Spectral Distribution Method to α-Induced Reactions in Stellar He-Burning Environments

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Introduction

- Stellar helium-burning is a critical phase in the evolution of low- and intermediate-mass stars. Helium burning occurs in stellar cores and shells after hydrogen exhaustion, at $T_9 \sim 0.1 - 0.4$ GK.
- Dominant energy-producing reactions:
  - Triple-α: $3\alpha \rightarrow {}^{12}\mathrm{C} + \gamma$
  - Carbon buildup: ${}^{12}\mathrm{C}(\alpha, \gamma){}^{16}\mathrm{O}$
- The key competing reactions on ^{22}Ne:
  - ${}^{22}\mathrm{Ne}(\alpha,\mathrm{n}){}^{25}\mathrm{Mg}$ (neutron source for the s-process)
  - ${}^{22}\mathrm{Ne}(\alpha,\gamma){}^{26}\mathrm{Mg}$ (neutron sink, reduces neutron availability)
- Neutron production in this phase drives the **s-process** nucleosynthesis of heavy elements. The competing ${}^{22}\mathrm{Ne}(\alpha,\gamma){}^{26}\mathrm{Mg}$ reaction reduces neutron flux by diverting material into non-neutron-producing pathways.
- At **low temperatures** ($T_9 < 0.2 GK$):
  - (α, γ) dominates (below neutron threshold)
- At **higher temperatures** ($T_9 > 0.25 GK$):
  - (α, n) becomes significant and overtakes
  - Provides neutrons for the *s*-process

- Precise knowledge of the competition between these two channels is essential to constrain neutron production and heavy-element yields.
- Recent experiments (e.g., **LUNA**) have improved resonance strength measurements, but large uncertainties persist at stellar energies.
- Accurate reaction rates of these channels are crucial for modeling stellar nucleosynthesis.
- Nuclear level densities and reaction inputs carry significant uncertainties at relevant stellar energies.
- This work applies the **Spectral Distribution Method (SDM)** to improve α-induced reaction predictions in stellar environments.

Spectral Distribution Method (SDM): Concept & Applications

- **SDM: A statistical shell-model based approach**
  - Describes nuclear many-body systems using moments of the Hamiltonian.
  - Assumes strength distributions follow a Gaussian (or modified Gaussian) shape.
- **Why use SDM?**
  - Avoids full diagonalization of large shell-model spaces.
  - Provides **microscopic, parity-dependent level densities** (NLDs) and transition strengths.
- **Applications:**
  - Neutron-induced reactions: (n,γ), (n,p), (n,α)
  - Proton-induced reactions: (p,γ), (p,n)
  - Alpha-induced reactions: (α,γ), (α,n)
- SDM-derived inputs are implemented in statistical model codes like **TALYS**.

Reference: T. Ghosh et al., Phys. Rev. C 105, 044320 (2022).

Spectral Distribution Method: Formalism

- **Strength distribution:** The transition strength between initial and final states is modeled as:

$$S(E) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(E - \bar{E})^2}{2\sigma^2}\right)$$

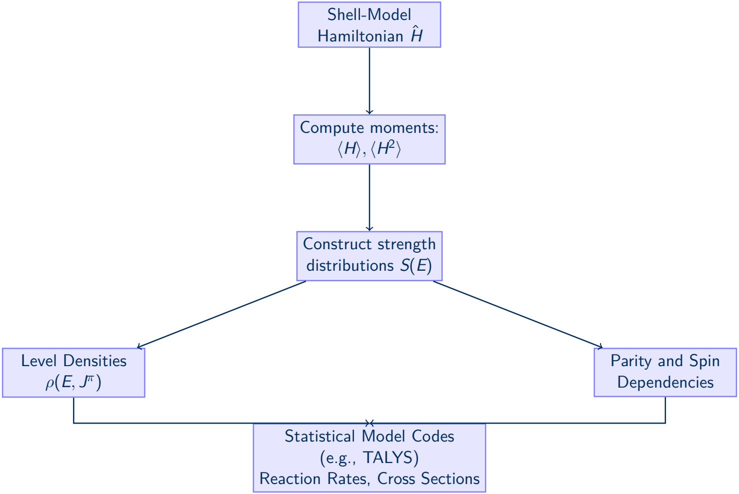
  where:
  - $\bar{E} = \langle H \rangle$: centroid of the Hamiltonian.
  - $\sigma^2 = \langle H^2 \rangle - \langle H \rangle^2$: variance.
- **Level density:** The many-body level density is similarly given by:

$$\rho(E) \approx \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(E - \bar{E})^2}{2\sigma^2}\right)$$

- These moments $(\bar{E}, \sigma^2)$ are computed from the nuclear shell-model Hamiltonian in the chosen configuration space.

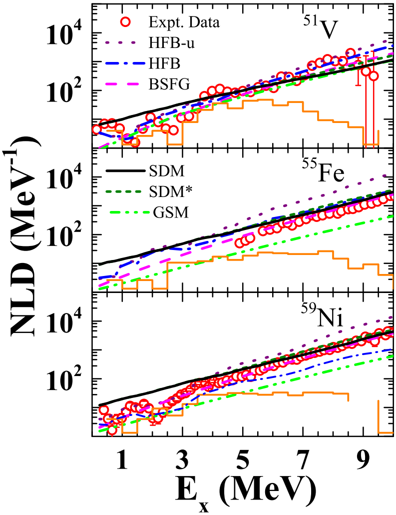
SDM provides parity-separated, spin-dependent $\rho(E, J^\pi)$ for reaction rate calculations.

Spectral Distribution Method: Workflow



SDM provides microscopic inputs to statistical models for predicting nuclear reaction observables.

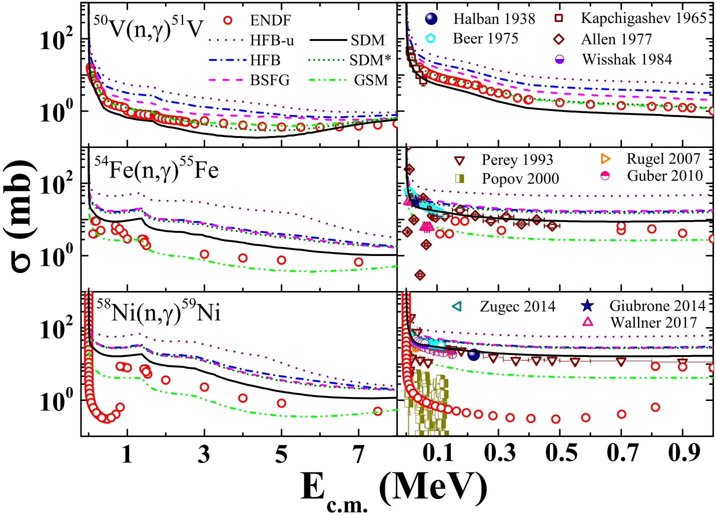
Nuclear Level Density (NLD) from SDM



- $^{50}V(n,\gamma)^{51}V$, $^{54}Fe(n,\gamma)^{55}Fe$ and $^{58}Ni(n,\gamma)^{59}Ni$.
- SDM provides microscopic, spin- and parity-dependent NLDs.
- Consistent with experimental systematics.
- Used as input to statistical model codes (e.g., TALYS).

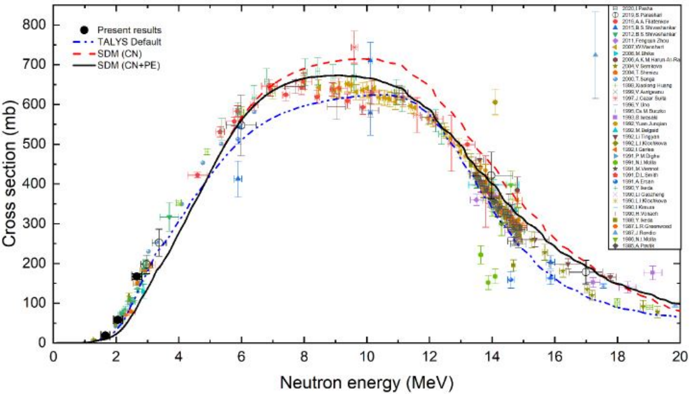
Reference: Sangeeta, T. Ghosh, B. Maheshwari, G. Saxena et al., *Phys. Rev. C* **105**, 044320 (2022)

Cross Section Predictions of a Few (n,γ) Reactions



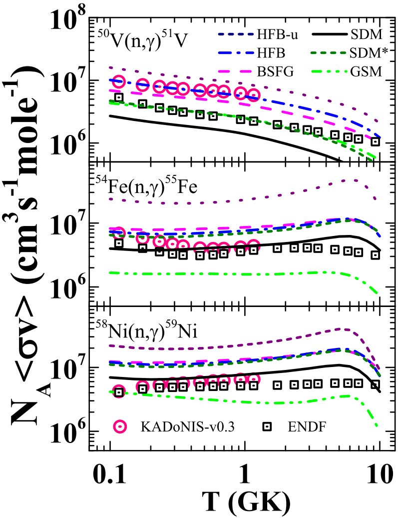
Reference: Sangeeta, T. Ghosh, B. Maheshwari, G. Saxena et al., *Phys. Rev. C* **105**, 044320 (2022)

Cross Section Predictions: (n, p) Reaction: $^{58}\mathbf{Ni}(n,p)^{58}\mathbf{Co}$



Reference: A. Hingu, G. Saxena et al., *Chin. Phys. C* **48**, 024001 (2024)

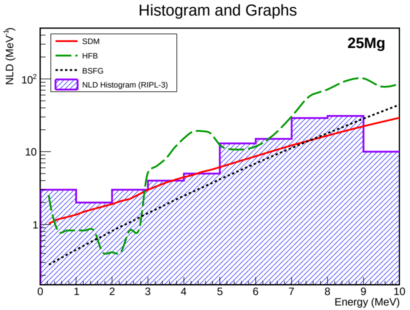
Astrophysical Reaction Rates



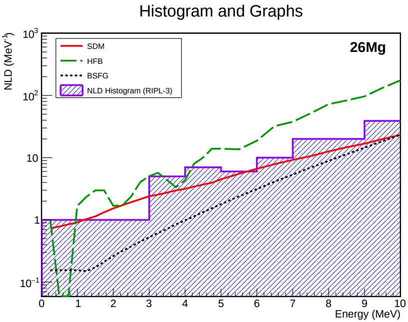
- Reaction rates with SDM-derived NLDs.
- Critical for *s*-process modeling.
- Consistent with stellar nucleosynthesis predictions.

Reference: Sangeeta, T. Ghosh, B. Maheshwari, G. Saxena et al., *Phys. Rev. C* **105**, 044320 (2022)

NLD for ^{25}Mg and ^{26}Mg



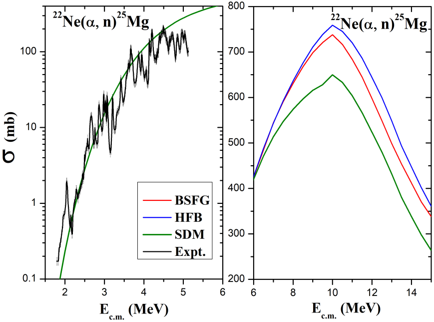
Nuclear Level Density for ^{25}Mg (SDM vs. models)



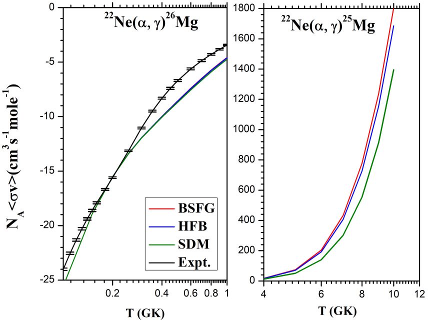
Nuclear Level Density for ^{26}Mg (SDM vs. models)

SDM-derived NLDs show good agreement with RIPL-3 data and models, improving predictive power for ^{22}Ne(α, n) and ^{22}Ne(α, γ) reactions.

Preliminary Results: Cross Section and Reaction Rates



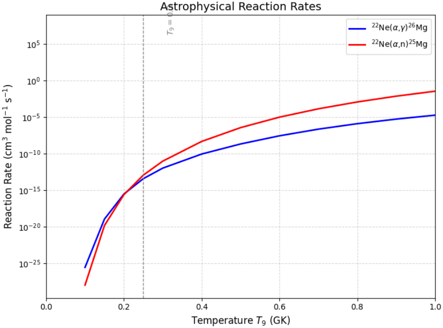
Cross section for ^{22}Ne$(\alpha, n)^{25}$Mg



Astrophysical reaction rates for ^{22}Ne$(\alpha, \gamma)^{26}$Mg

SDM-based predictions show promising agreement with available data and trends, supporting their role in stellar nucleosynthesis modeling.

^{22}Ne(α, n)^{25}Mg and ^{22}Ne(α, γ)^{26}Mg competition



- The two reactions compete as neutron **source** and neutron **sink** in He-burning environments.
- At $T_9 < 0.3$, (α, γ) dominates — reduces free neutrons (sink).
- At $T_9 > 0.3$, (α, n) becomes dominant — provides neutrons for *s*-process (source).
- The balance between these rates influences stellar nucleosynthesis and isotopic abundances.

Conclusion

- The Spectral Distribution Method (SDM) provides a microscopic and computationally efficient approach to calculate level densities with spin and parity dependence.
- SDM-derived inputs improve predictions of cross sections and astrophysical reaction rates for He-burning reactions.
- The balance between ^{22}Ne(α, n) and (α, γ) rates crucially determines neutron availability for *s*-process nucleosynthesis.
- SDM predictions show good agreement with experimental data and established models, enhancing confidence in stellar models.
- Future work: extend SDM to other key reactions, refine parity/spin-resolved inputs, and explore sensitivity in full reaction networks.

Thank you for your attention!

Acknowledgements

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Thank you.
Questions are welcome.