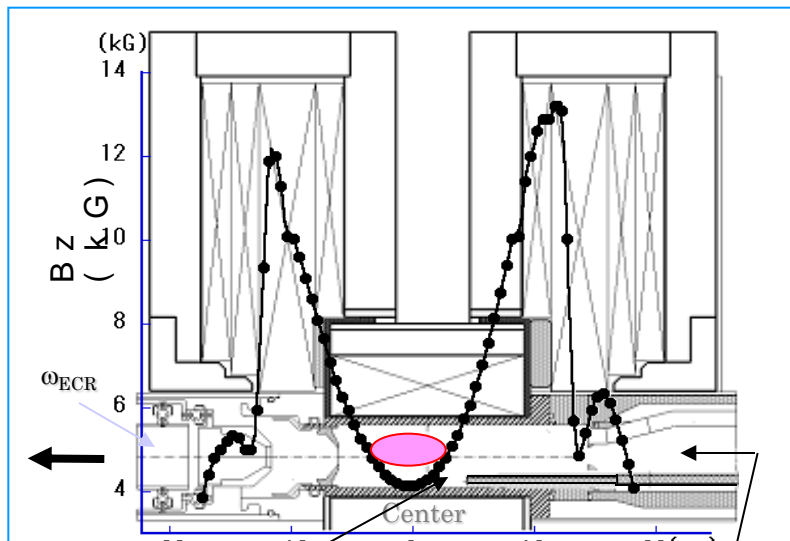
RI beam at CRIB /
Stable nuclei

Recent CRIB status and related topics

- 2010 The last NP-PAC to accept CRIB proposals.
- 2011. 3 The **earthquake**. We had no beam time during Mar. to Sep., 2011. (CRIB...a TMP was broken.)
- Jun. 2011, "Review Meeting on CRIB Activities".
- Nov. 2011, OMEG11 (Origin of Matter and Evolution of Galaxies), hosted by CNS (chaired by Prof. Kubono).
- Mar. 2012, Prof. Kubono retired (now at RIKEN), The new scheme to have a CRIB beamtime was approved.
- **Developments:**
 - **Ion source** Development of new beams (such as ^{42}Ca).
 - **Accelerator/Beam line** "Core monitor" for non-destructive readout of the beam current (*S. Watanabe et al., NIM A, 2011*).
 - **Cryogenic target** Used in every experiment. (*H. Yamaguchi et al., NIM A, 2008*.)
 - **Wien filter** Improvement of insulators, monitoring system.
 - **Active target (GEM-MSTPC)** Used in $^{22}\text{Mg}(\alpha, p)$.

Metal ion production at Hyper ECR .. by Y. Ohshiro (CNS)

◆ For stable ion extraction...crucible position is important



Rod method V O C method
(4 x 4 x 60 mm³) valve tuning

◆ Using a crucible with many exit holes

- Holes: $\Phi 2 \text{ mm} \times 5$
- Crucible

Positioning At first, move close to ECR zone to heat, and

move back

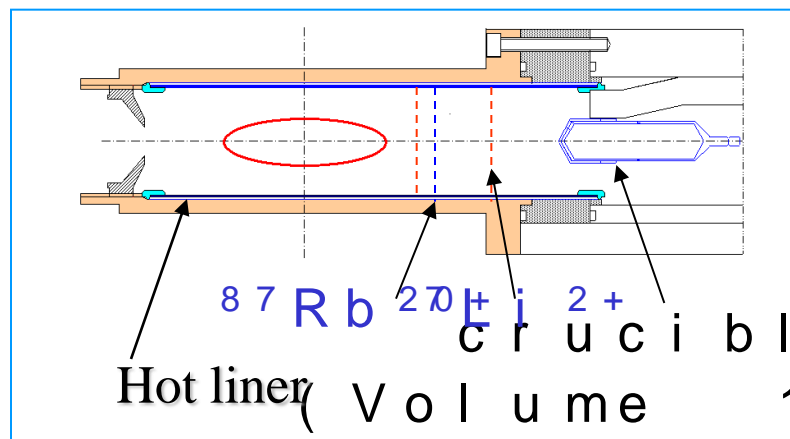
2012 Nov.

⇒ ${}^7\text{Li}^{2+}$

stable

production at $\sim 40 \text{ mm}$

In Italia



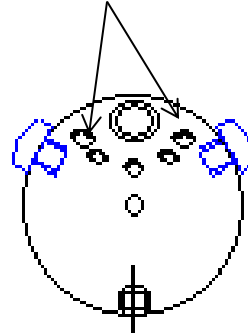
Dewar crucible with many holes

◆ Important points:

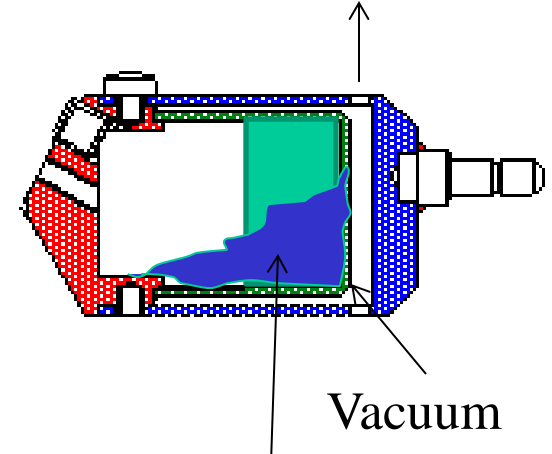
Multiple Holes...helps stable ion extraction.

Dewar...Temperature stable

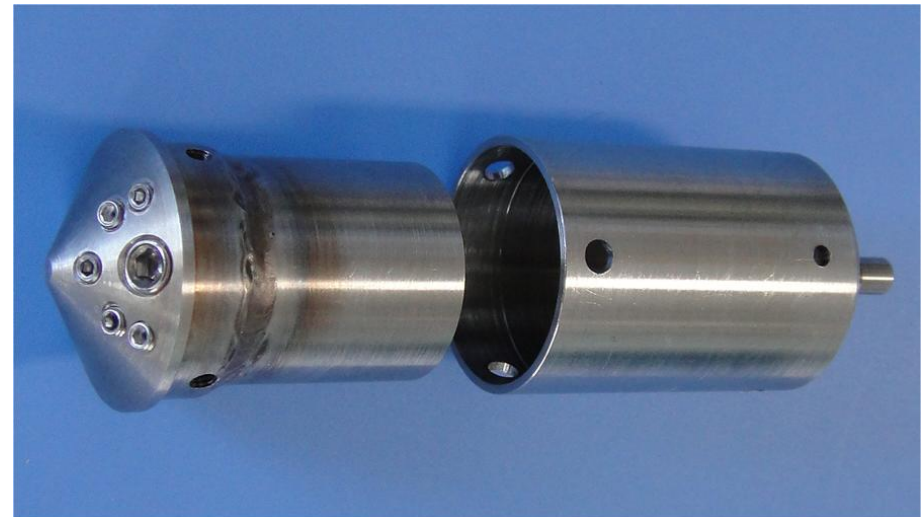
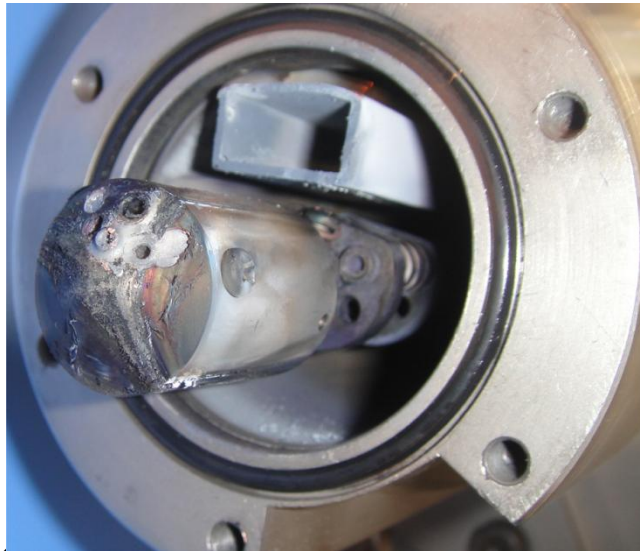
exit holes



evacuation

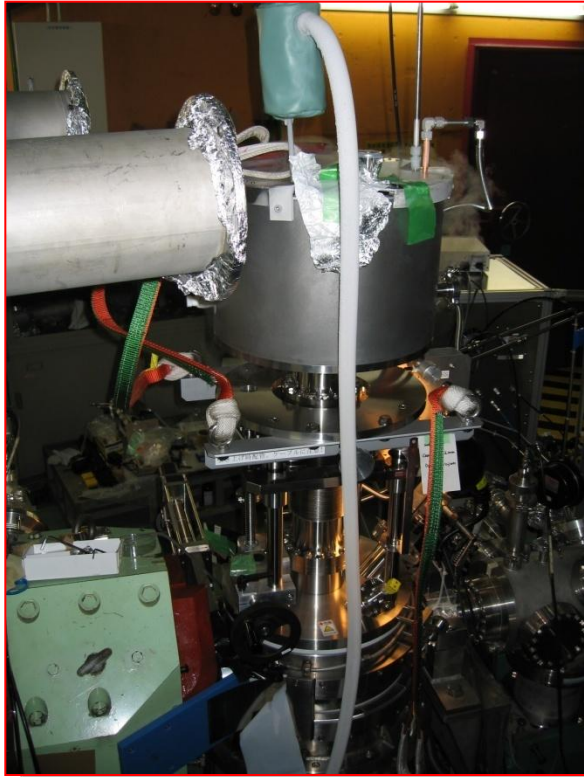


Melted lithium



Dewar crucible

Intense secondary beam production using cryogenic gas target



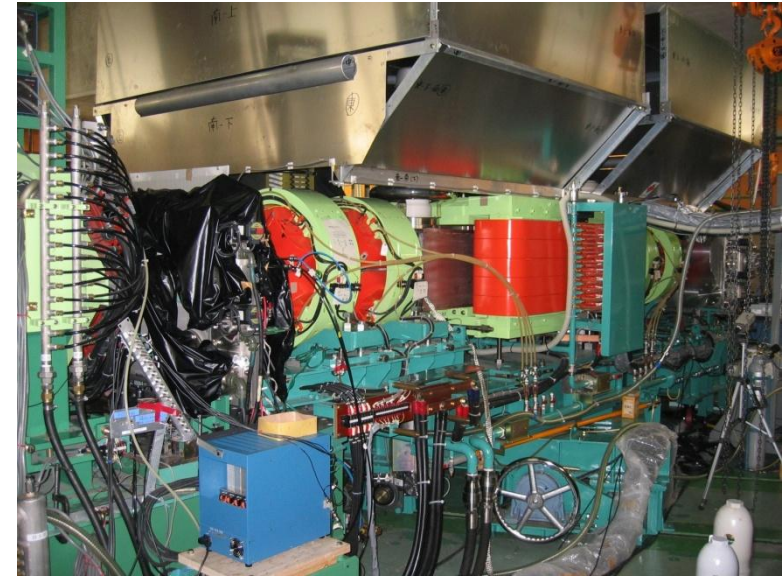
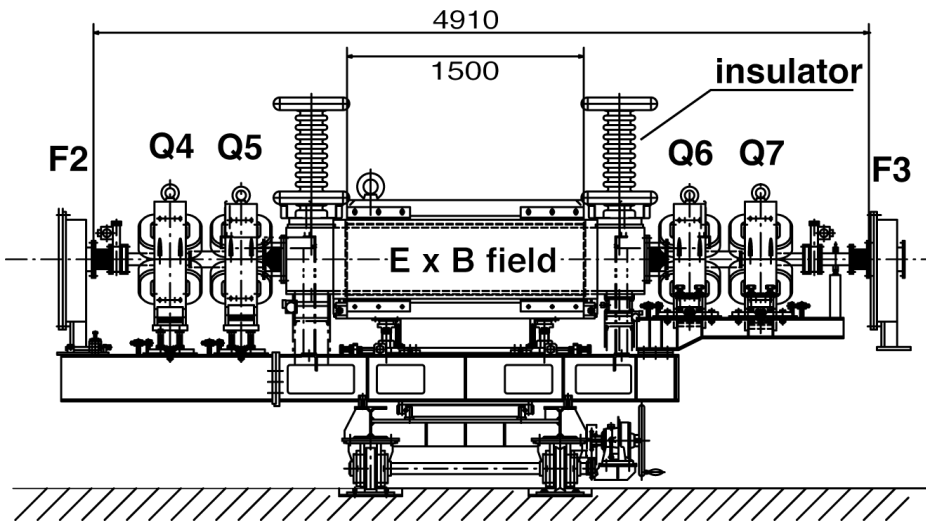
- H_2 gas target of 760 Torr and 80 mm-long worked at 85K stably for a ${}^7\text{Li}^{2+}$ beam of 1.3 μA . (which deposits heat of 7.4W).
- Secondary beam: ${}^7\text{Be}^{4+}$ at 4.0 MeV/u, purity 75% (without degrader/ WF),
 2×10^8 pps was achieved.

H. Yamaguchi et al., NIMA (2008)



Price of ${}^3\text{He}$ gas became 10 times higher in the last 4 years....a recycling system for ${}^3\text{He}$ gas was built.

Wien filter



- 1.5 m-long **HV electrodes**, 8 cm distant from each other, ± 200 kV applicable (stable up to ± 120 kV), horizontal E field.
- **Dipole magnet**, max. 0.3 T vertical magnetic field.
- Spending much effort for the **stabilization against discharge**.

INFN-CNS collaborations

- $^{18}\text{F}+p$, $^{18}\text{F}+d$ experiments have been performed in collaboration with LNS researchers in 2007/2008.
(*S. Cherubini, C. Spitaleri, S. Romano, R.G. Pizzone, M. La Cognata, L. Lamia, M.L. Sergi, V. Crucilla, S. Puglia, ...*)
- Now the NP-PAC approved CRIB beamtime is mostly for **Italian proposals**.
 - ◆ “Dynamics of the ^8B interaction with ^{208}Pb at the Coulomb barrier” by Cosimo Signorini et al. (8 days).
 - ◆ “Study of the beta-delayed alpha decay of ^{16}N ”, by Silvio Cherubini et al. (18 days).
 - ◆ (All other groups...~a week in total.)
- *We hope to keep our good collaboration in the future!*

Research projects (2010-)

•Proton/alpha resonant scattering

✓²⁶Si+p (Collaborated with Chung-Ang, Korea) H.S. Jung et al., published at PRC (2012).

✓⁷Li/⁷Be+α (CNS) H. Yamaguchi et al., PRC (2011).

✓²¹Na+p, ²²Na+p [¹⁸Ne(α,p), Ne-Na cycle] (IMP/CIAE, China)

✓¹⁷F+p [Resonances for ¹⁴O(α,p)](IMP/CIAE, China) ←Latest measurement in June!

•(α,p) reaction measurement, Active target (GEM-MSTPC)

✓¹⁸Ne(α,p) (CNS, Hashimoto (now at RCNP))

✓³⁰S(α,p) (CNS, Daid Kahl)

✓²²Mg(α,p) (IOP, Vietnam , Nguyen Ngoc Duy)

✓⁴⁴Ti(α,p) (KEK, Ishiyama) ... ⁴⁴Ti beam test in May successful.

•(α,γ)

¹⁶N⇒¹⁶O*⇒¹²C+α for ¹²C(α,γ) (S. Cherubini, Catania, Italy)

•Reaction mechanism

✓⁸B+Pb (Padova, Italy, C. Signorini)

•β-decay

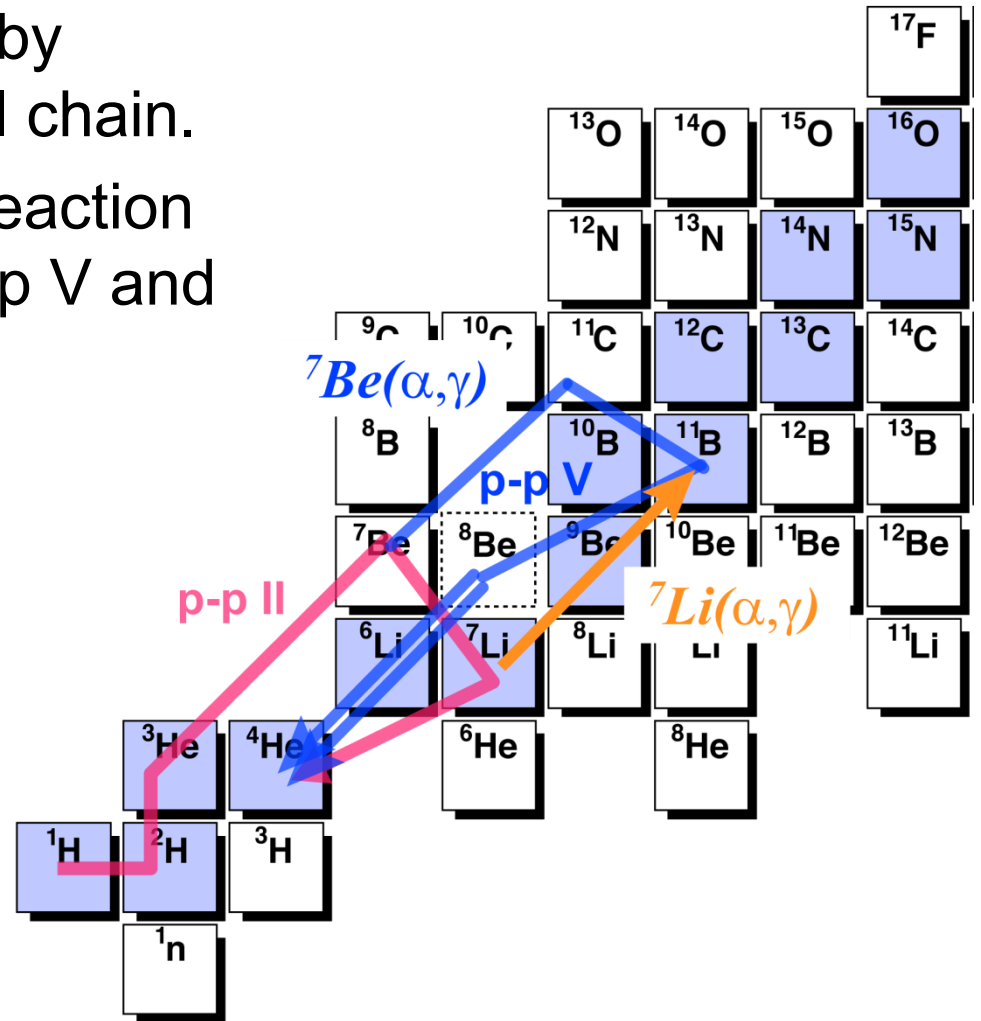
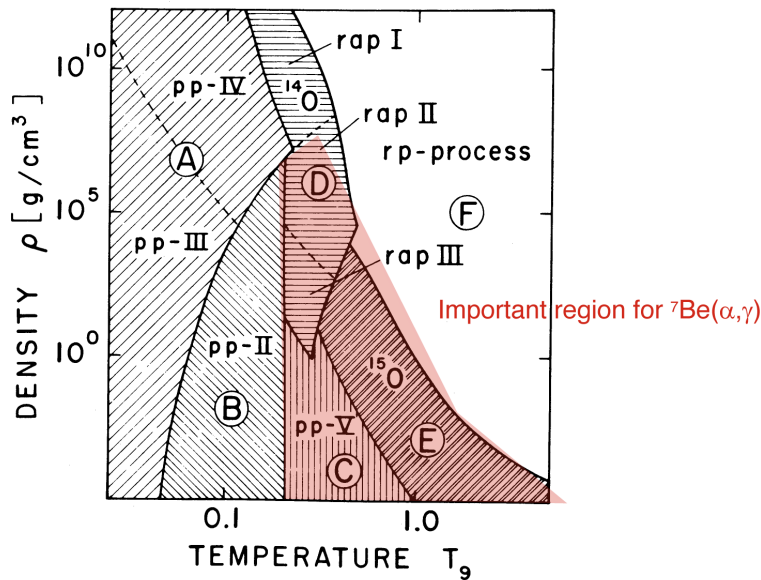
✓⁷Be lifetime in metal (Tohoku Univ, Otsuki)

2012 Nov.

In Italia

${}^7\text{Li}(\alpha,\gamma)$ and ${}^7\text{Be}(\alpha,\gamma)$ in the p-p chains

- ${}^7\text{Li}$...mainly destroyed by ${}^7\text{Li}(p,\alpha){}^4\text{He}$ in the p-p II chain.
- ${}^7\text{Be}(\alpha,\gamma)$...one of the reaction in the hot p-p chain (p-p V and “rap” processes).



${}^7\text{Li}(\alpha,\gamma)$; interests

- $T \ll 1$ GK; ${}^7\text{Li}(p,\alpha){}^4\text{He}$ (p-p chain). ${}^7\text{Be}(\alpha,\gamma){}^{11}\text{C}(\beta^+\nu){}^{11}\text{B}$ is more important.
- **High temperature**: triple- α should be fast, but ${}^7\text{Li}(\alpha,\gamma)$ may play important roles in some environments:
 - ◆ ${}^7\text{Li}/{}^{11}\text{B}$ ratio in core-collapse supernovae
 - ...the ν -process *T. Yoshida et al., PRL (2006),*

G.J. Mathews et al., PRD (2012).

${}^{11}\text{B}$ is produced **mainly through the ${}^7\text{Li}(\alpha,\gamma){}^{11}\text{B}$** reaction. (Some are via ${}^{12}\text{C}$.)

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

- ◆ Boron production in inhomogeneous big-bang nucleosynthesis.

PRL 96, 091101 (2006)

PHYSICAL REVIEW LETTERS

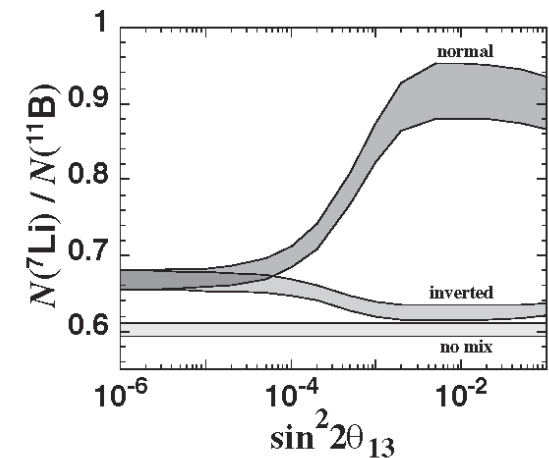
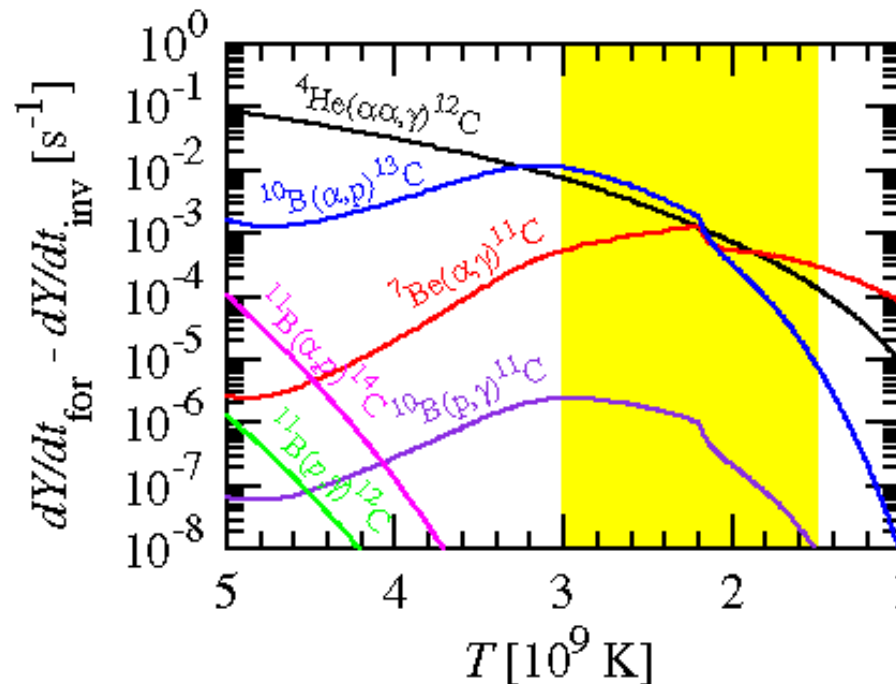


FIG. 3. The number ratio of ${}^7\text{Li}/{}^{11}\text{B}$ with the relation of $\sin^2 2\theta_{13}$. The shaded ranges include the uncertainties of neutrino energy spectra deduced from the calculations using three sets of neutrino temperatures and total neutrino energies (see text).

${}^7\text{Be}(\alpha,\gamma)$ and other low-mass (α,p)

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



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

${}^7\text{Li}/{}^7\text{Be}(\alpha,\gamma)$ experimental study

- ${}^7\text{Li}(\alpha,\gamma)$ and ${}^7\text{Be}(\alpha,\gamma)$ were directly measured **only at low-lying resonances**:

- *Paul et al., Phys. Rev. **164** (1967) 1332.*
- *Hardie et al., Phys. Rev. C, **29** (1984)1199.*

${}^7\text{Be}(\alpha,\gamma)$: only two resonances at $E_r < 1$ MeV are included in the NACRE evaluation.

E_r	J^π	$\omega\gamma$ (eV)	Γ_α (eV)	Γ_γ (eV)	Ref	
0.560	$3/2^-$	0.331 ± 0.041	11 ± 7	0.350 ± 0.056	HA84	I
0.877	$5/2^-$	3.80 ± 0.57	12.6 ± 3.8	3.1 ± 1.3	HA84	I

- Resonant reaction dominates the reaction rate. **Higher resonances** may contribute at **supernova temperature** (>1 GK).
- We studied higher-lying resonances by **the resonant elastic scattering method**, ${}^7\text{Li}(\alpha,\alpha)$ and ${}^7\text{Be}(\alpha,\alpha)$ **at CRIB** to obtain information on the resonances (energy, width, spin and parity).

Our approaches for alpha-induced reactions

1. (α,α) resonant scattering \Rightarrow study resonances relevant for (α,γ) reaction.
2. Direct measurement of (α,p) reaction
e.g. $^{11}\text{C}(\alpha,p)$ direct measurement (S. Hayakawa)
3. RI beam + $p \Rightarrow$ Information on (α,p) reaction in the reverse reaction.
e.g. $^{17}\text{F} + p$ to study $^{14}\text{O}(\alpha,p)$.
4. Transfer reaction; e.g. $(^6\text{Li},d)$ to simulate (α,γ)
5. Direct measurement of (α,γ) reaction

Would be possible. However, the RI beam intensity is often not sufficient at relevant energy (though 10^8 pps for 4.0 MeV/u ^7Be at CRIB).

Nuclear Cluster

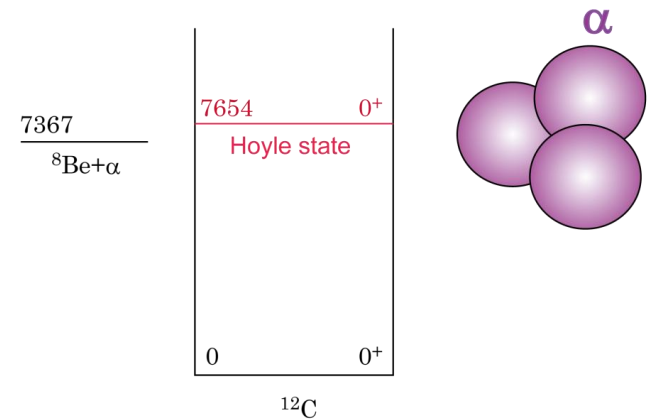
- Low-mass nuclei often have α -cluster states (large Γ_α).
- Those states may greatly enhance alpha-induced reaction rates. (Integrated resonant reaction cross section

$$\propto \Gamma_\alpha \Gamma_x / \Gamma.)$$

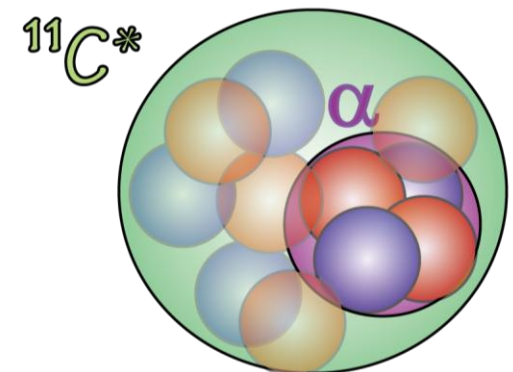
Hoyle state is a famous example.

- Those states should be observed as strong resonances by **resonant elastic scattering**.

${}^7\text{Be} + \alpha \dots$ cluster structure in ${}^{11}\text{C}$ can be studied.



Alpha-cluster structure

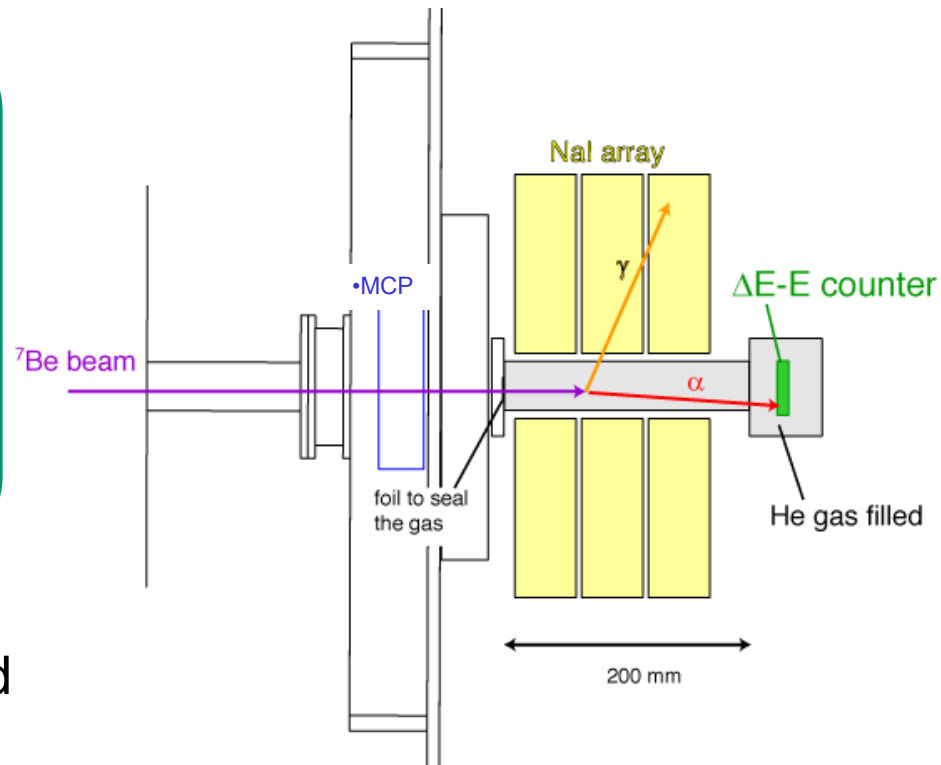


${}^7\text{Li}/{}^7\text{Be}+\alpha$; method

◆ “Thick target with inverse kinematics” Resonant elastic scatterings can be measured at $\theta_{\text{cm}}=180$ deg.

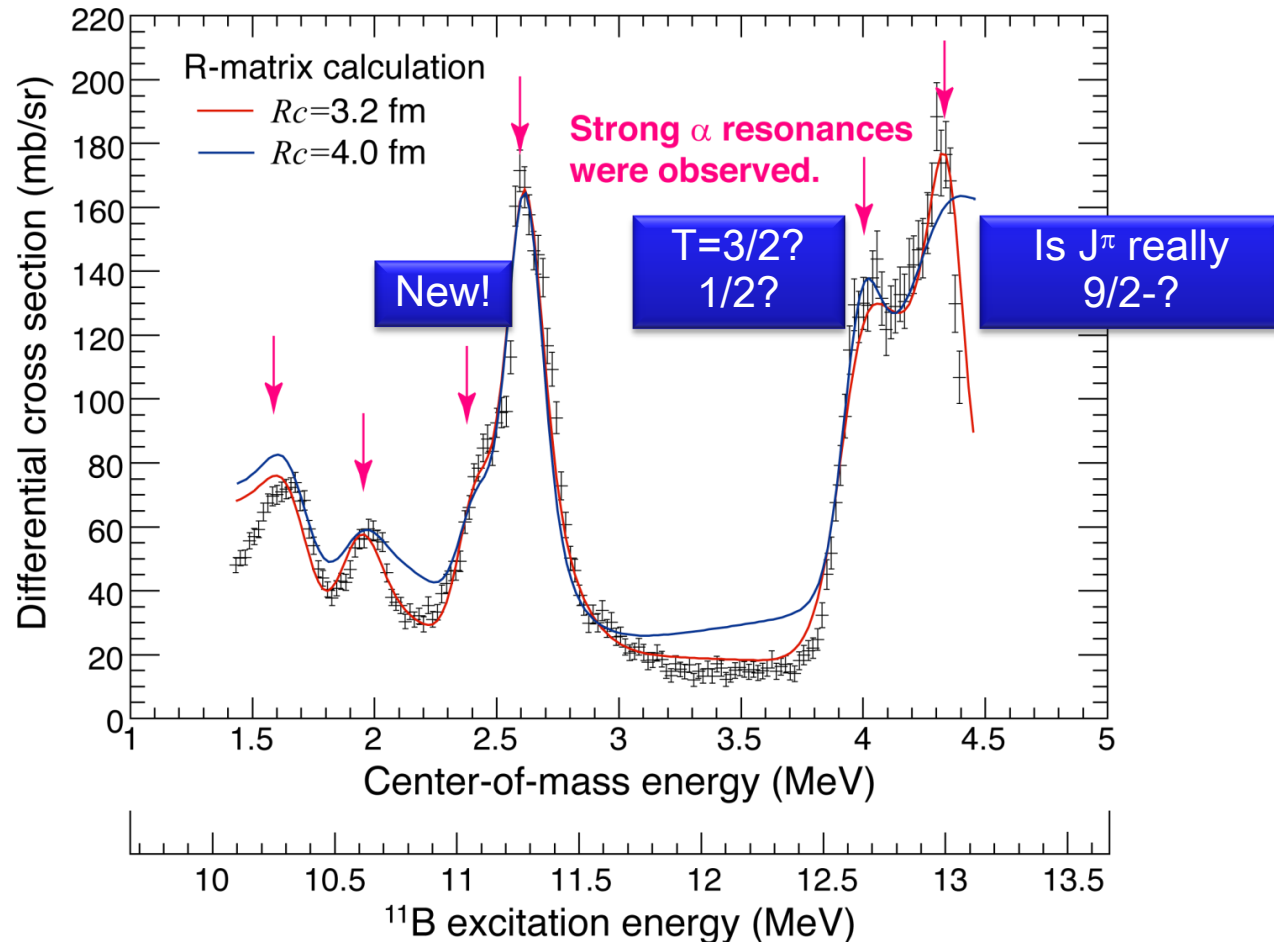
- ${}^{11}\text{C}+p$; T. Teranishi et al., Phys. Lett. B (2003).
- ${}^{13}\text{N}+p$; T. Teranishi et al., Phys. Lett. B (2007).
- ${}^{21}\text{Na}+p$, ${}^{22}\text{Mg}+p$; J.J. He et al, Eur Phys. J (2008) and Phys. Rev. C (2007).
- ${}^7\text{Be}+p$; H. Yamaguchi et al., Phys. Lett. B (2009).

◆ We applied the method for proton +RI beams, but how good it can work for alphas?
(Especially for light nuclei, where Z is not much different from 2.)



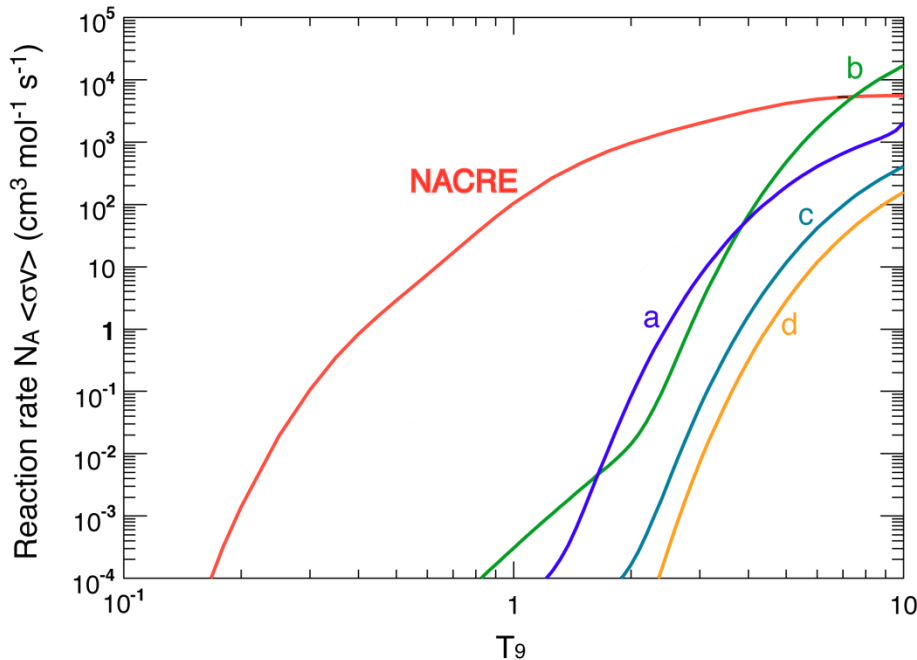
${}^7\text{Li}+\alpha$ result

- Strong alpha resonances were successfully observed, and we determined the α widths (Γ_α). *H. Yamaguchi et al., Phys Rev. C (2011).*



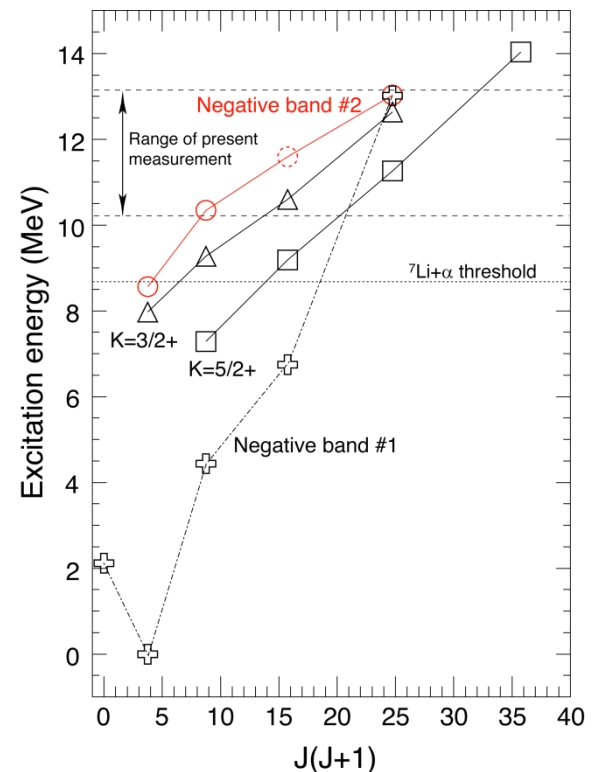
${}^7\text{Li}+\alpha$; results

- Resonant reaction rates for the observed resonances are compared with NACRE evaluation (including resonances below 11 MeV).



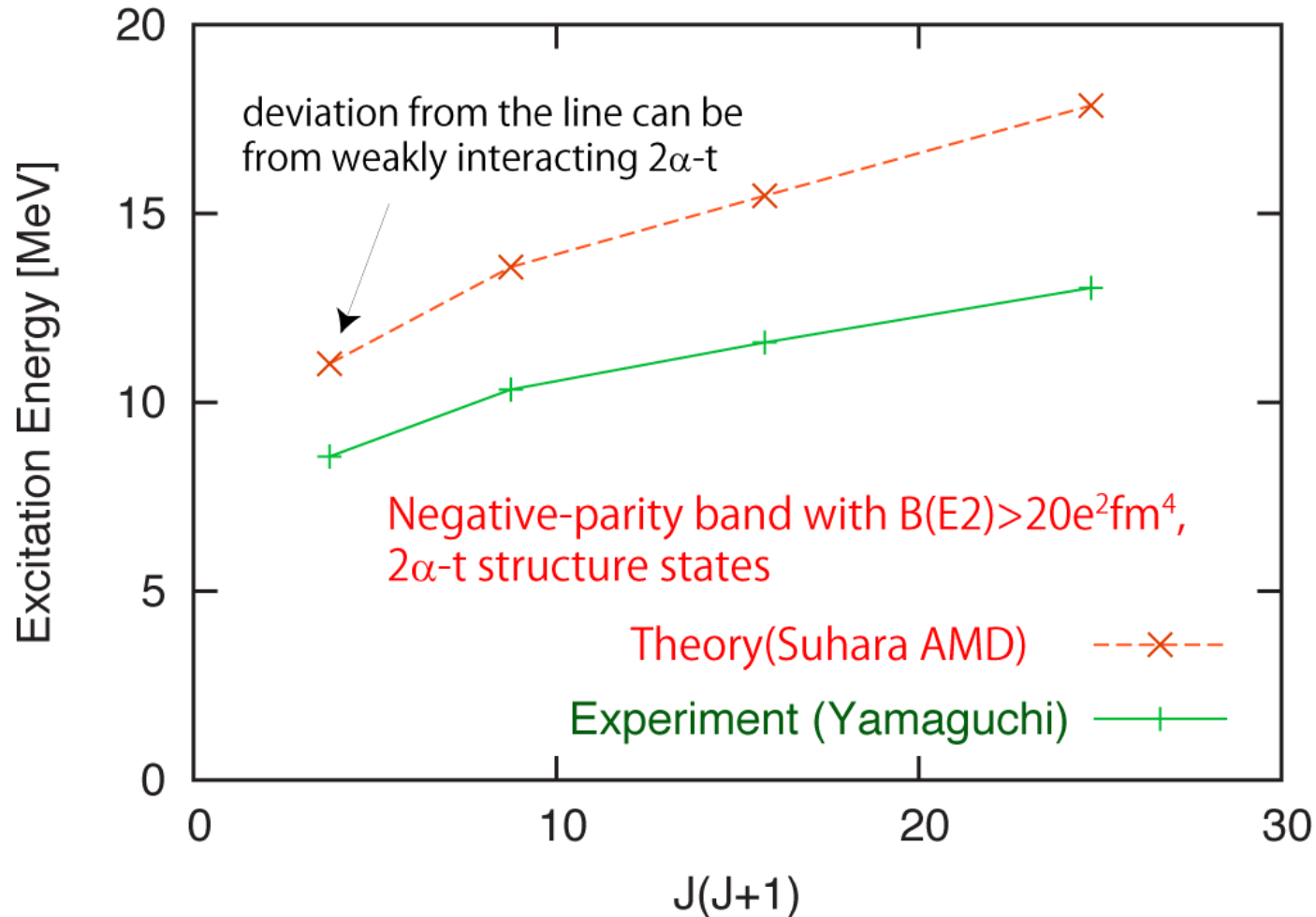
Conclusion: No need to modify NACRE evaluation (for $T_9 < 5$).

- Newly proposed a negative parity band.
 - It may not be a simple rotational band, but corresponds to a 2α -t structure [AMD Calc. by Suhara & En'yo]



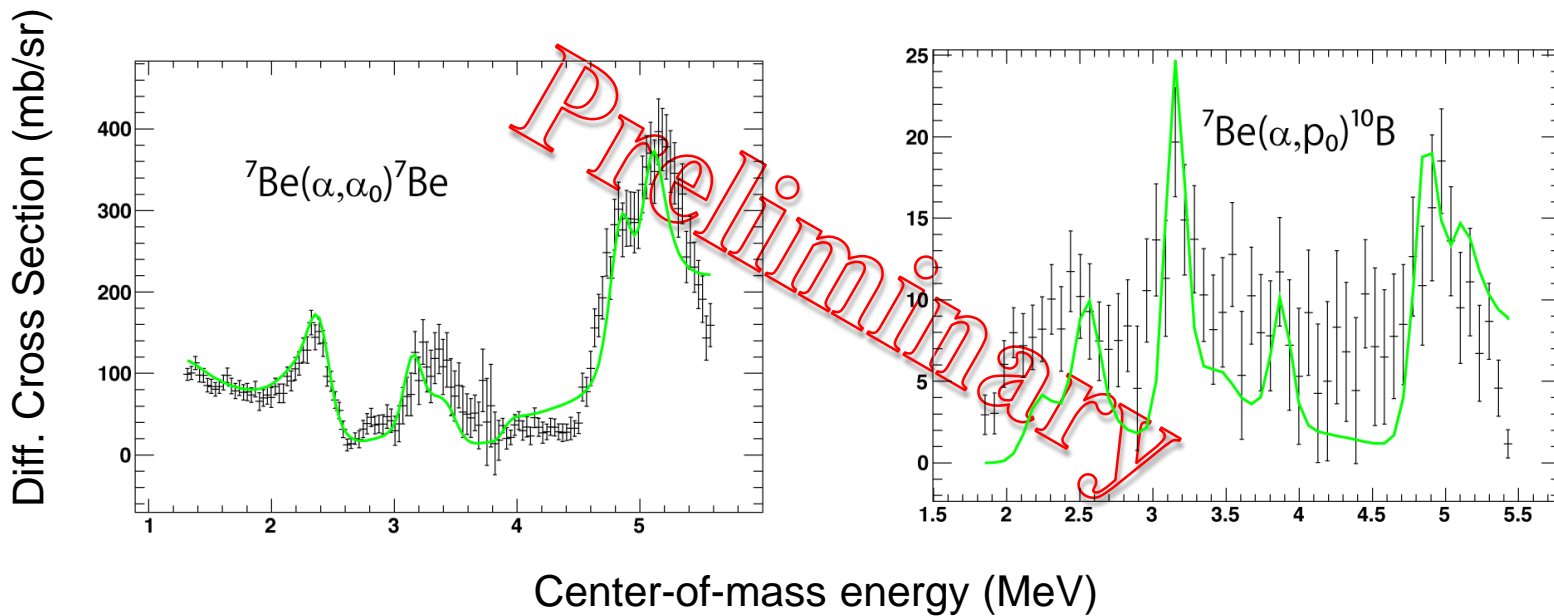
Interpretation of the new negative-parity band

Suhara & En'yo PRC(2012)



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

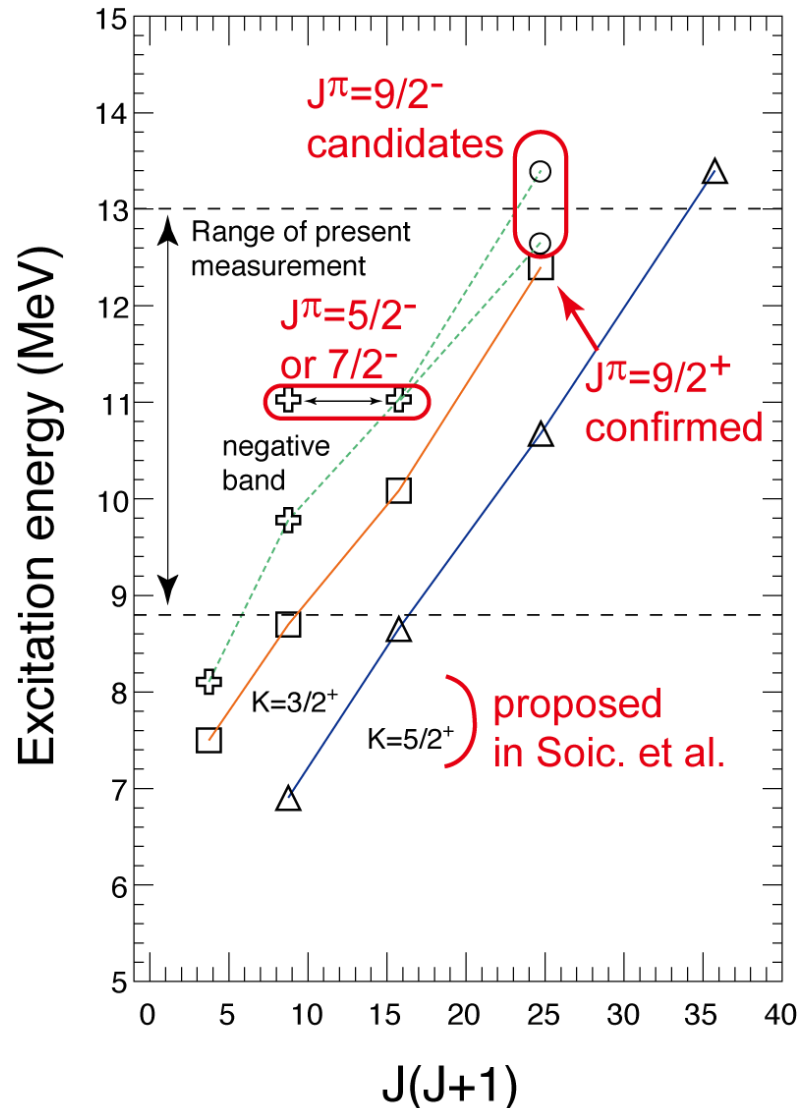
- Excitation functions of ${}^7\text{Be}(\alpha,\alpha)$ and ${}^7\text{Be}(\alpha,p)$ were obtained.
- ${}^7\text{Be}(\alpha,p)$...consistent with previous ${}^{10}\text{B}(p,\alpha)$ measurements.
- R-matrix analysis in progress....bringing new information on resonant widths, spin, and parity. **Many resonant parameters are still unknown in such unstable nuclei.**



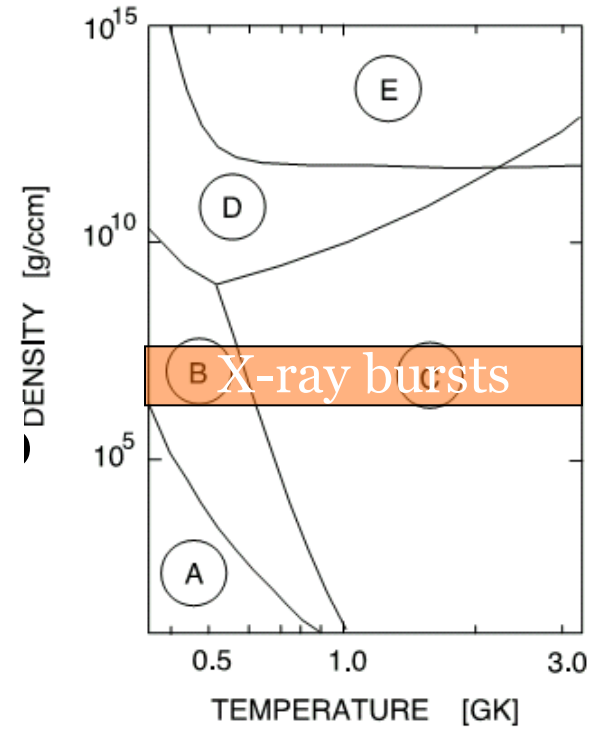
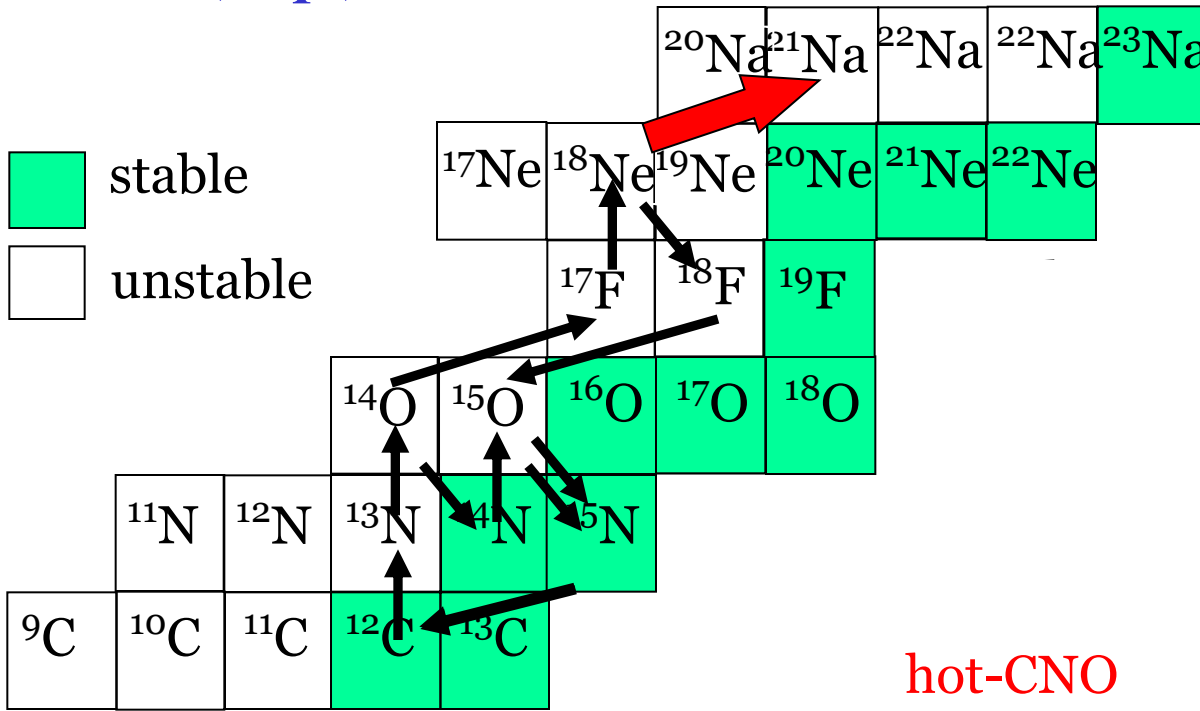
(Rotational) bands in ^{11}C

- 2 rotational bands ($K=3/2^+, 5/2^+$) were suggested in Soic. et al. (2004).
- $J^\pi=9/2^+$ was assigned for the resonance at 12.4 MeV, and it can be the member of $K=3/2^+$ band.
- A negative-parity band is proposed.

*(H. Yamaguchi et al.,
in preparation)*



$^{18}\text{Ne}(\alpha, p)$ (T. Hashimoto; RCNP)

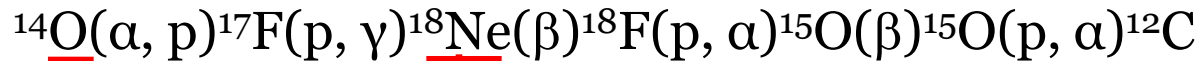


hot-CNO

J. Phys. G: Nucl. Part. Phys. 25 (1999)R133



second hot CNO cycle

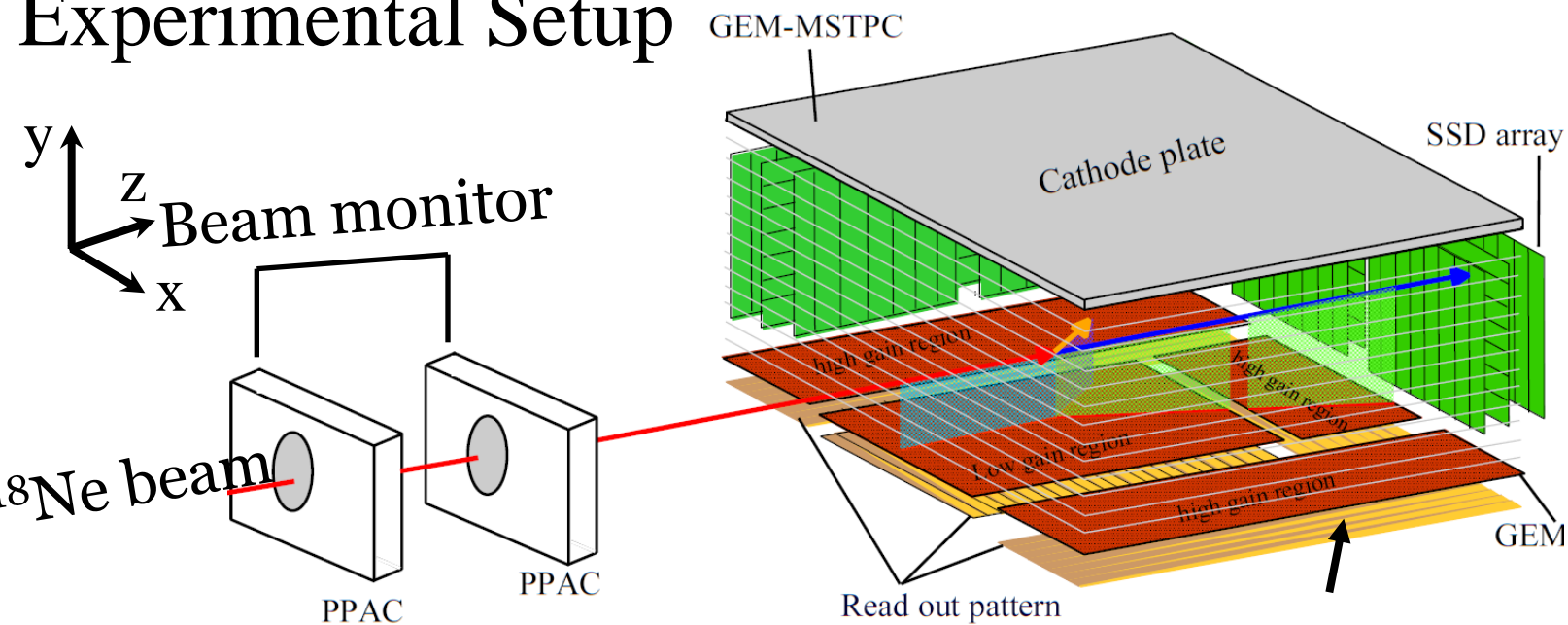


$^{18}\text{Ne}(\alpha, p)^{21}\text{Na}$ is an important breakout reaction from hot-CNO cycle to the rp-process (B to C in the figure)

Relevant energy (temperature):

$$E_{\text{cm}} = 0.5 - 3.8 \text{ MeV } (T = 0.6 - 3 \text{ GK}).$$

Experimental Setup

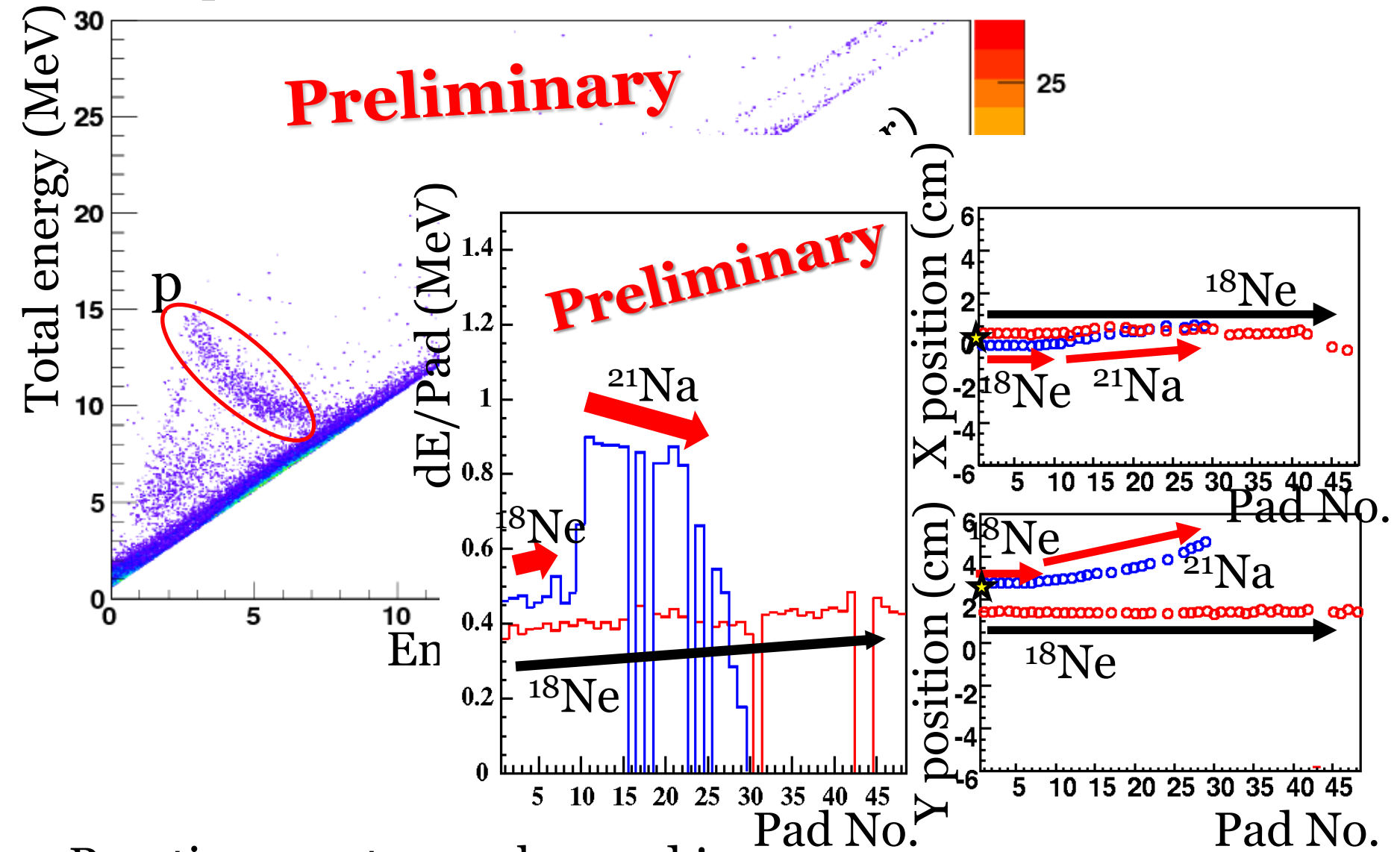


He (90%) + CO₂ (10%)
mixture gas(160 torr)

- Acts as a He target and a detector (TPC) simultaneously
- 3-dimentional trajectory and energy loss can be measured
⇒ Good event identification.

Typical event of $^{18}\text{Ne}(\alpha, p)^{21}\text{Na}$ reaction

Si telescopes

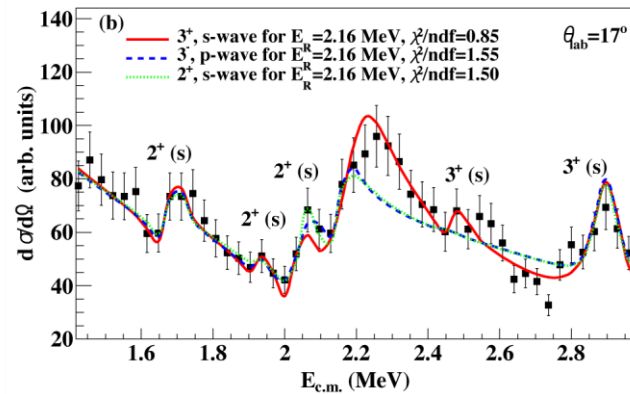
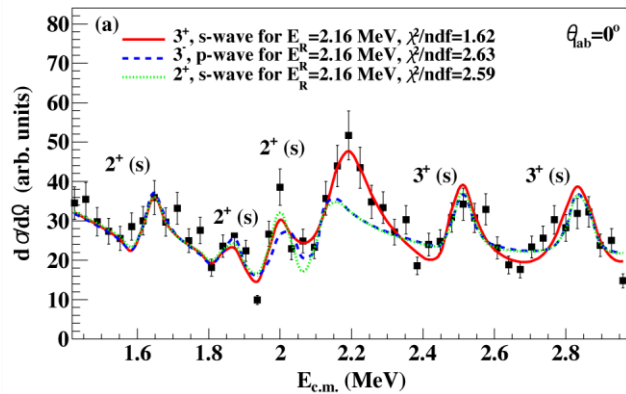


Reaction events are observed !

Analysis is in progress ...

From Recent Publications

- ${}^7\text{Li}+\alpha$; H. Yamaguchi et al., Phys. Rev. C (2011). ${}^7\text{Li}(\alpha,\gamma)$, α -cluster in ${}^{11}\text{B}$.
- ${}^{26}\text{Si}+p$ (Chung-Ang Univ., SNU) H.S. Jung et al., Phys. Rev. C (2012).
- ${}^{25}\text{Al}+p$; Jun Chen et al., Phys. Rev. C(2012): related to galactic gamma-ray from ${}^{26}\text{Al}$.

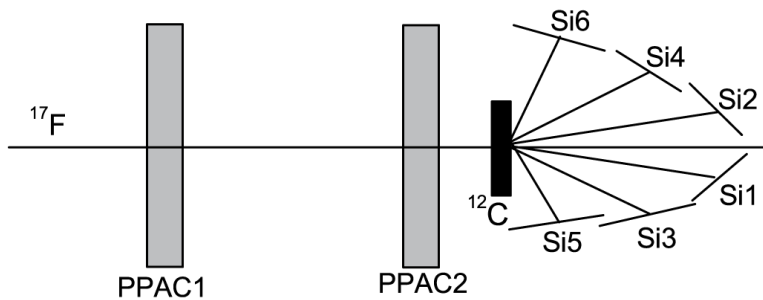


- ${}^{11}\text{C}(\alpha,p)$ direct reaction measurement; S. Hayakawa (CNS \Rightarrow INFN) Dr. thesis of Univ. of Tokyo (2012).
- ${}^{17}\text{F}+{}^{12}\text{C}$; Quasi-elastic scattering G.L. Zhang et al., Eur. Phys. J. A (2012).

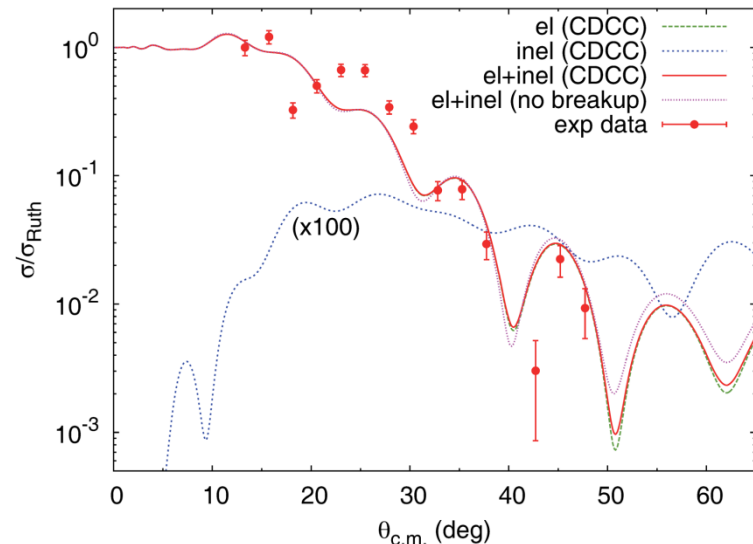
$^{17}\text{F}+^{12}\text{C}$

G.L. Zhang et al., Eur. Phys. J. A (2012).

- $^{17}\text{F}+^{12}\text{C}$...heavy-ion (quasi) elastic scattering
- Reaction mechanism...cross section can be enhanced for halo nuclei.
- No large breakup was observed.
- Total c.s....small deviation from the systematics.



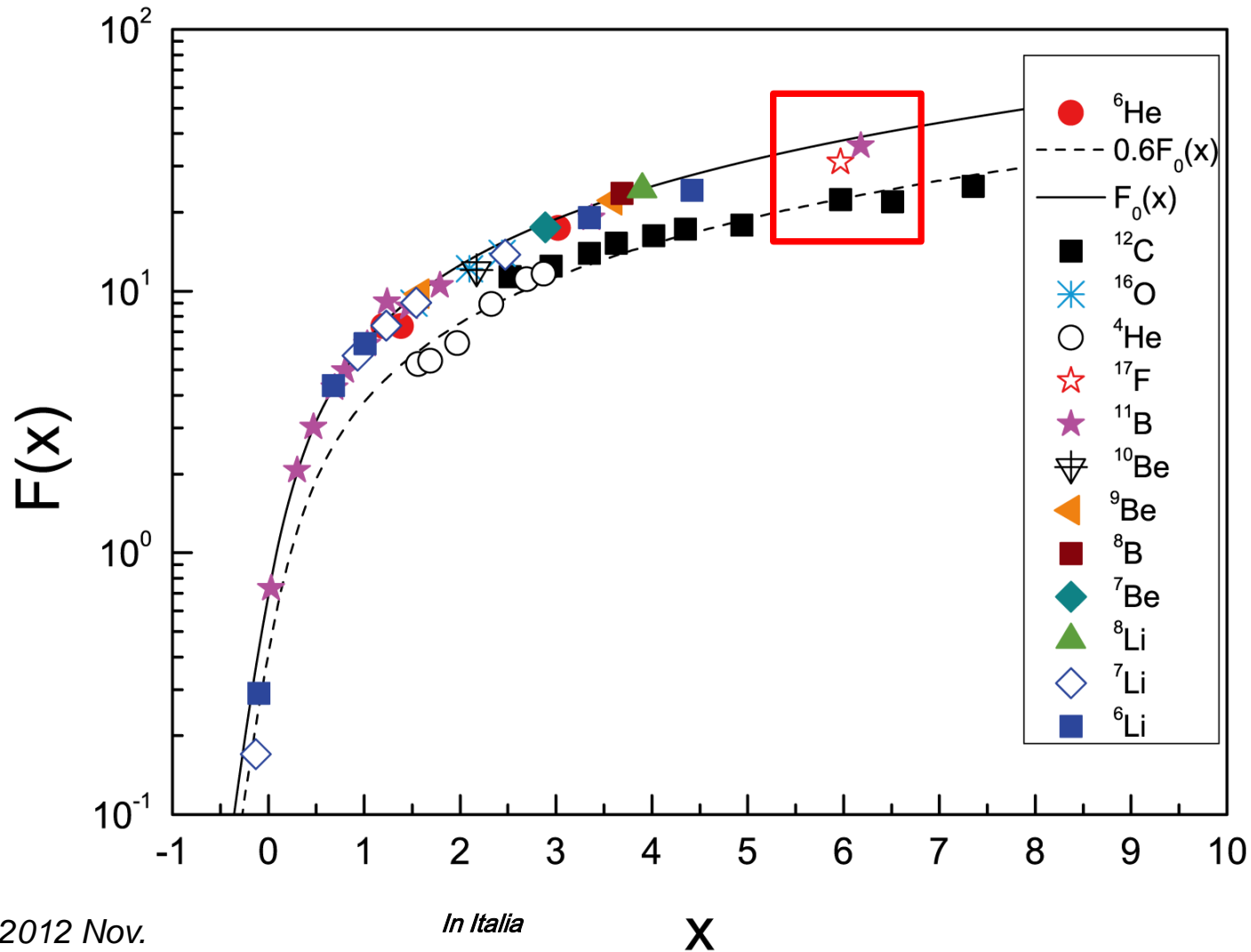
Schematic view of the experimental setup.



Elastic scattering; Exp vs CDCC calculation

$^{17}\text{F} + ^{12}\text{C}$

- Normalized total cross section, against normalized energy:



Development of a material-wear test with tracer implanted as an RI beam — Industrial use of ^7Be beam at E7-CRIB —

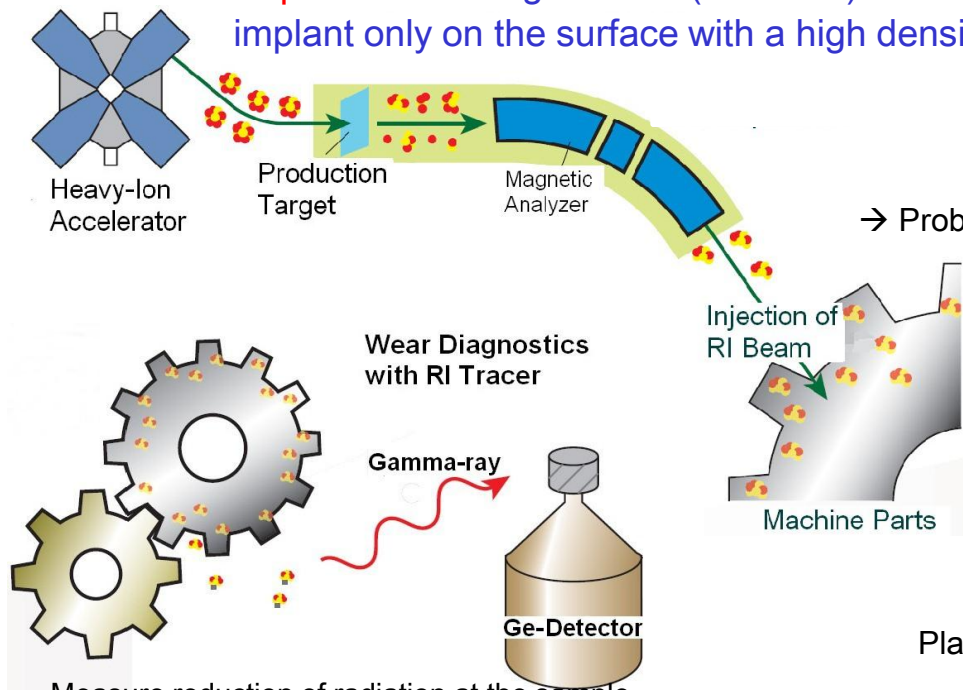
To measure surface wear of industrial material

Samples: (part of) engine, bearing, ceramic parts, lubricating oil

Purpose: real-time measurement of wear at the surface (100 μm thickness)

Requirements: long-lived RI (\sim months) [for off-line measurement]

implant only on the surface with a high density ($>100\text{kBq}$) [for sensitive test $\sim \mu\text{m}/\text{hour}$]



Previous method: direct activation

p, d, ^3He 10 ~ 20MeV, to activate the surface.

→ Problem: Must contain nuclides which become long-lived RI.
High heat and radiation damage

RI beam implantation

merit: Independent of composition of samples
low-heat, low-radiation damage
Implantation depth can be adjusted

Achieved: E6-RIPS, ^{22}Na (2.6y) 1.5×10^8 cps
Two trial beamtimes

Plan: E7-CRIB, ^7Be (53 days) 2×10^8 cps possible
First machine study in Jul, 2012.

Measure reduction of radiation at the sample,
or increasement of radiation at the oil

2012 Nov.

In Italia

Summary

- CRIB is a low-energy RI beam facility operated by CNS, University of Tokyo, providing RI beams of good intensity and purity.
- Manpower...Not sufficient. We are making experiments in a worldwide collaboration with external groups.
- Standard experiments: Proton/alpha resonant scattering, direct (α,p) reaction measurement using an active target (GEM-MSTPC)
- GEM-MSTPC
 - Has been used in several (α,p) measurements. Developments are on going, to make it a more reliable and stable system.
(avoiding discharges, gating grid, trigger system, DAQ, analysis framework)
- Resonant elastic scattering
 - ${}^7\text{Li}+\alpha, {}^7\text{Be}+\alpha$...strong resonances were observed. The “thick target method with inverse kinematics” could be applied to many nuclides. We can study astrophysical reactions and **alpha-cluster** structures.
 - ${}^{25}\text{Al}+p, {}^{26}\text{Si}+p$...related to cosmic gamma-ray.
- We welcome new users and new ideas!