Basic Simulation of s- and r- Processes in Stars and formation of heavy elements

Rajeev Singh

Institute of Nuclear Physics Polish Academy of Sciences, PL-31342 Krakow, Poland

E-mail: rajeev.singh@ifj.edu.pl

ABSTRACT: In this introductory project, we have studied the about the neutron capture processes which are responsible for the abundances of heavy elements than iron in different phases of stellar evolution. Our main aim is to understand the distribution of isotropic abundances in our universe. First we start with the discussion on nucleosynthesis and its types, then we discussed about the different types of neutron capture processes. After that we provide results of the simulation which we have done using Monte Carlo method. Finally we conclude with the importance of these processes and current research status.

KEYWORDS: Nucleosynthesis, Neutron capture processes, abundance of heavy elements.

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1 Introduction

Nucleosynthesis is simply an idea of how the chemical elements were created in the universe. In general, in the universe, hydrogen and helium are the prevalent constituents. Arthur Eddington was the first to put forward that stars get their energy by the fusion of hydrogen into helium and also discussed that heavier elements can form in stars [1, 2].
Due to the poor understanding of nuclear mechanism at that time, this idea of A. Eddington was not accepted by peers. But after the second world war, Hans Bethe explained nuclear mechanisms due to which hydrogen is fused into helium. Fred Hoyle's original work on nucleosynthesis of heavier elements in stars explained the production of all heavy elements. He also explained how the abundances of heavy elements is increasing with time. Hoyle's idea was further expanded in 1960 by William A. Fowler, Alastair G. W. Cameron, and Donald D. Clayton. Renowned 1975 paper [3] by E. M. Burbidge, G. R. Burbidge, Fowler and Hoyle is a well written summary of this field. The main aim of the theory of nucleosynthesis is to give explanation of the abundances of different types of chemical elements and their isotopes from the fundamental processes. There are various types of astrophysical processes which are responsible for nucleosynthesis. These processes occur in stars at the various stages of their lives, and these nuclear fusion processes are called as hydrogen burning (via the proton-proton chain or the CNO cycle), helium burning, carbon burning, neon burning, oxygen burning and silicon burning. These processes help to create elements upto iron and nickel. Heavy elements than iron are created by neuron capture processes.
In this introductory project, we have modeled the r- and s- process, using an artificial scenario and performed simulation to understand the basic mechanisms of formation of heavy elements.
Our main aim is to understand the distribution of isotropic abundances in our universe. First we start with the discussion on nucleosynthesis and its types, then we discussed about the different types of neutron capture processes. After that we provide results of the simulation which we have done using Monte Carlo method. Finally we conclude with the importance of these processes and current research status.

2 Nucleosynthesis

2.1 What is Nucleosynthesis?

It is a process of creating new atomic nuclei from pre existing nucleons (that is, protons and neutrons). After three minutes of Big Bang,the first hadrons were formed, and the process is known as Big Bang nucleosynthesis. Hence, it was known that hydrogen and helium were the content of the first stars. With time, stars formed and heavier nuclei were created from hydrogen and helium by the process of stellar nucleosynthesis.

In exploding stars, nucleosynthesis happens by fusing carbon and oxygen which is responsible for the abundances of elements between magnesium and nickel and the process is called supernova nucleosynthesis [4]. This process is also responsible for the creation of some elements heavier than iron in the type II supernova event. When these elements are created, these absorbs energy produced during supernova explosion. Some of these elements are created from r process in the last seconds of explosion. Some elements like helium, beryllium and boron which are not created by stellar nucleosynthesis are formed by cosmic ray spallation which impact the interstellar medium.

2.2 Types of Nucleosynthesis processes

- **Big Bang Nucleosynthesis**: The theory of BBN began with the mathematical calculations of cosmologist Ralph Alpher in 1940s when he published the paper which explained light element production in the early universe. This theory of BBN gives detailed mathematical explanation for the production of the light "elements" deuterium, helium-3, helium-4, and lithium-7.

  BBN happened around ten seconds after big bang when the temperature was low enough to allow deuterium nucleus not to be disrupted by highly energetic photons. At this time universe was highly radiation dominated and this dominance controls the relation between temperature and time. Sequence of some important reaction chain is shown below [5].

- **Stellar Nucleosynthesis**: This process is responsible for the creation of chemical elements and its abundances in stars because of nuclear fusion reactions. With time, stars evolve with changes in the abundances of the elements. Fusion in the core of the star increase the atomic weight of elements and the number of particles get reduced which in turn decrease the pressure and gravity leads to contraction, temperature increase and the balances of forces [6].

  When a star eject in its lifetime, it loses most of its mass which increases the abundance of elements which are heavier than helium in the interstellar medium. This stellar nucleosynthesis process used to explain the creation of elements during the evolution and explosion of a supernova star, this concept was given in 1954 by Fred Hoyle [7]. The discovery of variations in the abundances of elements which were found in our universe lead to the development of this theory. This stellar nucleosynthesis process is very important contributor for abundance of elements in our universe.

  During the year 1928, George Gamow derived Gamow factor which gives the probability of two nuclei to overcome the Coulomb barrier potential. This quantum mechanical

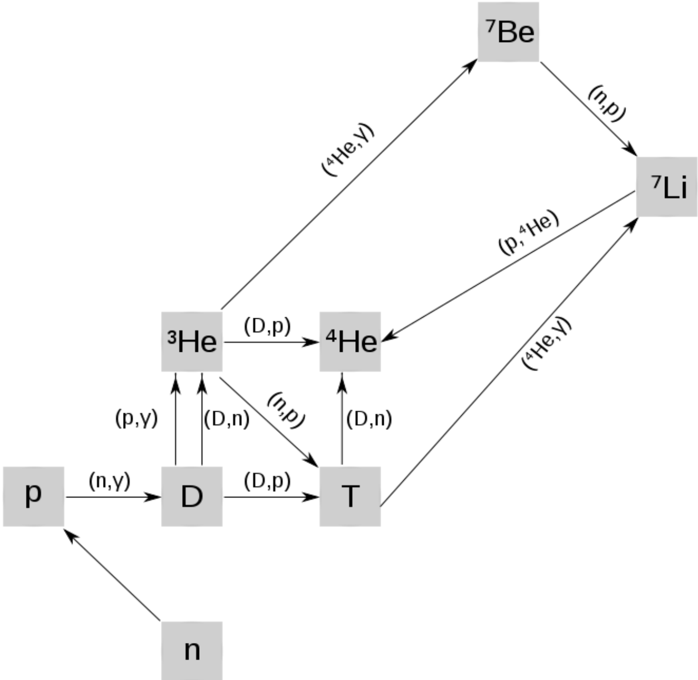

Figure 1. The nuclear reaction chains for Big Bang Nucleosynthesis.

formula was also used to find the rate of nuclear reactions proceeding at high temperatures. Hans Bethe calculated the possibilities for hydrogen fusion into helium in a paper namely "Energy Production in Stars" in the year 1939 [8]. He explained two processes, firstly, proton-proton (p-p) chain, which is the main contributor of energy source in stars like sun and secondly, Carbon-Nitrogen-Oxygen (CNO) cycle which is believed to be occurring in more massive stars [6].
Fred Hoyle in 1954 described that how fusion process in stars synthesize elements between carbon and iron. This provided a path to explain how the most abundant elements which was found on Earth had been synthesized from hydrogen and helium. This also explains the abundances of elements in galaxy. D. Clayton gave the time dependent models of S- process [9] and R- process [10] . He also gave model for the abundant of alpha particle nuclei and iron group elements from silicon burning [11, 12]. Important reactions in stellar nucleosynthesis:

1. Hydrogen Fusion
   - Deuterium fusion
   - proton proton chain
2. Helium Fusion
   - Triple alpha process
   - Alpha process
3. Fusion of Heavy Elements
   - Lithium burning

- Carbon burning
    - Neon burning
    - Oxygen burning
    - Silicon burning

4. Fusion of heavy elements than iron
    - Neutron capture: R- and S- processes
    - Proton capture: Rp process
    - Photo-disintegration: P- process

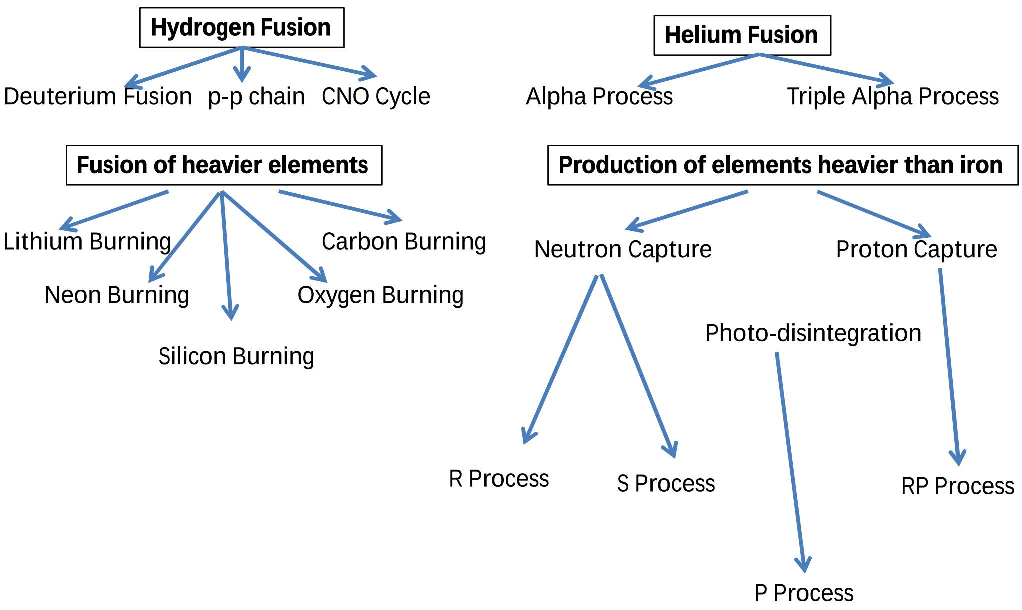

Figure 2. The nuclear reaction chains for Stellar Nucleosynthesis.

- **Supernova Nucleosynthesis**: This theory explain the creation of different elements during supernova explosions and this was advanced by Fred Hoyle. The fusion of lighter elements to heavy ones occurs during oxygen and silicon burning processes [13]. These fusion reactions help to create silicon, sulfur, chlorine, argon, sodium, potassium, calcium, scandium, titanium, vanadium, chromium, manganese, iron, cobalt and nickel. Due to the ejection from supernovae, abundances of these elements increases in the interstellar medium. Heavy elements than nickel are produced due to neutron capture processes, but they are less abundant than the primary elements. Some other processes are also there namely rp process and p process for the nucleosynthesis of elements.

Supernova which is a massive explosion of a star occurs under two conditions. Firstly, a white dwarf star explodes after reaching Chandrasekhar limit and secondly, when a massive star reaches nickel-56 by nuclear fusion and this isotope changes to iron-56 by radioactive decay. All the nuclear fusion reactions which produces heavy elements make the star to lose energy and these reactions are called endothermic reactions and the pressure which support the outer layers of star dramatically drops. When the outer layer is insufficiently supported by radiation pressure, gravity plays its role pulling the outer layers rapidly inward which collapses the star colliding with the core and produces a shock-wave. The pressure of the shock-wave is enough to induce the fusion and energy released makes the star to explode releasing material from the star into interstellar space.

Stellar Nucleosynthesis

Evolutionary Time Scales for a 15 M_{sun} Star

Fused	Products	Time	Temperature
H	^{4}He	10^{7} yrs.	4×10^{6} K
^{4}He	^{12}C	Few X 10^{6} yrs	1×10^{8} K
^{12}C	^{16}O, ^{20}Ne, ^{24}Mg, ^{4}He	1000 yrs.	6×10^{8} K
^{20}Ne +	^{16}O, ^{24}Mg	Few yrs.	1×10^{9} K
^{16}O	^{28}Si, ^{32}S	One year	2×10^{9} K
^{28}Si +	^{56}Fe	Days	3×10^{9} K
^{56}Fe	Neutrons	< 1 second	3×10^{9} K

Figure 3. Stellar Nucleosynthesis.

- **Cosmic ray spallation**: It is a natural form of nucleosynthesis and nuclear fusion. This process explains the formation of chemical elements from cosmic rays impact on any object. These cosmic rays are highly energetic and about one percent of these are consist of free electrons. When a particle impacts with the matter, large amount of nucleons releases from the object.

3 Astrophysical processes for the formation of heavy elements than iron

3.1 P Process

Proton rich nucleus can be formed when one or more protons are added to a nucleus. This type (p, γ) of nuclear reaction is known as proton capture reaction. When we add one proton, the atomic number of the nucleus increases and hence the element changes and therefore ratio of protons to neutrons also changes which makes the proton richer isotope of the next element. This was the main idea for the production of proton rich nuclei [3, 14]. Its not very efficient in producing p- nuclei by adding protons to stable nuclides, because electric charge increase with the increase in each proton leading to the increase in Coulomb repulsion (or Coulomb barrier). More the Coulomb barrier, more the kinetic energy required by a proton to get near to the nucleus and to be captured.
Even if the temperature of the stellar plasma gives the energy to the protons, protons will be removed faster by photo disintegration than they are captured by the nucleus at such high temperature. Therefore the possible solution is to have very large amount of protons for proton capture per second without any such high temperature. But this cannot occur in core collapse supernova [15, 16]. When there is a capturing of proton at very high proton densities, this process is known as rapid proton capture capture. These processes are rp-process, νp- process and pn- process.

3.2 Photo disintegration

When an atomic nucleus absorbs a high energy gamma ray, it enters into an excited state and decays after a subatomic particle. This nuclear process is known as photo disintegration. The gamma ray (or photon) kicks out one or more neutrons, protons or alpha particle and the reactions are $(\gamma, n)\,, (\gamma, p)\, and\, (\gamma, \alpha)$[6]. Its an endothermic process for atomic nuclei below iron and exothermic for atomic nuclei heavier than iron.

3.3 R- process

R- process means rapid neutron capture process, this a group of nuclear astrophysics reactions responsible for the nucleosynthesis of almost half of the nucleus heavier than iron (Fe). This involves a number of rapid neutron captures by a seed nuclei (like Iron 56). It should be rapid enough not to let undergo radioactive decay before the neutron arrives. For r- process, high flux of neutrons are required. High flux of neutrons can come from the material ejected from supernovae explosion and neutron rich matter ejected from the merging of neutron star. This process also occurs in thermonuclear weapon explosions though to a very small extent. This lead to the discovery of two new elements, that is, einsteinium (element 99) and fermium (element 100).

3.4 S- process

S- process means slow neutron capture process, its a group of nuclear astrophysics reactions occur particularly in AGB (Asymptotic Giant Branch) stars. This process is also responsible for the production of heavy elements than iron.

In this process, a seed nucleus captures neutron and form an isotope with one higher atomic mass, if this isotope is stable, then more isotopes will form with increase in mass, but it will undergo beta decay if its unstable, which will produce the element of next highest atomic number. Radioactive decay happens because this process of neutron capture is slow in comparison to rapid neutron capture process. Abundances of elements depends on the source and number of neutrons. Where there is high flux of neutrons are present, r-process dominates over s- process. These two processes are responsible for the abundance of elements heavier than iron. And the s- process is secondary to r- process meaning it need heavy isotopes to be present initially as seed nuclei to be converted to heavy elements.

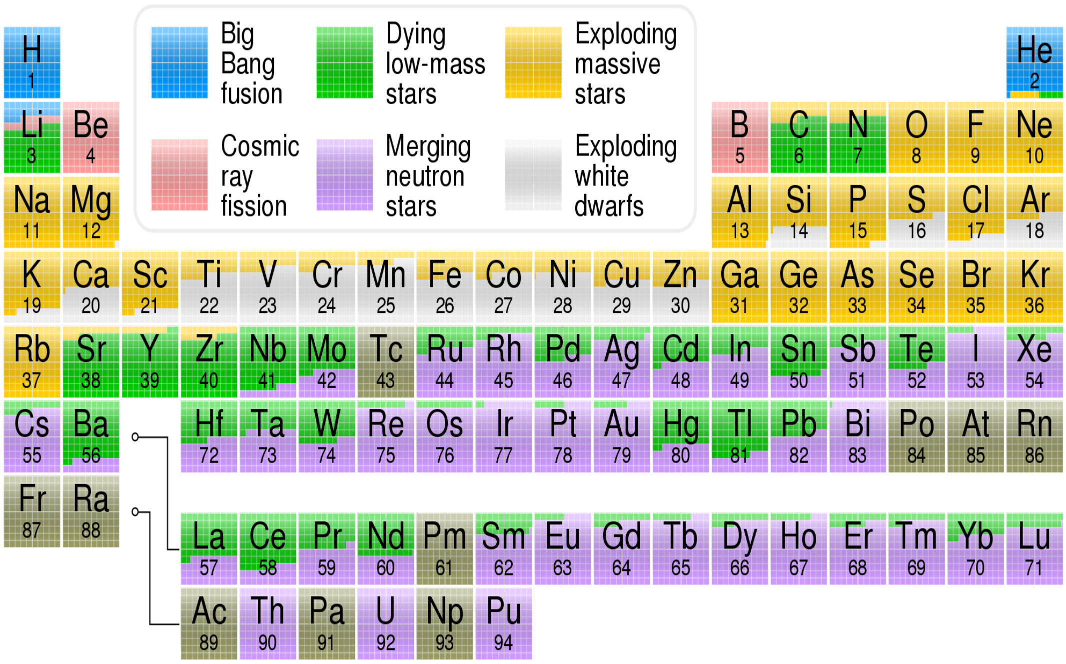

Figure 4. This figure shows the formation of elements by different astrophysical processes.

4 Methodology: A Basic Simulation Model

In this work, we have considered an artificial situation where there are two types of processes; neutron capture and β minus decay. Neutron capture leads to the increase of neutrons in the nuclei. β minus decay leads to the increase of proton number and decrease of neutron number. There are number of physics processes in the stars responsible for the overall elemental distribution. For a basic simulation, we are defining two probabilities,

- Neutron Production Probability ($P(n_{prod})$).
- Neutron Decay Probability ($P(n_{decay})$).

Approximately, these probabilities are a function of the following respective processes:

- P(n_{prod}) = flux(n) * f(n_e) * f(A, Z) * f($nucl_L$) * dρ/dt
- P (n_{decay}) = Q(A, Z) * Shell Effect (E) * Flux of photons * E$(N, Z)_{Asymmetry}$

where:
flux(n) = Number of Neutrons
f (n_e) = Neutron Energy
f(A, Z) = Number of Isotopes present initially
f($nucl_L$) = Nuclear Level Density
$d\rho/dt$ = Explains the magneto hydrodynamics of Stars
$Q(A, Z)$ = Q value
$E(N, Z)_{Asymmetry}$ = Asymmetry between neutrons and protons
Here we have done Monte Carlo basic simulation in C programming language using these two probabilities to know about Nucleosynthesis process.

5 Results

Below are various plots for different neutron production and neutron decay probabilities:

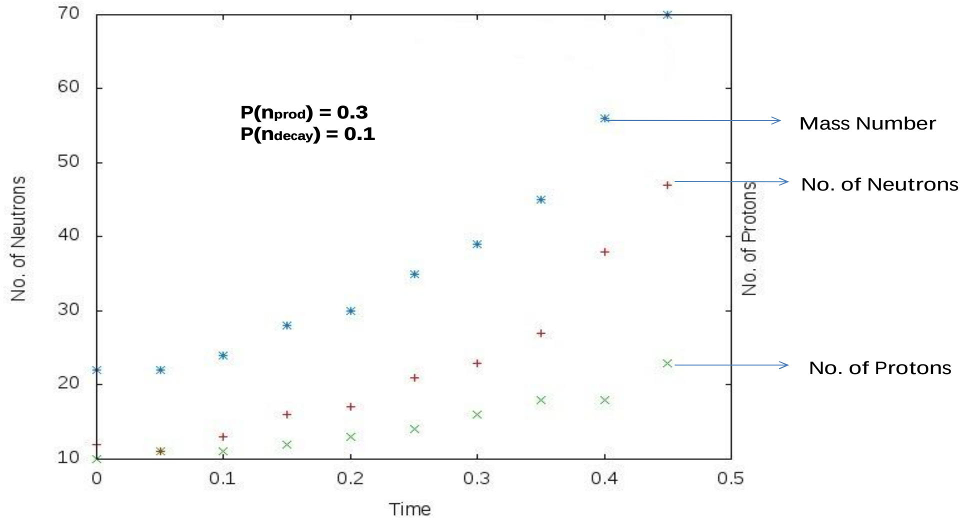

Figure 5. $P(n_{prod}) = 0.3$ and $P\ (n_{decay}) = 0.1$, with time on X-axis and No. of Neutrons and No. of Protons on Y-axis

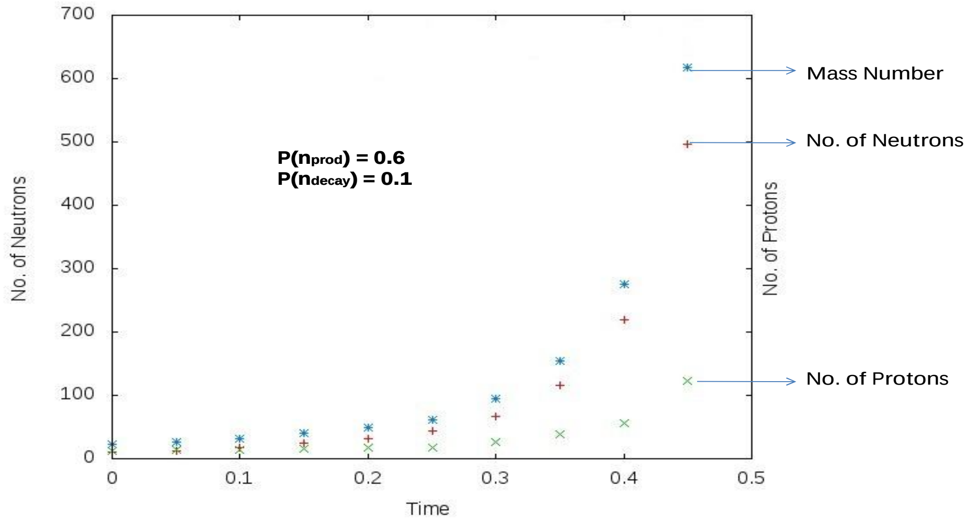

Figure 6. $P(n_{prod}) = 0.6$ and $P\ (n_{decay}) = 0.1$, with time on X-axis and No. of Neutrons and No. of Protons on Y-axis

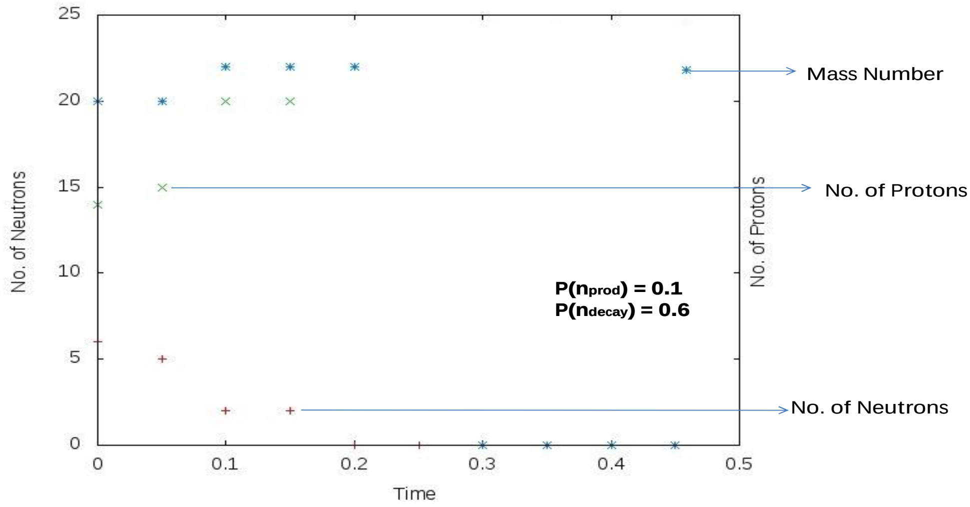

Figure 7. P(n_{prod}) = 0.1 and P (n_{decay}) = 0.6, with time on X-axis and No. of Neutrons and No. of Protons on Y-axis

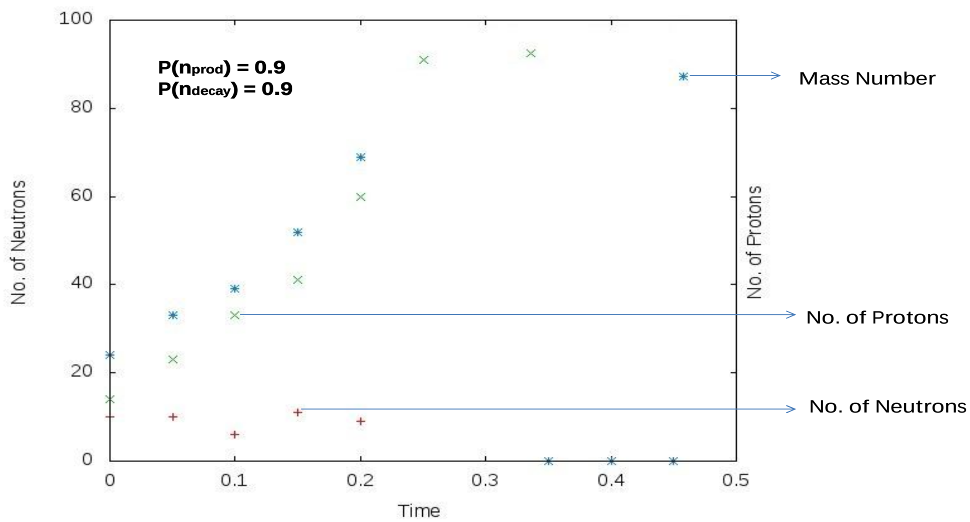

Figure 8. P(n_{prod}) = 0.9 and P (n_{decay}) = 0.9, with time on X-axis and No. of Neutrons and No. of Protons on Y-axis

6 Conclusion

Every time one question always comes in our mind, that how all these elements which we see in the periodic table actually came, and answer is nucleosynthesis. There are various classification of nucleosynthesis on the basis of energy that is, Big Bang nucleosynthesis, Supernova nucleosynthesis, Stellar nucleosynthesis and Cosmic Ray spallation. These nu-

cleosynthesis help to produce all the elements through various processes like proton capture process, neutron capture process, photo disintegration and thermonuclear reactions. In this report, we have briefly discussed all these processes with an emphasis on r- and s- process. Here, we used the methodology to know more about r- and s- process using two probabilities, neutron decay probability and neutron production probability. Using C programming language and Monte Carlo simulation method, we have drawn the plots for various values of probabilities.
In this project, we studied the about the neutron capture processes which are responsible for the abundances of heavy elements than iron in different phases of stellar evolution. We aim to understand the distribution of isotropic abundances in our universe. In future we will do the realistic calculations which will include all the term of physics happening in stars and will also include protons in our simulation.

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