Investigation of nuclear levels to improve the predictions of astrophysical neutron-capture reaction rate

Young Researchers and Young Engineers Days

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Outline

1. Verification of available nuclear level density for reaction calculation

- Systematic comparison of experimental results and calculations for unstable nuclei (β–Oslo data)
  - Improve the nuclear structure model (NLD) and determine the best one
- NLD impact on (n,γ) cross section

2. Impact of level scheme to nuclear reaction calculation

- Comparison of the calculation from experimental levels + NLD and from pure NLD
  - Improve the reaction model by including the contributions from “resolved” resonances extracted from NLD

3. Identify the effective energy of NLD

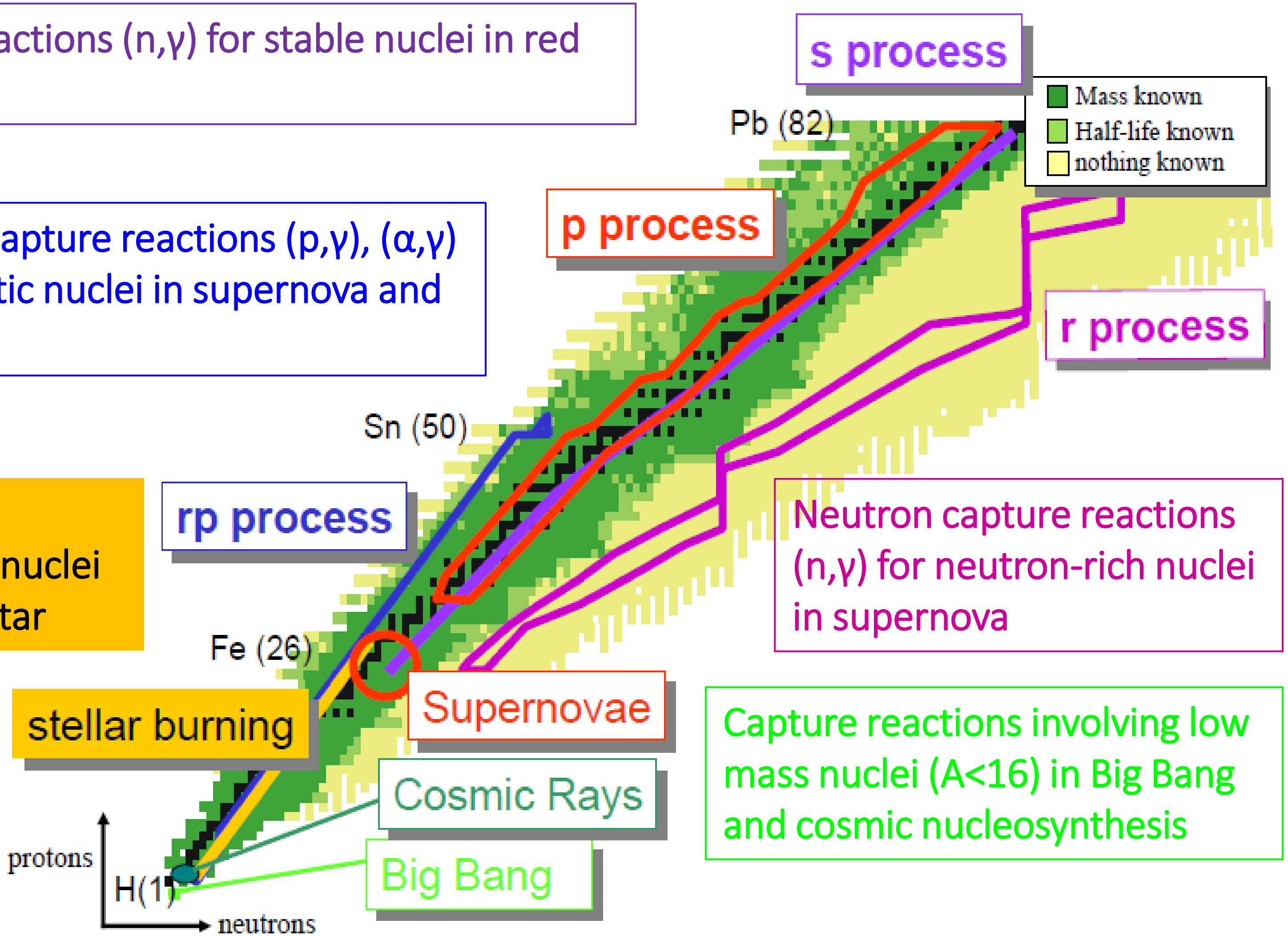
- Perform sensitivity study of cross section to NLD in different energy range
  - Guide future measurements of NLD

Background - astrophysical consideration

Neutron capture reactions (n,γ) for stable nuclei in red (super)giant star

Charged-particles capture reactions (p,γ), (α,γ) for proton-rich exotic nuclei in supernova and dwarf star

Capture reactions involving low mass nuclei in main sequence star



Neutron capture reactions (n,γ) for neutron-rich nuclei in supernova

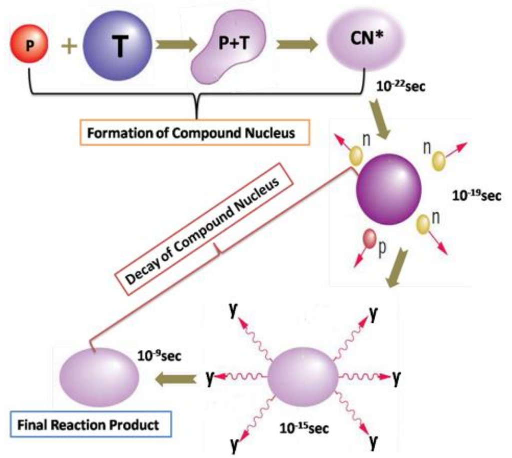
Capture reactions involving low mass nuclei (A<16) in Big Bang and cosmic nucleosynthesis

Figure taken from: H Grawe, K Langanke, and G Martinez-Pinedo, Reports on Progress in Physics (2007) 70 9

Background - reaction model

Hauser-Feshbach formalism of $\sigma_{(n,\gamma)}$

$$\sigma^{CNC}_{A+n\rightarrow B^x+Y} = \frac{\pi}{k^2}\sum_{J=mod(I_A+I_n,1)}^{l_{max}+I_A+I_n}\sum_{\Pi=-1}^{1}\frac{2J+1}{(2I_A+1)(2I_n+1)}\times\sum_{J_p=|J-J_A|}^{J+I_A}\sum_{l_i=|J_n-I_n|}^{J_n+I_n}\sum_{\lambda=|J-I_B^x|}^{J+I_B^x}\sum_{l_f=|\lambda-I_\gamma|}^{\lambda+I_\gamma}\delta^{\pi}_{C_n}\delta^{\pi}_{C_\gamma}$$
$$\times\frac{\langle T^J_{C_n,l_i,J_n}(E)\rangle\langle T^J_{C_\gamma,l_f,\lambda}(E_\gamma)\rangle}{\sum_{Clj}\delta^{\pi}_{C}\langle T^J_{C,l,j}(E_C)\rangle}W^J_{C_nl_iJ_nC_\gamma l_f\lambda}$$

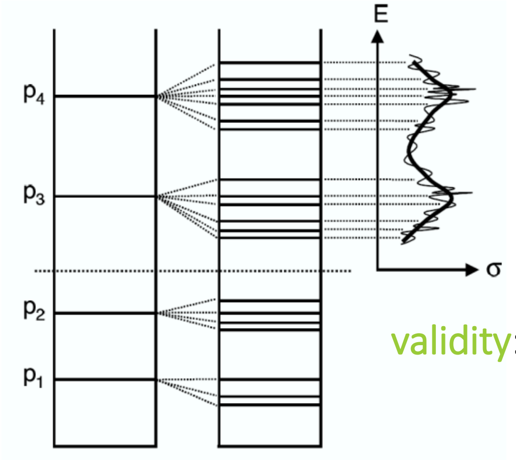


In $\sigma_{(n,\gamma)}$, the nuclear level density (NLD) is used

$$\rho^{\mathrm{tot}}(E_x) = \sum_J\sum_\Pi \rho(E_x, J, \Pi).$$

reaction rate

$$N_A\langle\sigma v\rangle = \left(\frac{8}{\pi m_{01}}\right)^{1/2}\frac{N_A}{(kT)^{3/2}}\int_0^\infty E\,\sigma(E)\,e^{-E/kT}\,dE$$



validity: if the number of resonances in the compound system is relatively high

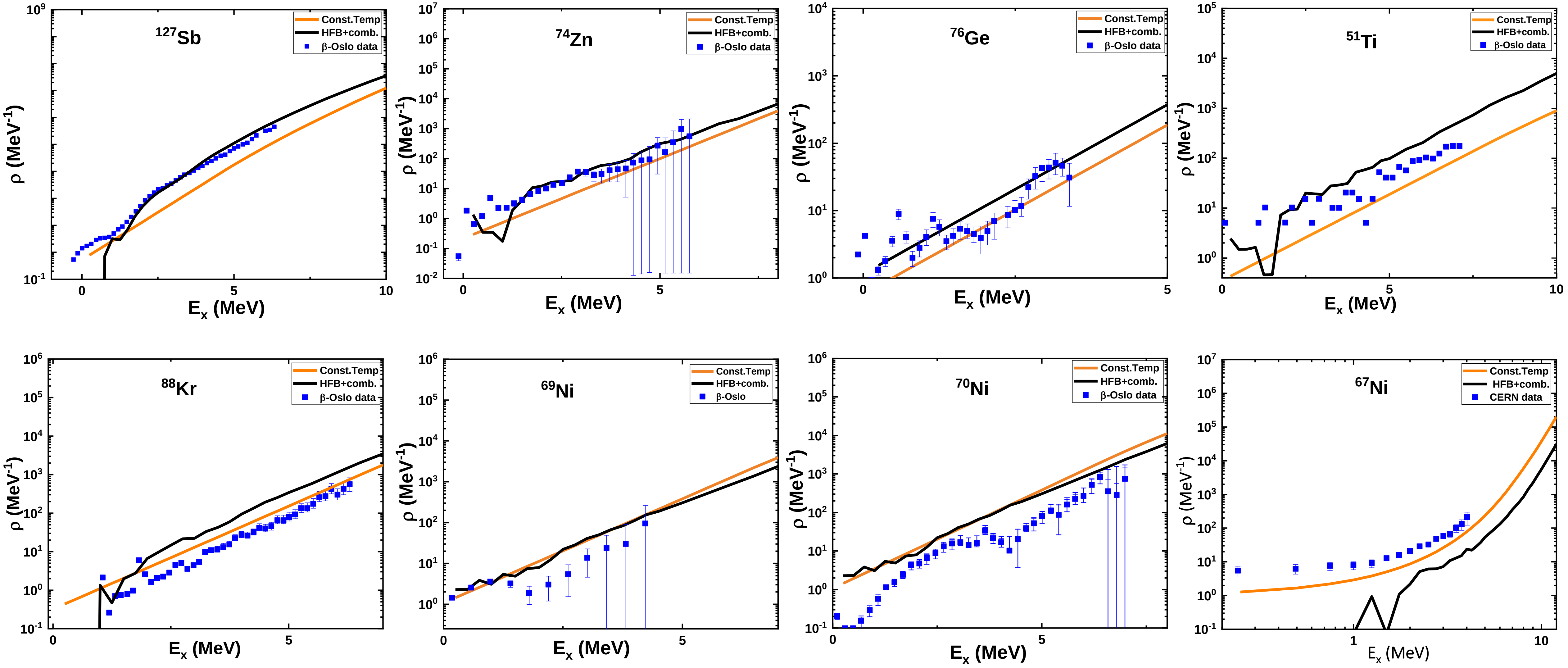
Improvement techniques of NLDs

- ✓ **β–Oslo** data of 7 nuclei and ^{67}Ni data measured with **Radioactive Ion Beam** at CERN (8 unstable nuclei)
- ✓ Why?
  - extracts statistical properties of the nucleus (γSF and NLD) for unstable nuclei, used as input in (n,γ) reaction calculations, using the Hauser-Feshbach model
  - constrains the astrophysical (n,γ) cross sections far from stability and the reaction rates for n^0-rich nuclei
  - provides a significantly small uncertainty in the (n,γ) cross section
- ✓ Nuclear structure input

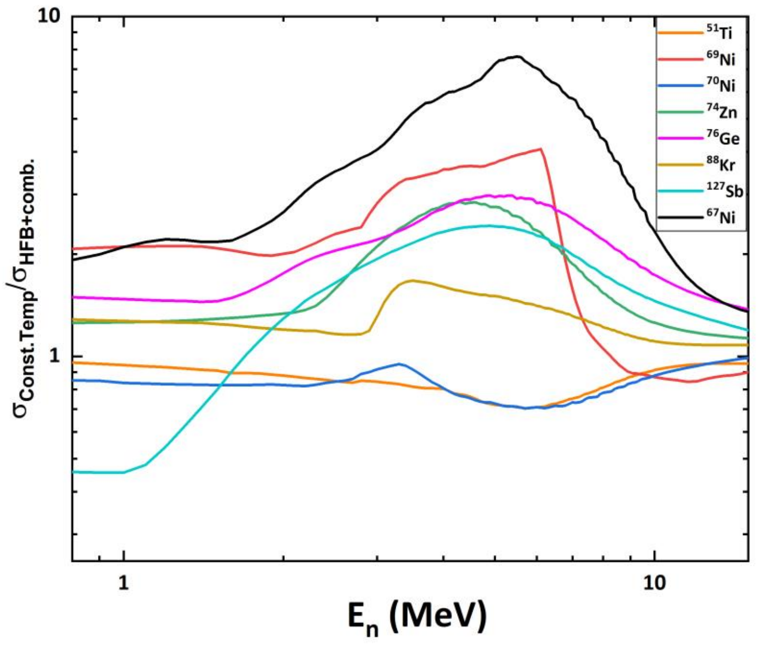
NLD = { Constant Temperature model
Hartree–Fock–Bogoliubov + combinatorial method

  - have been verified on stable nuclei
  - reproduce relatively precisely the available experimental data

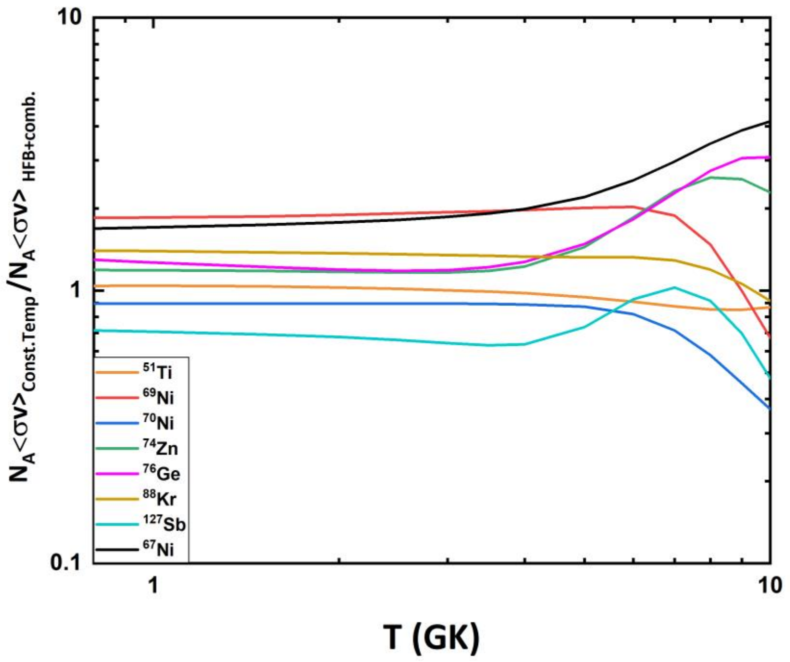
NLD of short-lived nuclei



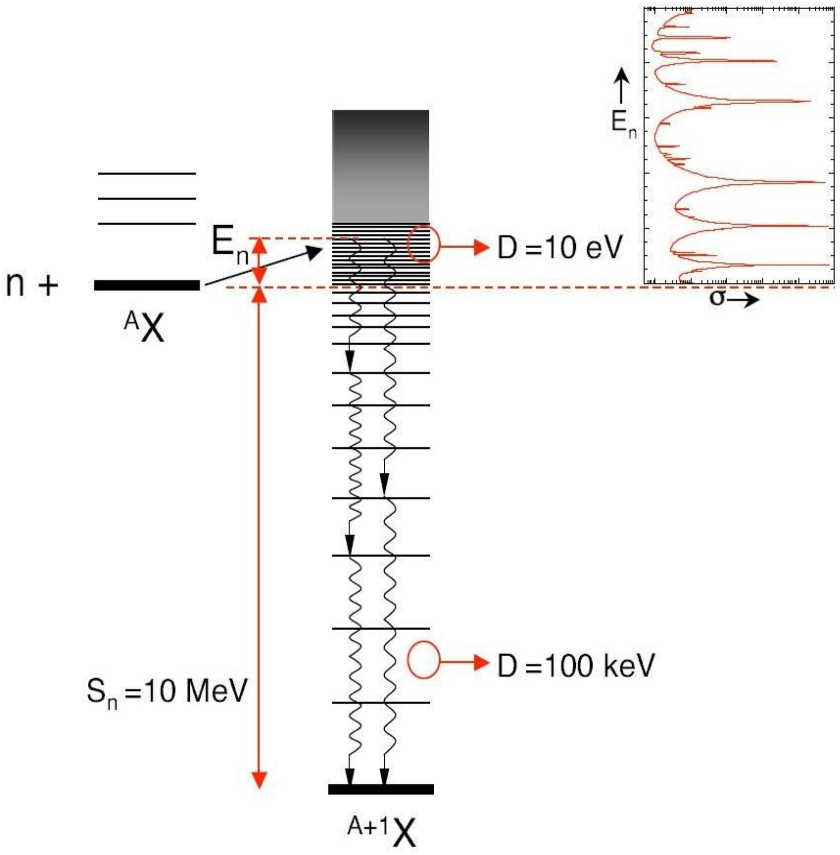
(n,γ) cross section



(n,γ) reaction rate



NLD impact on (n,γ) cross section

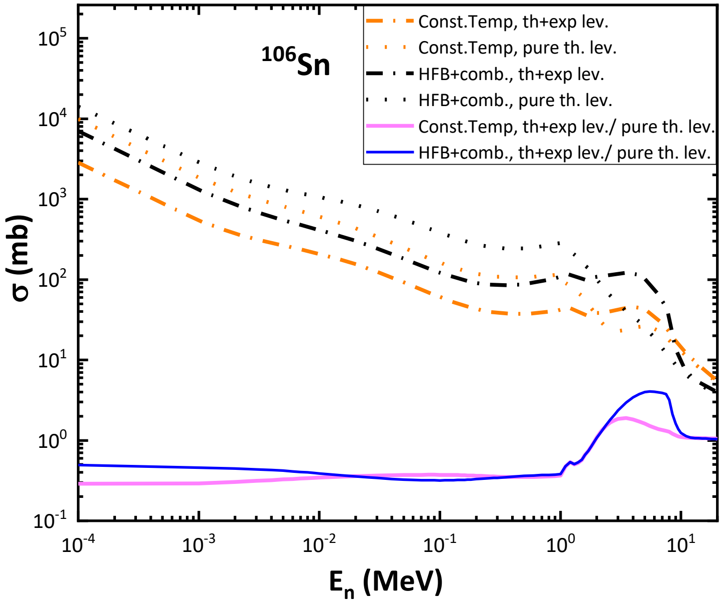


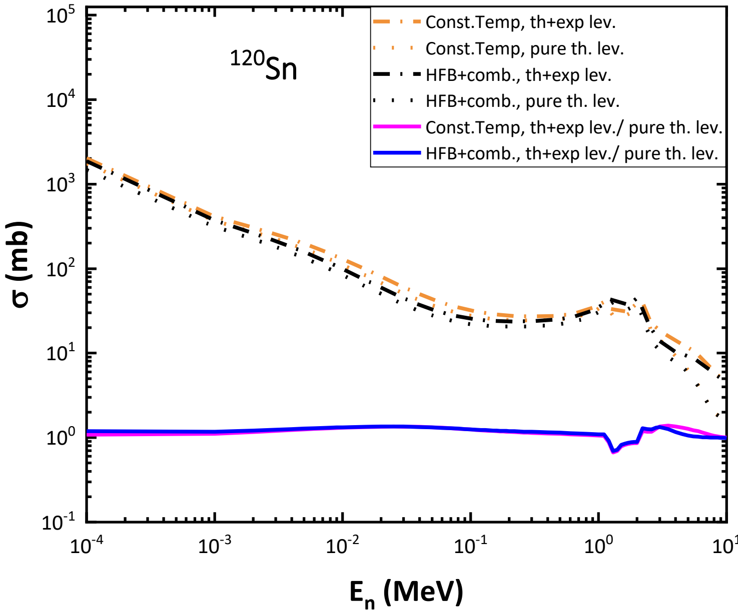
A schematic illustration of the compound nucleus formation and decay including typical values of neutron separation energy (Sn) and level spacing (D).

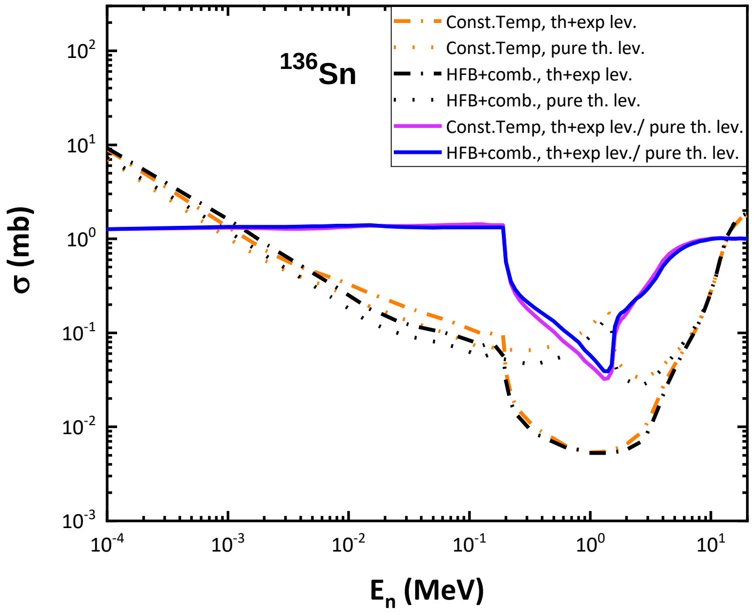
Higher energies: theoretical NLD levels overlap

Low-energy side: experimental known levels are incomplete

- Level scheme = discrete levels + theoretical NLD
- Ratio calculated from (a) discretel levels + theoretical NLD and (b) pure NLD levels
  - close to 1 ➡ level scheme is good for stable nuclei (^{120}Sn)
  - far away from 1 ➡ level scheme would be questionable for exotic nuclei (^{106}Sn and ^{136}Sn)







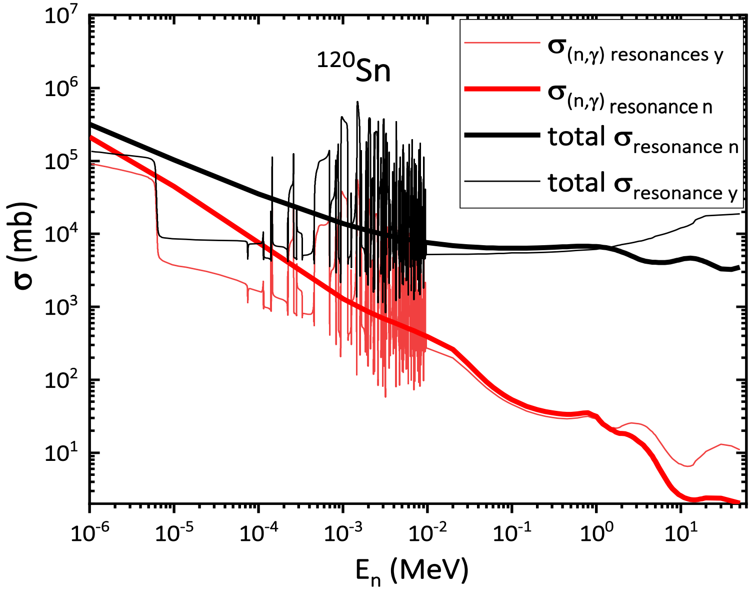
$\sigma_{(n,\gamma)}$ differ almost by a factor of 10

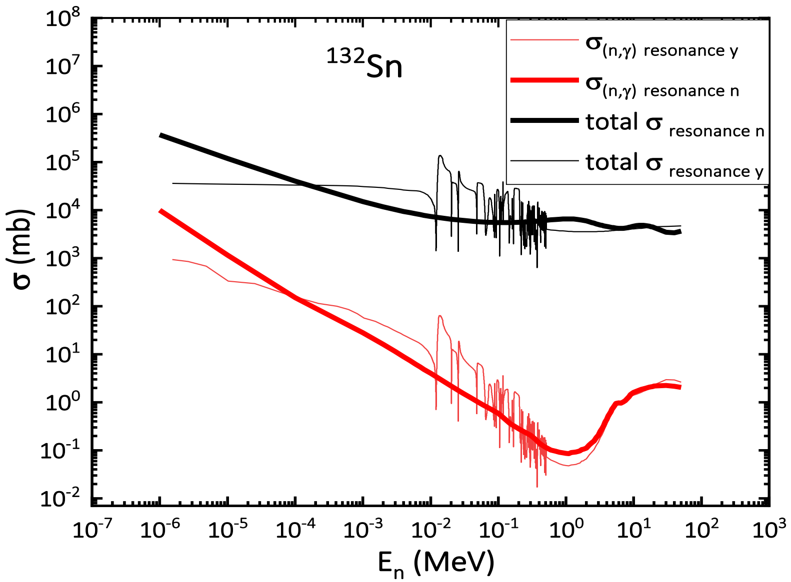
no. th. levels = no. exp. levels

NO exp. levels, only discrete levels

Comparison of purely theoretical NLD and experimental levels

NO exp. levels valuable for ^{106}Sn



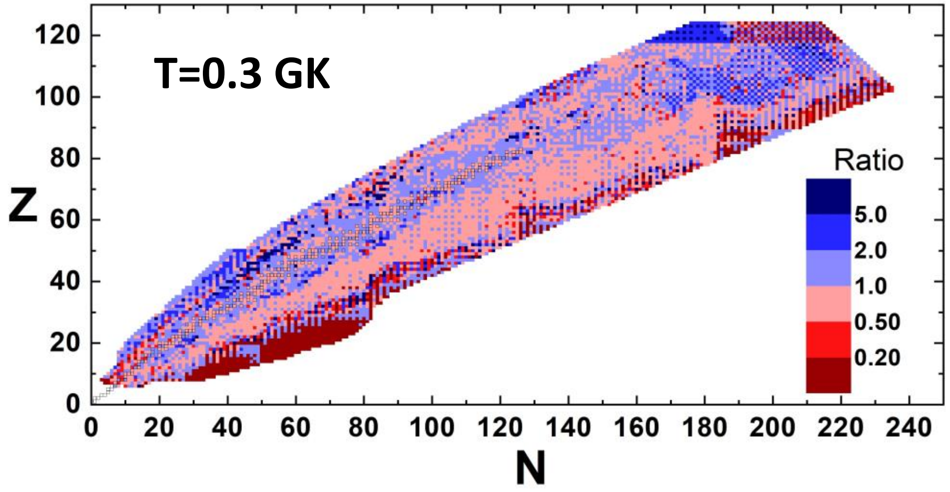


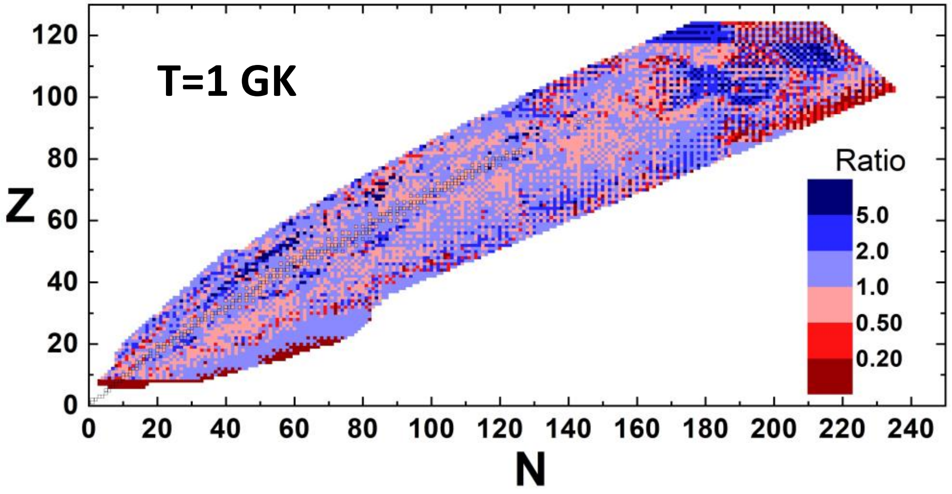
NO exp. levels valuable for ^{136}Sn

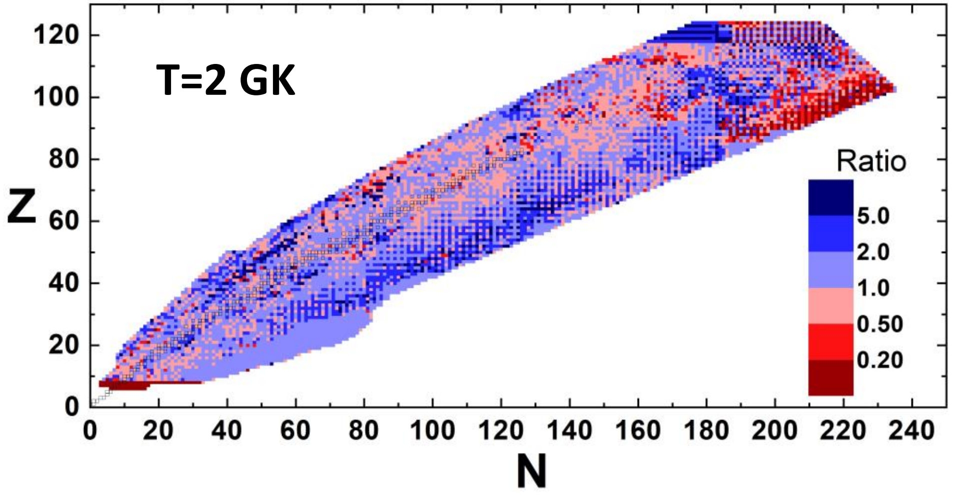
- ✓ Doubly magic nuclei have usually lower NLD than stable nuclei

Reaction rate at different astrophysical temperatures

- ✓ Reaction rate depends on the level scheme, which is constructed from experimental levels + theoretical NLD
- ✓ Rates calculated from (a) experimental levels + theoretical NLD and (b) pure NLD levels







At higher temperatures of astrophysical interest, the reaction rate becomes larger

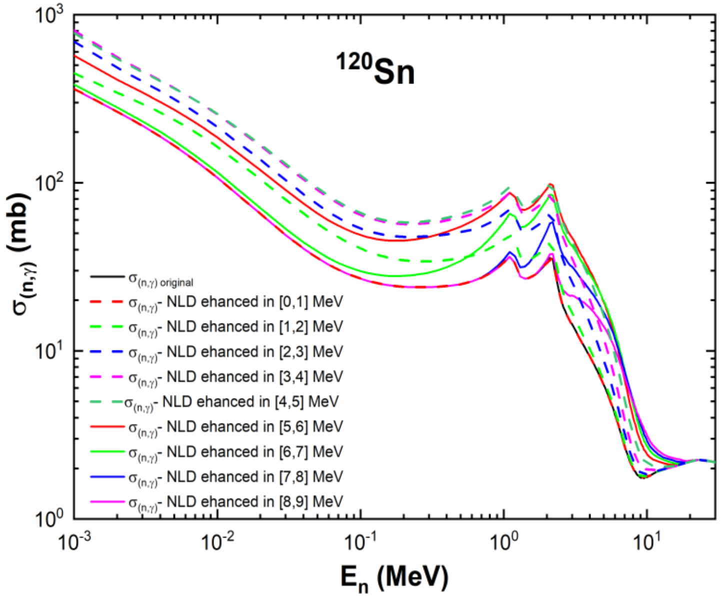
Sensitivity of (n,γ) cross section to NLD

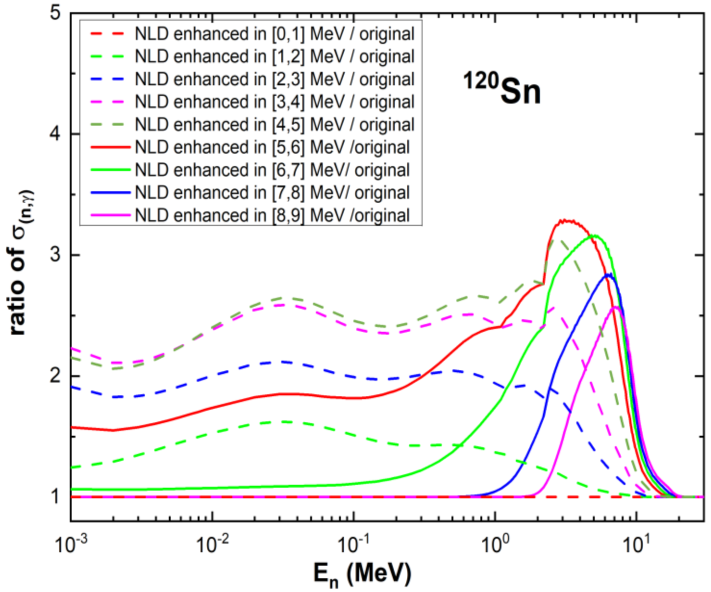
- ✓ Relative sensitivity

$$\Omega_{S_q} = \frac{v_\Omega - 1}{v_q - 1}$$

v_q → 10

- ✓ Procedure
  - microscopic HFB+ combinatorial method
  - successively scale the energy range of NLD by a factor of 10 within an energy interval of ΔE= 1 MeV from 0 up to 10 MeV for both positive and negative parities simultaneously





The most significant NLD energy ranges

- ✓ 4 - 5 MeV
- ✓ 3 - 4 MeV

Conclusions

- ✓ Theoretical predictions of Constant Temperature and microscopic HFB models do not reproduce the experimental data of unstable nuclei, with few exceptions
- ✓ ^{120}Sn is a stable isotope with a higher NLD than the exotic nucleus, ^{132}Sn ⟹ presents much more individual low-energy resonances
- ✓ At higher temperatures of astrophysical interest, the reaction rate becomes larger
- ✓ The most sensitive NLD energy ranges of ^{120}Sn: 4-5 Mev; 3-4 MeV

Thank you!