Direct determination of the $^{11}C(\alpha,p)^{14}N$ reaction rate with CRIB: an alternative synthesis path to the CNO elements

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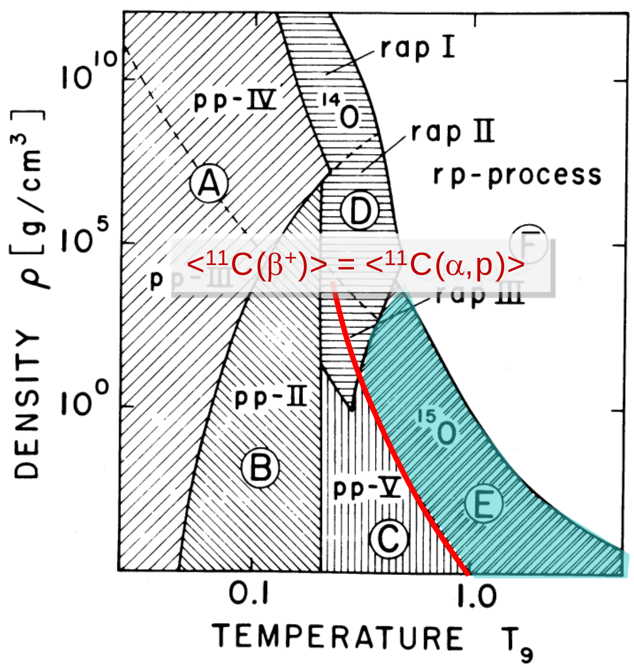
- Motivation
  - $^{11}C(\alpha,p)^{14}N$: Breakout path from pp-chain to CNO
  - What to measure
- Experiment
  - ^{11}C beam production
  - Experimental setup of the direct measurement
  - Experimental setup of the direct measurement
- Results
  - Event ID
  - $^{11}C(\alpha,p)$14N Cross sections
  - Reaction rates
- Summary

$^{11}C(\alpha,p)^{14}N$: A breakout path from pp-chain

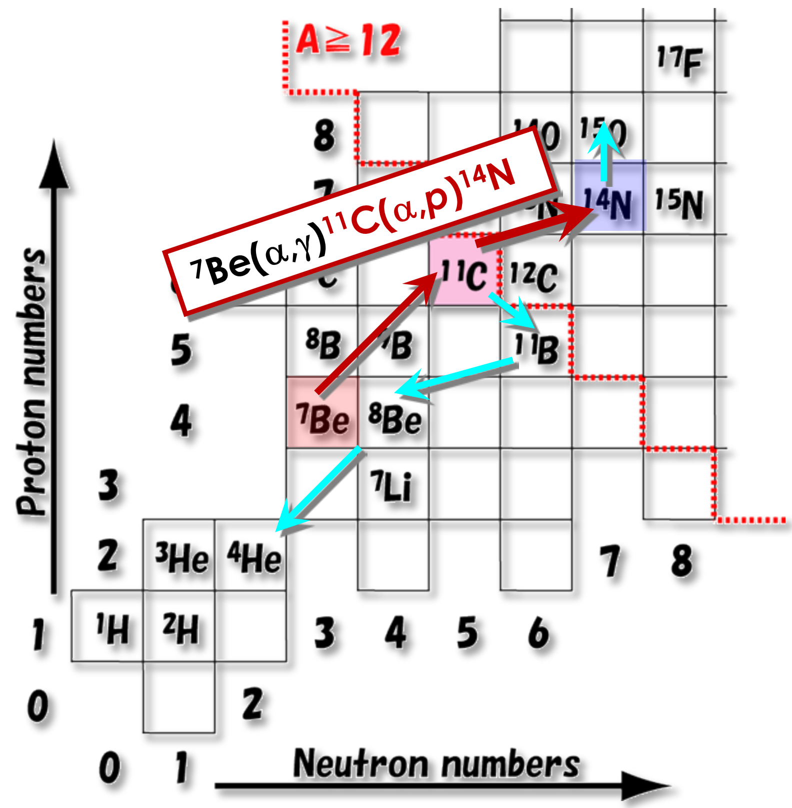
- Hot hydrogen burning processes:
  - Breakout from the hot pp-chain competing with the β-decay to ^{11}B

  → simulation of metal-poor stars (Wiescher et al.,1989)
  - Contributes in the νp-process in the neutrino-driven winds in core-collapse supernovae (Wanajo et al, 2010)

  → produce more intermediate-mass, less heavy nuclei around A = 100

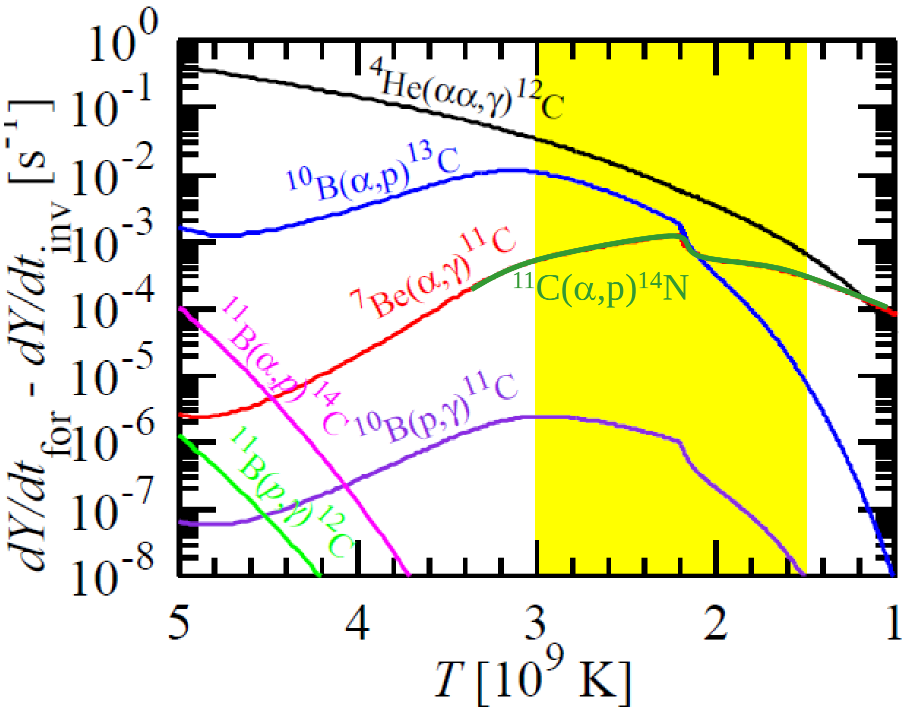


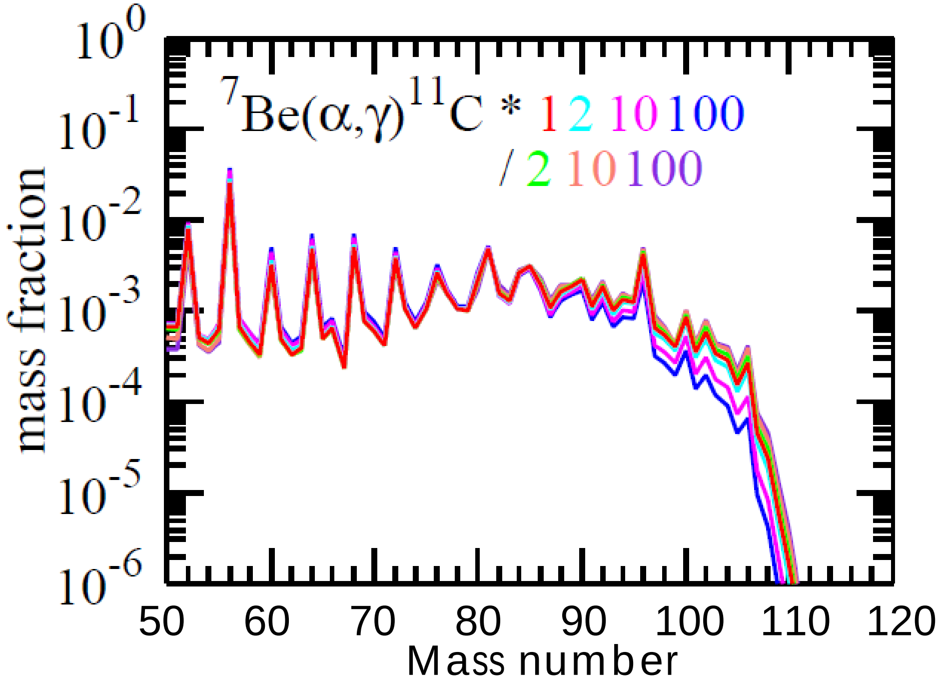
Wiescher *et al.*(1989)



$^{7}Be(\alpha,\gamma)^{11}C(\alpha,p)^{14}N$: Contribution in νp-process

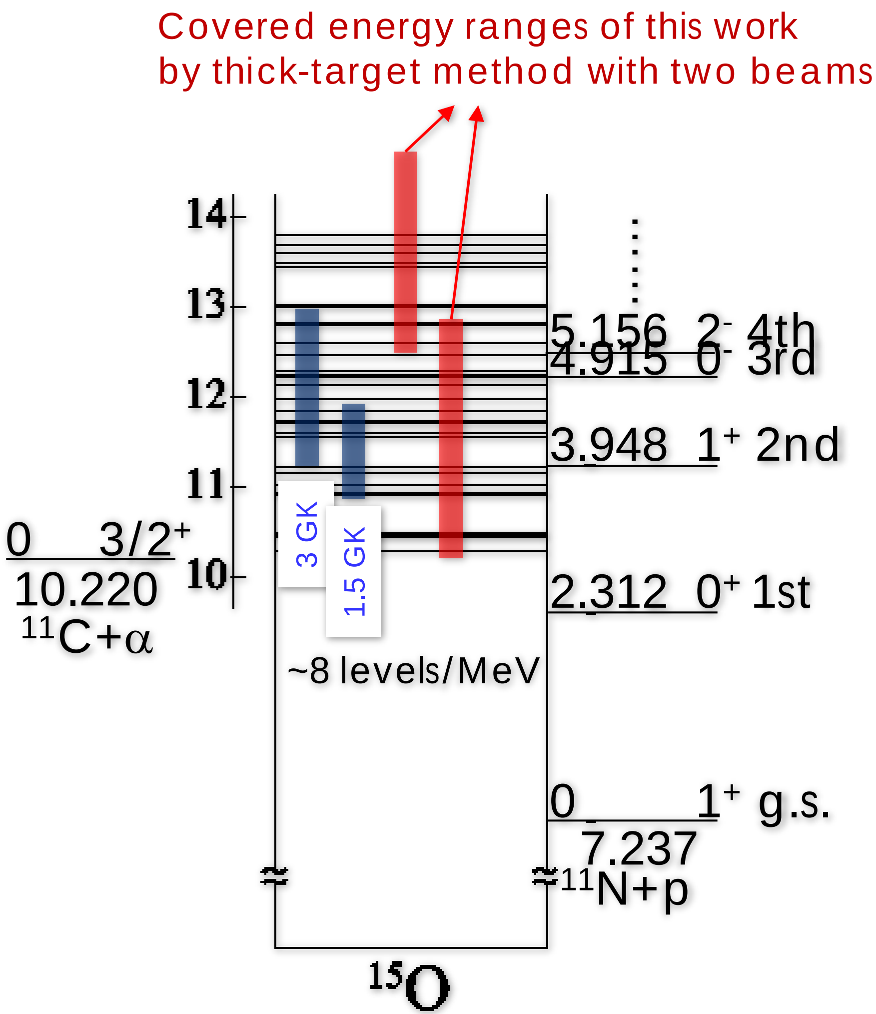
- Wanajo, Janka, Kubono, arXiv:1004.4487v1, 2010





- $^{11}C(\alpha,p)$ overlaps $^{7}Be(\alpha,\gamma)$
  - ⇒ ^{11}C is mostly produced from $^{7}Be(\alpha,\gamma)$, and then $(\alpha,p)^{14}N$ follows.
  - ⇒ $^{11}C(\alpha,p)$ rate > $^{7}Be(\alpha,\gamma)$ rate
- $^{7}Be(\alpha,\gamma)$ rate tends to less mass fraction around A = 100.
  - Limited resonance information only for $T_9 < 2$. (New measurement!! Yamaguchi, NIC_XI_124)
- $^{11}C(\alpha,p)$ rate would become more important if $^{7}Be(\alpha,\gamma)$ has a higher rate.
  - Time-reversal reaction studies by activation method. ⇒ Gives only $(\alpha,p_0)^{14}N_{g.s.}$

What to measure



- Only time-reversal reaction studies by activation method (Ingalls et al., etc.)

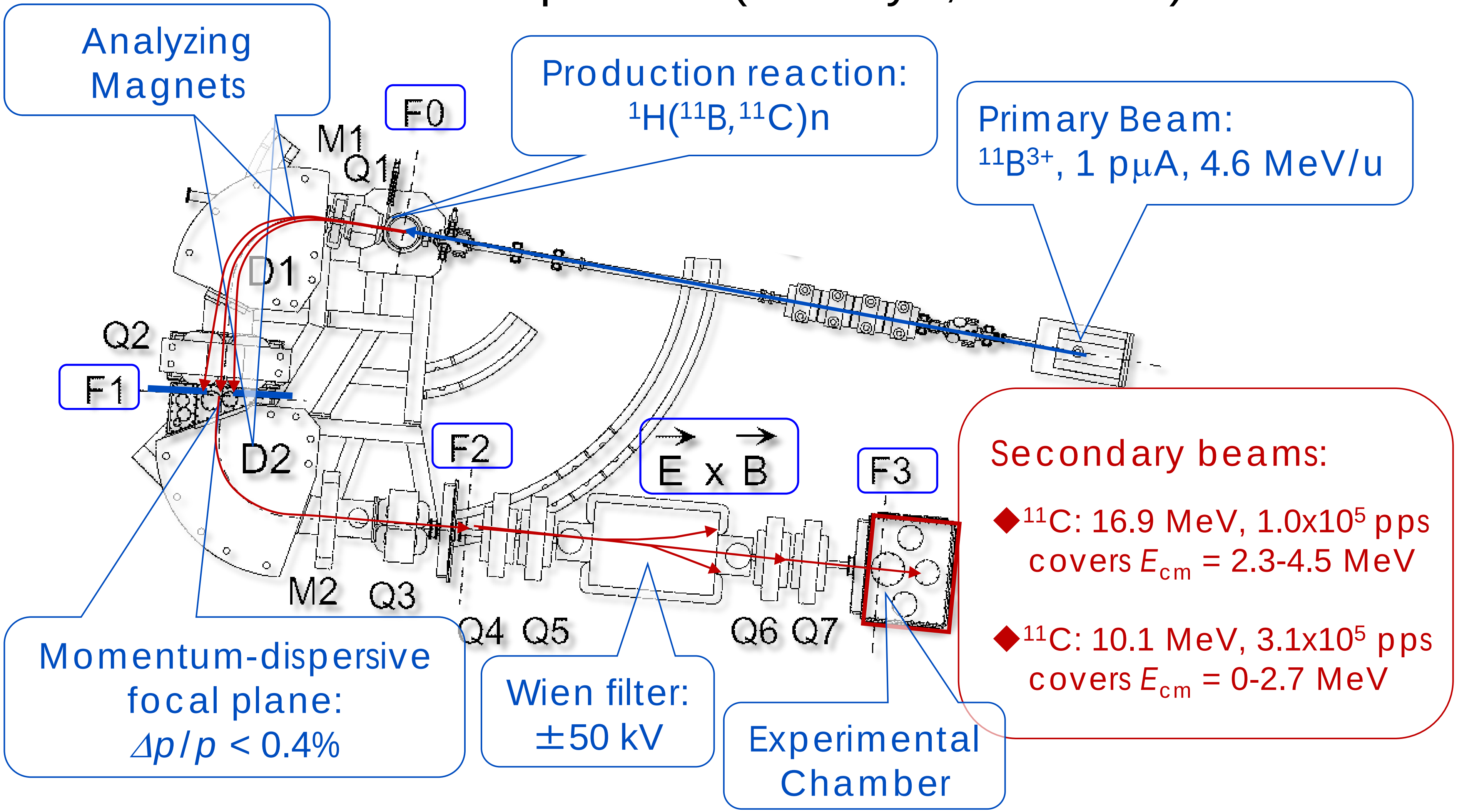
  ⇒ give no information for (α,p_1), (α,p_2), … cross sections
- Not enough resonance parameters are known.

- First direct measurement
  - Confirm (α,p_0) cross sections

    ⇔ data from time-reversal reaction experiments by activation method
  - Determine (α,p_1), (α,p_2), … cross sections

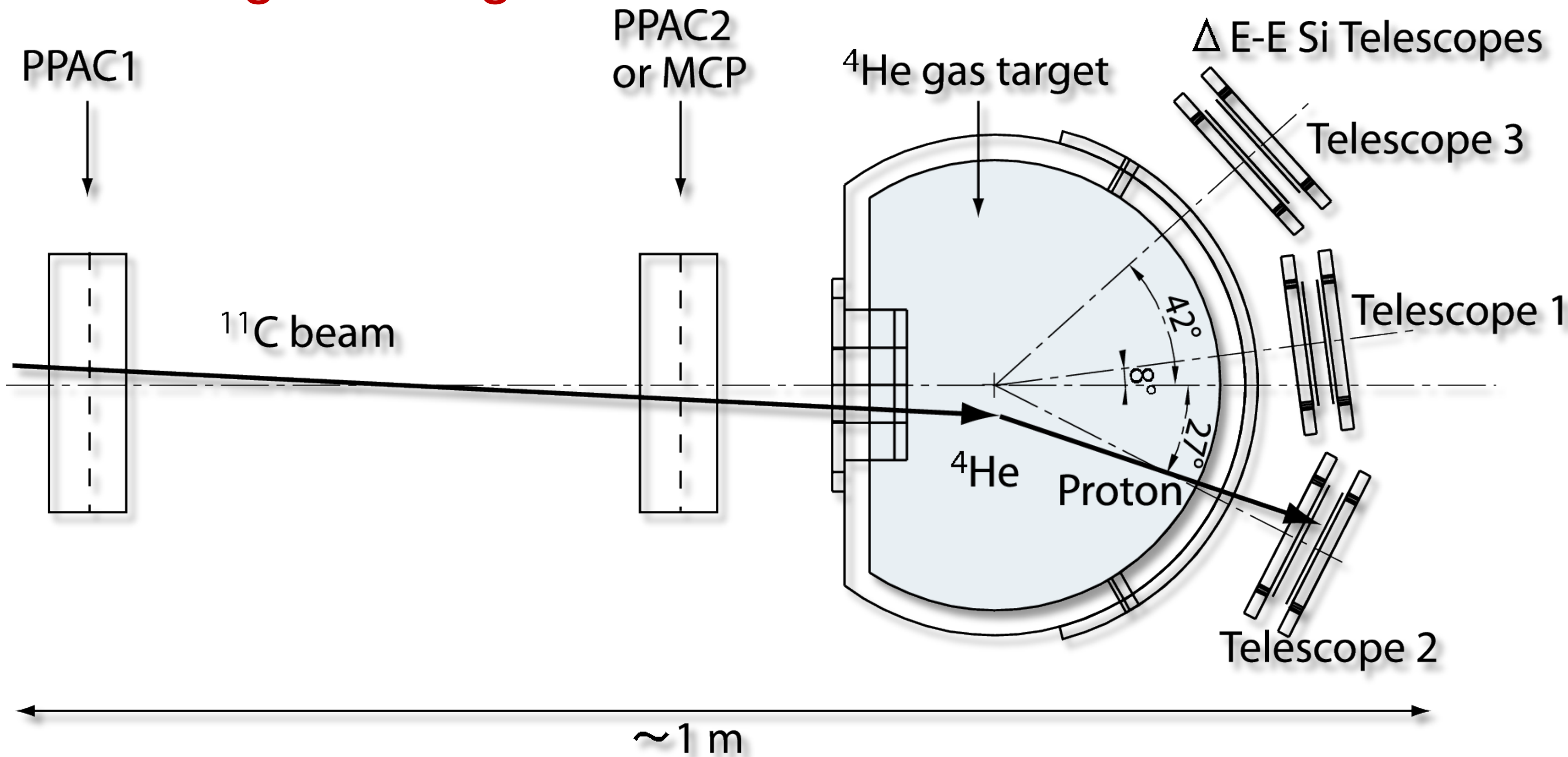
^{11}C Beam Production with CRIB

CRIB: Center for Nuclear Study Radioactive Ion Beam separator (U. Tokyo, at RIKEN)



Experimental Setup

- Thick "gas" target method in inverse kinematics

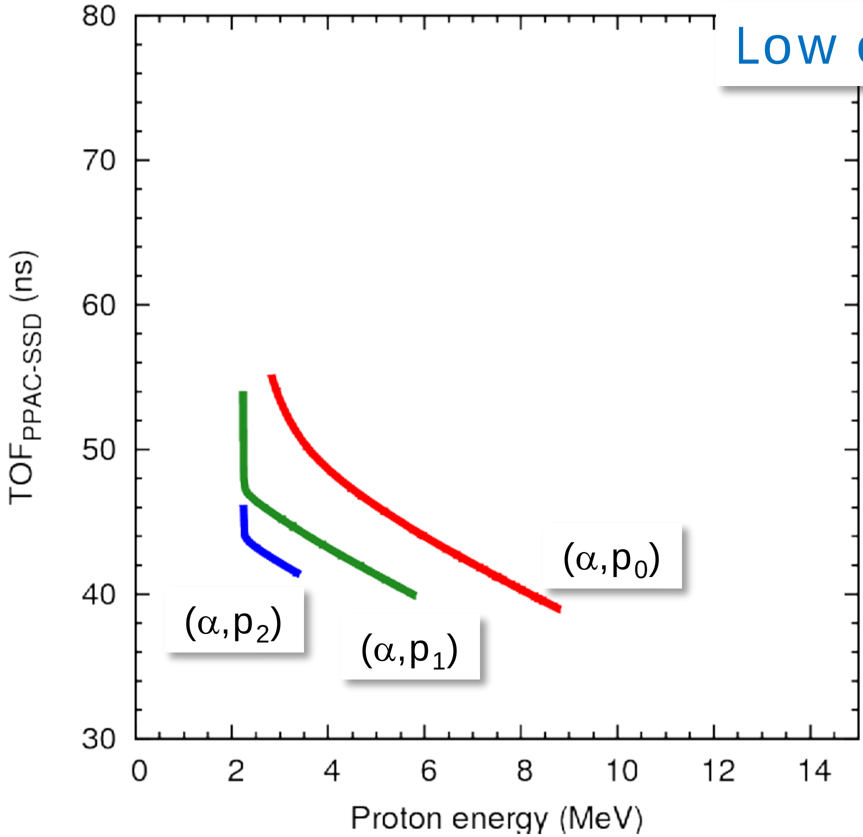


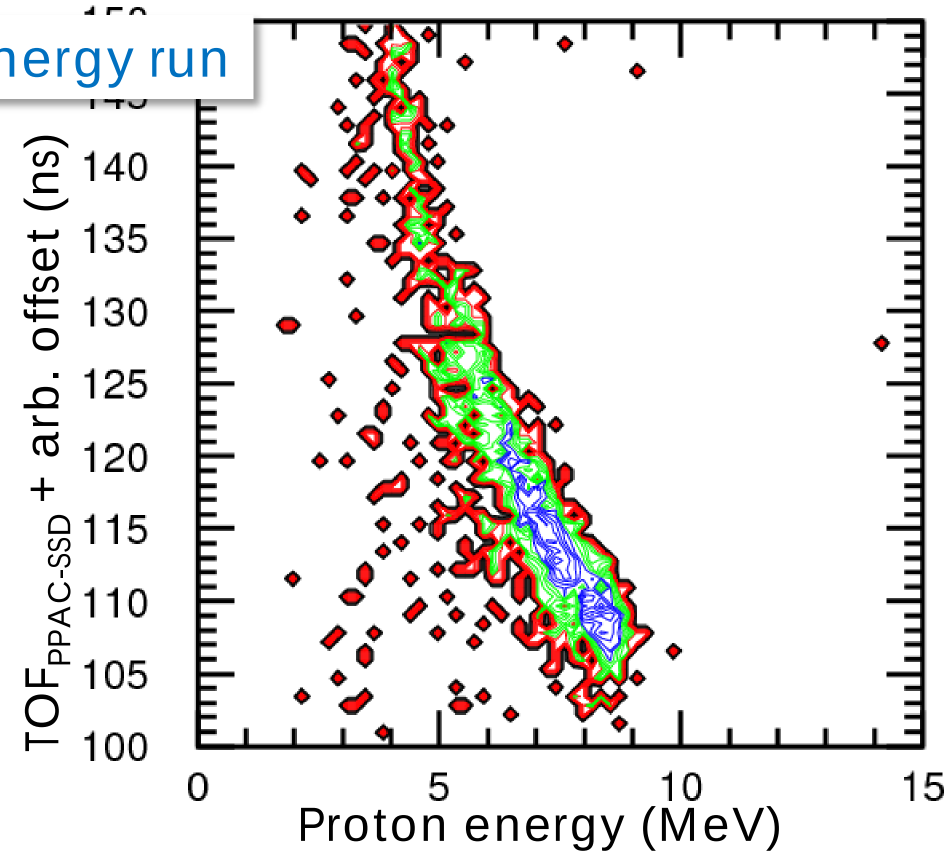
- Measurement: ☑Beam position ☑E_{beam} ☑Proton position ☑ E_{proton}
- 140-mm-long, 400-Torr gas target

  ΔT between different transitions; $(\alpha,p_0)^{14}N_{g.s.} \Leftrightarrow (\alpha,p_1)^{14}N_{2312}$: ~ 5 ns

  ⇒ event ID in TOF vs. E plots
- ΔE_{cm} ~ 50 keV, $\Delta\Omega/\Omega$ ~ 10%

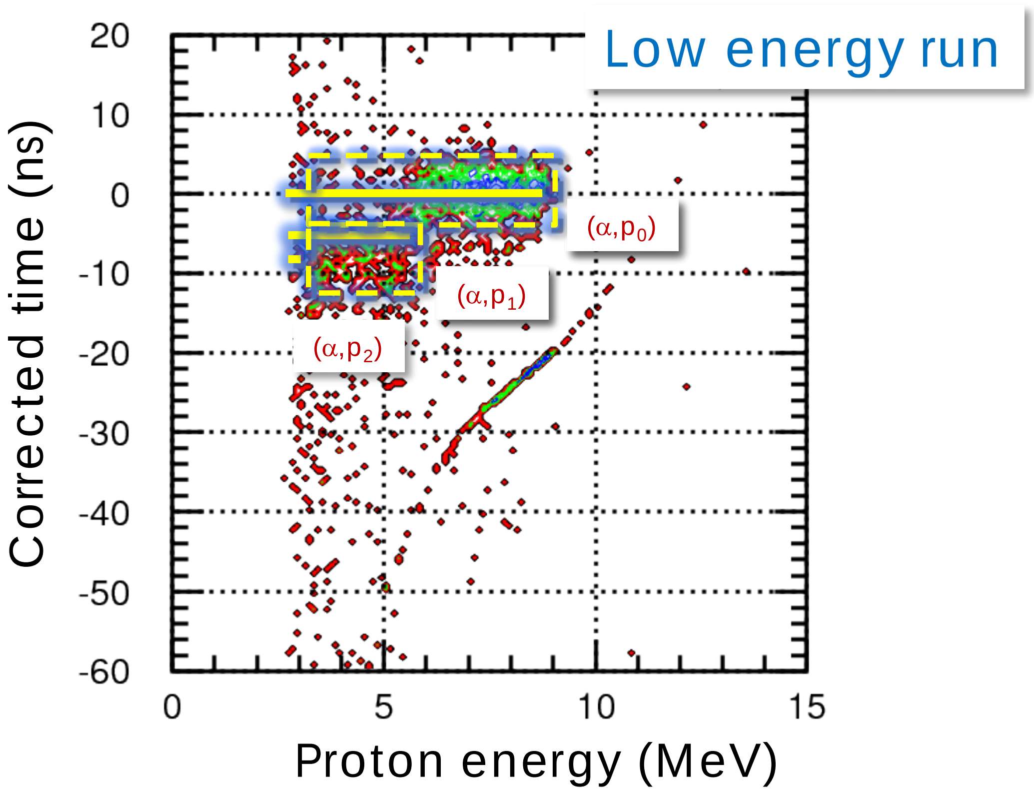
Event identification





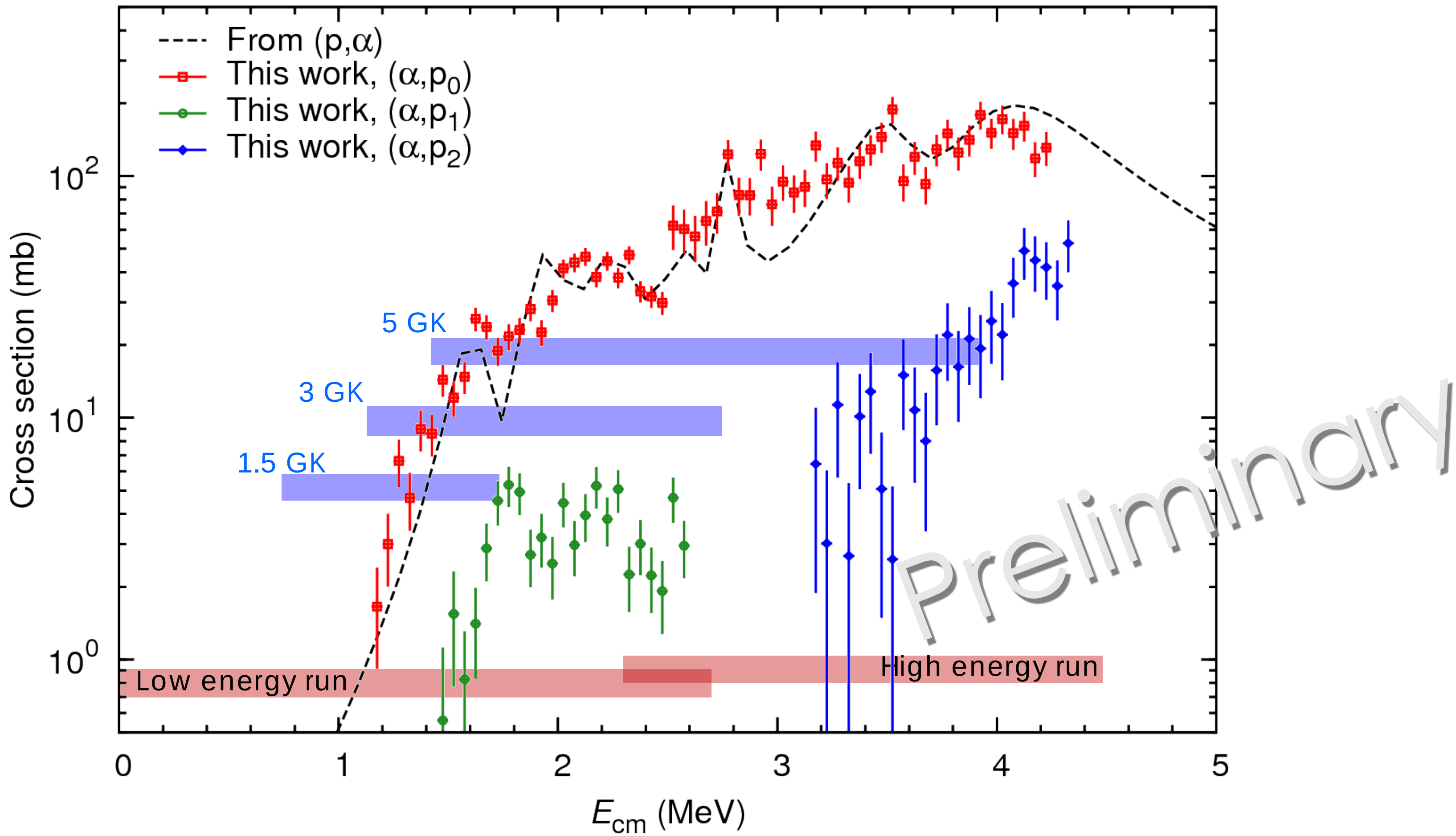
- Measured TOF looks stretched at lower energies.
  - ⇒ A slew correction is needed.
- The lines of each transition have similar derivations
  - ⇒ If (α,p_0) is linearized, other transitions are also linearized.

Event identification



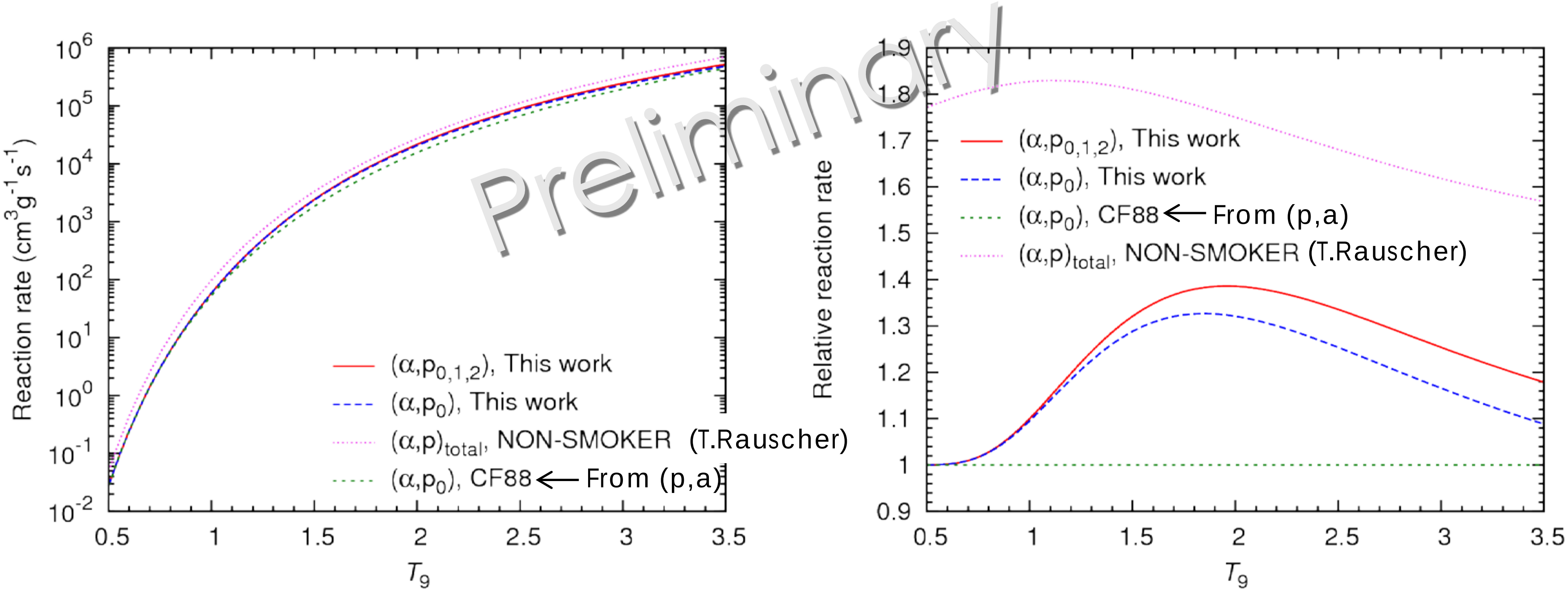
- Linearized the ‘raw’ TOF data
- The energy ranges for each transition are consistent with the calculations

$^{11}C(\alpha,p)^{14}N$ cross sections



- 'From (p,α)': Statistical fit to the several time-reversal reaction studies (Takacs et al.)
- 'This work': cross sections for (α,p_0), (α,p_1) and (α,p_{12}) integrated assuming isotropy
  ($\rightarrow$ indicated only the statistical errors).
- (α,p_0) mostly determines the reaction rate at stellar temperatures (T_9 = 1.5-3).

Reaction rates



- The new reaction rate including (α,p$_0$), (α,p$_1$) and (α,p$_2$) is enhanced by 40% at most, and still less than Hauser-Feshback reaction rate.

Summary

- The first direct measurement of the $^{11}C(\alpha,p)^{14}N$ reaction was successfully performed with CRIB by the thick-gas-target inverse-kinematics method at stellar energies. Each transition is separable.
- (α,p_0) cross section; mostly consistent with the one from the time-reverse reaction studies. The resonances around 1 MeV may enhance the reaction rate.
- $(\alpha,p_{1,2,\ldots})$ contributes about 10% at most for the stellar temperatures ($T_9 < 3$).

Collaborators

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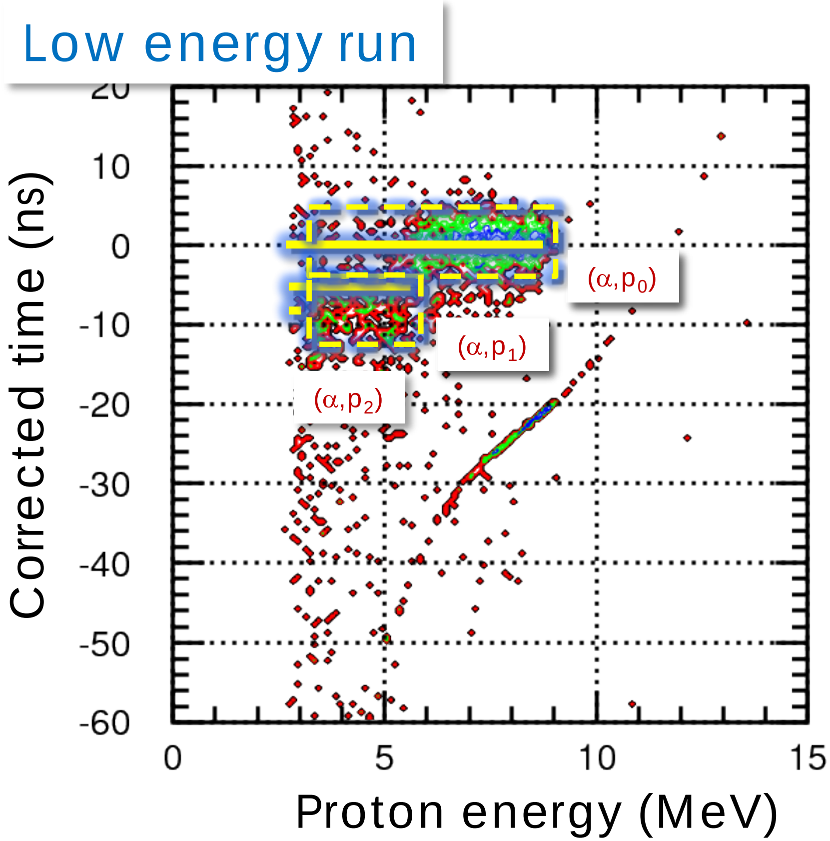
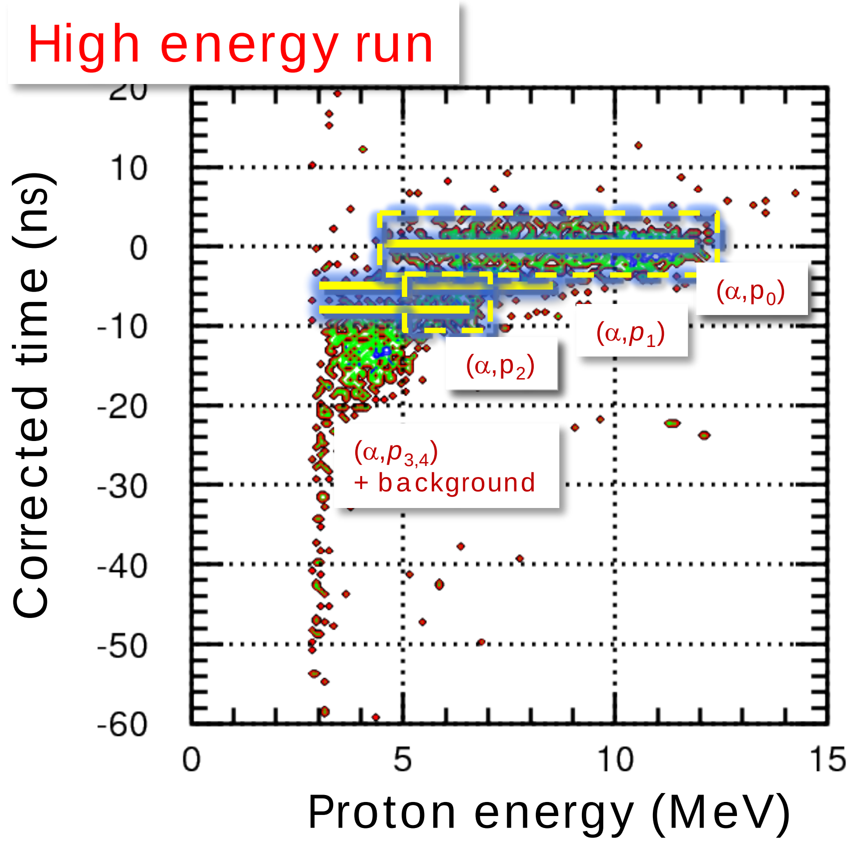
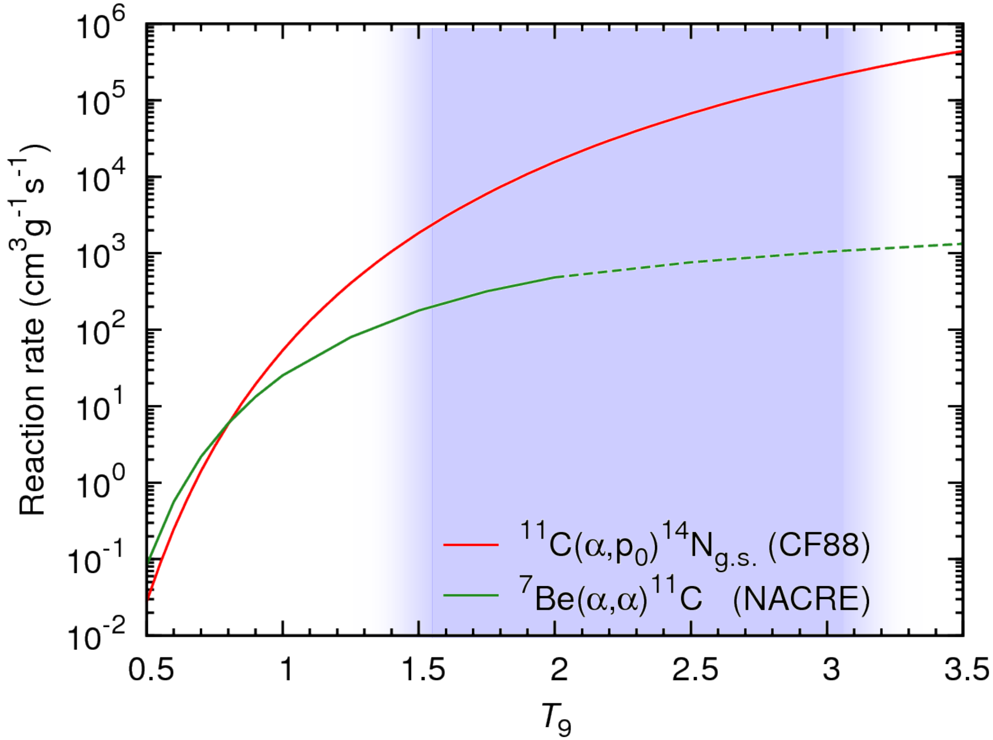
Event identification





<^{7}Be(α,γ)^{11}C> & <^{11}C(α,p)^{14}N> (current database)

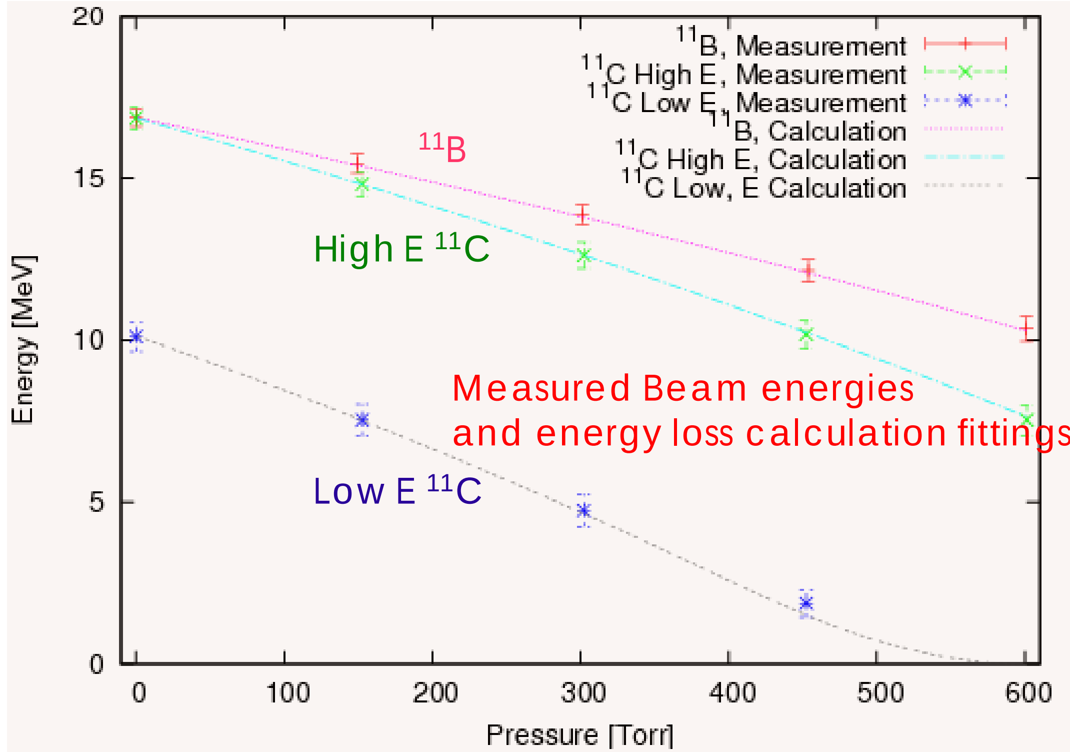


- ^{11}C(α,p)^{14}N: time-reversal reaction studies by activation method
  - Provides only (a,p$_0$) rate.
- ^{7}Be(α,γ)^{11}C: limited resonance information for only T_9 < 2 (Hardie et al. 1984)
  - ^{11}C(α,p)^{14}N could limit the rate of ^{7}Be-^{11}C-^{14}N sequence if ^{7}Be(α,γ)^{11}C ↑ and ^{11}C(α,p)^{14}N↓
  - New measurement of the ^{7}Be + α resonant scattering at CRIB

    ⇒Yamaguchi, poster session, NIC_XI_124

Summary of Beams

- Three kinds of beams
  ⇒ High E ^{11}C, Low E ^{11}C, ^{11}B
  - To cover the wide excited energy range
    (High E and Low E ^{11}C)
  - To confirm the validity of this method over the target
    (⇔ known ^{11}B(α, p) c.s.)
- Production and background runs (^{4}He, Ar)



	E_{Beam} [MeV]	ΔE_{Beam} (FWHM) [MeV] (ent. – exit)	E_{CM} range [MeV]	Purity [%]	Av. beam rate on target [pps]	^{4}He run time [hrs]	Ar run time [hrs]
High E ^{11}C	16.86	0.71 – 0.96	4.5 – 2.3	~ 100	1.0 x 10^5	28	4
Low E ^{11}C	10.12	0.92 – 1.00	2.7 – 0.0	~ 100	3.1 x 10^5	78	28
^{11}B	16.87	0.54 – 0.77	4.5 – 2.9	~ 100	2.6 x 10^5	11	6