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Hydrogen burning on Nitrogen isotopes in CNO and HCNO-cycles

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The role of the $p{}^{12\text{-}15}\mathrm{N}$ reactions in the CNO cycle

${}^{12}\mathrm{N}(p,\gamma){}^{13}\mathrm{O}$ - Exotic part of CNO cycle

${}^{13}\mathrm{N}(p,\gamma){}^{14}\mathrm{O}$ - Production, **hot** CNO only

${}^{14}\mathrm{N}(p,\gamma){}^{15}\mathrm{O}$ - Production, **hot** and **cold** CNO.
The slowest in **cold** CNO

${}^{15}\mathrm{N}(p,\gamma){}^{16}\mathrm{O}$ - Production, **hot** CNO only.
The main branching point
between **hot** and **cold** CNO

$\ldots{}^{11}\mathrm{C}(p,\gamma){}^{12}\mathrm{N}(p,\gamma){}^{13}\mathrm{O}(\beta^{+}){}^{13}\mathrm{N}\ldots$ [89%] or

$\ldots{}^{11}\mathrm{C}(p,\gamma){}^{12}\mathrm{N}(p,\gamma){}^{13}\mathrm{O}(\beta^{+}, p){}^{12}\mathrm{C}$ [11%]…

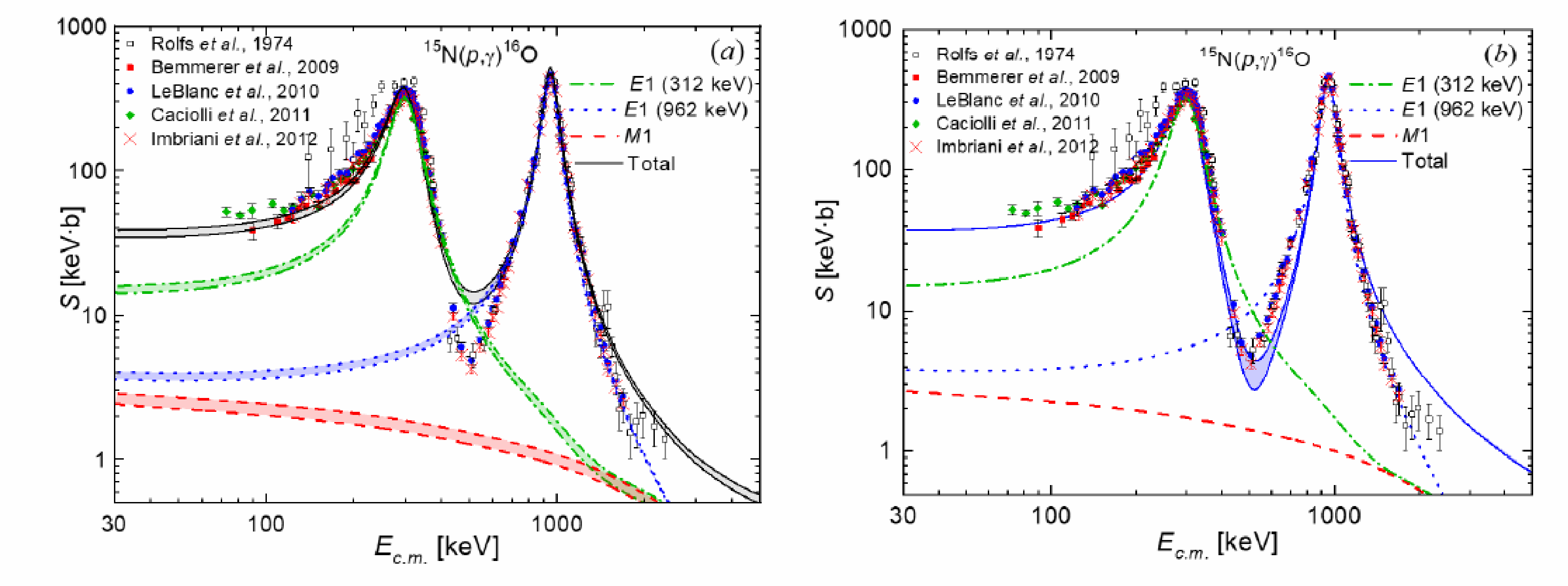
${}^{12}\mathrm{C}(p,\gamma){}^{13}\mathrm{N}(p,\gamma){}^{14}\mathrm{O}(\beta^{+}\nu){}^{14}\mathrm{N}(p,\gamma){}^{15}\mathrm{O}(\beta^{+}\nu){}^{15}\mathrm{N}(p,\alpha){}^{12}\mathrm{C}$

${}^{12}\mathrm{C}(p,\gamma){}^{13}\mathrm{N}(\beta^{+}\nu){}^{13}\mathrm{C}(p,\gamma){}^{14}\mathrm{N}(p,\gamma){}^{15}\mathrm{O}(\beta^{+}\nu){}^{15}\mathrm{N}(p,\alpha){}^{12}\mathrm{C}$

${}^{16}\mathrm{O}(p,\gamma){}^{17}\mathrm{F}(\beta^{+}\nu){}^{17}\mathrm{O}(p,\alpha){}^{14}\mathrm{N}(p,\gamma){}^{15}\mathrm{O}(\beta^{+}\nu){}^{15}\mathrm{N}(p,\gamma){}^{16}\mathrm{O}$

${}^{17}\mathrm{O}(p,\gamma){}^{18}\mathrm{F}(\beta^{+}\nu){}^{18}\mathrm{O}(p,\alpha){}^{15}\mathrm{N}(p,\gamma){}^{16}\mathrm{O}(\beta^{+}\nu){}^{17}\mathrm{F}(\beta^{+}\nu){}^{17}\mathrm{O}$

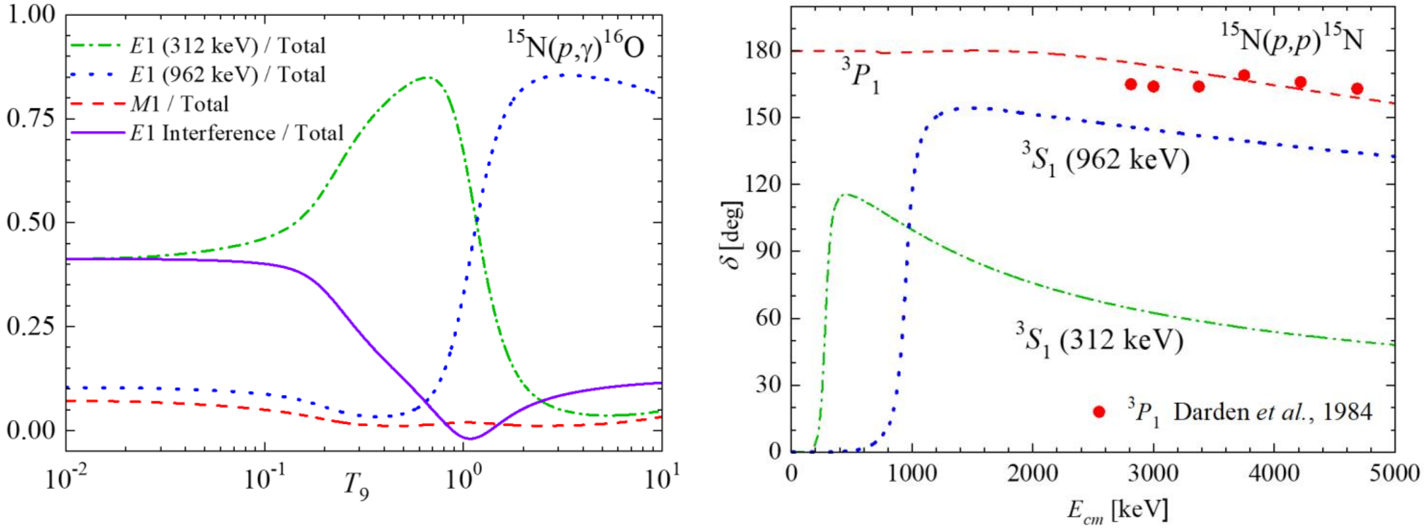
Astrophysical *S*-factor of $^{15}N(p,\gamma_{G.S.})^{16}O$



The astrophysical *S*-factor of radiative $p^{15}N$ capture on the ground state of ^{16}O.
(*a*) Present calculation in the **Modified Potential Cluster Model (MPCM).**
(*b*) Modeling of *S*-waves interference based on the Breit-Wigner fit of resonance phase shifts [1].

[1] S. B. Dubovichenko et. al., arXiv:2303.14680v2 [nucl-th]

^{15}N(p,γ)^{16}O reaction rate



$$\sigma_{E1}(E_{cm}) \sim \left|I(k,E1)\right|^2,$$

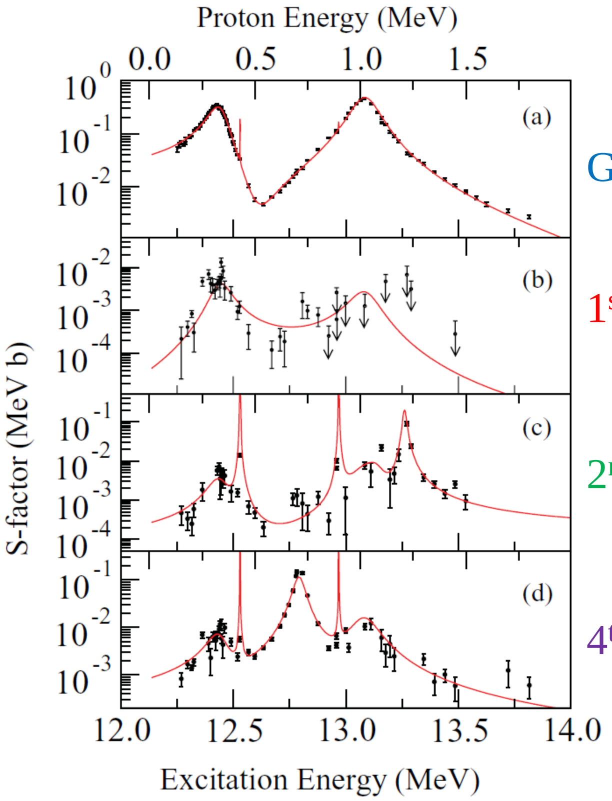
$$\left|I(k,E1)\right|^2 = \left|I_1\right|^2 + \left|I_2\right|^2 +$$

$$+2\cos\left(\delta_{{}^3S_1(312)} - \delta_{{}^3S_1(962)}\right) I_1 I_2$$

The dependence of the reaction rate of the ^{15}N(p,γ)^{16}O radiative capture on astrophysical temperature. The solid curve presents our calculations for the sum of $E1$ and $M1$ transitions. The inset shows the fractional contributions of the reaction rates from the $^3S_1$ resonances at **312 keV** and **962 keV**, **and non-resonance transition $^3P_1 \rightarrow {}^3P_0$** with respect to the reaction rate of ^{15}N(p,γ)^{16}O, as a function of astrophysical temperature. The resonances are identified with the c.m. energy in keV.

S.E. Darden, *et al.*, Nucl. Phys. A 429, 218 (1984).

The impact of the cascade transitions



GS, $^{15}N(p,\gamma_0)^{16}O$

1st ES, $^{15}N(p,\gamma_{(6.050)})^{16}O$,

2nd ES, $^{15}N(p,\gamma_{(6.130)})^{16}O$

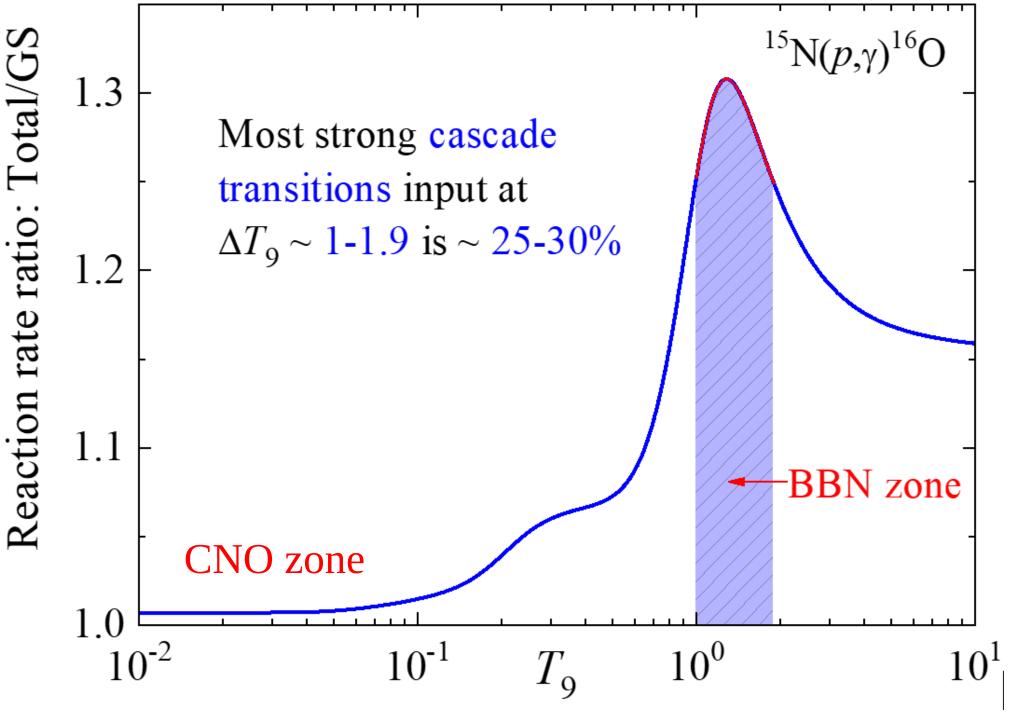
4th ES, $^{15}N(p,\gamma_{(7.117)})^{16}O$

Simultaneous fits to the data of Ref. [1].

E_x, MeV	J^π	Resonances
12.445	1^-	GS and 1st, 2nd and 4th ESs
12.530	2^-	2nd and 4th ESs
12.796	0^-	4th ES
12.9686	2^-	2nd and 4th ESs
13.090	1^-	GS and 1st, 2nd and 4th ESs
13.142	3^-	2nd ES
13.265	3^-	2nd ES

[1] G. Imbriani, *et al.*, Measurement of γ rays from $^{15}N(p,\gamma)^{16}O$ cascade and $^{15}N(p,\alpha_1)^{12}C$. Phys. Rev. C 85, 065810 (2012).

The impact of the **cascade transitions**

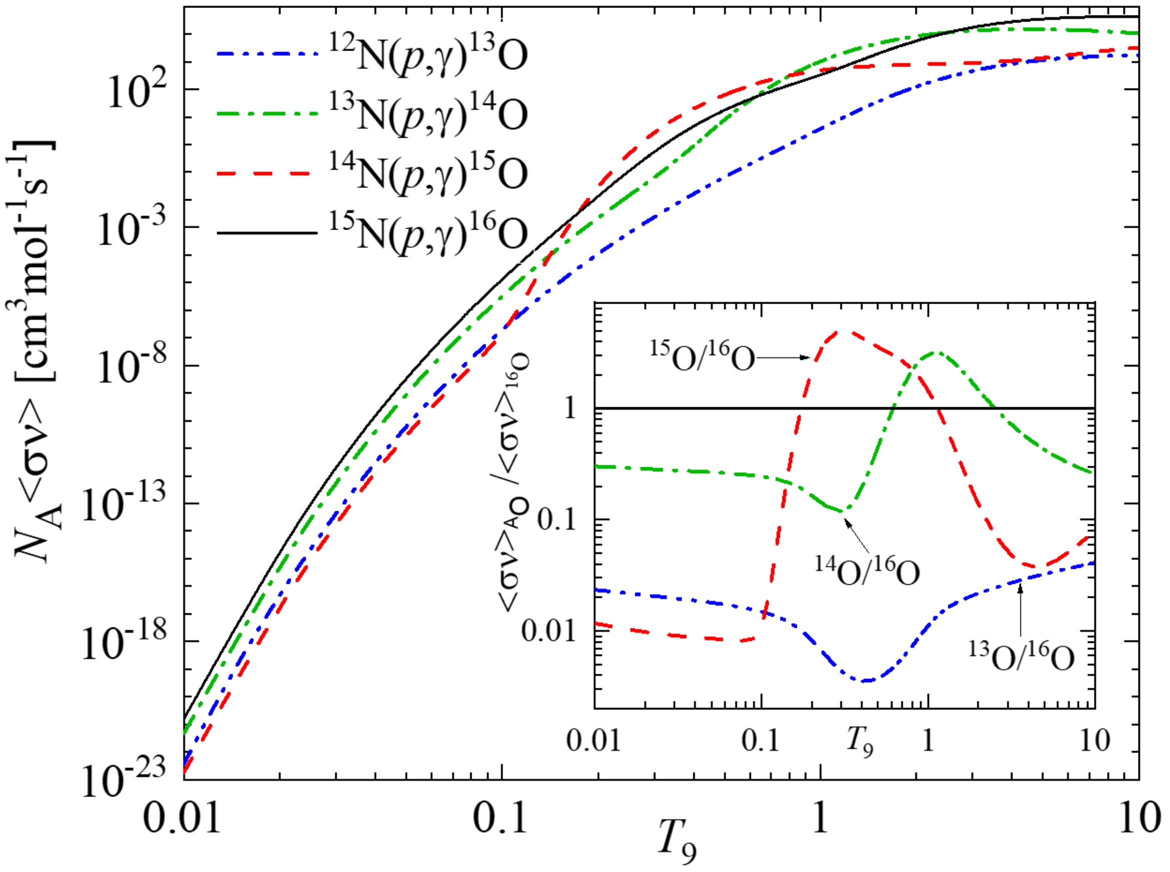


The dependence of the ratio of the total reaction rate which is the sum of contributions from the GS and cascade transitions **$^{15}N(p,\gamma_{(6.050)})^{16}O$**, **$^{15}N(p,\gamma_{(6.130)})^{16}O$**, and **$^{15}N(p,\gamma_{(7.117)})^{16}O$** and the reaction rate for the GS transitions on temperature.

In calculations are used the experimental data reported in Ref. [1].

[1] G. Imbriani, *et al.*, Measurement of γ rays from $^{15}N(p,\gamma)^{16}O$ cascade and $^{15}N(p,\alpha_1)^{12}C$. Phys. Rev. C 85, 065810 (2012).

Reaction rates for proton capture reactions on nitrogen isotopes

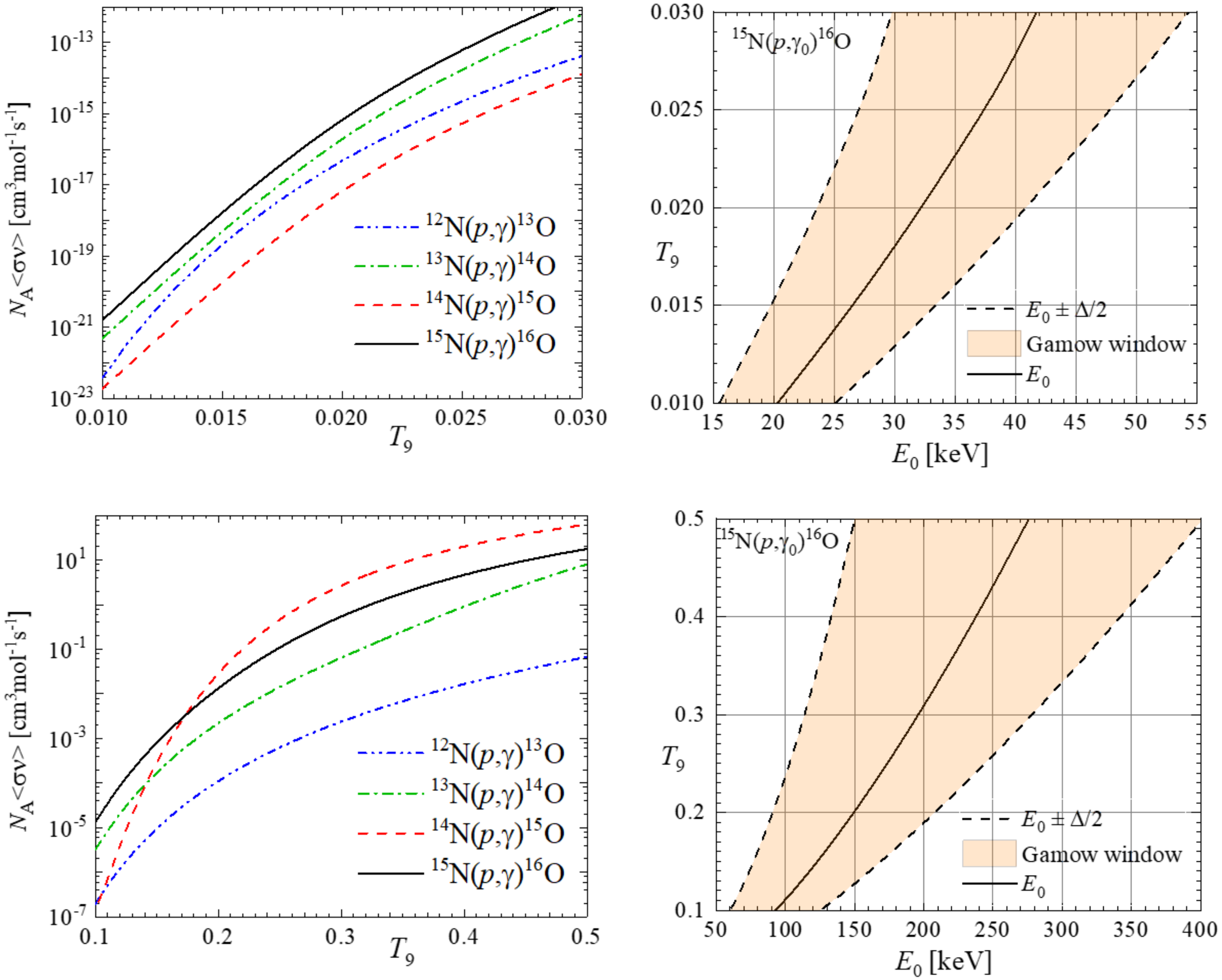


The reaction rates of the radiative proton capture on nitrogen isotopes leading to the production of oxygen isotopes as a function of astrophysical temperature.

The insert shows the fractional contributions from **$^{12}\mathrm{N}(p,\gamma)^{13}\mathrm{O}$ [1]**, **$^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}$ [2]**, **$^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$ [3]** with respect to the **$^{15}\mathrm{N}(p,\gamma)^{16}\mathrm{O}$** reaction rate as a function of astrophysical temperature.

[1] S. B. Dubovichenko et. al., Nucl. Phys. A 1028, 122543 (2022).
[2] S. B. Dubovichenko et al., Phys. Rev. C 102, 045805 (2020).
[3] S. B. Dubovichenko et. al., Int. J. Mod. Phys. E 29, 1930007 (2020).

The reactions rates and **Gamow range ΔE_G**



(*left panels*) Dependencies of reaction rates of the radiative proton capture on nitrogen isotopes on astrophysical temperature.
(*right panels*) The stellar temperatures as a function of the Gamow energy.

Gamow peak energy:

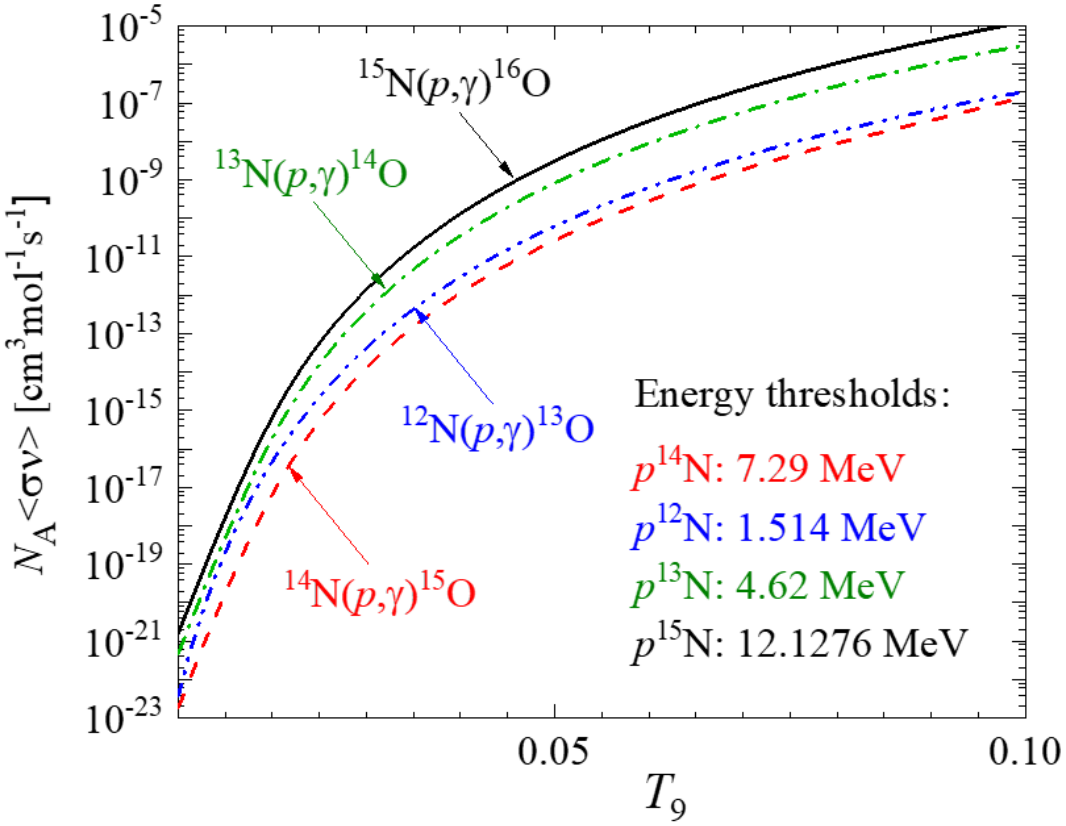
$$E_0 = \left[\frac{\pi^2}{\hbar^2}\left(Z_1 Z_2 e^2\right)^2 \frac{\mu}{2}\left(k_B T\right)^2\right]^{\frac{1}{3}}$$

$$E_0 = 466.4353\left[\mu T_9^2\right]^{\frac{1}{3}}$$

Gamow range E_G (in keV) around the Gamow energy E_0

$$\Delta E_G = 452.9821\left[\mu T_9^5\right]^{\frac{1}{6}}$$

Correlation between **threshold energies E_{th}** and the reaction rate



Correlation between the **threshold energies E_{th}** in the nitrogen channels and reaction rates at ultra-low T_9 is observed:

the higher E_{th}, the higher the reaction rate.

$E_{th}(p^{15}N) > E_{th}(p^{13}N) > E_{th}(p^{12}N)$

Exception $^{14}N(p,\gamma)^{15}O$

Due to $E2$ capture contrary $E1$ in other channels

Conclusion and prospects

^{15}N(p,γ)^{16}O:

- The interference of $^3S_1$(312) and $^3S_1$ (962) resonances leads to the significant increase of S-factor at the energies up to 300 keV.
- The strong interference effect of 1^- resonance states is demonstrated for reaction rate at CNO relevant temperatures $T_9 < 0.1$.
- Cascade transitions show minor role for standard and stellar CNO cycles.
- To evaluate the impact of cascade transitions the model calculations for the interference of 2^- and 3^- states are of strong demand.

^{12}N(p,γ)^{13}O, ^{13}N(p,γ)^{14}O, ^{14}N(p,γ)^{15}O, and ^{15}N(p,γ)^{16}O:

- The regularity of the energy thresholds and low-temperature reaction rates is observed: the higher E_{th}, the higher the reaction rate.
- The search of this regularity for the Li, Be, B, C isotopes is of practical interest.
- The extension of MPCM model on the 2s-1d nuclei is the future goal.

Thank you for attention!