Studying astrophysical reactions with low-energy RI beams at CRIB

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Outline

- Introduction of low-energy RI-beam facility "CRIB" (CNS, the Univ. of Tokyo).
  - ◆ Cryogenic gas target for RI beam production.
- Performed experiments
  - ◆ Resonant scattering experiments using thick-target method in inverse kinematics (TTIK). ^{7}Li/^{7}Be+α as a recent example.
  - ◆ Trojan Horse Method with RI beams

    ^{18}F(p,α) reaction cross section via ^{18}F(d,αn). [CNS&INFN-LNS collaborated work]
  - ◆ Direct measurements of (α,p) reactions using RI beams:

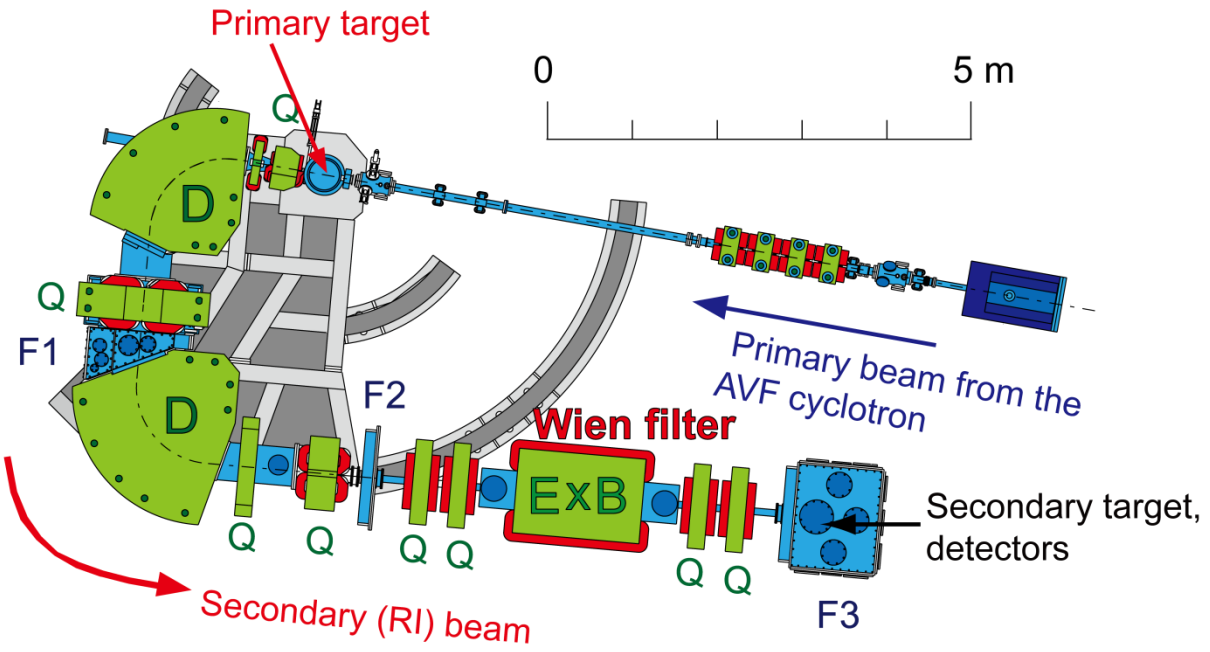
    with a normal gas target [^{11}C(α,p)] or an active target
  - ◆ Active target for decay measurement:

    ^{16}N beta-delayed α decay experiment performed in 2013.

    [CNS&INFN-LNS collaborated work]

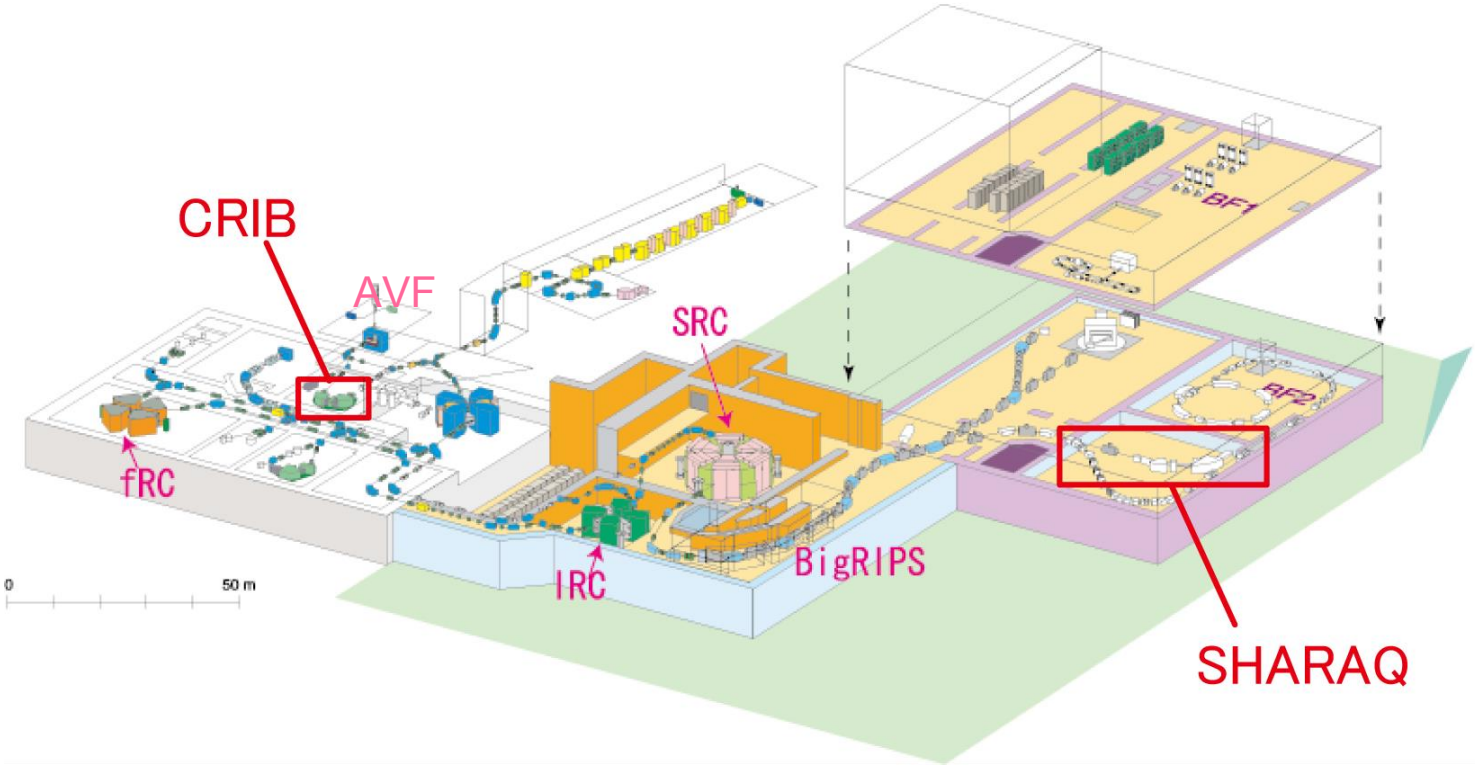
CRIB

- 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.



CRIB in RIKEN RIBF

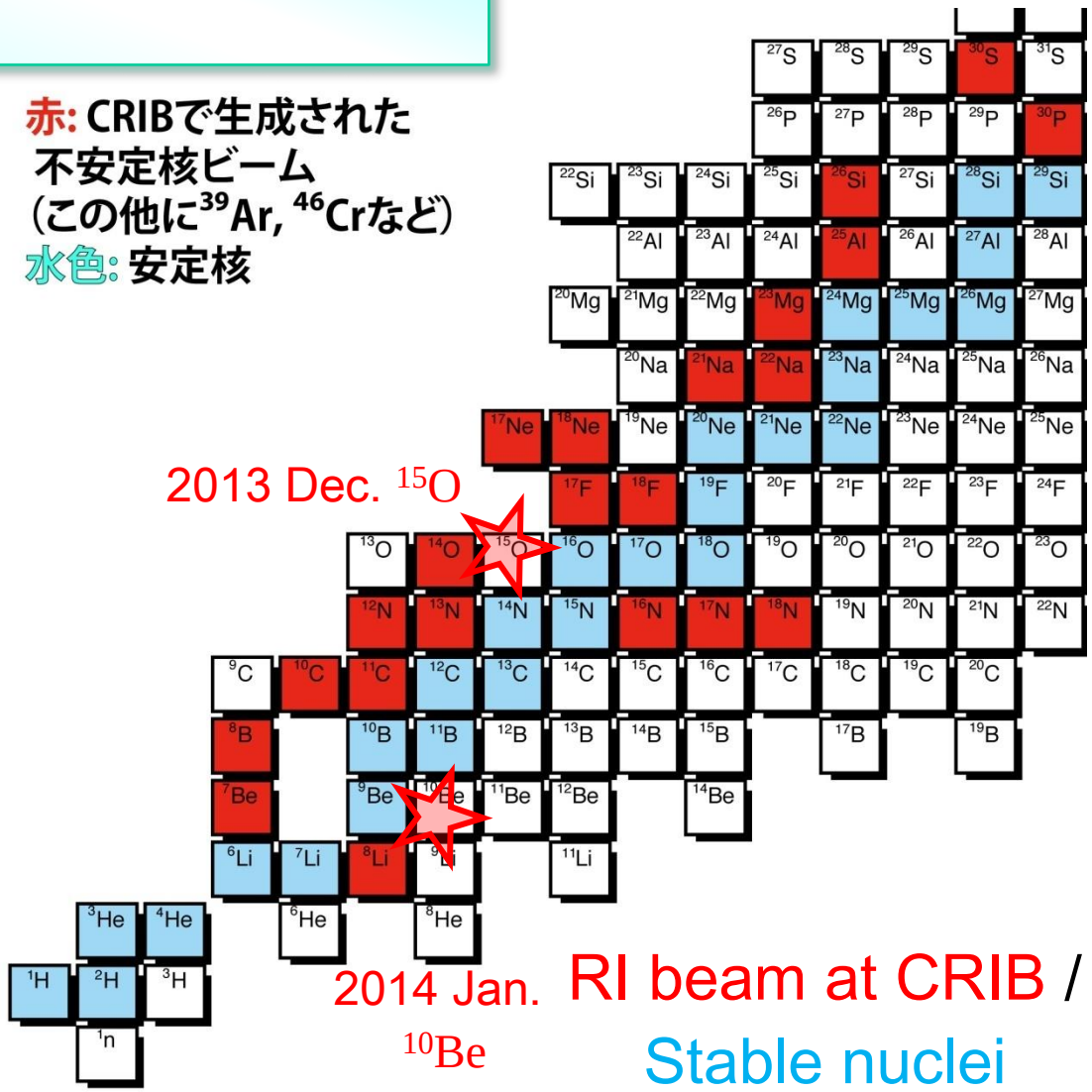
- AVF alone, operation cost ~1/10 of BigRIPS.
- Ion source / AVF/ CRIB…have been developed under CNS-RIKEN collaboration (joint venture).



Low-Energy RI beam Productions at CRIB

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



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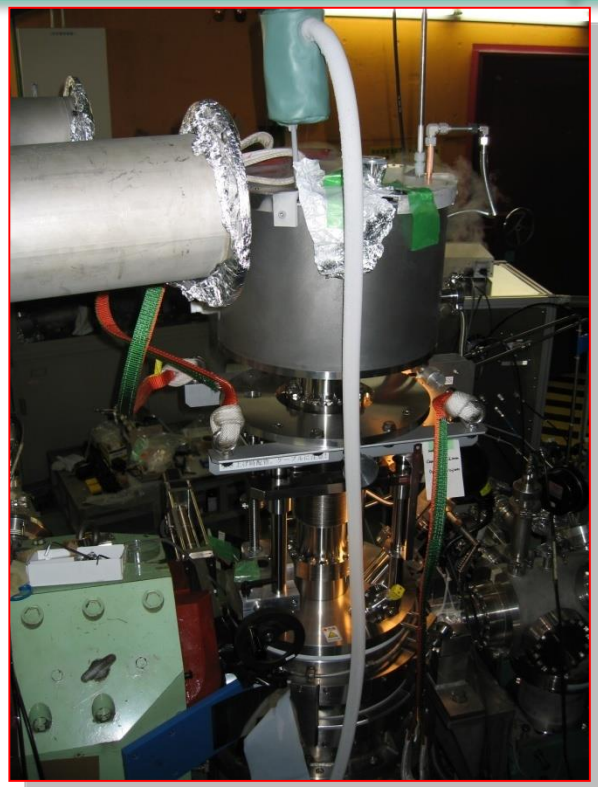
Intense secondary beam production using cryogenic gas target



- 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)

Recent research projects (2010-present)

- Proton/alpha resonant scattering
  - ✓^{26}Si+p (Collaborated with Chung-Ang, Korea) H.S. Jung et al., PRC (2012&2014).
  - ✓^{7}Li/^{7}Be+α (CNS) H. Yamaguchi et al., PRC (2011&2013).
  - ✓^{21}Na+p, ^{22}Na+p [^{18}Ne(α,p), Ne-Na cycle] (IMP/CIAE, China) PRC(R) & PRC (2013).
  - ✓^{17}F+p [Resonances for ^{14}O(α,p)](IMP/CIAE, China) PRC(2014).
- (α,p) reaction measurement, Active target (GEM-MSTPC)
  - ✓^{18}Ne(α,p) (Hashimoto; CNS ⇒ now at IBS)
  - ✓^{30}S(α,p) (CNS, Daid Kahl)
  - ✓^{22}Mg(α,p) (IOP, Vietnam , Nguyen Ngoc Duy)
  - ✓^{44}Ti(α,p) (KEK, Ishiyama) …^{44}Ti beam test successful.
- (α,γ)
  - ^{16}N⇒^{16}O*⇒^{12}C+α for ^{12}C(α,γ) (Catania, S. Cherubini) Measurement finished in Sep 2013.
- Reaction mechanism
  - ✓^{8}B+Pb (Padova, C. Signorini) Measurement finished in May 2014.
- Implantation (^{7}Be)
  - ✓^{7}Be implantation for commercial usage (RIKEN, A. Yoshida)
  - ✓The Brilliant+C project…Reaction study using implanted target

…and new alpha scattering projects

INFN-CNS(CRIB) collaborated works

2007/2008:

- "Study of the $^{18}F+p \rightarrow ^{15}O+\alpha$ reaction at astrophysical energies" $^{18}F+p$, $^{18}F+d$ THM experiments Spokesperson: S. Cherubini (INFN-LNS, France, Japan)

2013 Sep:

- "Study of the beta-delayed alpha decay of ^{16}N", Silvio Cherubini (18 days) (LNS, and many others).

2014 May:

- "Dynamics of the ^{8}B interaction with ^{208}Pb at the Coulomb barrier" Cosimo Signorini (8 days). (Padova, Napoli,+)…M. Mazzocco's talk on Tuesday.

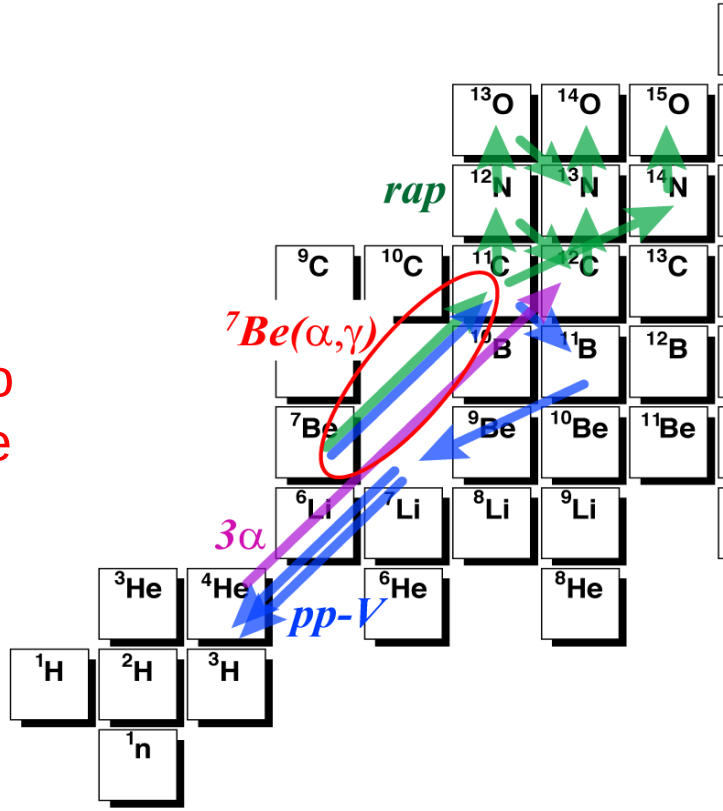
and many test experiments for the above projects.

- MoU on low-energy nuclear physics between INFN-LNS (Catania), SKKU (Korea) and CNS (Japan, Tokyo) was made in 2013.
- Sicily-East Asia Workshop initiated in 2014.
- Anche grazie mille per il questo invito!

^{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}Li/^{7}Be(α,γ) experimental study

- ^{7}Li(α,γ) and ^{7}Be(α,γ) 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.*

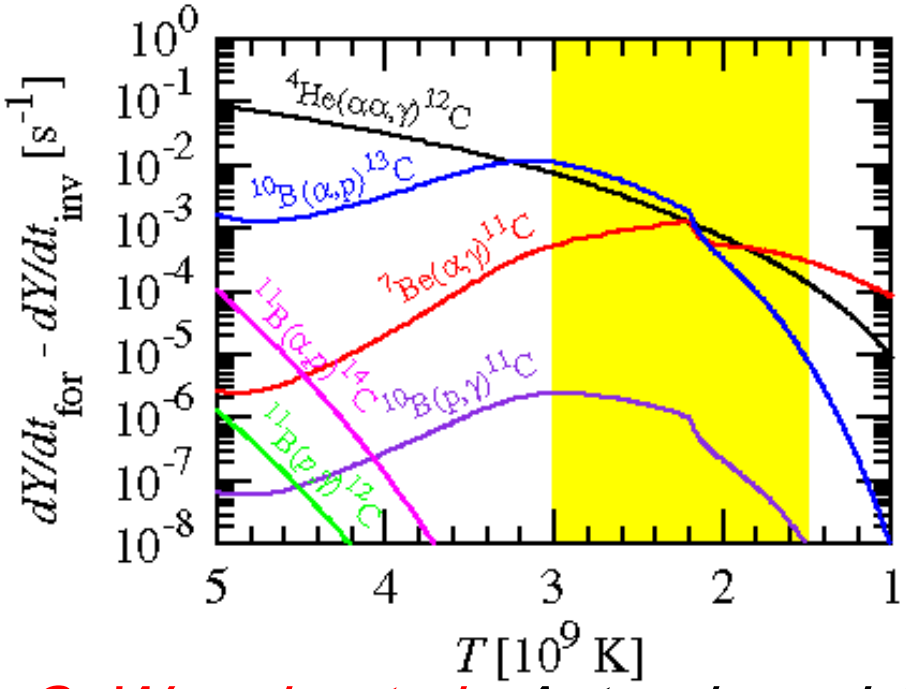
  ^{7}Be(α,γ): only two resonances at E_r<1 MeV are included in the NACRE evaluation.

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}Li(α,α) and ^{7}Be(α,α) at CRIB to obtain information on the resonances (energy, width, spin and parity).

^{7}Be(α,γ) in supernovae

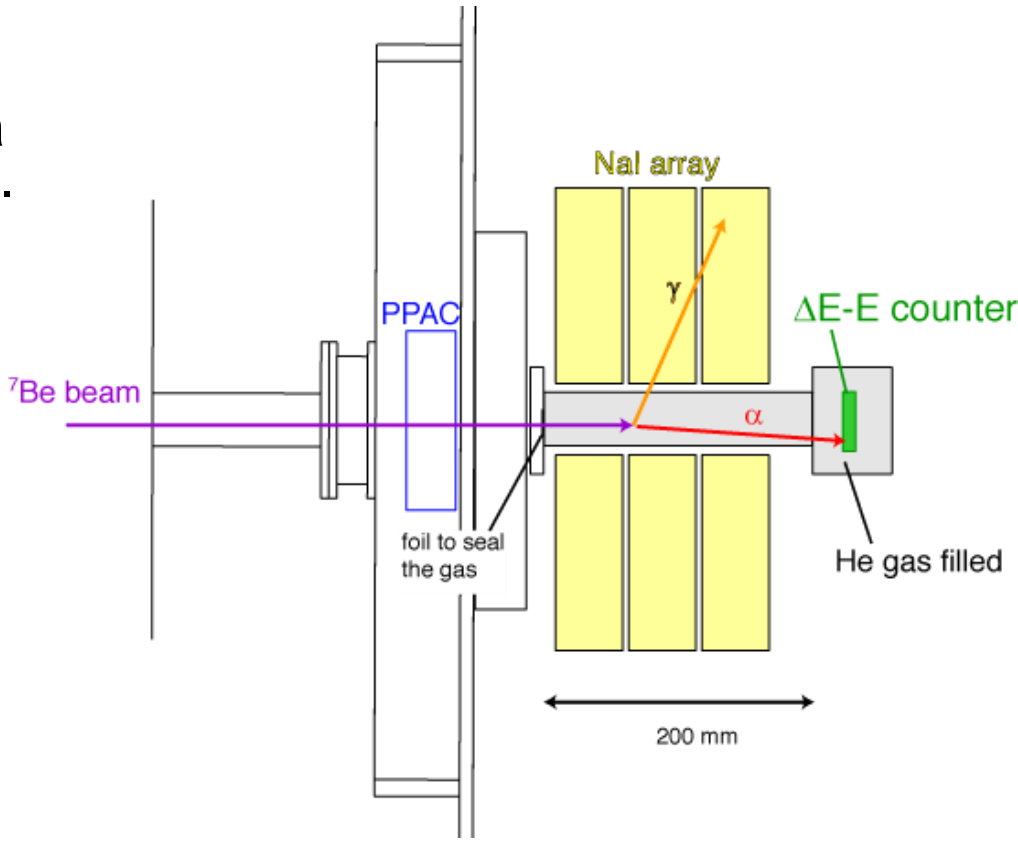
νp-process calculation (T_9>1) shows considerable contribution by ^{10}B(α,p)^{13}C and ^{7}Be(α,γ)^{11}C as much as the triple-alpha process.



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

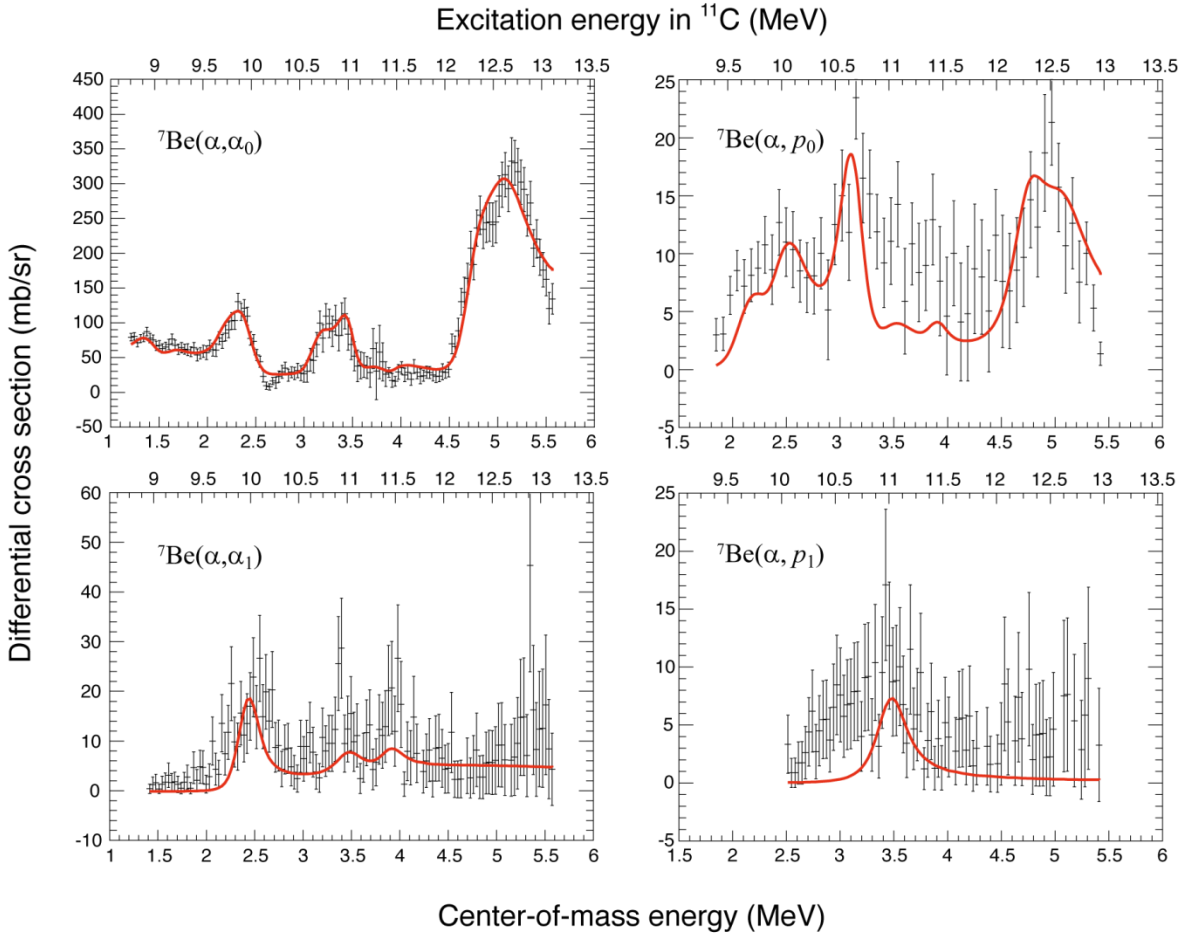
Setup for ^{7}Li/^{7}Be+α

- 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).



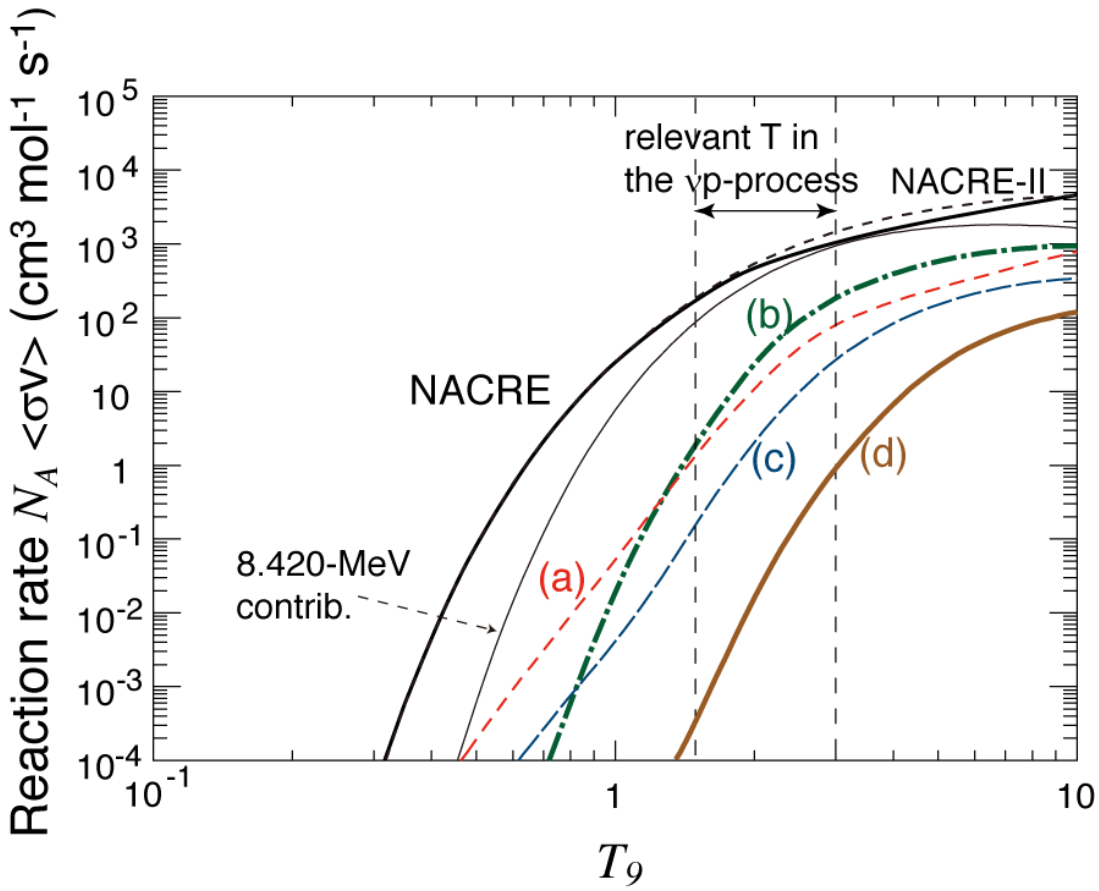
^{7}Be+α Excitation functions

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



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

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



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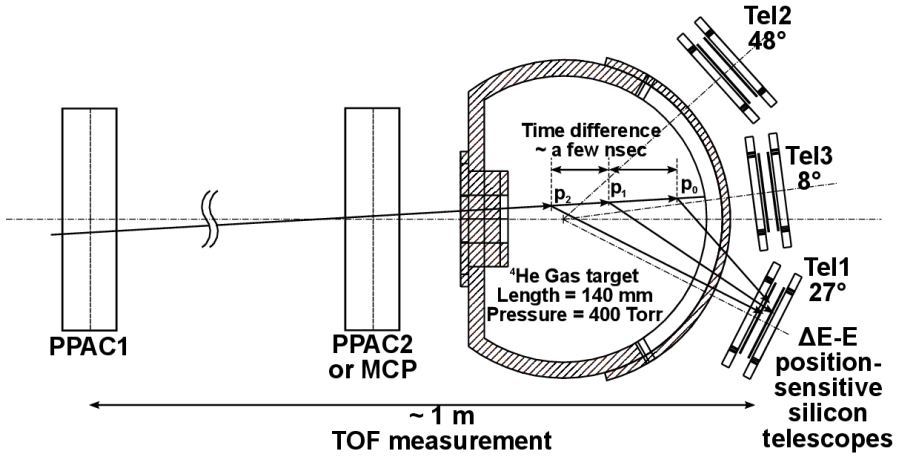
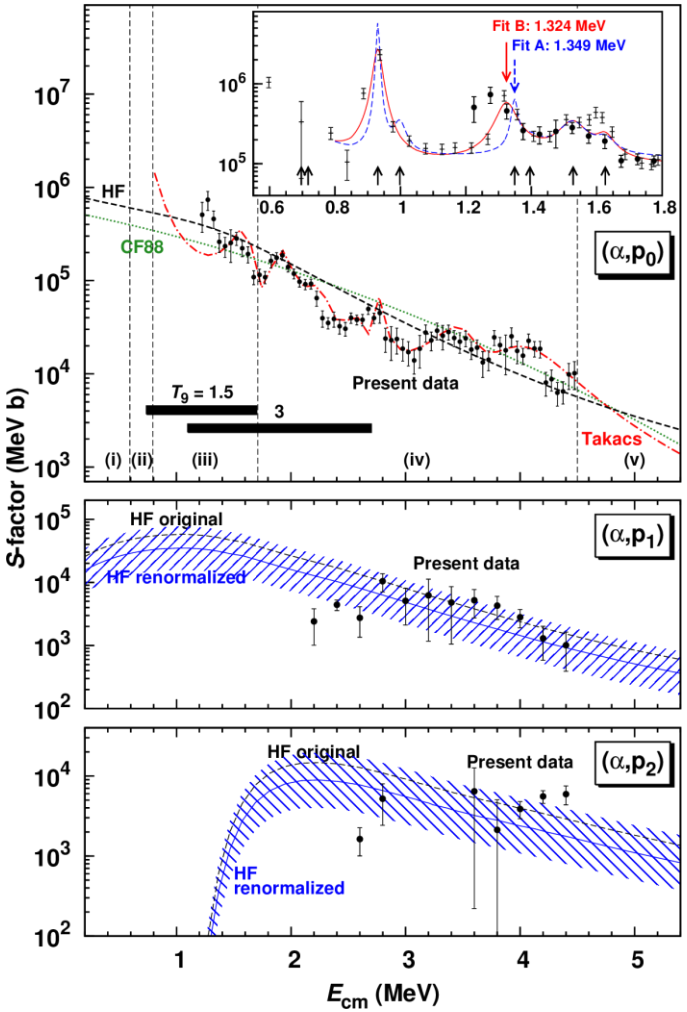
Direct measurement of (α, p) reactions

- ^{11}C(α,p)@CRIB [S. Hayakawa et al., in preparation]

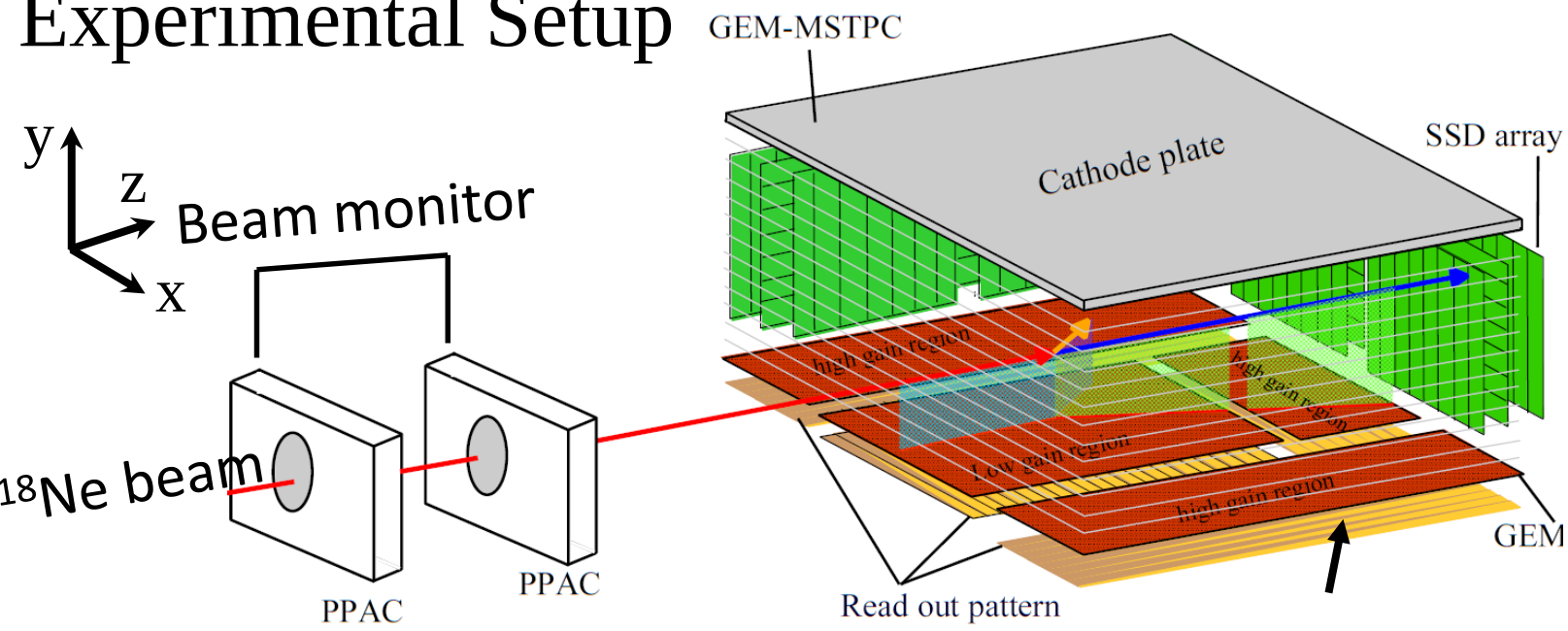




- GEM-MSTPC (active target)

Constructed and used for several (α, p) reaction studies.

Experimental 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
  ⇒ Good event identification.

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

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

- Measurement with Trojan Horse Method performed in 2008

…The first THM+RI beam experiment.

- The RI Beam at CRIB (after development):

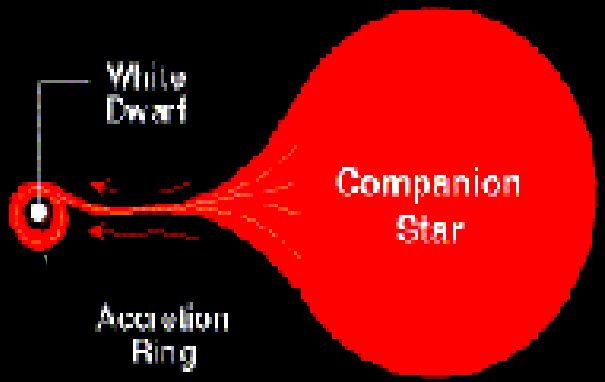
Primary beam: $^{18}O^{8+}$, 4.5-5 MeVA

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



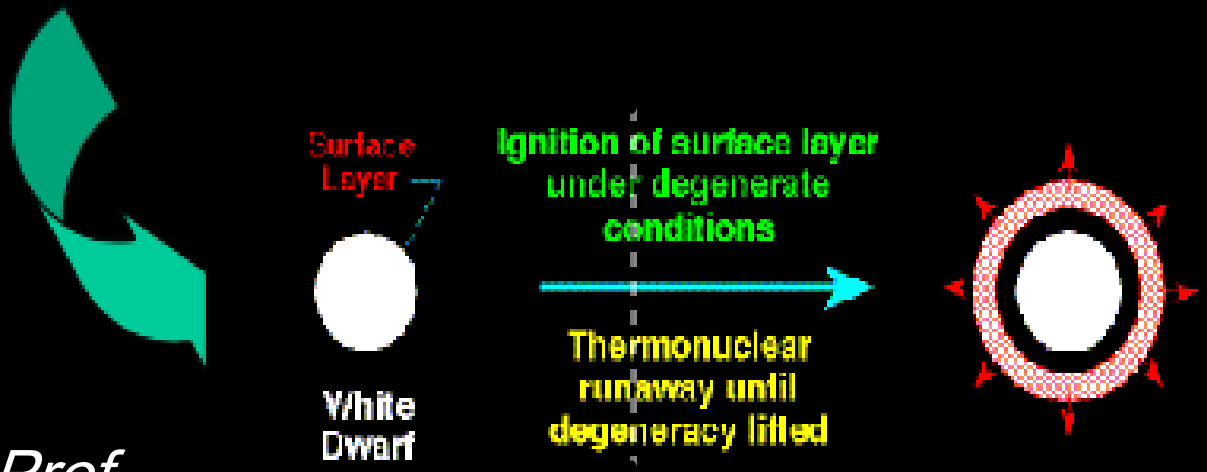
Thin hydrogen surface layer accumulated on white dwarf through accretion ring

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

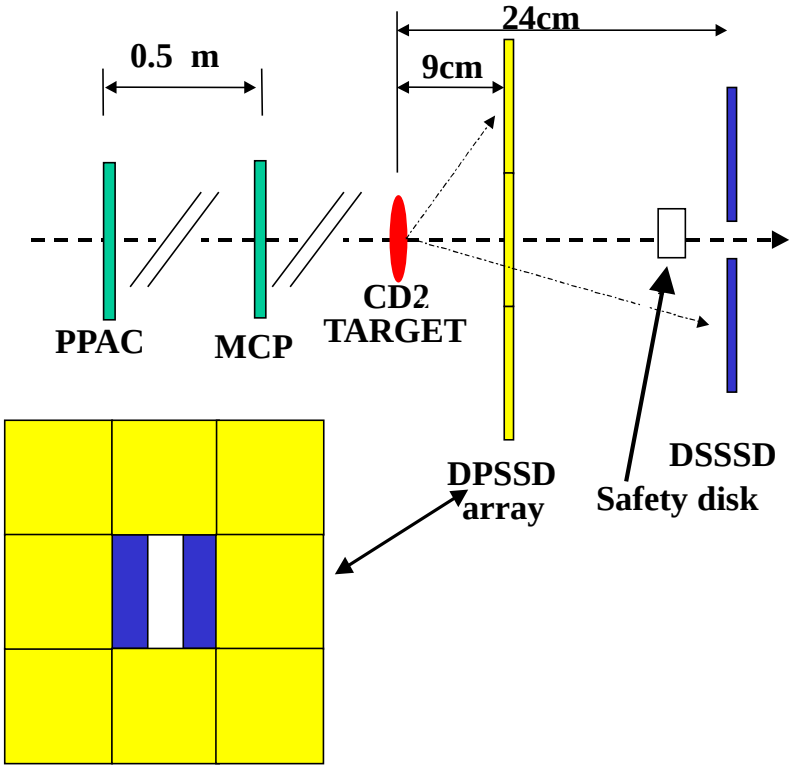
$^{18}F(p,\alpha)^{15}O$

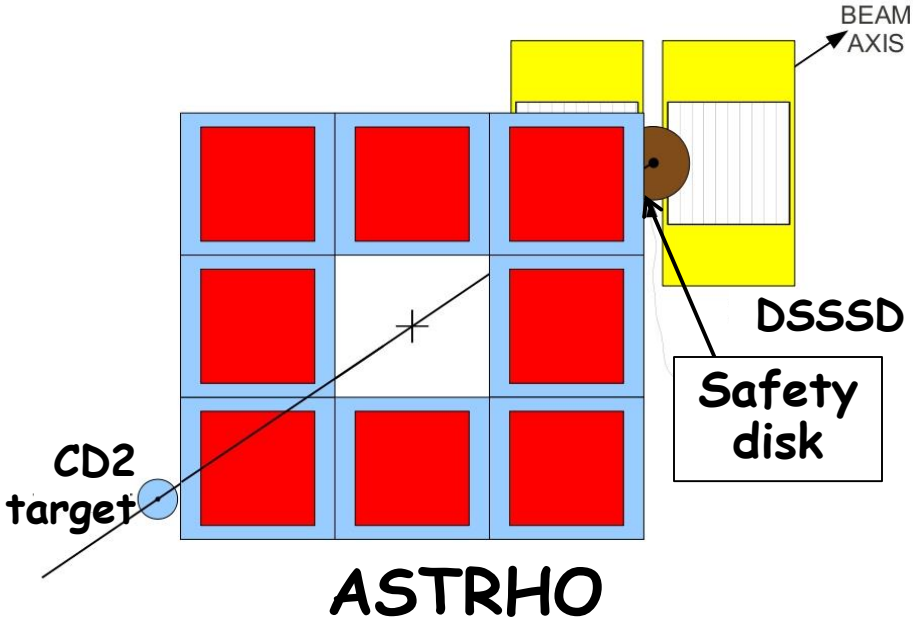


Slides by Prof. S. Cherubini

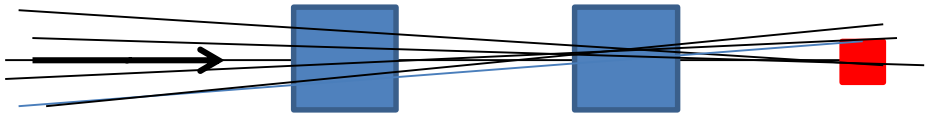
For the star energetics this is peanuts!

EXPERIMENTAL SETUP





ASTRHO



PPAC PPAC CD2

Beam track reconstruction

ASTRHO:
Array of Silicons for
TRojan HOrse

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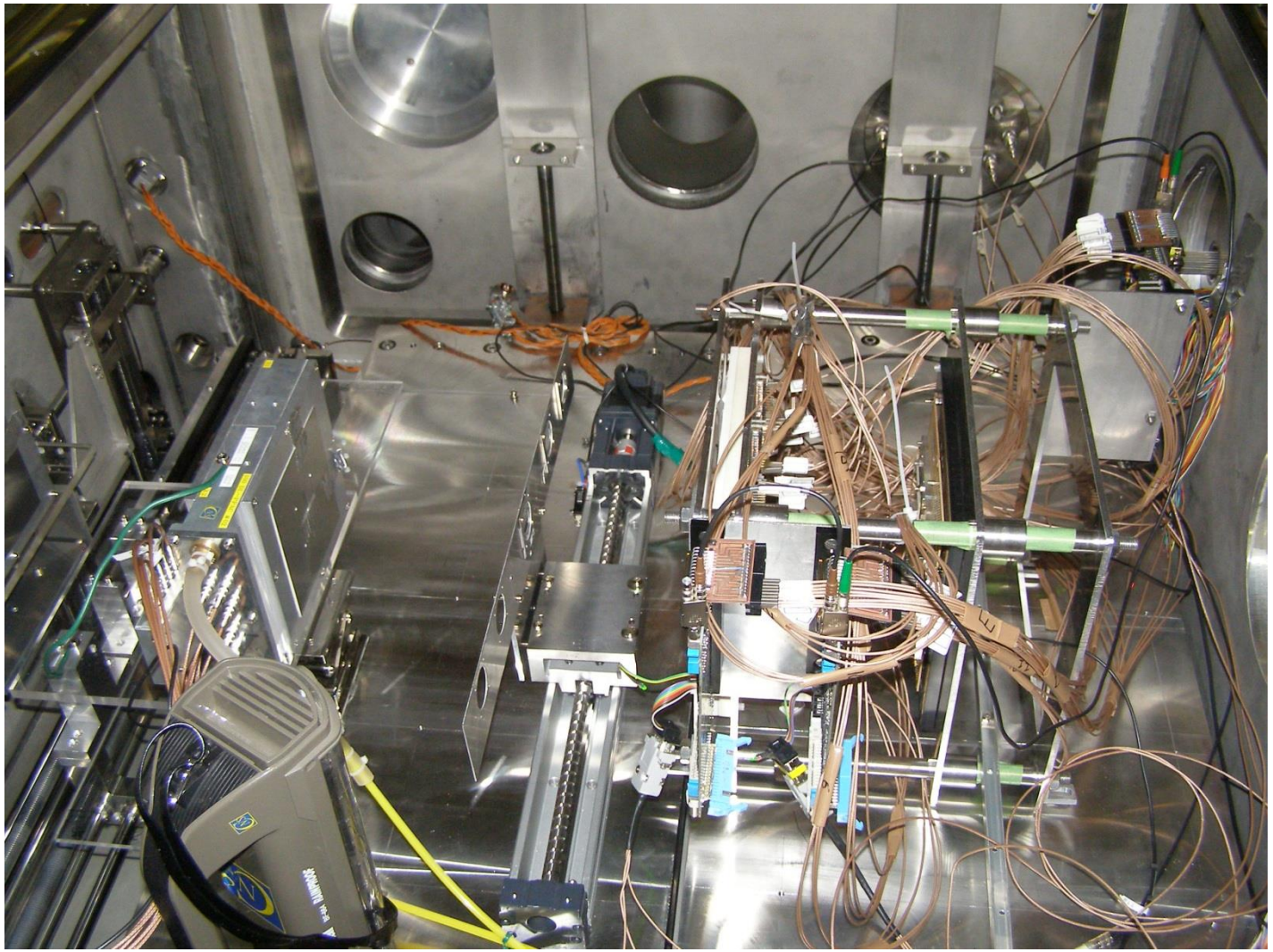

How the setup looks like in reality

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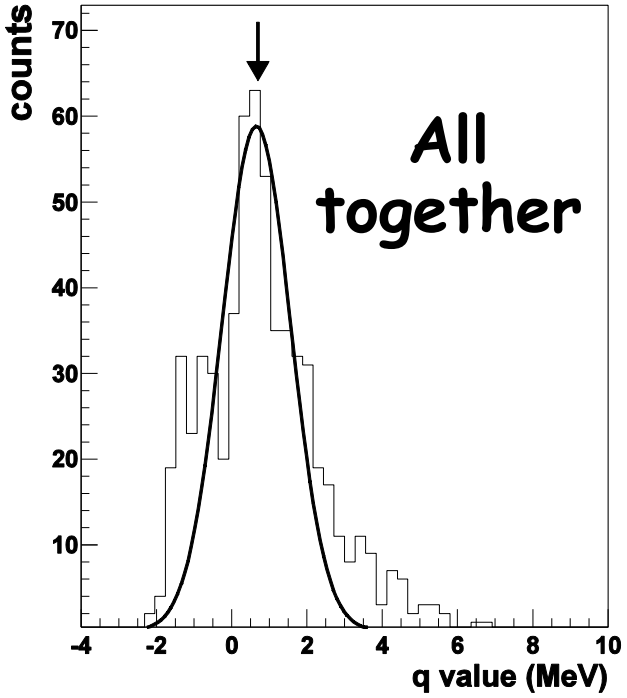
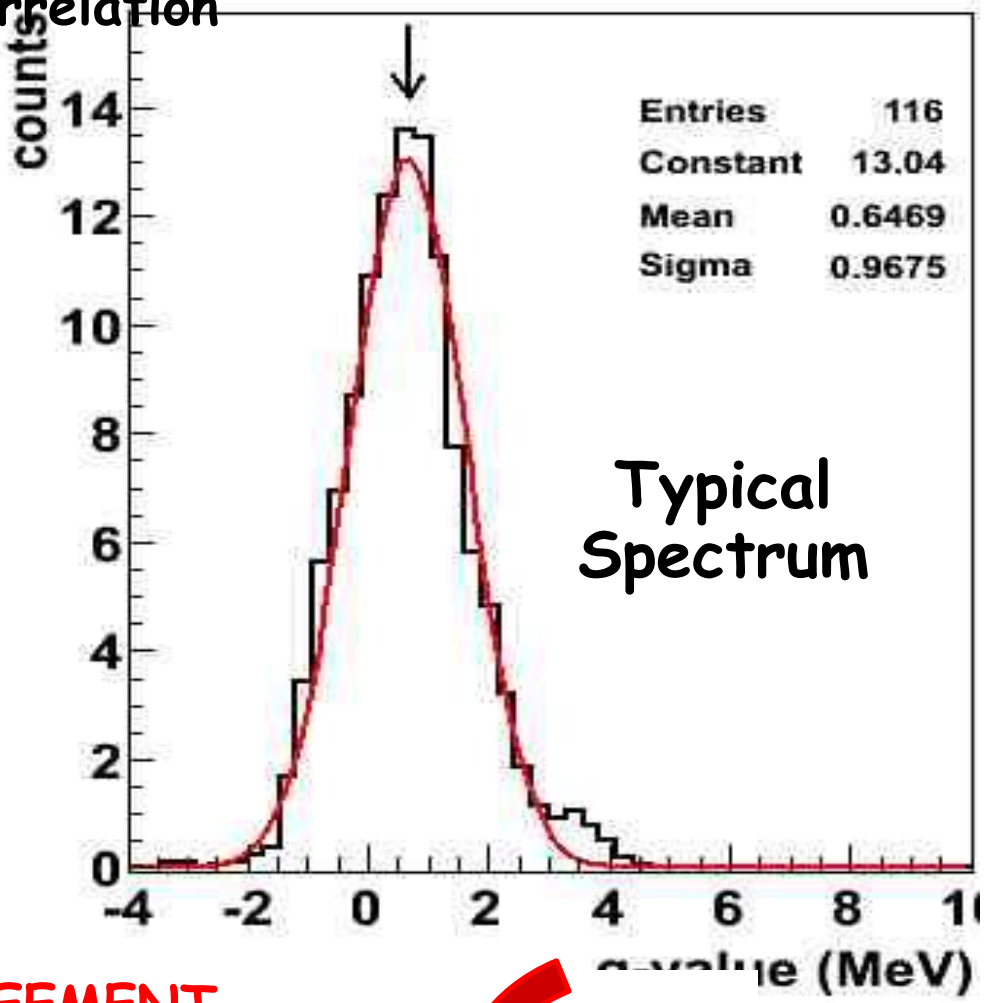
Q-VALUE SPECTRUM

Several beam pos&timing cuts + Erel-Erel correlation +E-Theta correlation





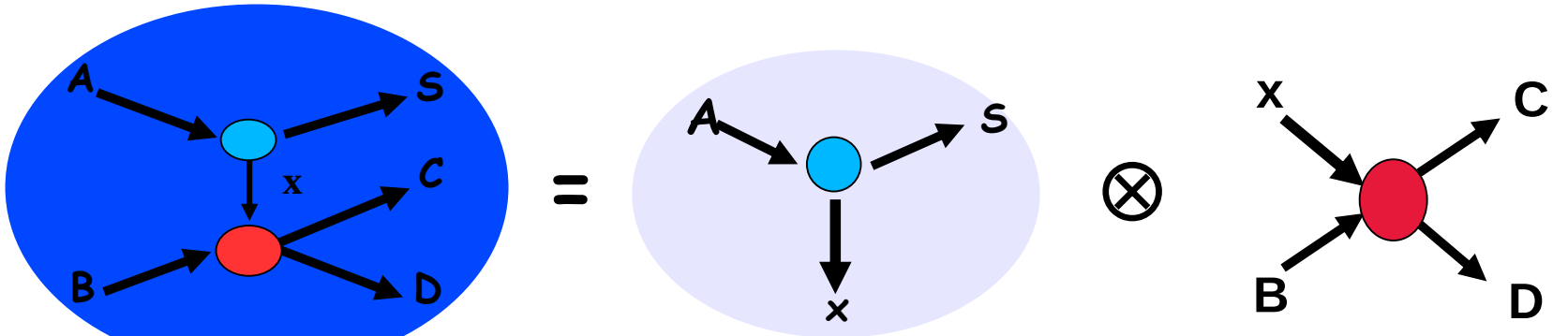
GOOD AGREEMENT

with Q-value expected position (0.658 MeV)

and beam profile (exp. Sigma 0.8 MeV)

Reaction channel identified

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



3-body Reaction

Virtual Decay

Virtual reaction
(astrophysical process)

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

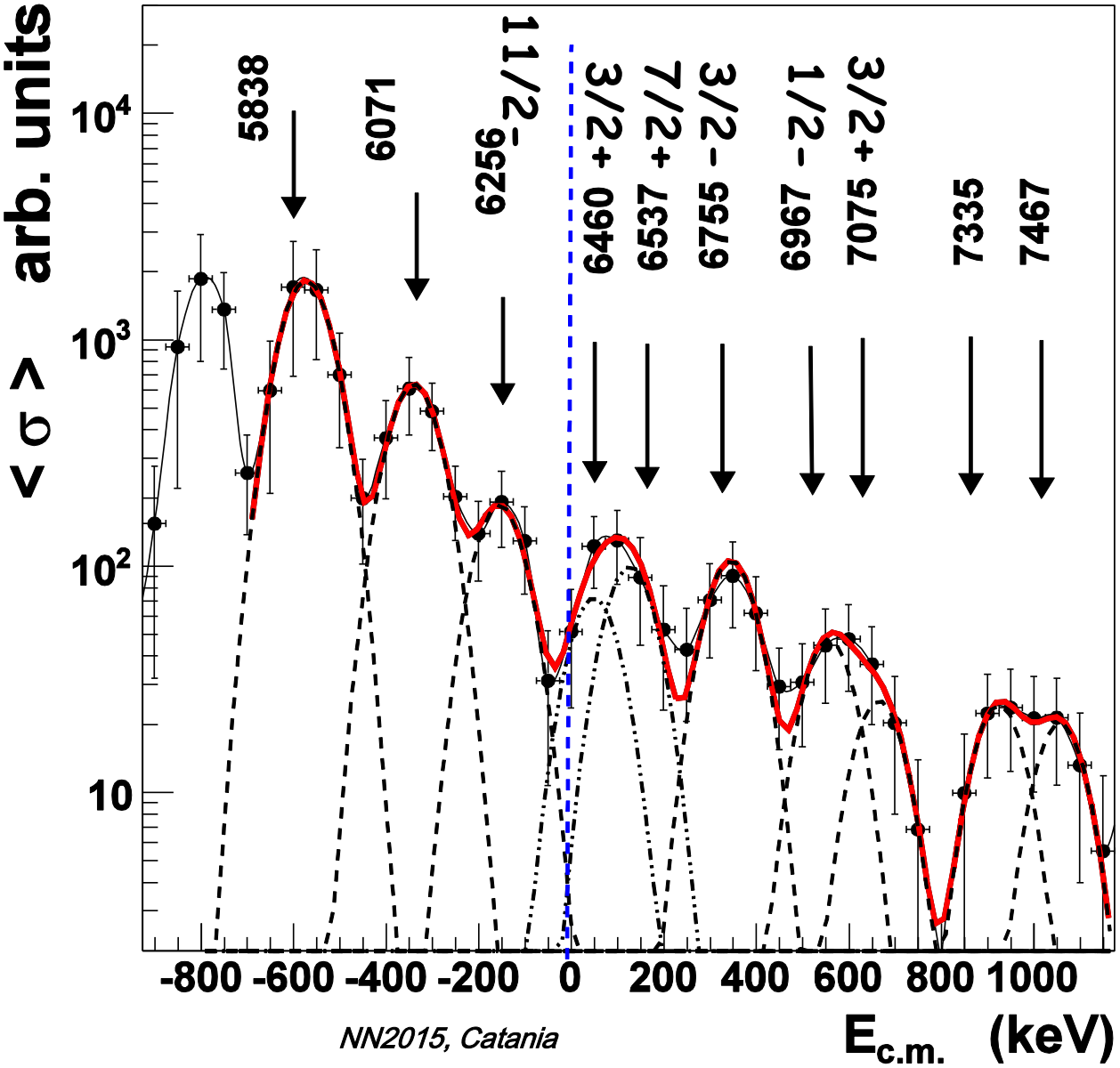
Measured at high energy

Calculated e.g. Montecarlo

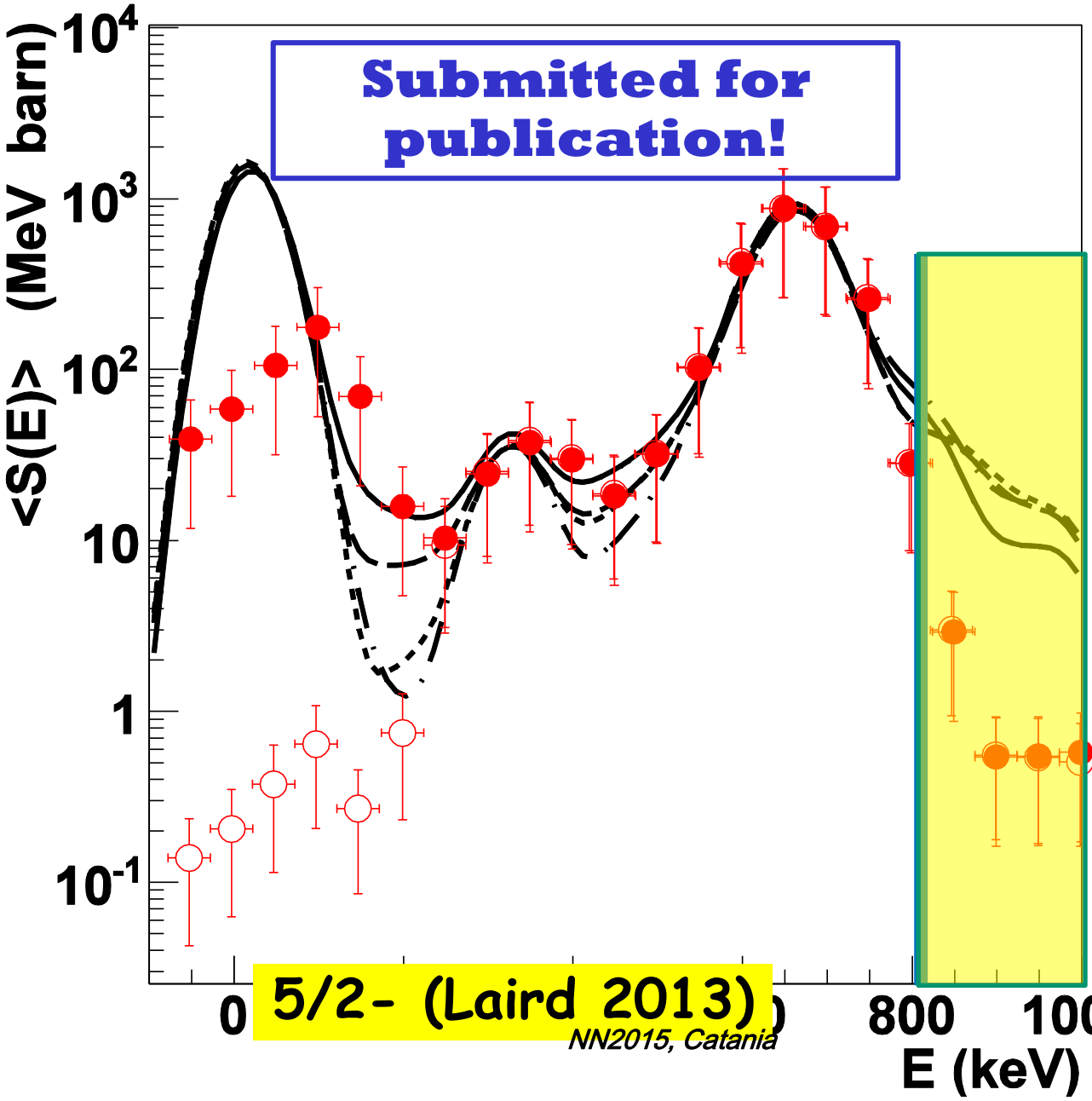
Indirectly Measured

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

THM(=barriers free) CROSS SECTION



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



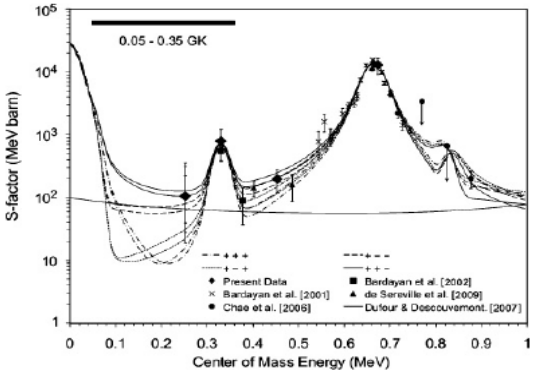


FIG. 3. The $^{18}F(p,\alpha)^{15}O$ S factors, calculated using the R matrix, for eight possible interference terms. The range in possible S factors arises from the interference between the $J^\pi = 3/2^+$ resonances. The interference between resonances dominates in the region of interest, resulting 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].

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

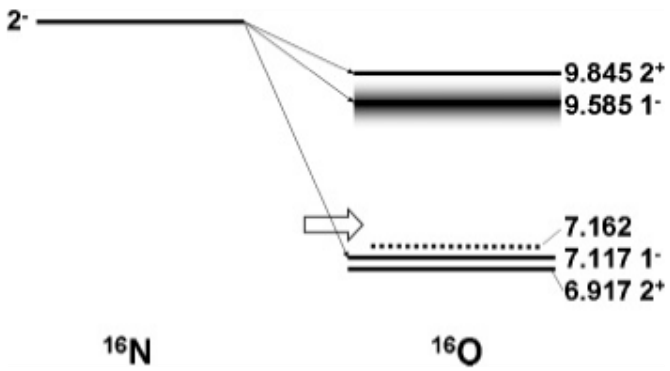
THM data

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

Smeared to THM resolution

^{16}N beta-delayed alpha decay

- $^{16}N \rightarrow {}^{16}O^* \rightarrow {}^{12}C+\alpha$ decay…carrying information of $^{12}C(\alpha,\gamma)$ reaction cross section (E1 component) at low energy.



- Tang et al. (Argonne)…measurement with 2 ionization chambers. (Low-energy events cannot be detected.)
- Using the active target for decay measurement…sensitivity at low-energy events
- Experiment at CRIB proposed and performed under a collaboration with INFN-LNS group (S. Cherubini et al.)

Performed measurement

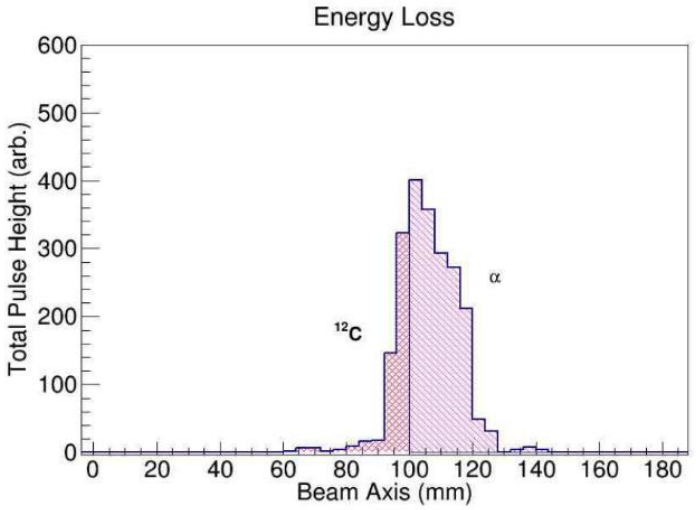
Measurement at CRIB performed in Sep. 2013.

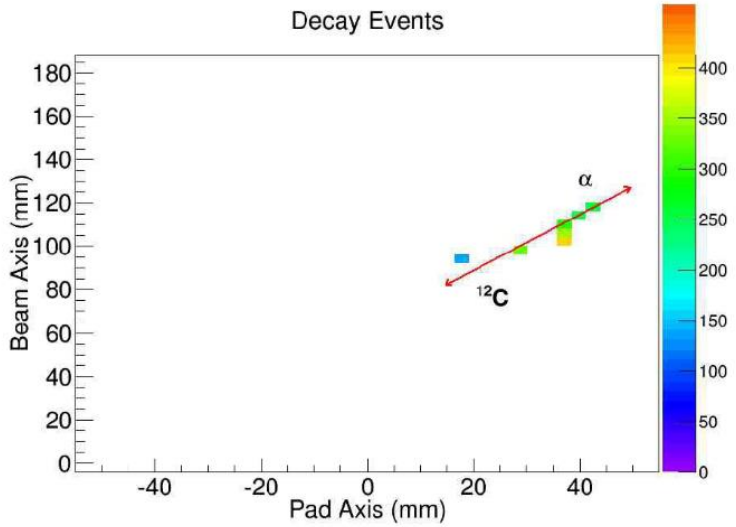
- RI Beam…^{16}N
  - Beam pulsing (on-off) operation by 50-ms interval.
  - 1-4 x 10^5 pps after the pulsing, purity 40-80%.
  - 30-MeV beam injected into the TPC, stopped in the middle of it.
- Total 16 days of beamtime, about 2 weeks of data accumulation.
- Branching ratio of α-decay…~10^{-5}

  $\Rightarrow$ a few decay events /sec.

Typical event (preliminary)

- Signals observed in several neighboring channels…candidate of α-decay event.
- Event selection by energy and tracking information.
- Analysis in progress.





Summary

- CRIB is a low-energy RI beam facility in RIBF operated by CNS, University of Tokyo, providing RI beams of good intensity and purity.
- Manpower…Minimum to carry out experiments. We are making experiments in a worldwide collaboration with external groups.
- GEM-MSTPC
  - Has been used in several (α,p) measurements, and recently also for alpha decay measurement of ^{16}N.
- Resonant elastic scattering
  - ^{7}Li+α,^{7}Be+α…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.
- Trojan Horse experiments
  - ^{18}F+d…the first RI beam+THM experiment
  - More to come.
- We welcome new users and new ideas!