Effectiveness of level density and γ-ray strength function in neutron capture 68Zn(n,γ)69Zn reaction cross-section

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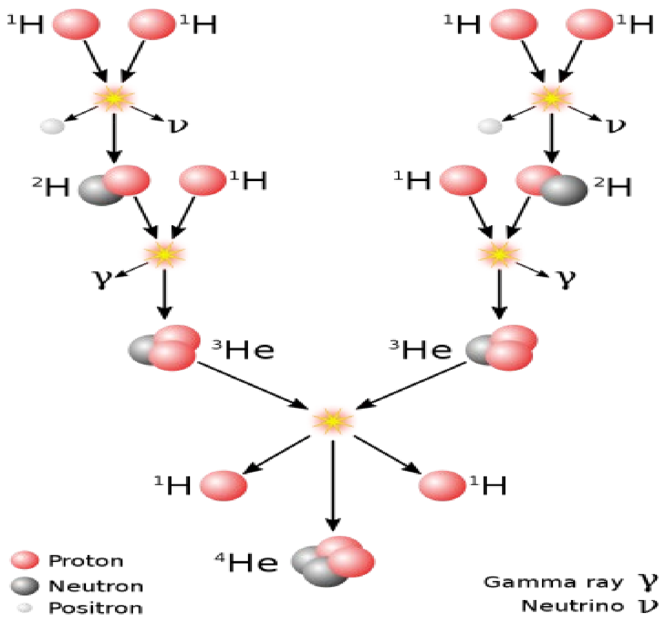
Introduction

Nuclear reaction is not only important for understanding how stars produce energy, but also crucial to perceive the origin of elements in our present universe.

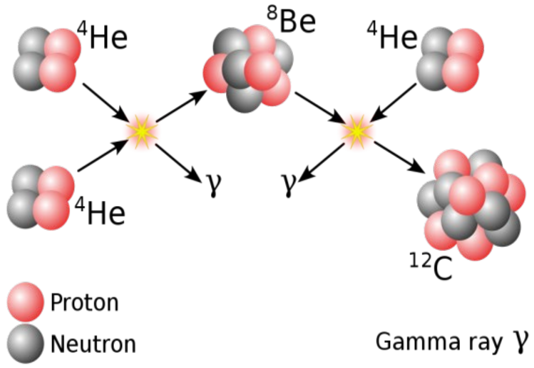
The elements up to iron are produced via fusion reaction while neutron-induced reactions (specifically neutron captures: s-process and r- process) are responsible for the creation of most of the elements heavier than iron.

Stellar Nucleosynthesis

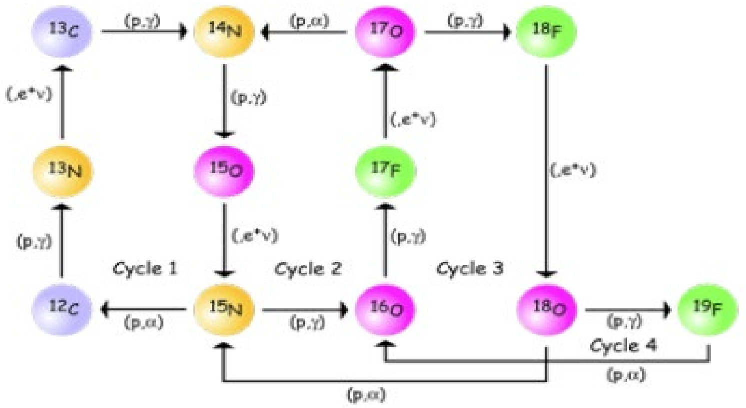
p-p chain



Triple – α process



CNO cycle



Carbon burning

$^{16}O + {}^{16}O \rightarrow {}^{32}S^*$

$^{16}O(\,^{16}O,p)\,^{31}P, {}^{16}O(\,^{16}O,\alpha)\,^{28}Si,$

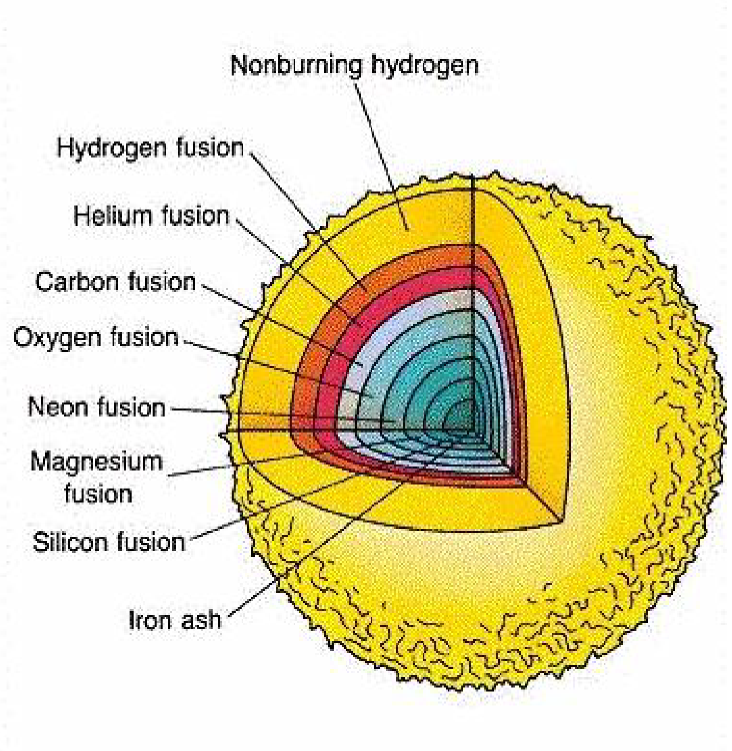
$^{16}O(\,^{16}O,n)\,^{31}S$

Oxygen burning

$^{12}C + {}^{12}C \rightarrow {}^{24}Mg^*$

$^{12}C(\,^{12}C,p)\,^{23}Na, {}^{12}C(\,^{12}C,\alpha)\,^{23}Ne,$

$^{12}C(\,^{12}C,n)\,^{23}Mg$



Silicon burning

$^{28}O + \gamma \rightarrow {}^{24}Mg + {}^{4}He$

$^{28}Si + {}^{4}He \rightarrow :::::: \rightarrow {}^{56}Ni$

$^{56}Ni \rightarrow \beta^-\ decay \rightarrow {}^{56}Fe$

Neutron Capture Processes and the Formation of heavier elements

s - process

1 — Time Scale

- capture time long relative to β-decay time
- neutron capture time scale: 100 years - 105 years

2 — Neutron Density

- $N_n = 10^8 n/cm^3$,

kT = 0.3 - 300 keV

3 — Sites

AGB stars

4 — Products

the elements between iron and bismath

r - process

1 — Time Scale

capture time short relative to β -decay time.

neutron capture time scale: 0.01 s - 10 s

2 — Neutron Density

Nn = 1020−30n/cm3,

kT > 100 keV

3 — Sites

Supernova explosion, neutron star merger

4 — Products

Heaviest isotopes of elements

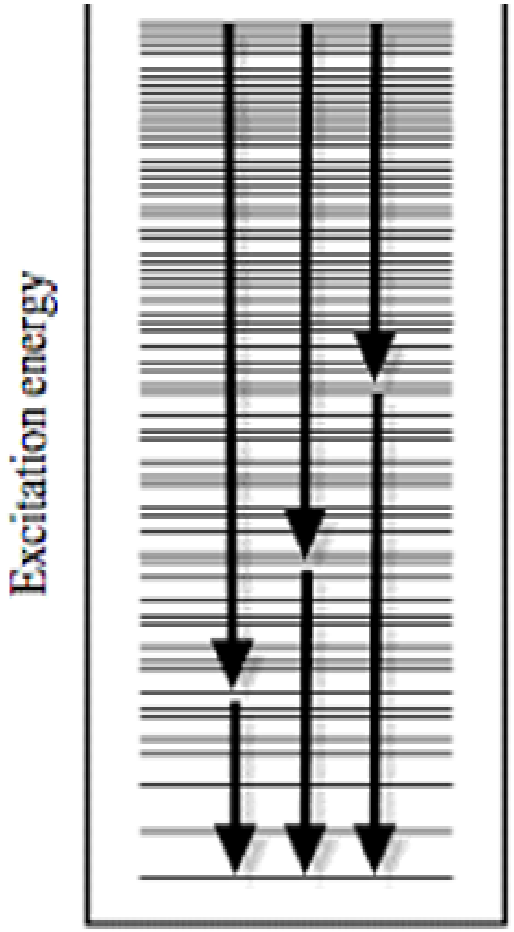
Hauser-Feshbach (HF) statistical model calculations is widely used to estimate the reaction cross-section. A frequent approach to improve on the reliability of the statistical model is to compare experimental data to HF calculations obtained with different combinations of NLD and γ-SF.

NLD and γ-sf are the major source of uncertainties while calculating the reaction cross-sections.

Nuclear Level density

- Number of single particle energy levels per unit energy at certain excitation energy is nuclear level density

- Nuclear level density increases rapidly with increase in excitation energy



Gamma-ray strength function (γ-sf)

The gamma-ray transmission coefficient for multipolarity l of type X (where X = M or E) is given by

$$T_{Xl}(E_\gamma) = 2\pi f_{Xl}(E_\gamma)\, E_\gamma^{(2l+1)}$$

$f_{Xl}(E\gamma)$ is the energy-dependent gamma-ray strength function.

Objective

The objective of this work is to find the best possible combination of NLDs and γ-SF models in order to describe the neutron capture cross-section as precise as possible.

TALYS— nuclear reaction code

Used for analysis of basic nuclear reaction experiments and it can provide a complete and accurate simulation of nuclear reactions up to energies of ~200 MeV

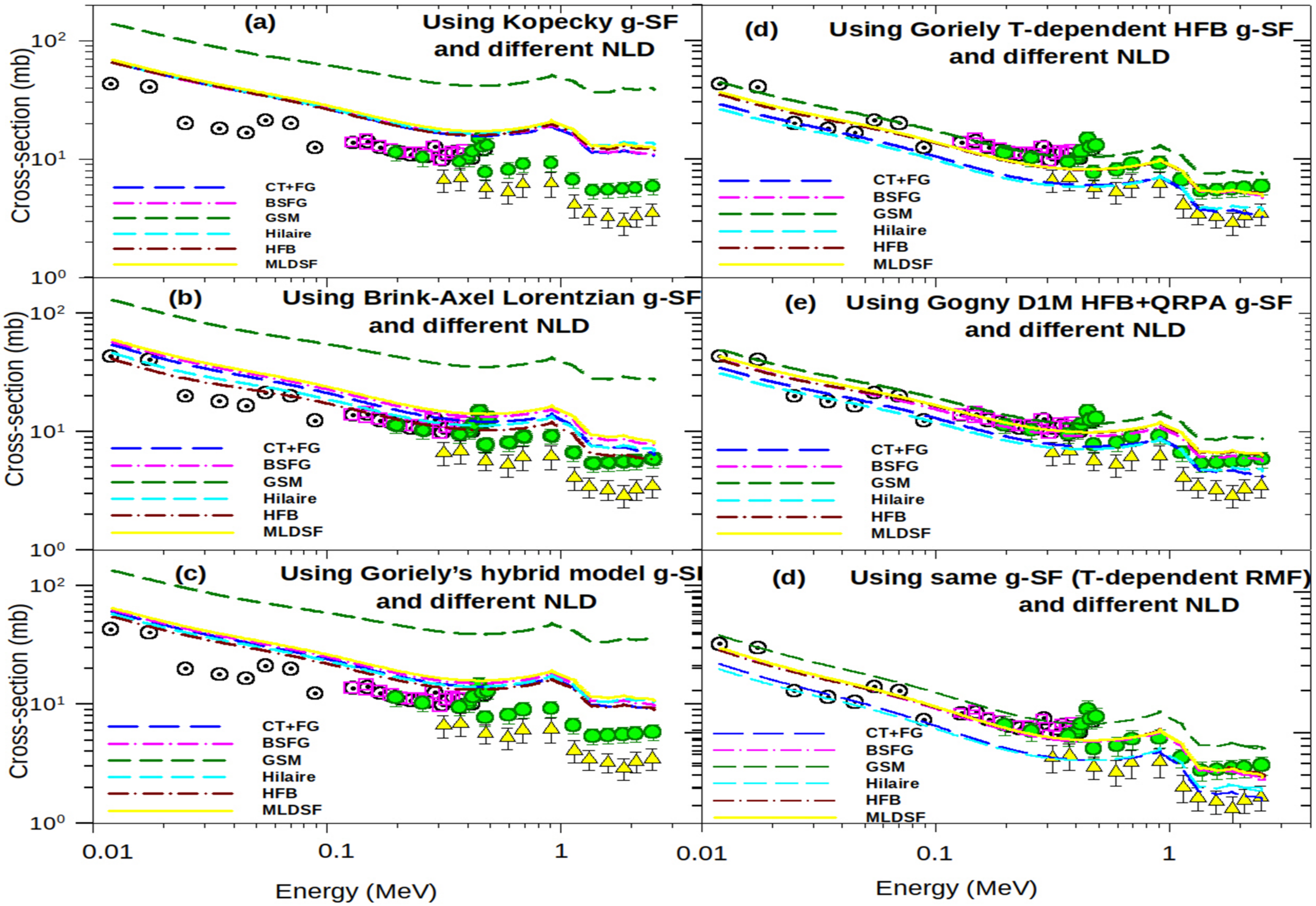
Existing formalism of NLD

1. *Constant temperature plus Fermi gas (CTFG)*
2. *back shifted Fermigas (BSFG)*
3. *generalized superfluid model (GSM)*
4. *Hilaire*
5. *Hartree-Fock-Bogolyubov (HFB) etc.*

Existing formalism of γ-SF

1. *Kopecky,*
2. *Brink-Axel,*
3. *Goriely's table,*
4. *Goriely's T-dependent HFB,*
5. *Gogny D1M HFB+QRPA,*
6. *HFBCS etc.*

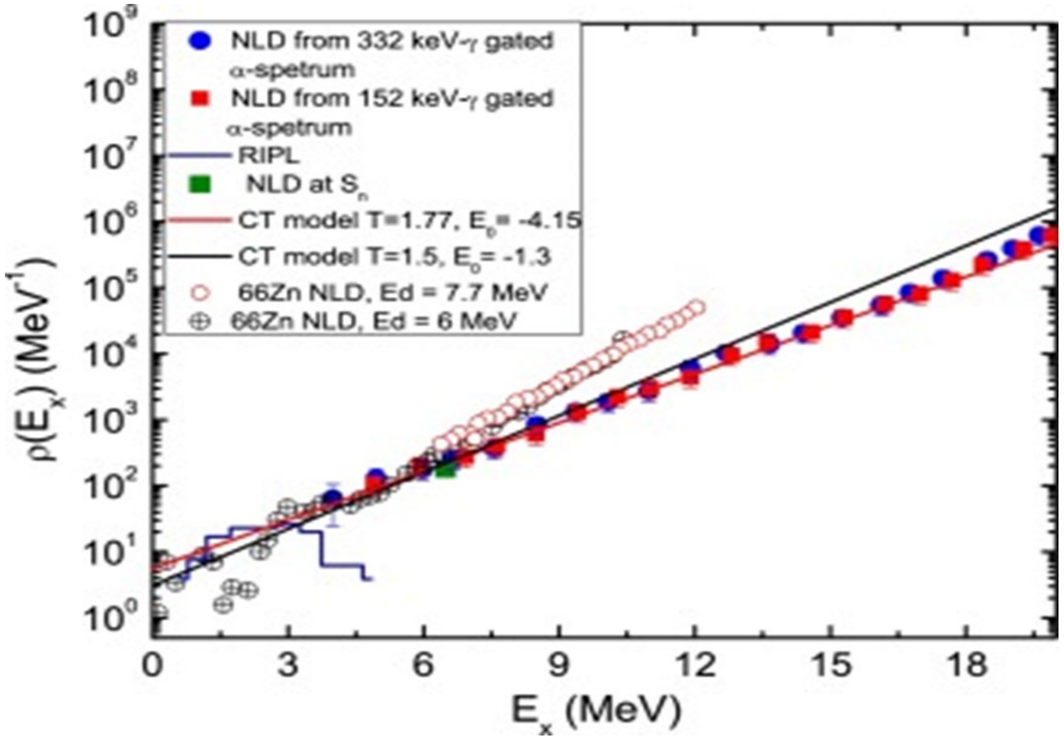
Comparison with Existing Models



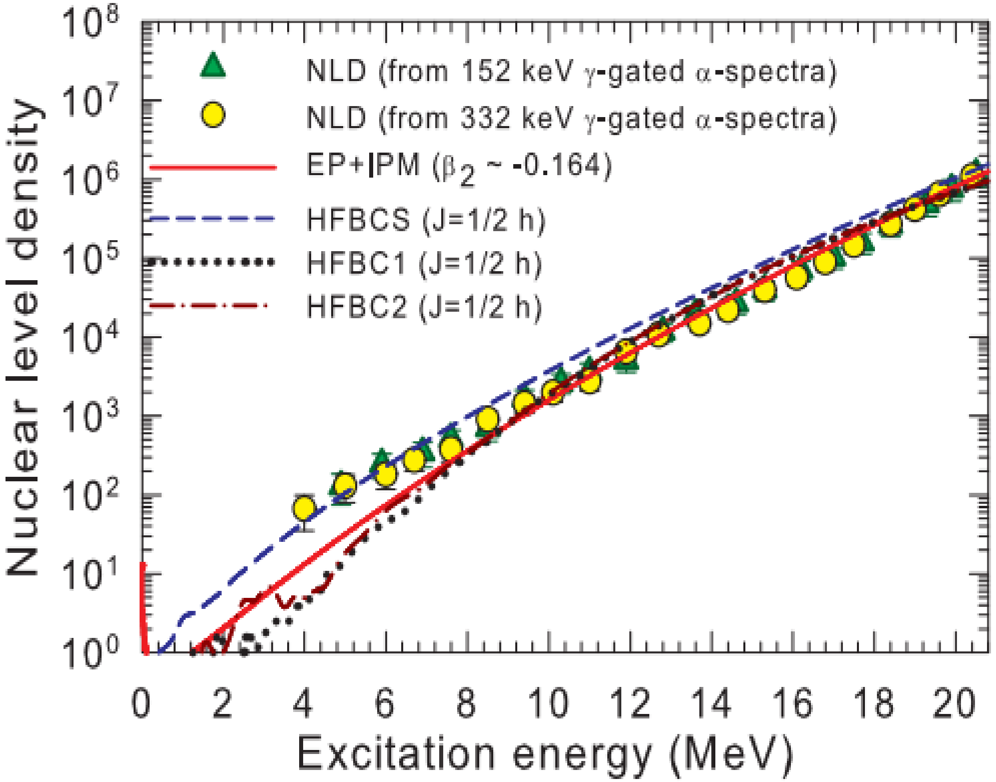
Motivation

Microscopic calculations, such as HFBT, HFBC, HFBCS, Gogny D1M HFB+QRPA, etc reasonably explains the experimental data. Therefore, we have performed microscopic EP+IPM and EP+PDM calculations to obtain the NLD and γ-SF, respectively, and used them in TALYS-1.95 code to check their applicability while calculating the astrophysical reaction cross-section.

Inclusion of New Formalism

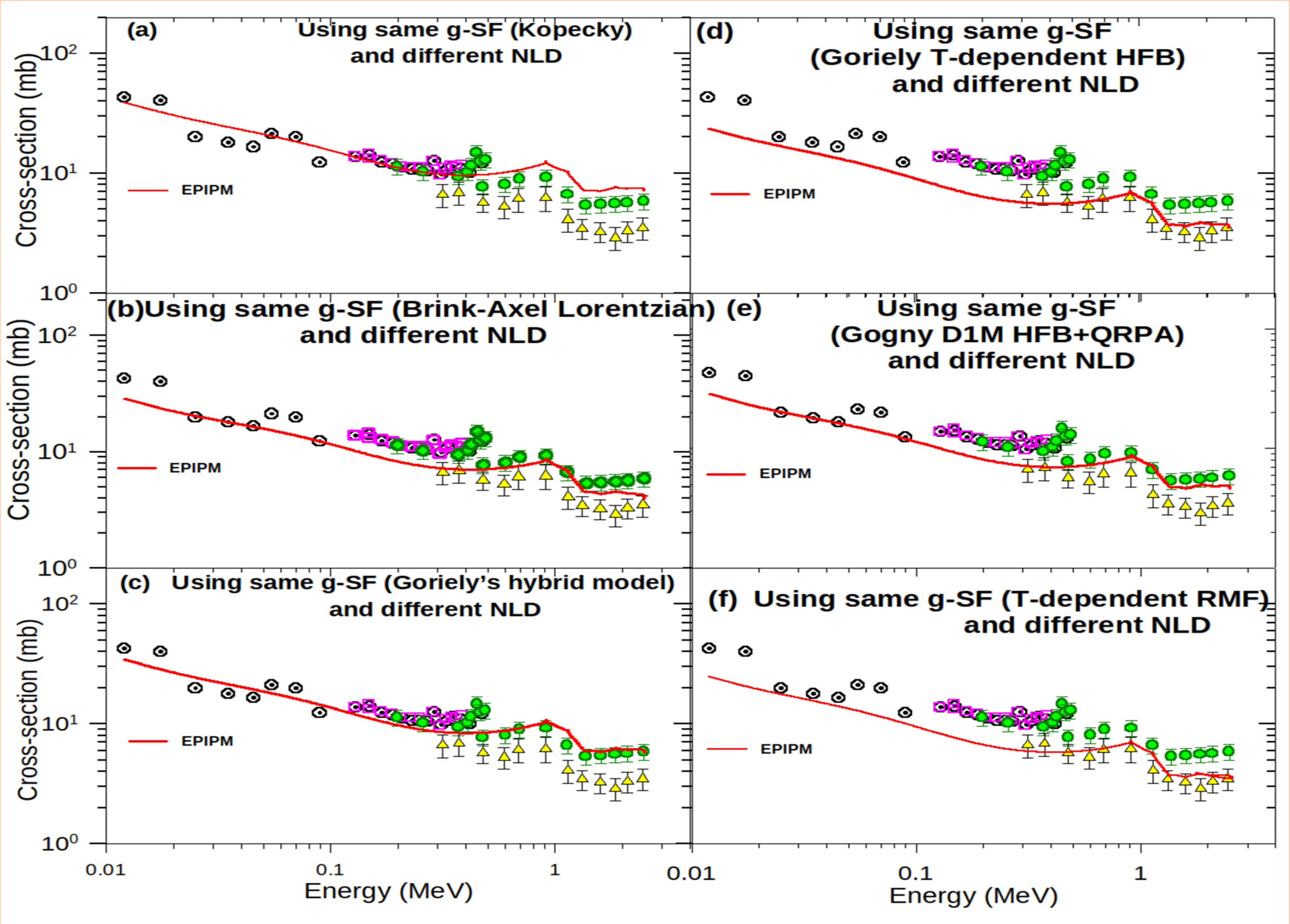


Phys. Lett. B 806, 135487



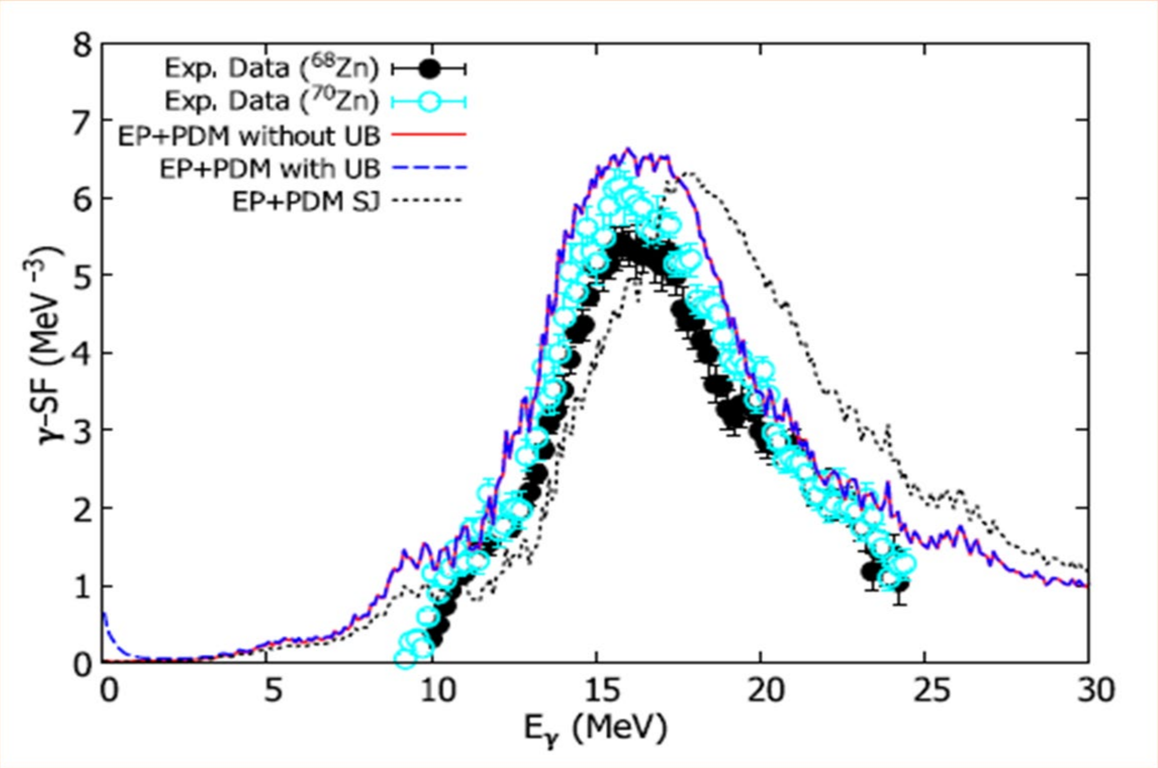
The experimental NLD shows excellent agreement with the EP+IPM calculations.

Results with EP+IPM



Inclusion of EP+PDM

line



The experimental γ-ray strength function of ^{68,70}Zn with the results obtained from the EP+PDM without (red continuous line) and with (blue dashed line) upbend (UB) structure for 69Zn. The black dotted line corresponds to the EP+PDM γ-SF calculated by using the global parameterization of Stenwendel–Jensen.

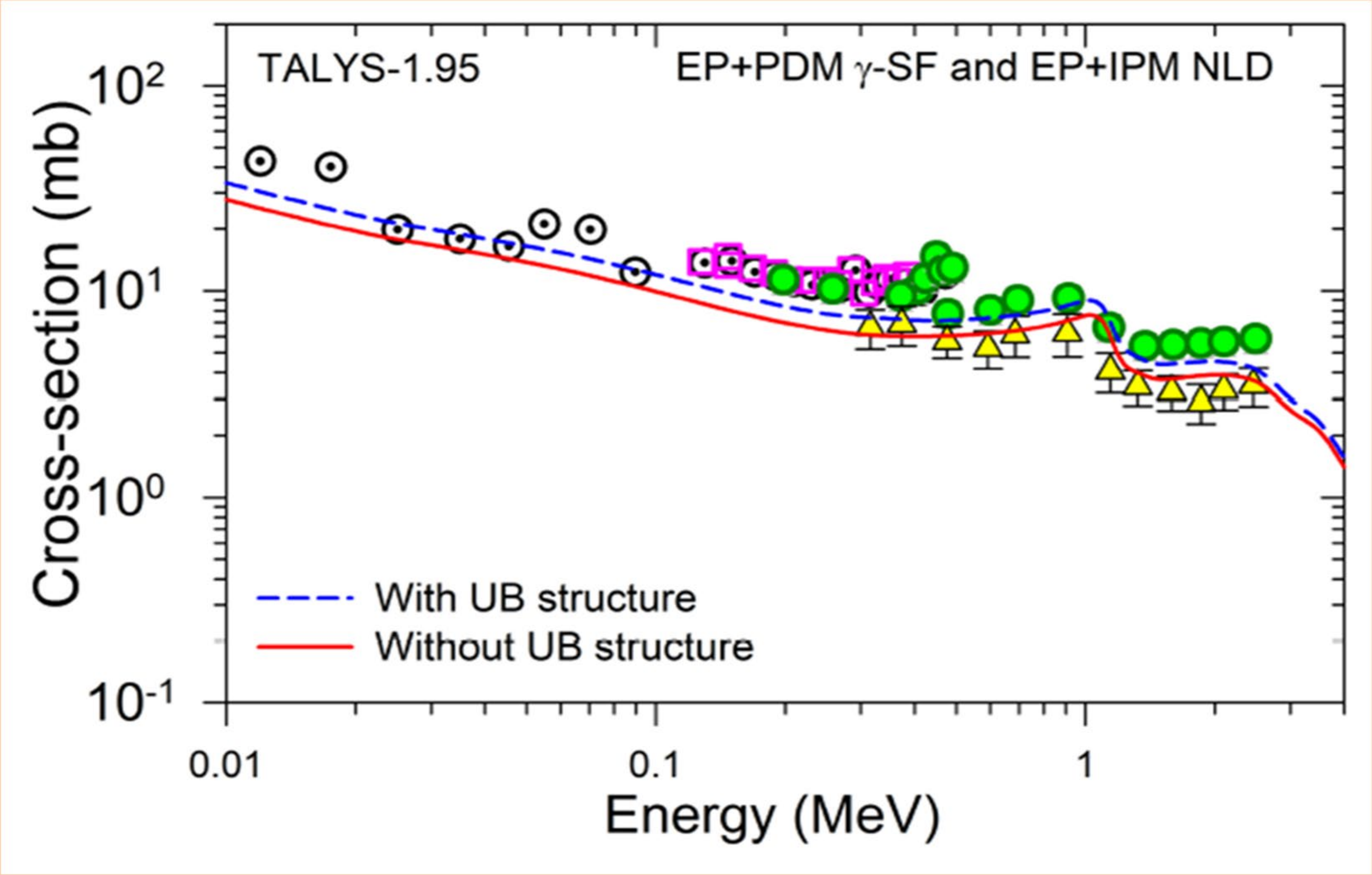
Theoretical framework:

IPM $$H\psi = E\psi$$

EP+IPM $$(H+H_{pair})\psi = (E + \Delta E)\psi$$

EP+PDM $$\left(H_{PDM} + H_{pair}\right)\psi = E'\psi$$

Results with EP+PDM



The experimental cross-section of 68Zn(n, γ)69Zn reaction has been taken from https://www.nndc.bnl.gov/exfor

Summary

1. Existing formalism of NLD & γ-sf cannot be able to explain the neutron capture 68Zn(n,γ)69Zn reaction cross-section.
2. Microscopic EP+IPM NLDs explain the neutron capture $^{68}Zn(n,\gamma)^{69}Zn$ reaction cross-section data much better than the other existing combination of NLDs and γ-SF.
3. Implementation of γ-SF obtained from EP+PDM in TALYS code and Furthermore, the inclusion of an Up-bend(UB) structure in the EP+PDM γ-SF improves the result.
4. The combination of EP+IPM NLD & EP+PDM γ-SF can be a good choice to calculate the n-capture cross section data. However, we need to study more system to find the applicability of these two as input models in TALYS.

References

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THANK YOU