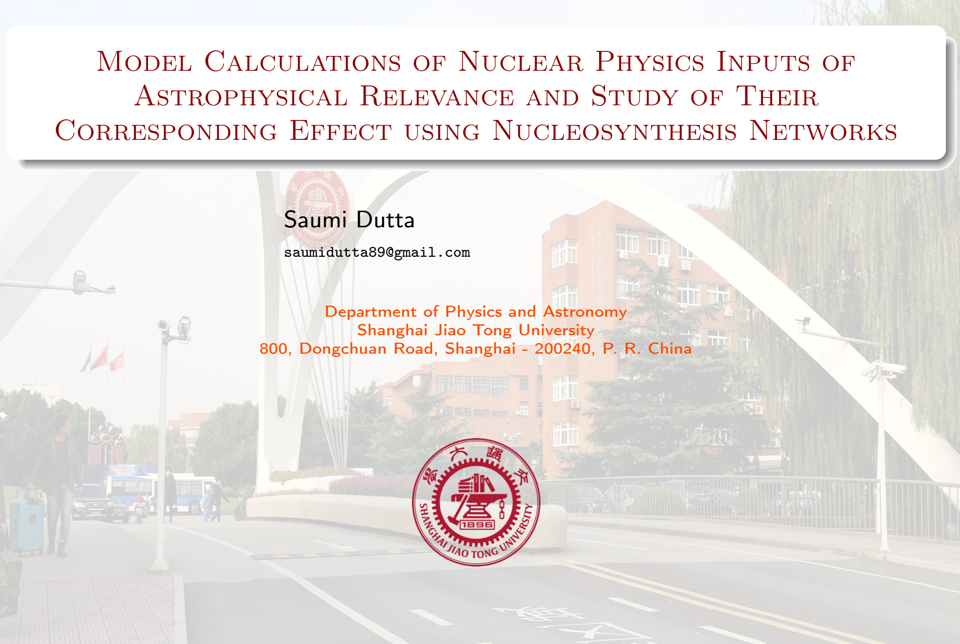

MODEL CALCULATIONS OF NUCLEAR PHYSICS INPUTS OF ASTROPHYSICAL RELEVANCE AND STUDY OF THEIR CORRESPONDING EFFECT USING NUCLEOSYNTHESIS NETWORKS

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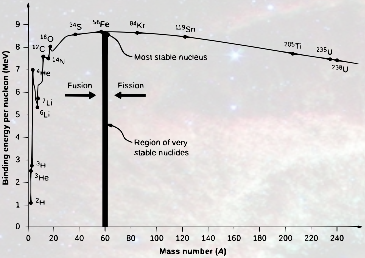
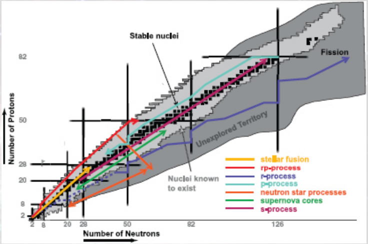
NUCLEAR ASTROPHYSICS: NEED OF THEORY

- Nuclear astrophysics → interdisciplinary field→ Nuclear physics → integral component
- A detailed understanding of astrophysical phenomena rely on input nuclear data, e.g.,
  1. for nuclear reaction studies, → cross sections, astrophysical S-factors, nuclear level densities, strength functions, etc.
  2. for nuclear structure studies, → nuclear masses, decay lifetimes, resonance properties, etc.
- Most of these nuclear physics information are still difficult to determine experimentally.
- The inputs from theoretical research are highly demanded.
- Sophisticated theoretical models are required to make the predictions.

AGENDA

1. INTRODUCTION
2. RADIATIVE NEUTRON CAPTURE: THEORETICAL FRAMEWORK → MICROSCOPIC OMP → RESULTS
3. FUTURE PLAN
4. SUMMARY





Introduction

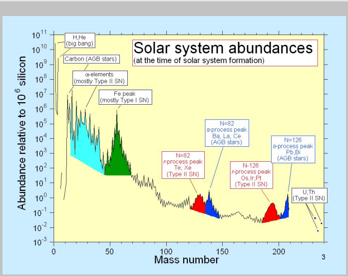
- Heavy element nucleosynthesis beyond iron → neutron capture on seeds → *s*-process and *r*-process → difference in timescales.
- *s*-process → neutron capture timescale > β-decay timescale → along valley of β-stability.
- *r*-process → neutron capture timescale < β-decay timescale → along neutron drip line.
- *p*-process → proton-rich side → contribution is very small ∼ 1% to total solar abundance.

MOTIVATION

- Abundances → network calculations.

$$\begin{aligned}\frac{dN_s(Z,A)}{dt} &= -[(\lambda_n(A)+\lambda_\beta(A))N_s(Z,A)] \\ &+[\lambda_n(Z,A-1)N_s(Z,A-1) \\ &+\lambda_\beta(Z-1,A)N_s(Z-1,A)]\end{aligned} \tag{1}$$

  N_s: s-abundance, $\lambda_n = n_n \sigma v_T$, $\sigma = (n,\gamma)$ cross section, n_n = neutron density, $v_T = \sqrt{\frac{2K_BT}{m}}$, T = stellar temperature; λ_β = β-decay rate
- Neutron capture cross sections/ rates and β-decay rates are crucial inputs.
- Many unstable nuclides, radioactive branch-point isotopes → experimental data absent→ theory is indispensable.
- Old measurements → uncertainties.
- Stellar environment → Maxwellian-averaged cross section (MACS) values are needed over broad energy range.
- Nuclear model predictions are necessary.



- Compound nuclear Hauser-Feshbach formula:

$$\langle \sigma_{re}(\alpha, \alpha') \rangle = \frac{\pi}{k_\alpha^2} \sum_{J\pi} \frac{(2J+1)}{(2I_1+1)(2I_2+1)} \frac{\left[\sum_{sl} \hat{T}_l(\alpha)\right] \left[\sum_{s'l'} \hat{T}_{l'}(\alpha')\right]}{\sum_{\alpha'' s'' l''} \hat{T}_{l''}(\alpha'')} \tag{2}$$

- Transmission coefficients $\hat{T}_l$ → important inputs
- Neutron optical potential→ constructed a novel microscopic folding model formalism.
- Density-dependent M3Y interaction (DDM3Y):

$$v(r, \rho, E) = 2.07(1 - 1.624\rho^{2/3}) \left[7999 \frac{e^{-4r}}{4r} - 2134 \frac{e^{-2.5r}}{2.5r} - 276(1 - \frac{E}{200A})\delta(r)\right] \tag{3}$$

$E \rightarrow$ c.m. energy in MeV, r in fm.

- Real DDM3Y interaction folded with target radial matter density.

$$V_{fold}(\mathbf{r}, \rho, E) = \int v(|\mathbf{r} - \mathbf{r}'|, \rho, E)\rho(\mathbf{r}')d\mathbf{r}' \tag{4}$$

- Identical real and imaginary part → normalized with factors A_r and A_{im}
- Final form.

$$V_{omp} = A_r V_{fold} + A_{im} V_{fold} \tag{5}$$

- A spin-orbit term Spin-orbit term is included in the potential.

OTHER IMPORTANT INPUTS

- Dominant E1 γ-ray strength function → Hartree-Fock-Bogolyubov model Ref. Nucl. Phys. A **739**, 331 (2004).
- Nuclear level densities → Goriely's microscopic calculation in combinatorial method, Ref. Phys. Rev. C **78**, 064307 (2008).
- Width fluctuation corrections → Moldauer's formula (Ref. Phys. Rev. C, **14** 0764 (1976), Nucl. Phys. A, **344** 185 (1980))
- Densities are obtained from RMF model calculations.
- RMF Lagrangian density → contains nonlinear terms for meson self couplings → FSU Gold parameterization (Phys. Rev. C **93**, 024602 (2016)). **Lagrangian density** **FSU Gold parameters**
- Point proton density ρ_p is convoluted with Gaussian form factor $F(r)$ to obtain charge density $\rho_{ch}(\mathbf{r})$.

$$\rho_{ch}(\mathbf{r}) = e \int \rho_p(\mathbf{r}')F(\mathbf{r}-\mathbf{r}')d\mathbf{r}' \tag{6}$$

$$F(r) = (a\sqrt{\pi})^{-3} exp(-r^2/a^2) \tag{7}$$

$a = \sqrt{\frac{2}{3}}a_p$, a_p=0.8 fm (rms charge radius of proton).

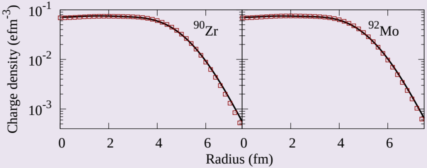


FIGURE : Charge densities in magic nuclei.

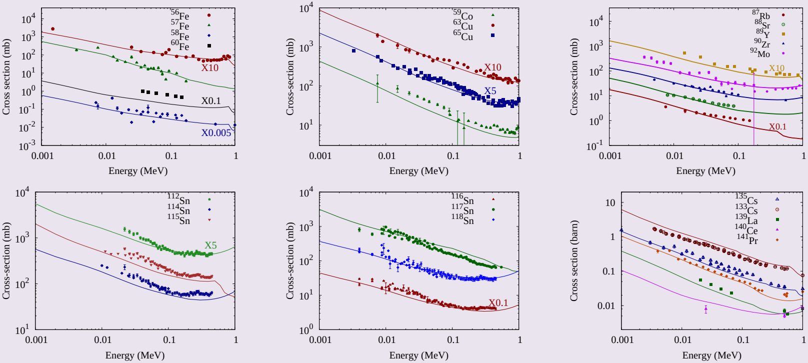


FIGURE : The (n, γ) cross sections from 1 keV to 1 MeV for nuclei in and around shell closures.

Comparison with two different OMPs

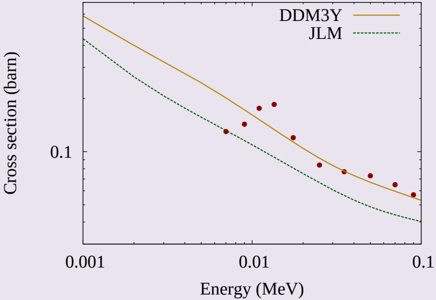


Figure : Radiative neutron capture cross-sections for ^{144}Sm target from our microscopic OMP has been compared with that obtained using JLM potential JLM OMP and plotted against experimental data represented by red points.

THE NETWORK AND SENSITIVITY STUDY

- A network for *s*-process with nearly 400 nuclides → solved numerically.
- Major *s*-process components → weak $(56 < A < 100)$ and main $(A > 100)$
- Present work → main component → in thermally pulsating asymptotic giant branch (TP-AGB) stars $(1 < M/M_\odot < 3)$.
- The $^{13}C(\alpha, n)$ neutron source reaction → temporal temperature and neutron density profiles.
- Statistical neutron capture rates have been included as inputs.

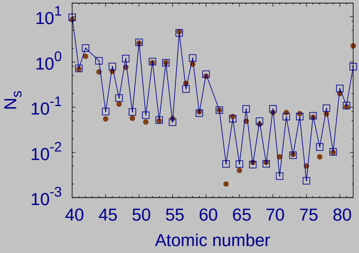


FIGURE : Elemental abundance distribution from Zr up to Pb. Abundances are normalized to Sm.

- A sensitivity study is done → to identify important neutron capture rates in *s*-process.

LIST OF PUBLICATIONS I

1. *Microscopic folding model analysis of the radiative* (n,γ) *reactions near the* $Z = 28$ *shell-closure and the weak s-process*, Saumi Dutta, G. Gangopadhyay, and Abhijit Bhattacharyya, Physical Review C **94**, 054611 (2016). doi: 10.1103/PhysRevC.94.054611
2. *Neutron capture reactions relevant to s-process and p-process in the domain of the* $N = 50$ *shell closure*, Saumi Dutta, G. Gangopadhyay, and Abhijit Bhattacharyya, Physical Review C **94**, 024604 (2016). doi: 10.1103/PhysRevC.94.024604
3. *Neutron capture reactions near the* $N = 82$ *shell-closure*, Saumi Dutta, Dipti Chakraborty, G. Gangopadhyay, and Abhijit Bhattacharyya, Physical Review C **93**, 024602 (2016). doi: 10.1103/PhysRevC.93.024602

4. *Radiative proton capture cross sections in the mass range* $40 - 55$, Dipti Chakraborty, Saumi Dutta, G. Gangopadhyay, Abhijit Bhattacharyya, Physical Review C **94**, 015802 (2016). doi: 10.1103/PhysRevC.94.015802
5. *Low-energy proton capture reactions in the mass region* $55 - 60$, Saumi Dutta, Dipti Chakraborty, G. Gangopadhyay, and A. Bhattacharyya, Physical Review C **91**, 025804 (2015). doi: 10.1103/PhysRevC.91.025804
6. *Microscopic study of* (p,γ) *reactions in the mass region* $A = 110 - 125$, Dipti Chakraborty, Saumi Dutta, G. Gangopadhyay, Abhijit Bhattacharyya, Physical Review C **91** 057602 (2015). doi: 10.1103/PhysRevC.91.057602

- One interesting region in the nucleosynthesis path → Cd-In-Sn region
- Astrophysical origins of rare isotopes ^{113}In, ^{114,115}Sn are puzzle

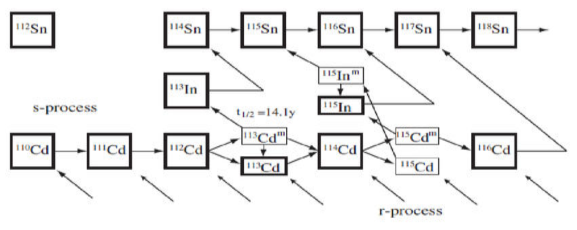


FIGURE : Nucleosynthesis path near the Cd-In-Sn region; figure taken from Hayakawa *et. al.*, The Astrophysical Journal **707**, 859 (2009).

- Presence of many long-lived isomers → interplay of all three nucleosynthesis processes
- Our focus → three isomers ^{113m}Cd ($t_{1/2}$ = 14.1 years), ^{115m}Cd ($t_{1/2}$ = 44.56 days), ^{113m}In ($t_{1/2}$ = 1.6975 hours)
- Astrophysical significance → isomeric branchings impart small *s*-contribution to the nuclei ^{113}In, ^{114,115}Sn → finally all merge at ^{116}Sn
- Astrophysical plasma → hot photon bath → thermally induced transitions → populated excited states can significantly contribute

EFFECTIVE β-DECAY RATES I

- Effective β-decay (EBD) rates (temperature-dependent) are used assuming the states are in thermal equilibrium.

$$\lambda^{\beta}_{eff}(T) = \sum_i n_i(T)\lambda^{\beta}_i \tag{8}$$

- Gateway levels → excited states above isomer and ground states → couple ground states and isomers to thermal equilibrium by (γ, γ') transitions
- Thermalization rate (λ_{th}) can be estimated (Ref. Klay *et. el.* Phys. Rev. C **44**, 2839 (1991)).

$$\lambda_{th} = -\frac{V(1-V)}{\tau_i}\frac{g_i}{g_m}e^{-(E_i-E_m)/kT} \tag{9}$$

  Here, V: γ-branch factor; g_i and g_m: spin factors, E_i and E_m: energies of gateway level and metastable states; τ_i: lifetime of the gateway level
- If IT rates are not fast enough or the ground and isomeric states have very different rates → thermal equilibrium is not a valid assumption
- Defining a single EBD rate is ambiguous → EBD rate for individual ground and isomeric states → each state should be included in nucleosynthesis network

EFFECTIVE β-DECAY RATES II

- Starting from an initial abundance (N_i) of a state → allow it to evolve with time.

$$\dot{N}_i = \sum_j (\lambda_{ji} N_j - \lambda_{ij} N_i) - \left(\sum_d \lambda_i^d \right) N_i \tag{10}$$

- The time (τ_{eff}) at which the abundance falls $1/e$ times the initial value, defines the EBD rate

$$\sum N_i(\tau_{eff}) = 1/e \sum_i N_i(t = 0) \tag{11}$$

- Our goal → to calculate the effective β-decay rates for all astrophysically significant states → to implement them in nucleosynthesis code.

SUMMARY

- The (n, γ) cross sections and β-decay rates are crucial inputs for heavy element neutron capture processes.
- In my doctoral tenure,
  - The radiative neutron and proton capture cross sections have been studied in statistical Hauser-Feshbach formalism with microscopically folded neutron optical model potential.
  - DDM3Y NN interaction has been chosen and folded with target radial matter densities and densities are extracted from relativistic-mean-field model.
  - A network for *s*-process with nearly 400 nuclei has been built and solved numerically.
- Future aim is to calculate decay rates of important long-lived isomers of astrophysical importance and implement them in nucleosynthesis network.

Thank You