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Nucleosynthesis in Neutron Stars Crust

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Abstract: We address the problem of the origin of heavier and super heavy elements in nature. Believing rapid neutron capture process (r-process) is responsible for synthesis of heavy and super heavy elements in the remnants of supernovae explosions and neutron star crusts under extreme conditions, we developed a computer code in order to understand the formation of elements in extreme astrophysical systems. We carried out Nuclear Statistical Equilibrium (NSE) as well as static r-process calculations for a wide range of input parameters.

Keywords: Neutron stars, r-process, NSE, Nucleosynthesis, Nuclear Statistical equilibrium

1. INTRODUCTION

Understanding the formation of heavy and super heavy nuclei in the universe is another challenging problem [1]. It is predicted that the rapid neutron-capture process (r-process) could be responsible for the synthesis of heavy and super heavy elements in supernova explosions and [NS] crust under extreme physical conditions [6].

Though it is known how the astrophysical conditions for a successful r-process can be estimated, the astrophysical sites, in which ideal r-process conditions are met, are yet to be identified. Supernova, where presumably the r-process is successful for a choice of model parameters could not reproduce the observed solar abundances of r-process elements and has been abandoned by recent studies [9].

Neutron-rich ejecta of compact binary mergers are now believed to be a perfect candidate for an astrophysical r-process [9]. In the events of merging of binary neutron star or a neutron star with a black hole, the crust matter can be dynamically stripped and ejected. Most of the material ejected when a neutron star is tidally disrupted, originates from the NS's neutron-rich outer

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core, which has a typical electron fraction Ye$\sim$0.1 set by β-equilibrium under highly degenerate conditions. The neutron-rich nuclei emit neutrons as the material expands to lower density.

Once the density decreases below neutron drip, ß-decay channels begin opening in full, and a conventional r-process begins leading to the formation of very heavy nuclei when the seed nuclei rapidly capture the free neutrons. Meyer showed that the decompression of initially cold neutron star material heats up during the expansion and forms r-process nuclei [2]. Recently it has been shown that the decompression of the neutron star matter from the outer crust provides suitable condition for nucleosynthesis of r-nuclei with $A \leq 140$ [8]. They used the existing results of binary neutron star and neutron star-black hole merger events and studied the evolution of the ejected mass. Although mergers are promising candidates for r-process site, they too, face challenges due to uncertainty in high-density EoS, electron fraction and effects of neutrino transport. Decompressing neutron matter from the neutron star ejecta has come up as an additional or alternate site for r-process nucleosynthesis.

The decompression is triggered by a phase transition to strange quark matter at the core of a neutron star that ejects neutron-rich matter at the surface [7, 10].

2. NUCLEAR STATISTICAL EQUILIBRIUM

In the course of the fusion reactions inside the star, once silicon burning stage is reached, the temperature rises upto a limit, when various nuclei reach one large equilibrium group which stretches from p, n, α to the iron peak nuclei, this condition is known as Nuclear Statistical Equilibrium.

Considering, astrophysical plasma that composed of photons, free neutrons and protons and mix of seed nuclei such as ^{56}Fe, with temperature and density high enough that the nuclear reactions assembling nuclei from free neutrons and protons are much faster than the expansion time scale. For large enough temperatures $T_9 = T/(10^9)$ K, the system would reach NSE with equal forward and backward reaction rates.

For NSE conditions, the balance equation is given by,

$$Z_i \mu_p + N_i \mu_n = \mu_i \tag{1}$$

Where, μ_i is the chemical potential of the nuclei i, with Z_i, N_i and A_i being the corresponding atomic number, neutron number and mass number, respectively.

Taking Maxwell-Boltzmann statistics into consideration, the particle number densities for all the nuclei are given by,

$$n_i = g_i \left(\frac{2\pi kTm_i}{h^2}\right)^{3/2} \exp\left(\frac{\mu_i + B_i}{kT}\right) \tag{2}$$

Where B_i's are the binding energies of nuclei and g_i's are the degeneracy factors. From mass and charge conservation,

$$\sum A_i Y_i = 1 \tag{3}$$

$$\sum Z_i Y_i = Y_e \tag{4}$$

Combining Eqs.(1) and (2) with conservation eqs. (3) and (4),

$$\sum_i A_i n_i \left(\mu_p, \mu_n\right) - \rho N_A = 0 \tag{5}$$

$$\sum_i Z_i n_i \left(\mu_p, \mu_n\right) - Y_e \rho N_A = 0 \tag{6}$$

For a given value of electron fraction, temperature and mass density, We solve Eqs. (5) and (6) by the Newton-Raphson method for μ_p, μ_n and use these values to obtain the mass fraction of different nuclei and number densities of protons and neutrons.

The Static r-process

A number of reactions can occur simultaneously for producing and destroying nucleus i, whose reaction induced density evolution is given by,

$$\left(\frac{dn_i}{dt}\right)_{\rho=const} = \sum_j N_j^i r_j + \sum_{j,k} N_{j,k}^i r_{j,k} \tag{7}$$

Here the individual N^i's in the above eq. are positive and negative numbers showing the creation and annihilation. The number abundances Y_i and mass abundances X_i are given by,

$$Y_i = \frac{n_i}{\rho N_a} \tag{8}$$

$$X_i = \frac{m_i n_i}{\rho N_A} \tag{9}$$

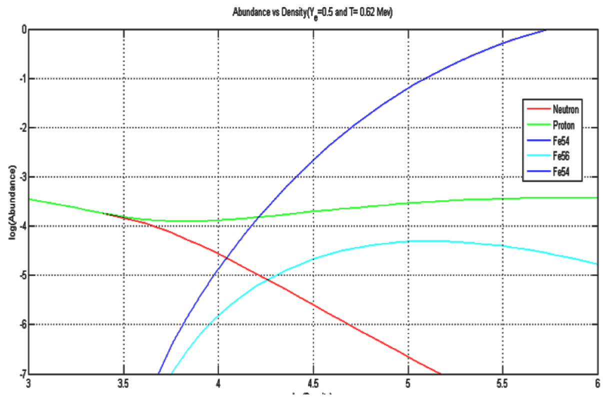

Figure 1: Abundance vs Density.

Considering the values of r_j and $r_{j,k}$ and writing eq.(7) in terms of Y_i,

$$\dot{Y}_i = \sum_j N^i_j \lambda_j Y_j + \sum_{j,k} \frac{N^i_{j,k}}{1+\delta_{jk}} \rho N_A \langle \sigma v \rangle_{jk} Y_j Y_k \qquad (10)$$

Where, is the Kronecker delta and $\langle \sigma v \rangle_{jk}$ is the thermally averaged reaction cross section.

Applying this to the r-process, we consider the neutron capture, photodisintegration and β-decay interactions.

Since, we consider waiting point approximation which sets lower limits on the temperature of 2×10^9 K and neutron number density of 10^{20} cm^{-3} for our simulations, photodisintegrations and neutron captures are faster than β-decay. Assuming the steady flow when high density and high temp is considered, we can have Y(Z, A) = 0.

3. RESULTS

In this paper, we use the equations and theories of [4] and try to reproduce some of the plots of this reference taking different values of the input parameters for various nuclei. Initially we consider for NSE and static r-process simulation. Fig.1. shows high densities favor large nuclei due to ρ-dependence. As density increases, heavy nuclei are formed, number of free neutrons reduced. Fig.2. shows the variation of abundance with electron fraction Elements are present in low Ye region due to Coulomb barrier effect and from Fig. 3. It's clear that high temperature favors light nuclei. At high temperatures, heavy nuclei dissolves into nuclear matter Fig.4. shows the variation of relative abundance

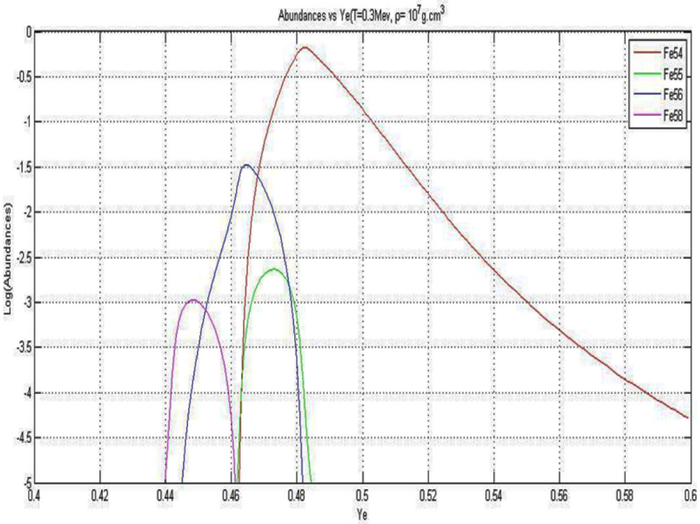

Figure 2: Abundance vs Ye.

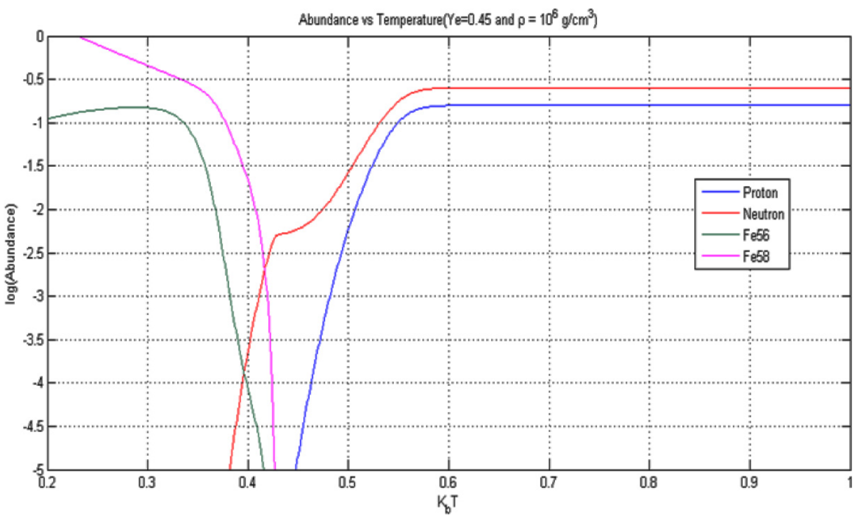

Figure 3: Abundance vs Temp.

with atomic number. In this figure the peaks correspond to magic numbers emphasizing waiting point approximation.

In Fig 1, we plotted Abundance vs. Density in log scale for electron fraction (Y_e) = 0.5 and temp (T) = 0.62 MeV.

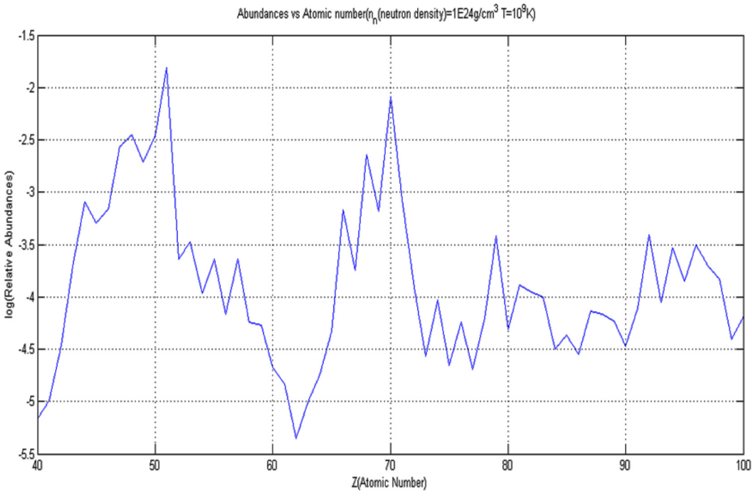

Figure 4: Relative abundance vs Atomic number (Z).

In Figure 2, we plotted Abundance in log scale vs Electron fraction (Y_e) for T = 0.3 MeV and $\rho = 10^7$ g-cm^{-3}

In Figure 3, we plotted Abundance vs. temp for Ye = 0.45 and $\rho = 10^6$ g-cm^{-3}.

In Figure 4, we plotted relative abundance vs atomic number for T = 10^9 K and neutron density = 10^{24} g-cm^{-3}.

CONCLUSION AND FUTURE ASPECT

Our work is still in a developing stage. We would like to investigate the dynamical situation next before doing a more realistic investigation of r-process in neutron star ejecta.

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