Nuclear inputs in astrophysical s-process nucleosynthesis

G. Gangopadhyay*
Department of Physics, University of Calcutta, Kolkata 700 009

Astrophysical s-process and r-process are the principal mechanisms of production of elements beyond the iron peak nuclei. The s-process takes place in AGB stars where capture of neutrons, produced in situ, and subsequent beta decay produce nuclei heavier than iron-nickel. Nuclei with magic number of nucleons act as bottlenecks in the s-process. We present radiative neutron capture cross section calculations in some of these nuclei. We also apply our results to a simple s-process scenario to study the sensitivity of the process with regard to nuclear reactions and beta decay.

1. Introduction

The framework for nucleosynthesis in stars was laid by Burbidge *et al* in a seminal work [1]. Elements between carbon and iron-nickel are produced in stellar interiors in hydrostatic burning process. Heavier elements are principally synthesized through capture of neutrons on existing iron-group seed elements in two processes, *viz.* the slow and the rapid processes. The former is called the s-process and takes place in AGB stars with neutrons produced in situ. (See [2] for a recent review). The latter is known as r-process and present theory prefers neutron star merger and supernova neutrino wind as its sites.

Radiative neutron capture cross sections are crucial in the study of heavy element nucleosynthesis as they are important inputs of s-process networks. In the talk, we will present our calculation of some of the reaction cross sections. We will also look at the importance of these reactions and some beta decay lifetimes on the s-process in a simple scenario.

Nuclei around magic numbers act as bottlenecks in the s-process because their neutron capture cross sections are small. It is clear that these reaction cross sections are important. At the same time, this also means that measurements in astrophysically relevant energies are difficult. Further, s-process nucleosynthesis takes place in astrophysical plasma where the neutrons follow a Maxwell-Boltzmann distribution. Hence, Maxwellian-averaged cross section (MACS) values should be used in s-process network calculations. Most of the experimentally determined MACS values are available only at a single temperature $kT = 30$ keV. However, recent realistic astrophysical calculations require values over a larger range of temperatures. One also needs capture cross sections in some unstable nuclei. Reactions in these nuclei are difficult, and sometimes impossible, in terrestrial laboratories. Thus, in many instances the capture rates have to be theoretically calculated.

*Electronic address: ggphy@caluniv.ac.in

2. Calculation

In the present work, astrophysically relevant radiative neutron capture cross sections and reaction rates have been calculated using semi-microscopic compound-nuclear Hauser-Feshbach (HF) model. An optical model potential has been constructed in microscopic folding model using effective NN interactions. Nuclear density needed for this model has been calculated using the relativistic mean field model using the Lagrangian density FSU Gold.

We have employed the TALYS code[3] for calculation of cross section in the HF approach. We have modified the code to include the DDM3Y NN interaction which we use to construct the semi-microscopic optical potential.

One important part of a reaction network calculation is the sensitivity study. We have analyzed the effect of the reaction rates for the main component of s-process. This occurs in low-mass thermally pulsating AGB stars. With proper choices of neutron density and temperature profiles for the reaction pockets, we perform a simple network calculation to identify the important nuclear inputs.

3. Results

Calculations have been carried out in medium and heavy nuclei near magic numbers[4]. We calculate the cross section values and compare with experiments to find an optimum parameter set for the NN interaction. The MACS values for some nuclei near N=82 are shown in Table I.

TABLE I: Maxwellian averaged cross-sections at $kT = 30$ keV for nuclei near the $N = 82$ shell closure. MOST refers to another HF calculation[5]. Nuclei with $N = 82$ are in bold fonts.

	MACS(mb)		
Nucleus	Pres.	Exp.	MOST
$^{135}_{55}$Cs	147	160±10	148
$^{137}_{55}$**Cs**	16.1		
$^{137}_{56}$Ba	81.8	76.3±2.4	95.4
$^{138}_{56}$**Ba**	4.14	4.00±0.20	2.79
$^{139}_{57}$**La**	31.0	32.4±3.1	45.9
$^{140}_{58}$**Ce**	12.7	11.0±0.4	6.71
$^{141}_{58}$Ce	198.8		58.4
$^{142}_{58}$Ce	33.5	28±1	16.7
$^{141}_{59}$**Pr**	101	111.4±1.4	130

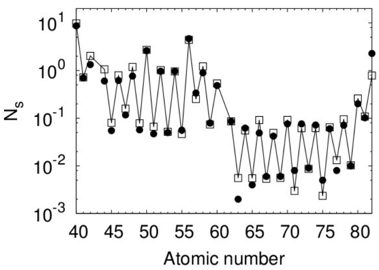

FIG. 1: Present (square) and classical (circle) elemental abundance distribution from Zr to Pb in the main component of s-process.

A simple s-process network that includes neutron capture, photodisintegration, electron and positron beta decay and alpha decay at the end in Pb-Bi region has been constructed. This includes 350 nuclei and starts at Fe-Ni seed nuclei. A solar-like seed abundance is assumed. Neutron density and temperature profiles for the ^{13}C pocket in a single inter-pulse period of a typical TP-AGB star are taken from literature[6]. For the main s-process, the abundance is normalized to the s-only isotope ^{150}Sm. Fig 1 shows the result of our calculation and compare it to a classical model.

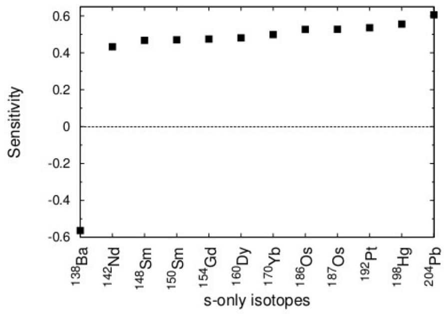

FIG. 2: Sensitivity of abundance with respect to the neutron capture reaction in ^{138}Ba.

Sensitivity study has been carried out to find out the important cross sections and beta decay rates for our model. Fig. 2 shows the sensitivity of one reaction.

Acknowledgments

The work was carried out with Dr. Saumi Dutta and constitutes a part of her Ph.D. thesis. Financial assistance of the University Grants Commission under the UGC-DRS II Programme is gratefully acknowledged.

References

[1] M. E. Burbidge *et al*, Rev. Mod. Phys. **29**, 547 (1957)
[2] F. Käppeler *et al*, Rev. Mod. Phys. **83**, 157 (2011).
[3] www.talys.eu
[4] S. Dutta *et al*, Phys. Rev. C **93**, 024602 (2016); **94**, 024604 (2016); **94**, 054611 (2016).
[5] S. Goriely, Phys. Lett. **B 436**, 10 (1998).
[6] R. Gallino *et al*, Astrophysical Journal **497**, 288 (1998).