Novae and the $^{13}N(p,\gamma)^{14}O$ reaction

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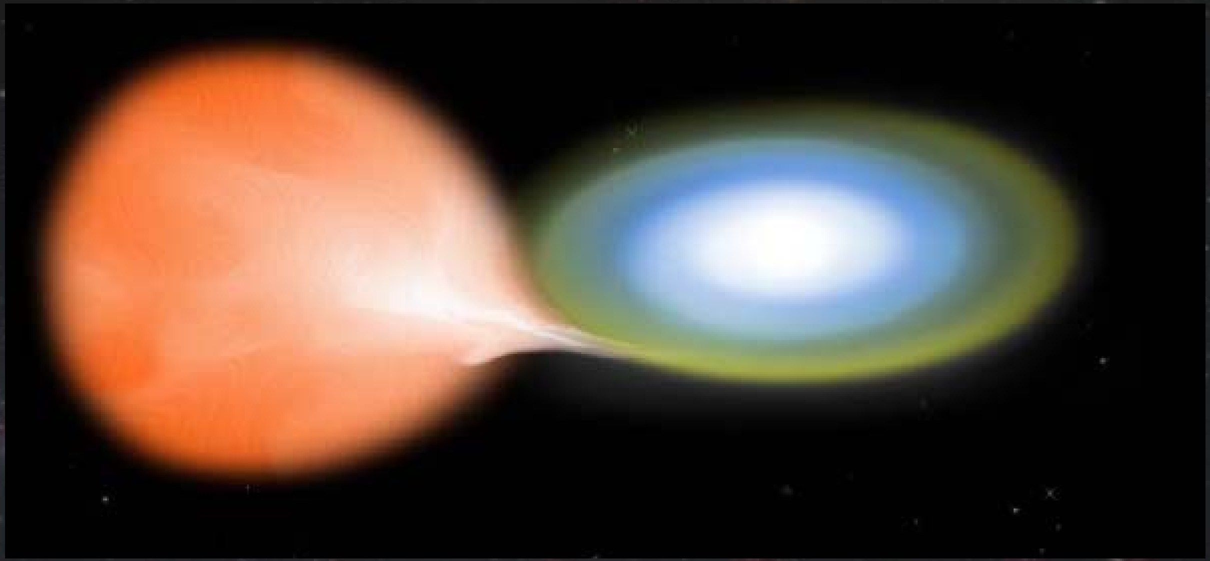
Classical Novae



- Accretion of material from companion star to the surface of a white dwarf.
- H Burning
- Outburst caused by Thermal Nuclear Runaway

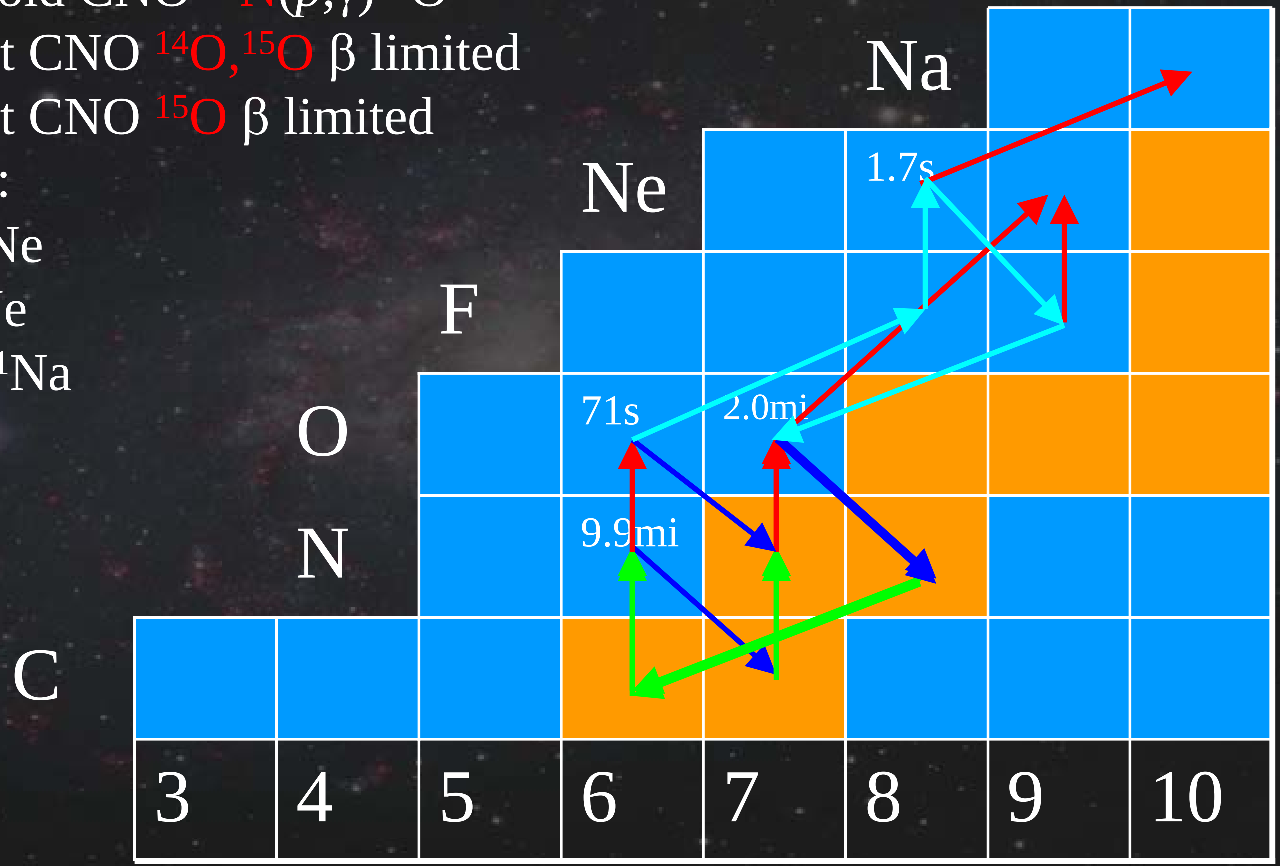
The CNO cycles in Novae

- T_9~0.02 cold CNO $^{14}N(p,\gamma)^{15}O$
- T_9~0.1 hot CNO ^{14}O,^{15}O β limited
- T_9~0.3 hot CNO ^{15}O β limited
- Breakout :

$^{15}O(\alpha,\gamma)^{19}Ne$

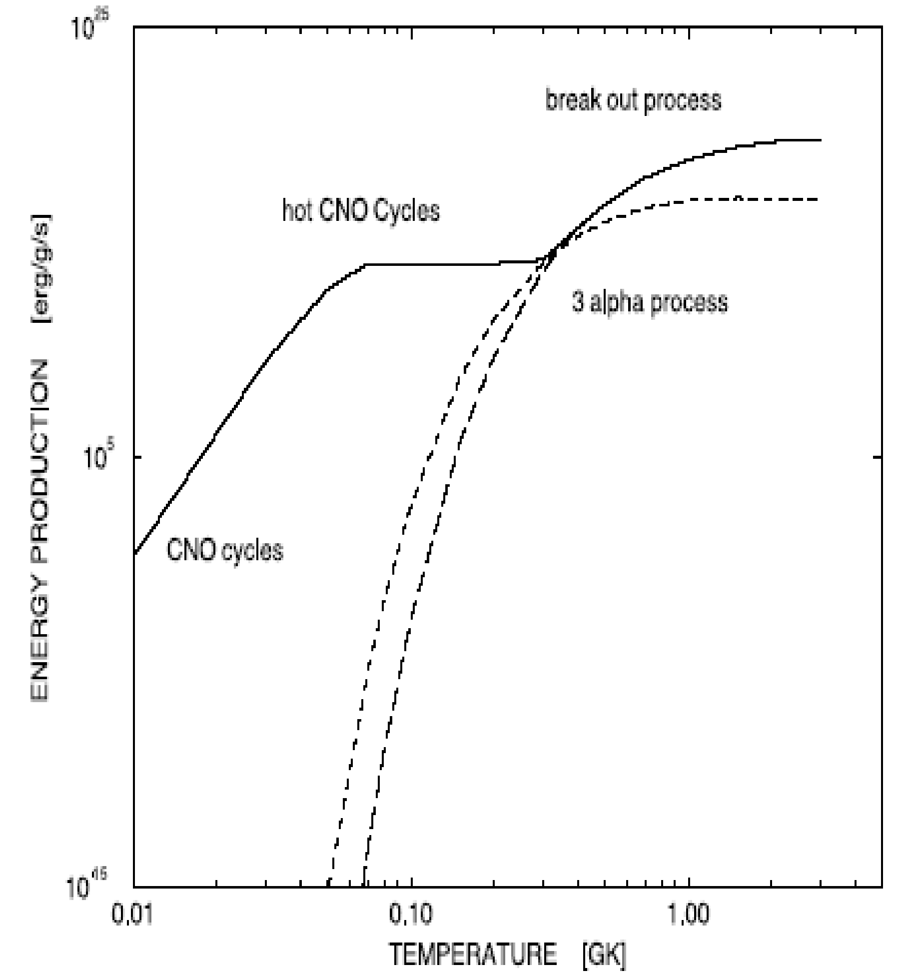
$^{18}F(p,\gamma)^{19}Ne$

$^{18}Ne(\alpha,p)^{21}Na$



For novae,T_9(peak)<0.35, no breakouts; Novae explosion is driven by hot CNO cycles.

Energy Generation Rate



- Cold CNO cycle is limited by ^{14}N(p,γ)^{15}O. (extremely temperature sensitive, rich in ^{14}N)
- Hot CNO cycle is limited by the beta decays of ^{14}O and ^{15}O. (temperature independent, rich in ^{14}O(^{14}N) and ^{15}O(^{15}N))

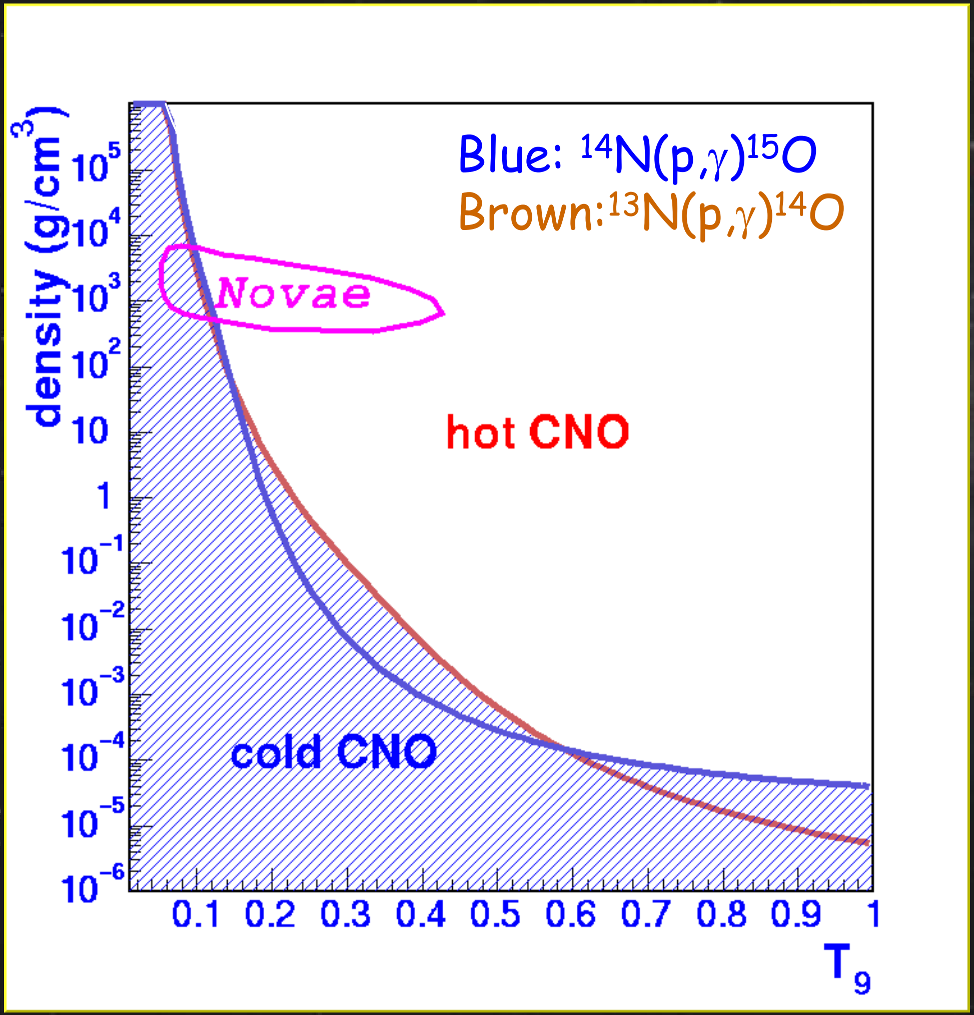
$$\varepsilon \propto <\sigma v>_{14N(p,\gamma)}$$

$$\varepsilon \propto 1/(\lambda^{-1}_{14O(\beta+)} + \lambda^{-1}_{15O(\beta+)}) = \text{const}$$

- The transition condition ^{13}N(p,γ)^{14}O,^{14}N(p,γ)^{15}O vs. the β decays of ^{14}O and ^{15}O

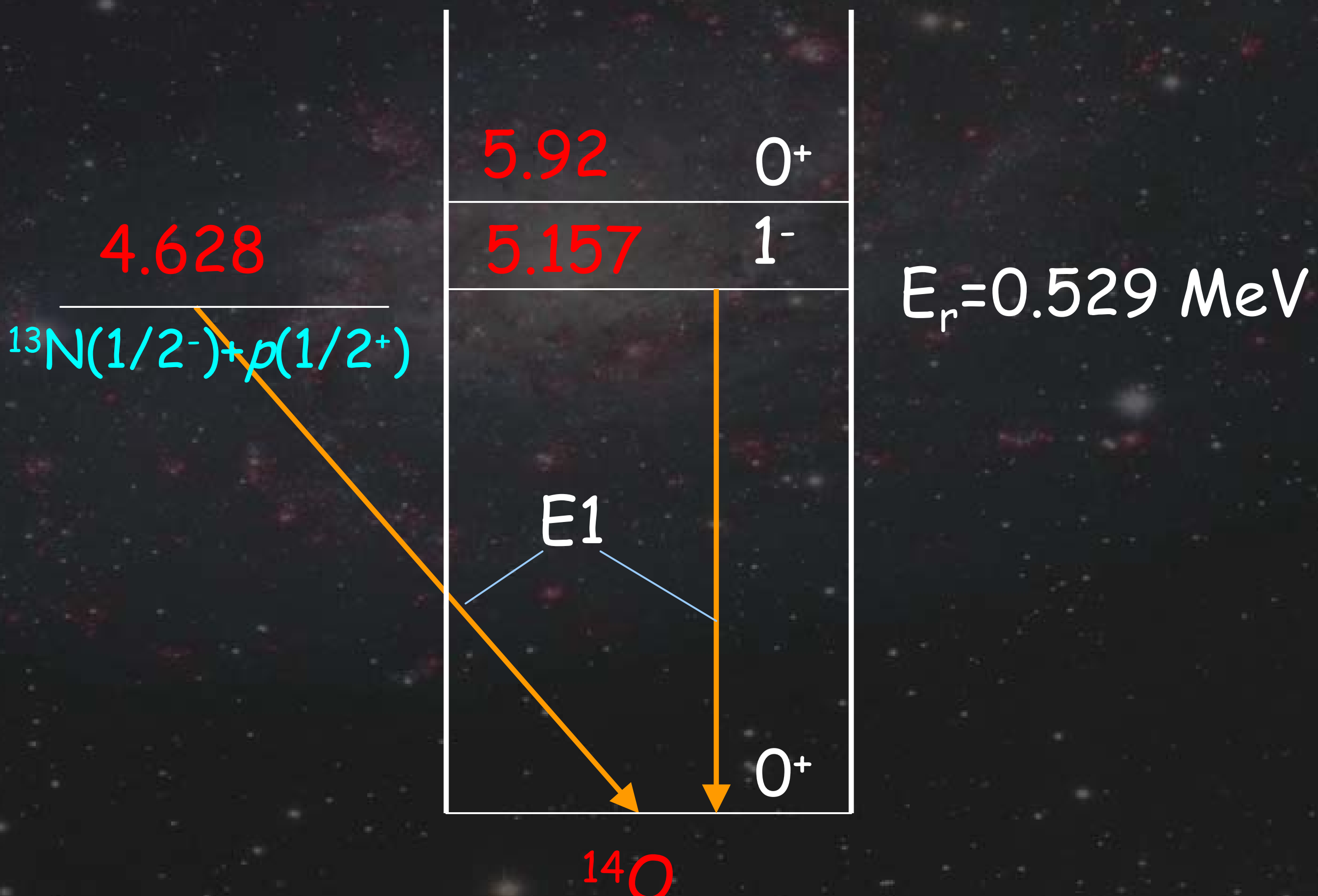
$$\rho = 1.0/[(\tau_{14} + \tau_{15}) X_H (N_A < \sigma v >_{min})]$$

The importance of $^{13}N(p,\gamma)^{14}O$

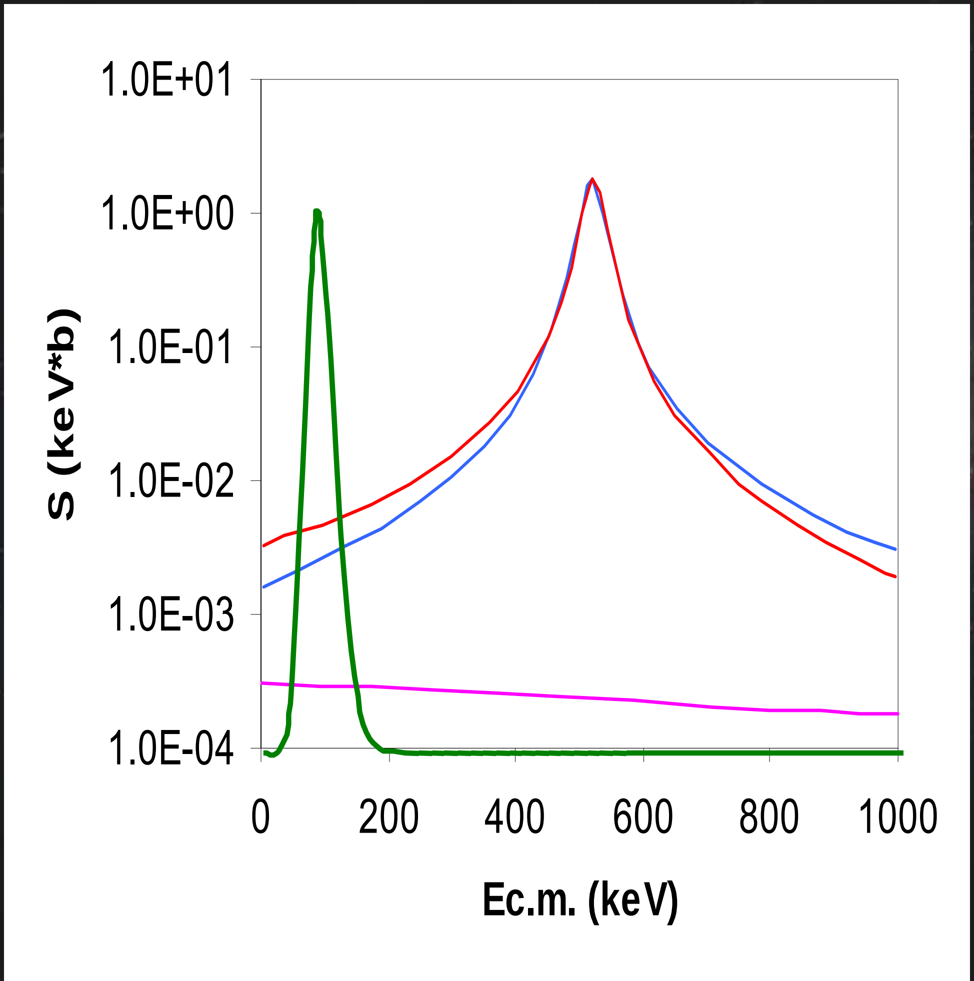


- Define the onset of hot CNO cycle (flow path)
- The rates of $^{13}N(p,\gamma)^{14}O$ and $^{14}N(p,\gamma)^{15}O$ define the transition condition for energy generation rate
- Affect nucleosynthesis and energy generation rate

^{14}O Energy Level



$^{13}N(p,\gamma)^{14}O$



P. Decrock et al., PRC48, 2057(1993)

$$\Gamma_{tot} = 37.3 \pm 0.9 keV$$

$$(^{14}N(^{3}He,t)^{14}O, p(^{13}N,p)^{13}N)$$

$$\Gamma_{\gamma} = 3.36 \pm 0.72 eV$$

$$(^{13}N(p,\gamma)^{14}O, ^{12}C(^{3}He,n\gamma)^{14}O,$$

$$^{1}H(^{14}N,^{14}O)n, ^{208}Pb(^{14}O,^{13}Np)^{208}Pb)$$

$$S = 0.90(0.23)$$

$$(^{13}N(d,n)^{14}O)$$

$^{14}N(^{13}N,^{14}O)^{13}C$

Direct Radiative Proton Capture

$$\sigma \propto |M|^2 \qquad [S(E) = Ee^{2\pi\eta}\sigma]$$

M is: $$M = \left\langle \phi_A(\xi_B, \xi_p, \xi_{Bp}) \middle| \hat{O}(r_{Bp}) \middle| \phi_B(\xi_B)\phi_p(\xi_p)\psi_i^{(+)}(r_{Bp}) \right\rangle$$

Integrate over ξ: $$M = \left\langle I_{Bp}^A(r_{Bp}) \middle| \hat{O}(r_{Bp}) \middle| \psi_i^{(+)}(r_{Bp}) \right\rangle$$

Low B.E.: $$I_{Bp}^A(r_{Bp}) \overset{r_B > R_N}{\approx} C_{Bp}^A \frac{W_{-\eta_A, l+\frac{1}{2}}(2\kappa_{Bp} r_{Bp})}{r_{Bp}}$$

Find: $$\sigma_{capture} \propto (C_{Bp}^A)^2$$

Asymptotic Normalization Constant

Peripheral Transfer Reaction

$$T_{if} = J_0 \int d\vec{r}_i \int d\vec{r}_f \, x_f^{(-)*}(k_f, r_f) F(\vec{r}_1, \vec{r}_2) x_i^{(+)}(k_i, r_i)$$

$$F(\vec{r}_1, \vec{r}_2) = \left\langle I_{Ap}^{B}(\vec{r}_2) \middle| \Delta V \middle| I_{bp}^{a}(\vec{r}_1) \right\rangle$$

Peripheral Transfer Reaction: transfer reaction happens around the surfaces of the nuclei. Matrix element mostly determined by tails. σ^{norm} is insensitive to changes of r_0,a. (**forward angle cross section**)

$$F(\vec{r}_1, \vec{r}_2) = C_{Ap}^{B} C_{bp}^{a} \frac{1}{b_{Ap}^{B}} \frac{1}{b_{bp}^{a}} \left\langle u_{Ap}^{B}(\vec{r}_2) \middle| \Delta V \middle| u_{bp}^{a}(\vec{r}_1) \right\rangle$$

σ^{exp} σ^{norm} σ^{DW}

r_0,a

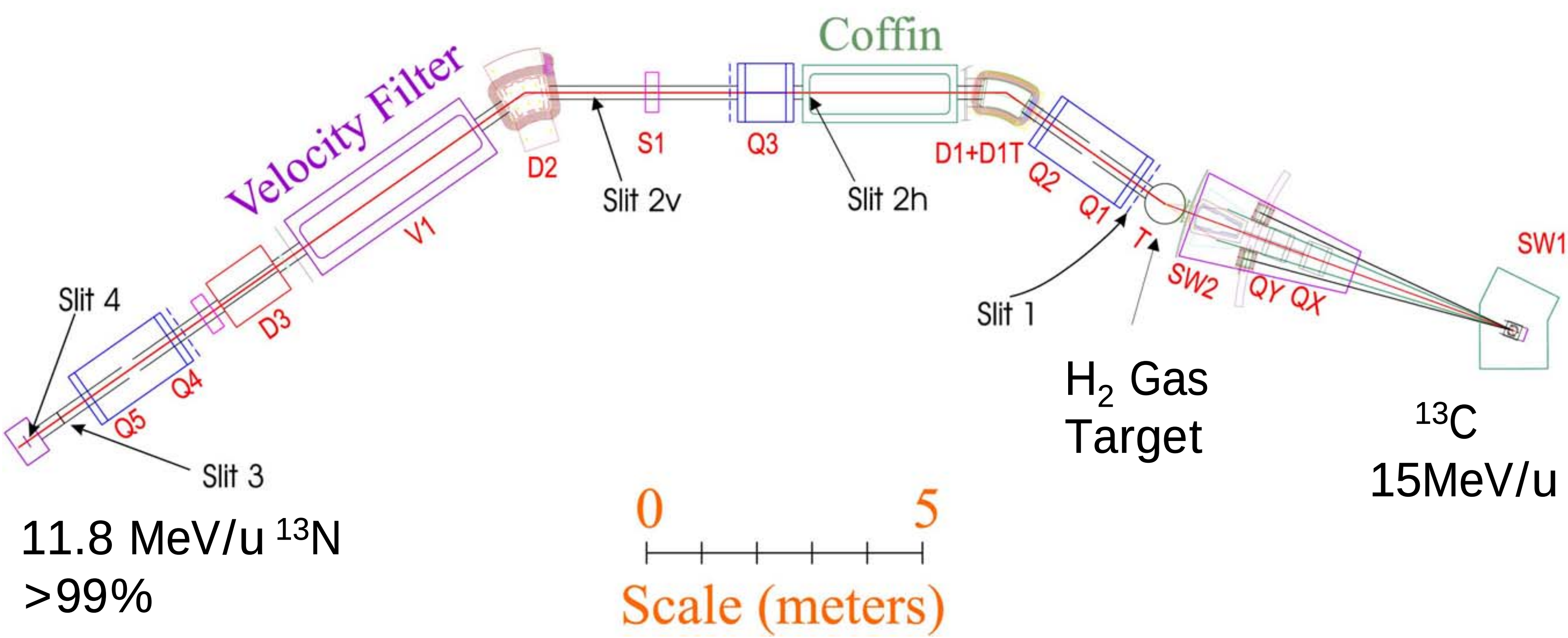
$$\sigma^{\exp} = \left(C_{Ap}^{B} C_{bp}^{a}\right)^2 \sigma^{norm} = \left(\frac{C_{Ap}^{B} C_{bp}^{a}}{b_{Ap}^{B} b_{bp}^{a}}\right)^2 \sigma^{DW}$$

From $^{14}N(^{13}N,^{14}O)^{13}C$ to $^{13}N(p,\gamma)^{14}O$

$$\sigma_{exp} = (C^{^{14}O}_{p_{1/2}})^2 \left(\left(\frac{C^{^{14}N}_{p_{1/2}}}{b^{^{14}O}_{p_{1/2}} \, b^{^{14}N}_{p_{1/2}}} \right)^2 \sigma^{DW}_{p_{1/2},p_{1/2}} + \left(\frac{C^{^{14}N}_{p_{3/2}}}{b^{^{14}O}_{p_{1/2}} \, b^{^{14}N}_{p_{3/2}}} \right)^2 \sigma^{DW}_{p_{1/2},p_{3/2}} \right),$$

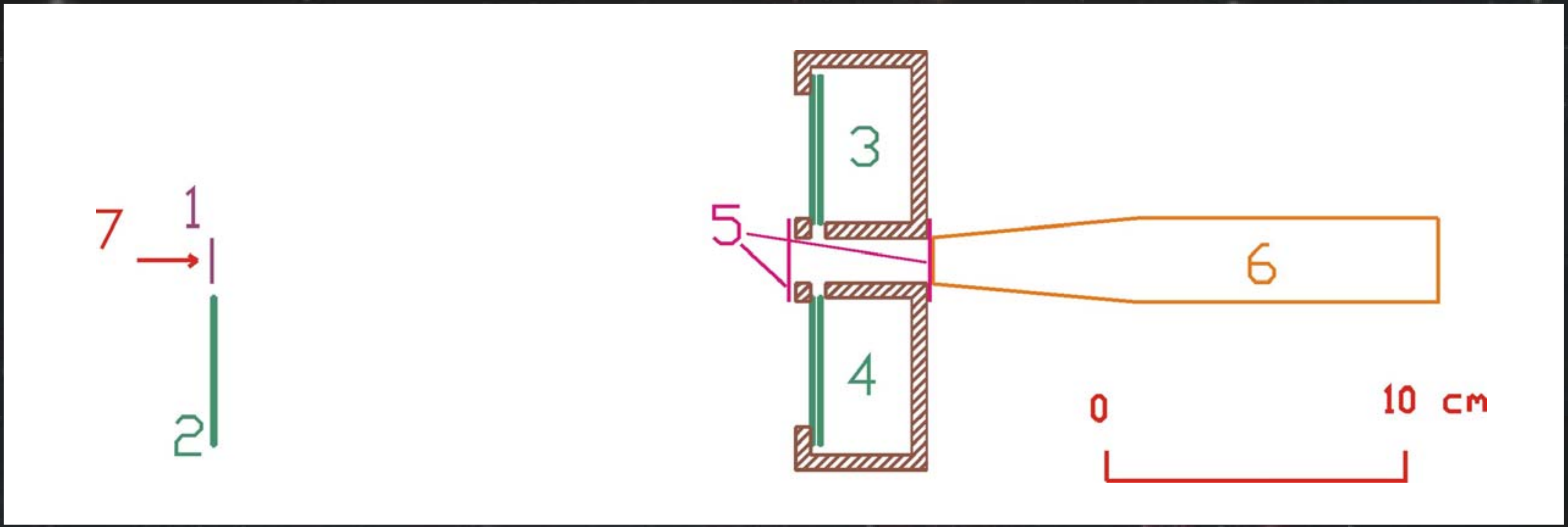
- $^{14}N(^{13}N,^{14}O)^{13}C$@10 MeV/u is peripheral transfer reaction.
- ANCs of $^{14}N(^{13}C+p)$ have been determined via $^{13}C(^{14}N,^{13}C)^{14}N$ and $^{13}C(^{3}He,d)^{14}N$
- Update direct capture contribution in $^{13}N(p,\gamma)^{14}O$ with ANCs

Momentum Achromat Recoil Separator



Primary Beam : $^{13}C^{3+}$@15 MeV/u, 600 enA
Primary Reaction : $^{13}C(^{1}H,n)^{13}N$
Secondary beam : ^{13}N
Intensity>600 kHz, PURITY>99%
E=11.8 MeV/u, ΔE=2.3 MeV (FWHM)
ΔX=3 mm (FWHM), ΔY=3.2 mm (FWHM)
$\Delta\theta$=1.8 deg(FW), $\Delta\phi$=1.9 deg (FW)

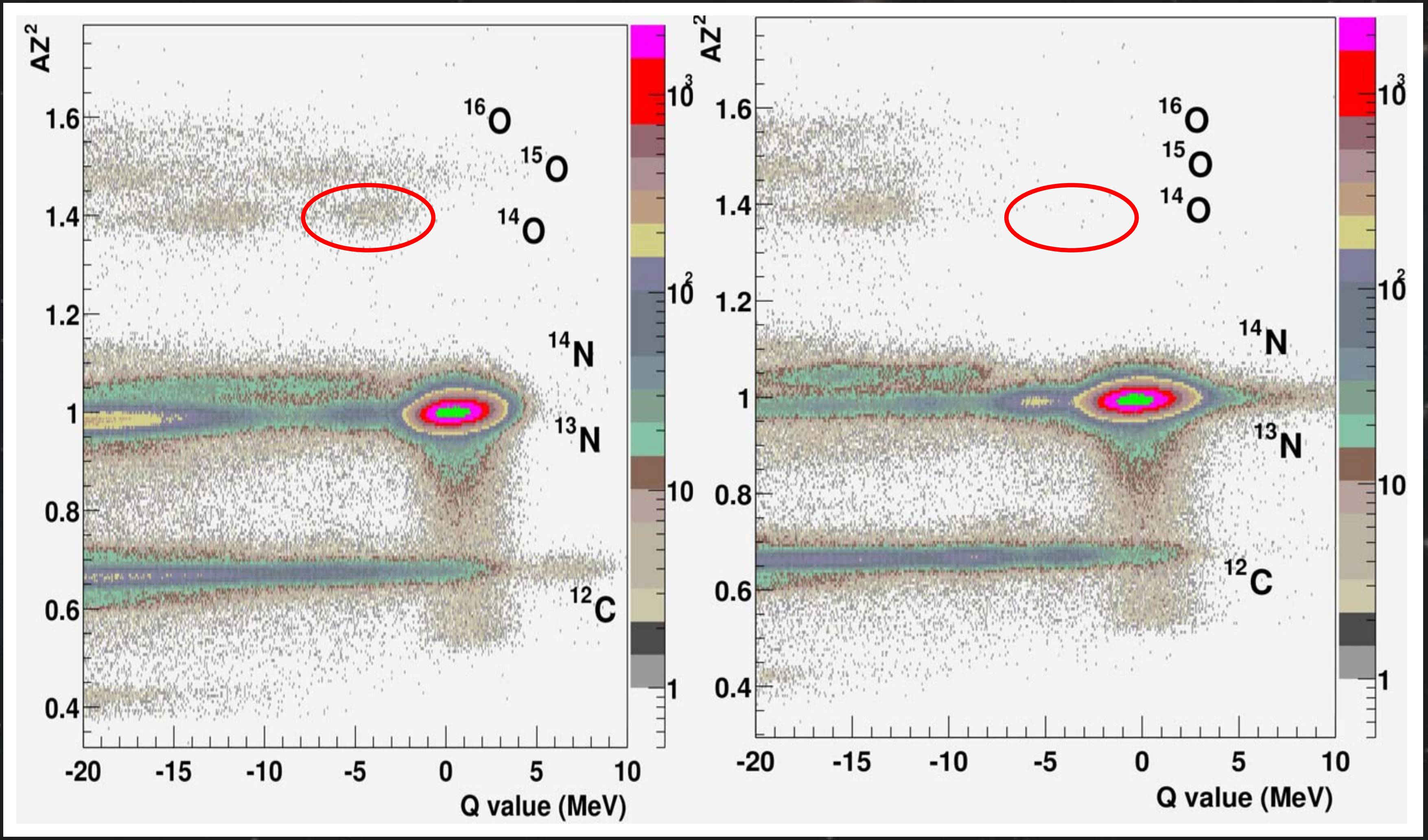
Detector System



•Target:
melamine ($C_3H_6N_6$) 1.5 mg/cm^2
•Detector: (D-T: 200 mm, T1-T2: 28 mm)
70um(16 strip)+500um Si detector
(4 deg< θ_{lab} < 17 deg, 7.6 deg < θ_{cm}<32.4 deg)
25*15 mm scintillator with double screens (1.53%, 6.5 kHz)

(1) target (2) target detector
(3,4) telescope 1,2 (5) screen
(6) scintillator (7) ^{13}N beam

PID vs. Q value (^{13}N)

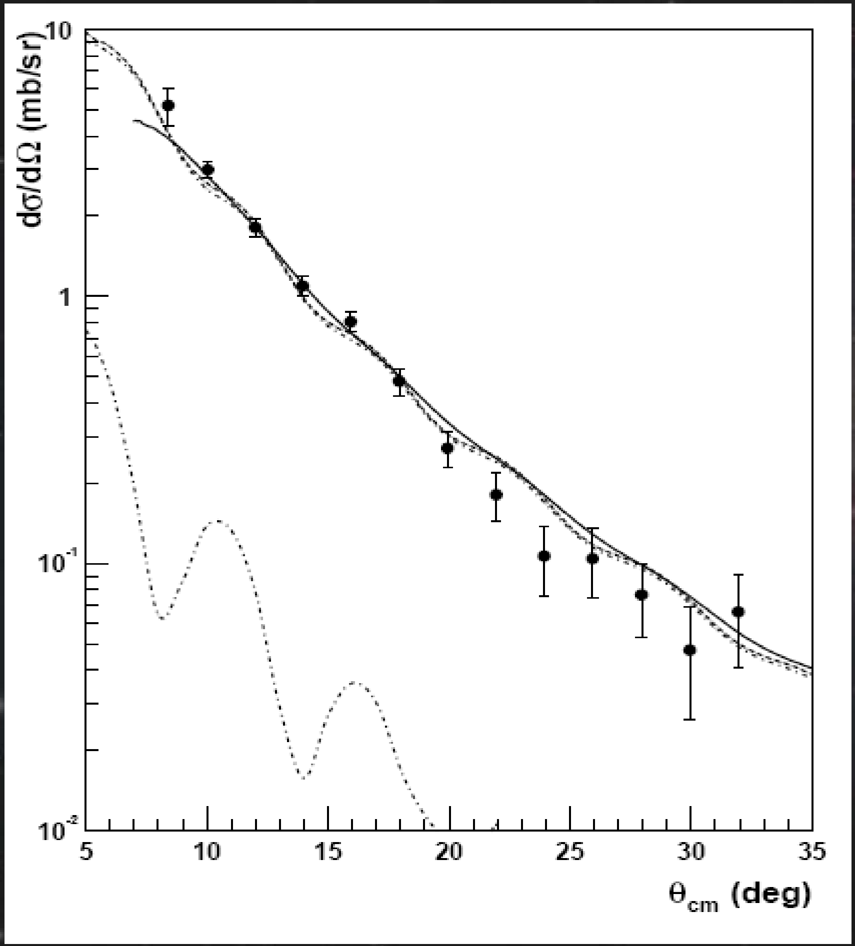


Melamine($C_3H_6N_6$)

^{12}C(w Ta contamination)

$^{14}N(^{13}N,^{14}O)^{13}C$

(ANC for $^{14}O \rightarrow ^{13}N + p$)

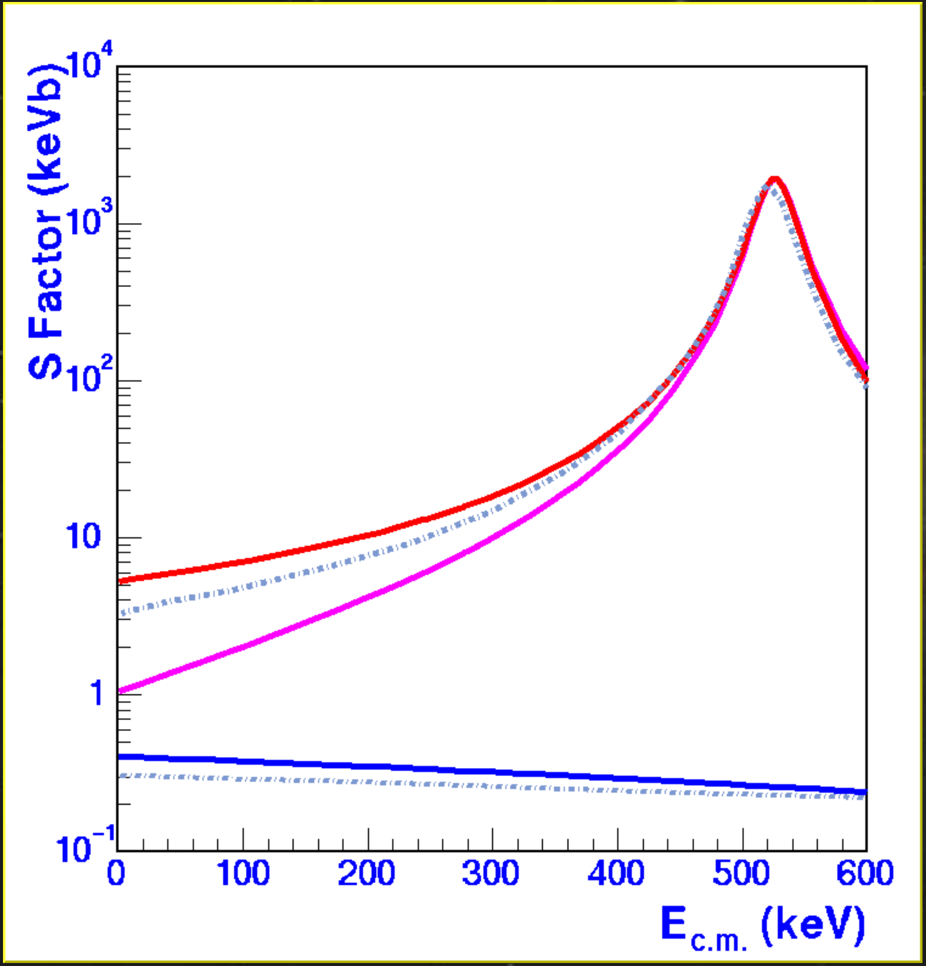


$$\sigma_{exp} = (C^{^{14}O}_{p_{1/2}})^2 \left(\left(\frac{C^{^{14}N}_{p_{1/2}}}{b^{^{14}O}_{p_{1/2}} \, b^{^{14}N}_{p_{1/2}}} \right)^2 \sigma^{DW}_{p_{1/2},p_{1/2}} + \left(\frac{C^{^{14}N}_{p_{3/2}}}{b^{^{14}O}_{p_{1/2}} \, b^{^{14}N}_{p_{3/2}}} \right)^2 \sigma^{DW}_{p_{1/2},p_{3/2}} \right),$$

$$\left(C^{^{14}O}_{^{13}N \frac{1}{2}} \right)^2 = 29 \pm 4.3 \ fm^{-1}$$

DWBA by PTOLEMY and FRESCO (5% difference)

S Factor for $^{13}N(p,\gamma)^{14}O$

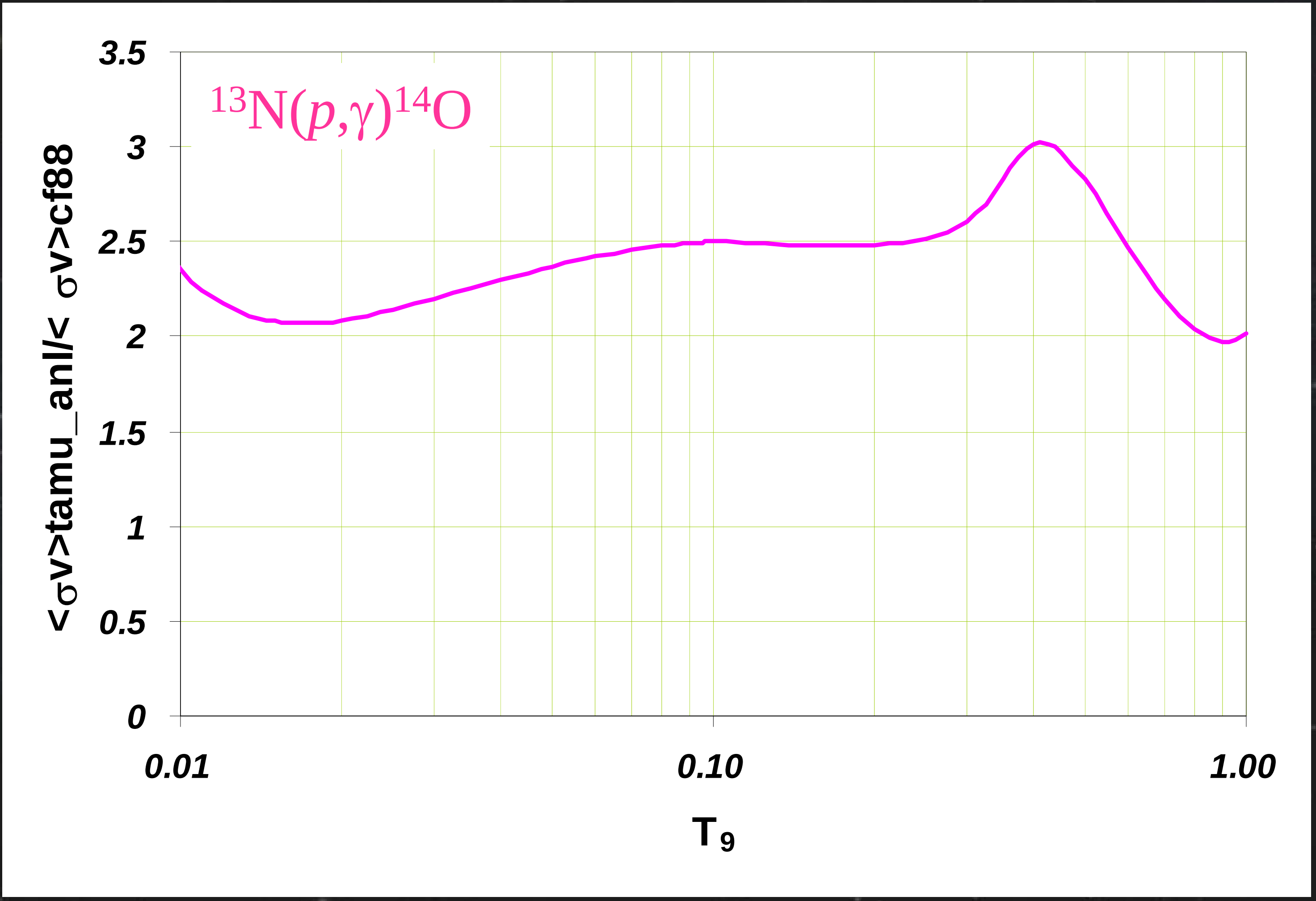


For Gamow peak at T_9=0.1,

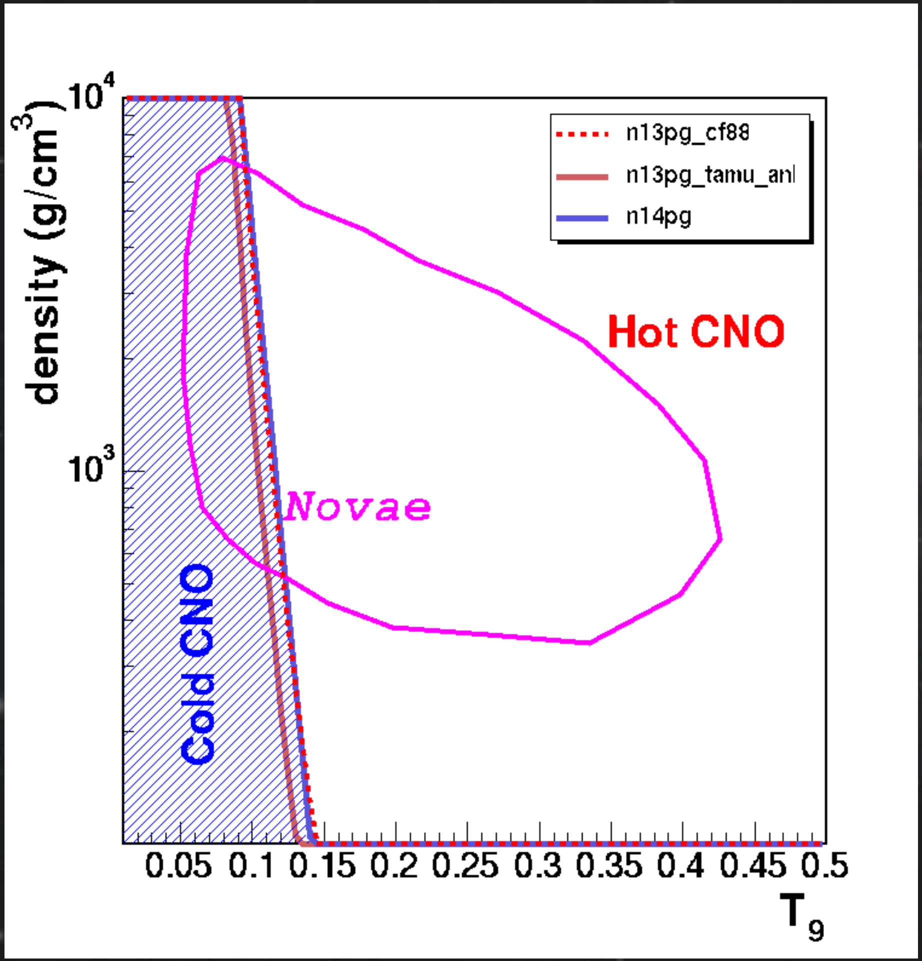
- DC/Decrock_dc = 1.4
- Constructive/Decrock_tot
- =1.4
- Constructive/Destructive =4.0
  (expected constructive interference for lower energy tail, useful to check)

The sign of the interference can be checked with direct measurement of $^{13}N(p,\gamma)^{14}O$ at high energy side.

New Rate vs. Reaclib



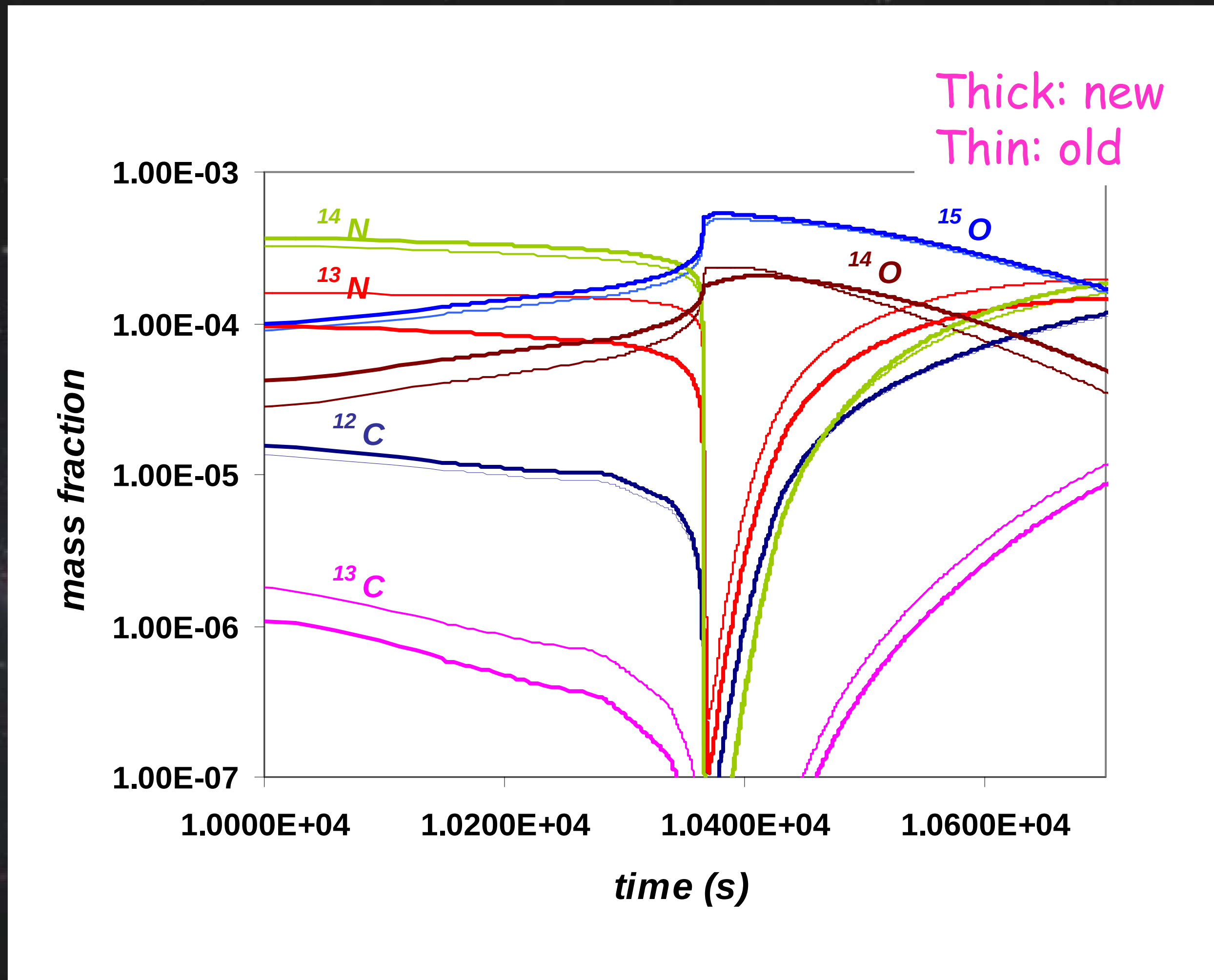
Updated transition condition



- With higher $^{13}N(p,\gamma)^{14}O$ reaction rate, the hot CNO can operate at lower temperature.

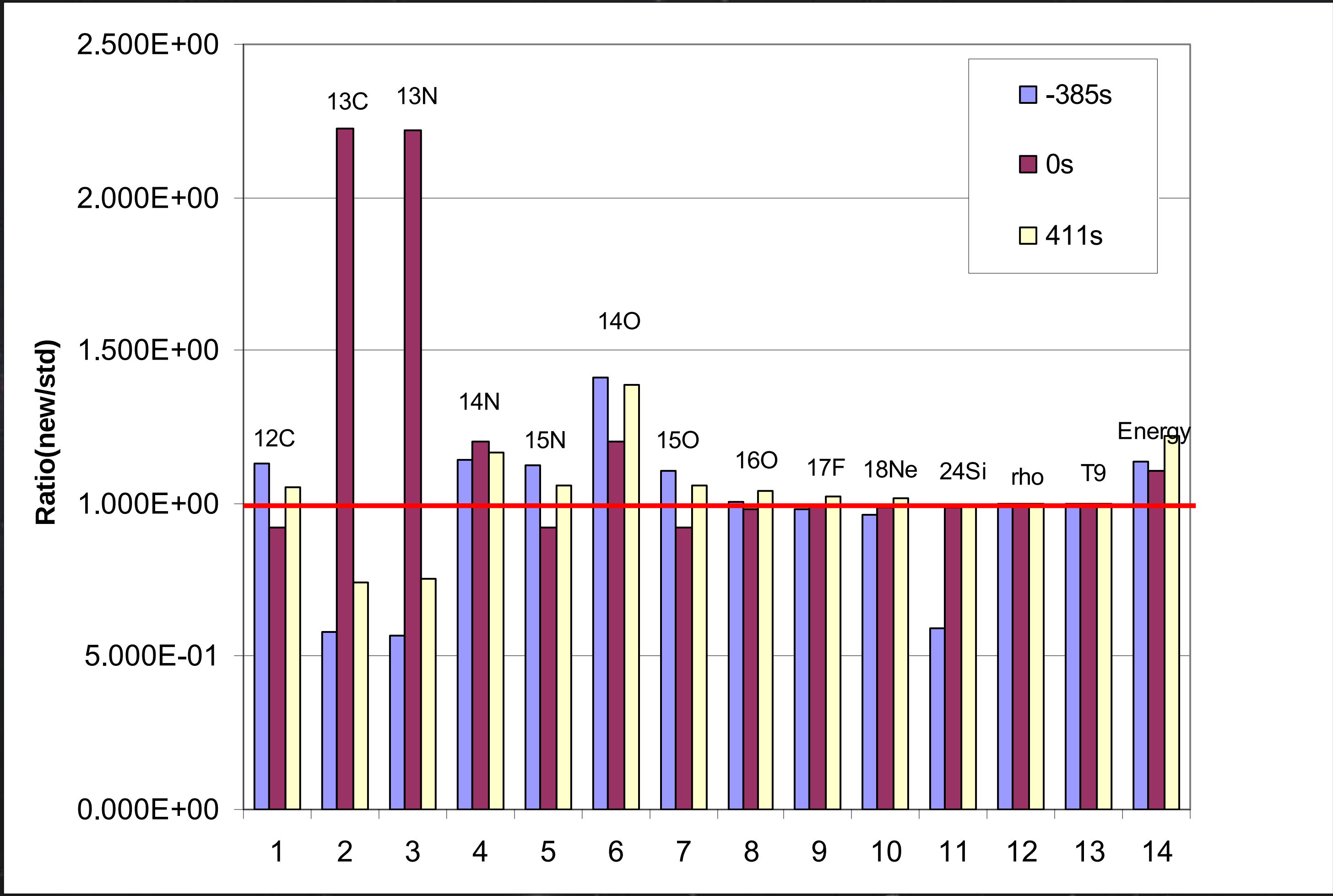
- The transition of energy generation rate is controlled by the slower proton capture reaction $^{14}N(p,\gamma)^{15}O$. (Latest $^{14}N(p,\gamma)^{15}O$ rate is slightly less than NACRE compilation)

One Zone Novae Model



^{14}N, ^{14}O, ^{12}C
^{13}C, ^{13}N

Effects On Nucleosyntheis



Conclusion

- The reaction rate of $^{13}N(p,\gamma)^{14}O$ has been updated. The new rate is about a factor of 2.5 times higher than reaclib rate. Details are available in PRC 69 (2004) 055807.

- For novae, with higher $^{13}N(p,\gamma)^{14}O$, hot CNO cycles can operate at lower temperature. However, the transition of the energy generation rate is still controlled by the slower reaction $^{14}N(p,\gamma)^{15}O$.

- With a one zone model, some abundance changes were found for CNO nuclei, such as ^{14}O, ^{15}O, ^{13}N, ^{13}C and ^{12}C.

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