Radiative neutron capture reaction rates for r-process nucleosynthesis

Vinay Singh,* Joydev Lahiri, and D. N. Basu
Variable Energy Cyclotron Centre, 1/AF Bidhan Nagar, Kolkata 700064

Introduction

In neutron star merger events, the occurrence of rapid neutron-capture process (r-process) has been established. About half of the elements beyond iron are synthesized in stars by r-process. In stellar environments very high neutron flux in a short time (∼ a few seconds) can be attained which leads to the creation of progressively neutron-rich nuclei until the waiting point is reached. At this point no further neutron capture reactions can proceed and highly neutron-rich nuclei become stable via β^- decay. A detailed understanding of the r-process remains illusive. In the present work, the theoretical predictions of radiative neutron capture (n,γ) cross sections of astrophysical importance and the reaction rates using the Hauser-Feshbach statistical model formalism have been investigated for Fe, Co, Ni, Cu, Zn, Ga, Ge, As and Se isotopes (around the first r-process peak near mass 80). These calculations have been compared with the JINA REACLIB reaction rates. The inherent uncertainties remain large in cases of neutron-rich nuclei. When the low-energy enhancement exists, it results in significant increase in the reaction rate for neutron-capture.

Theoretical formalism

The radiative neutron capture cross section varies inversely as velocity in the range of thermal energies. At these energies, the feature of $\sigma(E) \propto E^{-1/2}$ leads to approximate constancy of thermonuclear reaction rates with respect to plasma temperature. However, above thermal energies, especially in the domain of astrophysics, the neutron induced reaction cross section deviates from the $1/v$ law. Thus it is expected that $\langle\sigma v\rangle$ has to have a temperature dependence. The computer code TALYS [1] allows a comprehensive astrophysical reaction rate calculations apart from other nuclear physics calculations. To a good approximation, in the interior of stars the assumption of a thermodynamic equilibrium holds and nuclei exist both in the ground and excited states. This assumption along with cross sections calculated from compound nucleus model for various excited states facilitates Maxwellian-averaged reaction rates. The Hauser-Feshbach statistical model calculations have been extended by adding some new and important features. Apart from coherent inclusion of fission channel it also includes reaction mechanism that occurs before equilibrium is reached, multi-particle emission, competition among all open channels, width fluctuation corrections in detail, coupled channel description in case of deformed nuclei and level densities that are parity-dependent. Nuclear models are also normalized for available experimental data using separate approaches such as on photo-absorption data, the E1 resonance strength or on s-wave spacings, the level densities.

The astrophysical nuclear reaction rate can be calculated by folding the Maxwell-Boltzmann energy distribution for energies E at the given temperature T with the cross section $\sigma^{\mu}_{\alpha\alpha'}(E)$. The relative populations of various energy states of nuclei with excitation energies E^{μ}_x and spins I^{μ} in thermodynamic equilibrium follows the Maxwell-Boltzmann distribution. In order to distinguish between different excited states the superscript μ is used along with the incident α channel in the formulas that follow. Taking due account of various target nuclei excited state contributions, the effective nuclear reaction rate in the entrance channel $\alpha \to \alpha'$ can be expressed as

$$N_A\langle\sigma v\rangle^*_{\alpha\alpha'} = \left(\frac{8}{\pi m}\right)^{1/2} \frac{N_A}{(kT)^{3/2}G(T)} \qquad (1)$$
$$\times \int_0^\infty \sum_\mu \frac{(2I^\mu+1)}{(2I^0+1)} \sigma^\mu_{\alpha\alpha'}(E) E \exp\left(-\frac{E+E^\mu_x}{kT}\right) dE$$

where N_A is the Avogadro number, k and m are the Boltzmann constant and the reduced mass in the α channel, respectively, and

$$G(T) = \sum_\mu (2I^\mu+1)/(2I^0+1)\exp(-E^\mu_x/kT)$$

is the temperature dependent normalized partition function.

Calculations and Results

The cross sections for nuclear reaction and its convolution with Maxwell-Boltzmann distribution of energies are important for the explanation of various processes occurring under extreme conditions. In the main-sequence stars and compact stars which are in their ultimate stages of evolution, such environments of very high density and temperature prevail. The exothermic fusion reactions causes nuclear explosions in the surface layers of the accreting white dwarfs (nova events), in the cores of massive accreting white dwarfs (type Ia supernovae) and in the surface layers of accreting neutron stars (type I X-ray bursts and superbursts. Precise knowledge of the rates of thermonuclear reactions obtained by folding Maxwell-Boltzmann distribution of energies with energy dependent cross sections becomes necessary for describing these astrophysical phenomena.

*Electronic address: vsingh@vecc.gov.in

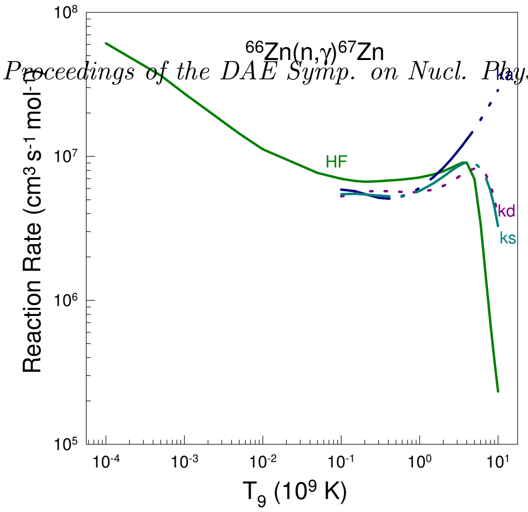

FIG. 1: Comparison of the predictions of ^{66}Zn(n,γ) reaction rates (HF) with the data from JINA REACLIB [2, 3].

The calculations have been performed using the most recent level density based on temperature dependent Hartree-Fock-Bogolyubov calculations using the Gogny force and for the gamma-ray strength function Brink-Axel Lorentzian has been used [1]. The radiative neutron capture cross sections as functions of incident neutron energy have been calculated and the computed reaction rates as functions of of temperature for Fe, Co, Ni, Cu, Zn, Ga, Ge, As and Se isotopes have been compared with experimental results of JINA REACLIB reaction rates of I. Dillman et al. (ka,kd) [2] and KADoNiS (ks) [3]. In Figs.1-2, some of these plots for have been shown.

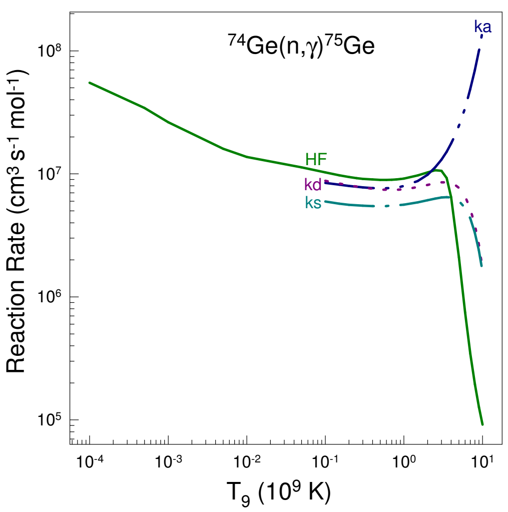

FIG. 2: Comparison of the predictions of ^{74}Ge(n,γ) reaction rates (HF) with the data from JINA REACLIB [2, 3].

Summary and Conclusion

To summarize, in the present work the theoretical predictions of radiative neutron capture (n,γ) cross sections of astrophysical importance and the reaction rates for Fe, Co, Ni, Cu, Zn, Ga, Ge, As and Se isotopes using the Hauser-Feshbach statistical model reaction calculations have been investigated. It is observed that the experimental results are uncertain by a few orders of magnitude for nuclei even in the vicinity of the valley of stability. Some key reactions which may have significantly large impact on the final abundances in the region of mass number around eighty have been explored. The calculations of the (n,γ) reaction rates have been compared with the JINA REACLIB reaction rates. Since in several cases large deviations among fits to experimental data of ka, kd and ks do exist, estimates of present calculations can be termed as good. In addition, it is recognized that the uncertainties due to the factors such as level densities and mass models may have substantial effects on the rates while the low-energy upbend in the γ-strength function has a little (though non-negligible) effect on the rates. To conclude, it is envisaged that to constrain the (n,γ) reaction rates near the mass region eighty there is an acute need of more data. In order to exclude or establish certain model inputs, new experimental techniques, namely, the surrogate method for neutron rich nuclei and the beta-Oslo method may contribute some crucial information of paramount importance.

Acknowledgments

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