Proton Capture Reactions and Network Calculations on $^{46}$Ti, $^{64}$Zn, $^{114}$Sn and $^{116}$Sn Relevant to the rp-Process

Ravin S. T. Kodikara
Western Michigan University

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PROTON CAPTURE REACTIONS AND NETWORK CALCULATIONS
ON $^{46}$Ti, $^{64}$Zn, $^{114}$Sn and $^{116}$Sn RELEVANT TO THE rp-PROCESS

by

Ravin S. T. Kodikara

A Dissertation
Submitted to the
Faculty of the Graduate College
in partial fulfillment of the
requirements for the
Degree of Doctor of Philosophy
Department of Physics
Advisor: Michael Famiano, Ph.D.

Western Michigan University
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The rp-process makes an important contribution to the stellar nucleosynthesis by producing many of the light proton rich nuclei. Successive proton captures on seed nuclei followed by occasional $\beta$-decays and electron captures are the key features of this mechanism. For a detailed rp-process analysis, proton capture cross sections and reaction rates are essential. However, the lack of experimental data forces the researcher to largely depend on statistical model predictions.

This dissertation research is an attempt to investigate the proton captures of four particular nuclides; $^{46}$Ti, $^{64}$Zn, $^{114}$Sn and $^{116}$Sn. At Western Michigan University Van de Graaff accelerator facility, target nuclides were irradiated using a proton beam with energy ranging from 1MeV to 3.7MeV. The resulting gamma radiation was detected by HPGe detectors at a dedicated counting station.

Proton capture cross sections and astrophysical S-factors were measured and a good agreement between the experimental S-factor results and the NON-SMOKER predictions was observed, especially in the higher proton energies. With respect to reaction rates, NON-SMOKER predictions were much closer to the experimental results, while MOST code predictions were slightly higher than the actual experimental results.
Furthermore, a reaction network model code (GAMBLER) was used to simulate the stellar rp-process and photodisintegration reaction. Abundance distributions of $^{47}\text{Ti}$, $^{47}\text{V}$, $^{65}\text{Zn}$, $^{65}\text{Ga}$, $^{115}\text{Sn}$, $^{115}\text{Sb}$, $^{117}\text{Sn}$ and $^{117}\text{Sb}$ were calculated and compared with theoretical predictions. Comparison of experimental abundance results and theoretical predictions for above elements revealed sufficient correlation between them and proved the applicability of the network code in rp-process and photodisintegration simulations.
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This dissertation is dedicated to my parents, Ranjan and Padmamala.

Ravin S. T. Kodikara
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CHAPTER I

INTRODUCTION

Stellar Nucleosynthesis

Nucleosynthesis of elements has its roots dating back to the beginning of the Universe. Clouds of interstellar gas and dust condensed into stars and began to produce elements in stellar interiors. During various stellar evolutionary stages, matter ejected back to the interstellar medium, nourishing it with new elements. This is a fascinating phenomenon of nature which is still repeating, and is known as the ‘Stellar Nucleosynthesis’. Extensively studied but not yet fully understood, this process has become a challenging area in both nuclear and astrophysics research.

Birth of a Star

Interstellar medium consist of dense nebulae known as molecular clouds where much of the hydrogen is in the molecular form (Rolfs and Rodney, 1988). The hydrostatic equilibrium of such a giant molecular cloud (GMC) remains stable as long as the thermal energy of the molecular gas is in balance with its gravitational potential energy (Blitz and Shu, 1980). However in a GMC, gravity can overcome the gas pressure leading to a gravitational contraction and the molecular cloud could become fragmented. These fragments, while further collapsing, will increase the internal pressure and release gravitational potential energy as heat. The increasing pressure and the heat of the
fragments form them into spheres of extremely hot gas, which are known as 'proto-stars'—the early stage of the formation of stars (Rolfs and Rodney, 1988; Iliadis, 2008). The initial mass of the proto-star or the stellar progenitor is the crucial factor which determines its evolution and termination. If the initial mass is less than 0.08 solar masses, such an object, also known as a 'brown dwarf' will never be able to initiate the hydrogen fusion reactions due to insufficient internal temperature. If the initial mass falls in the region between 0.08 and 0.4 solar masses, the star known as a 'red dwarf' can fuse hydrogen and helium in consecutive fusion reactions. In stars with higher mass accumulations, further fusion cycles can be observed (Iliadis, 2008).

Stellar Burning Phases

Depending on the initial mass accumulation, a star will evolve through several different burning phases (fusion cycles), before it comes to the extinction. These stellar burning phases primarily consist with exothermic nuclear reactions which consume H, He, C, O, Ne and Si as the nuclear fuel.

H and He Burning Phases

The internal temperature and the density of the proto-star will increase as the gravitational contraction increases. If the initially accumulated mass is greater than 0.08 solar masses, hydrogen can ignite inside the core region. In a star with mass comparable to or lower than the Sun and with a lower core temperature, 99% of the energy production occurs via fusion of four protons into one helium nucleus. This reaction is known as the 'p-p chain reaction' and consists of four different burning processes to give the end result (Wallace and Woosley, 1981). The other significant contribution to the
energy production is provided by the ‘C-N-O cycle’ which also consumes hydrogen and produces helium as the end product while carbon, nitrogen and oxygen act as catalysts for the reaction. The energy generation of these two processes relative to the core temperature is compared in figure 1 where Sun is shown as a reference. In a star with mass higher than 1.5 solar masses and with a much higher core temperature, C-N-O cycle is the dominant contributor for energy production (Ostlie, 2007).

Once all the hydrogen is consumed, further energy production ceases and the star begins to contract due to gravity. This contraction increases the density and hence the temperature of the core, which mainly consists with helium. When the core temperature rises up to about $10^8$ K, a helium burning reaction can take over, producing carbon as the end result. This is a two step reaction where two helium (alpha) nuclei fuse together to produce a short-lived beryllium nucleus which then fuses with another helium nucleus to produce a stable carbon nucleus. Because of the involvement of three helium nuclei this process is referred as the triple alpha ($3\alpha$) process and produces a net energy of 7.275 MeV. In addition, a smaller contribution to the energy generation occurs via the fusion of carbon and helium producing oxygen (Clayton, 1983).

Carbon, Oxygen, Neon and Silicon Burning

Once all the helium is consumed, another gravitational contraction commences as there is no internal energy production to counter the gravity. If the initial mass is less than about 5 solar masses, further ignition does not occur and the star becomes a ‘white dwarf’ with a dense core of carbon and oxygen. On the other hand, if the initial mass is higher than the above mentioned limit, carbon can ignite in a star when core temperature reaches
about $5\cdot10^8$ K and the density reaches about $2\cdot10^8$ kgm$^{-3}$ (Bertout, Siess, and Cabrit, 2007). In general carbon burning starts before oxygen since carbon has the lower Coulomb barrier compared to oxygen. The most significant reactions referred to as carbon burning are $^{12}\text{C}(^{12}\text{C},\alpha)^{20}\text{Ne}$, $^{12}\text{C}(^{12}\text{C},p)^{23}\text{Na}$ and $^{12}\text{C}(^{12}\text{C},n)^{23}\text{Mg}$ (Clayton, 1983; Bertout, Siess, and Cabrit, 2007).

![Figure 1. Energy generation by p-p chain and CNO cycle.](image)

When all the carbon is burned out resulting contraction initializes photodisintegration reactions on neon. Around $10^9$ K temperature region $^{20}\text{Ne}(\gamma, \alpha)^{16}\text{O}$ reaction begins producing oxygen. In a similar manner alternating burning and contraction cycles occur in the star burning neon, oxygen and silicon while increasing the temperature and density. The last burning phase, Si burning, is ignited at $4\cdot10^9$ K, where high energy photons photo disintegrate silicon nuclei by $^{28}\text{Si}(\gamma, \alpha)^{24}\text{Mg}$ reaction (Clayton, 1983). These burning sequences are shown in figure 2 along with average burning temperatures.
Beyond this point a series of alpha captures on the remaining silicon nuclei result in creating heavier elements up to nickel. At these high temperatures, a nuclear statistical equilibrium can arise between alpha capture reactions and photodisintegrations aborting further production of nuclides heavier than $^{56}\text{Ni}$. Elemental abundances are determined by the temperature and the density of the plasma, the neutron-to-proton ratio, as well as by the binding energies of the respective nuclei. Since the nucleus with the highest binding energy per nucleon is $^{56}\text{Ni}$ ($Z=N=28$), mainly $^{56}\text{Ni}$ and its stable decay product $^{56}\text{Fe}$ are formed (Rolfs and Rodney, 1988; Bertout, Siess, and Cabrit, 2007).

![Schematic of a star showing different burning layers and the temperatures.](image)

Figure 2. Schematic of a star showing different burning layers and the temperatures.

The evolved star now has a Fe/Ni core which is surrounded by gaseous shells (onion-shell-like structure) containing unburned carbon, neon, oxygen and silicon. Again
the gravitational contraction acts on the star increasing its temperature and density and igniting burning scenarios in its outer shells. In contrary to previous burning cycles, no ignition occurs in the Fe/Ni core this time because these two elements have very high binding energies which prevent them from involving in further fusion reactions (Heger et al., 2002; Thielemann, Nomoto, and Hashimoto, 1996). As there is no counter force from the core against the gravity, the star begins to collapse rapidly with a sudden increase in temperature. This results in photodisintegration reactions on iron by energetic gamma radiation which produces neutrons, protons and electrons. Electron captures on protons produce neutrinos which escape the core and reduce the electron density of the core. The reduction of electron density reduces the electron pressure inside which results a catastrophic collapse of the star. The inner core eventually reaches typically a diameter of about 30 km and a density of about $2 \cdot 10^{17} \text{kg/m}^3$. Further contraction is rapidly blocked by strong force interactions and by degeneracy pressure of neutrons. The in-falling matter abruptly comes to a stop and rebounds, producing a shock front that propagates outward from the core. This explosive scenario is known as a ‘core collapse supernova explosion’ (Hayakawa et al., 2006; Heger et al., 2002).

Nucleosynthesis of Heavy Elements

When a star evolved to a stage where it has a Fe/Ni core, the effectiveness of fusion reactions reduces due to the higher stability of the elements in its core. Beyond this region, a noticeable method of nucleosynthesis is the radiative particle capture process. Neutron capture reactions play a superior role since neutrons do not feel the increasing Coulomb barrier repulsion from the nucleus. Even though their significance is small,
radiative proton capture reactions also contribute to the synthesis process (Boyd, 1998; Boyd, 2007).

Two unique neutron capture processes which contribute to the synthesis of elements beyond the iron region are known as the ‘s-process’ and the ‘r-process’ (Burbidge et al., 1957; Langanke, 2001). These two mechanisms differ from each other mainly due to the time scales associated with them, the abundances of the elements they produce and the stability of the produced elements. Similar to s- and r-processes which produces stable and neutron rich nuclides, there is another assembly of reaction mechanisms known as the ‘p-process’ (Boyd, 2007; Wallerstein et al., 1997) contributes to the nucleosynthesis by producing proton rich nuclides. Two dominant mechanisms involved are the ‘rp-process’ and the ‘photo-dissociation’ (Boyd, 2007; Woosley and Howard, 1978; Woosley and Howard, 1990).

![Figure 3](image_url)  
**Figure 3.** A comparison of the relative abundance of elements. Source (Anders and Grevesse, 1989)
The solar abundances of s-, r- and p-process elements relative to Si=10^6 are shown in figure 3. It can be seen that s and r-process elements have a relatively close abundance distribution up to A=120 mass region, while the mass region beyond A=150 is dominated by the r-process. Compared to r and s-process elemental abundances, the p-process nuclei are about 2 orders of magnitude less abundant in the solar system with few exceptions. The peaks in the p-process distribution arise due to the neutron-magic numbers of \(^{92}\text{Mo}\) (N=50) and \(^{144}\text{Sm}\) (N=82) p-isotopes.

The s-process

The s-process which proceeds along the valley of stability in the chart of nuclides has a time scale typically spans from 100-1000 years. It begins with stable Fe and Ni seed nuclei and subsequent neutron captures followed by \(\beta\) decays leads the process towards heavier stable elements. Considering the different temperature conditions, mass regions and the neutron fluxes involved, s-process can be separated into two sub categories; the weak s-process and the main s-process (Kappeler, 2007). In massive stars, when the core temperature reaches about \((2-3)\times10^8\) K, weak s-process produces most of the s-process isotopes between iron and strontium with masses \(56 < A < 90\). Neutrons are provided by the \(^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}\) reaction, which is activated at the end of the convective He-burning core and in the subsequent convective C-burning shell. The main s-process can take place during the helium shell flashes of low-mass AGB stars (Asymptotic Giant Branch) when temperature reaches about \(10^8\) K. A lower neutron density of \(10^7\) cm\(^{-3}\) is provided by the \(^{13}\text{C}(\alpha,n)^{16}\text{O}\) reaction. The main s-process contributes to the nucleosynthesis of heavy elements by producing most of the isotopes in the mass region between \(A=90\) to \(A=209\).
Both weak and main s-processes together synthesize approximately half of the isotopes of the elements heavier than iron (Kappeler, Beer, and Wisshak, 1989; Pignatari et al., 2010).

The r-process

In stellar explosive scenarios like core collapse Supernovae where the neutron density is enormous (> \(10^{20}\text{ s}^{-1}\text{cm}^{-2}\)) and the temperature is high, rapid neutron capture process can take place effectively (Wallerstein et al., 1997). Due to the vast neutron densities, seed nuclei can capture several neutrons during a time interval which is short compared to the \(\beta\)-decay half-lives of the products. These neutron captures drive the r-process path along the isotopic chains to very neutron-rich species until \((\text{n},\gamma)/(\gamma,n)\) equilibrium is established at the so-called waiting points. At an equilibrium point, a \(\beta\)-decay will produce a new element with a higher proton number and then r-process will continue until a new equilibrium is achieved. The r process is responsible for the production of about half of the heavy-element abundances including Th and U (Cowan, Thielemann, and Truran, 1991; Langanke, 2001; Thielemann, Nomoto, and Hashimoto, 1996).

Proton Rich Nuclei

The chart of nuclides can be divided into three distinctive sections according to the neutron and proton constitution of nuclides. In the figure 4, the line of elements represented by thick black squares is known as the line of beta stability. The elements belong to this section are stable against beta decay and are primarily produced by the s-
A nuclide is identified as a proton rich nuclide if it contains one or more protons than its beta stable isotope. In the chart of nuclides, proton rich isotopes of an element span from the line of stability to the proton drip line with varying decay half-lives (Schatz et al., 1998). Production of proton rich nuclides occurs by a combination of several different synthesis mechanisms collectively known as the p-process (Rayet, Prantzos, and Arnould, 1990; Woosley and Howard, 1978). Many of the light proton rich nuclides
synthesized by the successive proton captures on stable seeds, which is known as the rp-process (Boyd, 1998; Wallace and Woosley, 1981). Heavier proton rich elements primarily produced by the photo-dissociation of stable or neutron rich elements (Woosley and Howard, 1978). While the above mentioned mechanisms are responsible for producing the bulk of the p-nuclides, some neutrino induced mechanisms such as the $\nu$-process (Langanke, 2001), the $\alpha$-rich freezeout (Boyd, 2007; Jordan, Gupta, and Meyer, 2003) and the up-process (Frohlich et al., 2006; Pruet et al., 2006) contribute to the p-process by producing some of the least abundant p-nuclides. Although these processes are equally important in a detailed p-process study, this dissertation is mainly focused on reactions relevant to the rp-process.

The rp-process

The rp-process, also known as the ‘rapid proton capture process’ proceeds by successive proton captures on seed nuclei with occasional $\beta^+$-decays or electron captures (Wallace and Woosley, 1981). Similar to the role played by neutron capture reactions (s-process and r-process) in producing stable and neutron rich nuclides, rp-process is important for synthesizing many of the light p-nuclides in the proton rich side of the nuclear valley of stability. The reaction mechanism and the stellar environments favoring the rp-process will be discussed in detail in the following context.

Stellar Environment

A stellar environment favorable to this process should be proton-rich (hydrogen-rich) and should have a temperature above at least 0.1 GK. Therefore the rp-process cannot occur inside the core of a star until the later stages of its burning cycle due to the
insufficient temperature (Schatz et al., 1999). Accretion on to a white dwarf or a neutron star creates the much favorable stellar conditions to the rp-process with temperatures in the range 0.1 $T_9$ K~2.0 $T_9$ K. Accretion of matter from the companion star forms a thin surface layer on the receiving star which is abundant with hydrogen. Similar stellar conditions can exist in a type II supernova explosion as well (Busso et al., 1992; Thielemann et al., 1994).

Binary star systems can be often found in the universe with a white dwarf or a neutron star as one of the two companions in the system. The two stars orbit around a common center of mass as shown in figure 5. Gravitational fields of the two stars form an equipotential surface known as the ‘Roche Lobe’ which prevents the transfer of materials between them. However when the companion main sequence star goes through its’ later burning stages, it can expand beyond the inner Lagrangian point and breech in the strong gravitational field of the neutron star (or the white dwarf). This triggers a continuous flow of hydrogen rich material from the expanding companion to the receiver, forming an ‘accretion disk’ around the receiver’s surface (Rebetzky et al., 1990).

![Figure 5. Schematics of a binary system.](image-url)
When accreting to a white dwarf, the hydrogen rich accreted matter falls on to the surface of the white dwarf releasing the gravitational potential energy. This energy dissipation heats the surface layer of the dwarf to a temperature of $0.1\sim0.5 \, T_9 \, K$, triggering the rp-process. In the case of a neutron star, due to the much stronger gravitational field, energy release can be as high as $200 \, \text{MeV}$ per nucleon and temperature can reach up to $1\sim2 \, T_9 \, K$ (Boyd, 2007; Rebetzky et al., 1990). Due to the high energy production during a short period of time, typically tens of seconds, X-ray bursts can often be observed together with neutron star accretions (Bildsten, 1995; Joss, 1977).

CNO and HCNO Cycles

The Carbon-Nitrogen-Oxygen cycle (CNO cycle) and the Hot-CNO cycle (HCNO cycle) are also important to rp-process studies. In a favorable stellar environment as mentioned above, rp-process initiates at the end of the CNO cycle. The transition period between the CNO cycle and the rp-process is identified as the ‘hot’ CNO or the HCNO cycle (Champagne and Wiescher, 1992; Kubono, Kajino, and Kato, 1995). As shown in figure 6, in a hydrogen rich environment, if the temperature is above $0.2 \, T_9$, the CNO cycle (indicated with black arrows) can breakout via the $^{14}\text{O}(\alpha,p)^{17}\text{F}$ reaction and move to the HCNO cycle. With a further increment of temperature above $0.5 \, T_9$, HCNO cycle can breakout via the $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$ reaction to begin the rp-process (Kubono, Kajino, and Kato, 1995). A detailed explanation of these breakout processes can be found in the references (Herndl et al., 1995).
rp-process Mechanism

Starting from the A~20 mass region, rp-process advances via successive proton captures on seed nuclei and synthesizing nuclei towards the proton drip line. The most important mechanism which contributes to the rp-process is the radiative proton capture reaction which is also known as the (p,\gamma) reaction. Here an incoming energetic proton is captured by the seed nucleus while emitting a photon in the form of a gamma ray (Boyd, 1998; Kubono, Kajino, and Kato, 1995). A general representation for a radiative proton capture reaction is shown below.

\[ \frac{4}{2}X + p \rightarrow \frac{4}{2}Y + \gamma . \]  \hspace{1cm} (1.1)

where \( X \) is the target nucleus and \( p \) is the projectile (a proton). The nucleus formed by capturing the proton is represented by \( Y \) where \( \gamma \) indicates an emission of a gamma ray. \( A \) and \( Z \) represent the mass number and the proton number respectively.

Figure 6. Transition from CNO cycle to rp-process via HCNO cycle.
As long as the newly produced nucleus is stable, repeated proton captures on the seed can lead towards the proton drip line. As the number of protons increases, the nucleus become unstable and hence can undergo $\beta^+$-decay or capture an electron to become stable. The result is a new higher-mass element, and the proton capturing cycle will repeat. This general formalism was initially proposed by (Burbidge et al., 1957), and has been improved by many researchers thereafter (Boyd, 1998; Wallace and Woosley, 1981). A portion of the rp-process reaction network involving Ne, Na, Mg, Al and Si is shown in figure 7.

![Diagram](image)

Figure 7. A section of a typical rp-process reaction network.

p-nuclides

The rp-process can synthesize proton rich nuclides effectively up to the mass region $A \sim 120$, where further production is terminated near the Sn-Sb-Te cycle due to several reasons including increased Coulomb repulsion from the seed nucleus and cycling.
reactions leading back to lighter nuclei (Schatz, 2006; Schatz et al., 1998). In figure 8, the
thick blue line shows the rp-process path progressing along the proton drip line. The
characteristic step-like pattern arises from consecutive proton captures and $\beta^+$-decays, as
described in figure 7. Solar abundances of the 35 generally accepted p-nuclides are
shown in table 1.

![Figure 8](image-url)

Figure 8. rp-process path shown on the chart of nuclides.

Here values were normalized to the abundance of silicon ($\text{Si} = 10^6$) for the
comparison purpose. The most notable characteristic common to these nuclides is their
rarity compared to the other isotopes of the respective element. Although some nuclides
in this table were also produced by the s- or r-processes; the contribution from these two
processes to the total abundance is insignificantly small (Wallerstein et al., 1997).
Table 1

Solar and isotopic abundance of p-process nuclides.

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Z</th>
<th>Solar system abundance (Si=10^6)</th>
<th>Isotopic abundance (%)</th>
<th>Nucleus</th>
<th>Z</th>
<th>Solar system abundance (Si=10^6)</th>
<th>Isotopic abundance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>74Se</td>
<td>34</td>
<td>5.50·10^{-1}</td>
<td>0.88</td>
<td>132Ba</td>
<td>56</td>
<td>4.53·10^{-3}</td>
<td>0.1</td>
</tr>
<tr>
<td>78Kr</td>
<td>36</td>
<td>1.53·10^{-1}</td>
<td>0.34</td>
<td>138La</td>
<td>57</td>
<td>4.09·10^{-4}</td>
<td>0.09</td>
</tr>
<tr>
<td>84Sr</td>
<td>38</td>
<td>1.32·10^{-1}</td>
<td>0.56</td>
<td>136Ce</td>
<td>58</td>
<td>2.16·10^{-3}</td>
<td>0.19</td>
</tr>
<tr>
<td>92Mo</td>
<td>42</td>
<td>3.78·10^{-1}</td>
<td>14.84</td>
<td>138Ce</td>
<td>58</td>
<td>2.84·10^{-3}</td>
<td>0.25</td>
</tr>
<tr>
<td>94Mo</td>
<td>42</td>
<td>2.36·10^{-1}</td>
<td>9.25</td>
<td>144Sm</td>
<td>62</td>
<td>8.0·10^{-3}</td>
<td>3.1</td>
</tr>
<tr>
<td>96Ru</td>
<td>44</td>
<td>1.03·10^{-1}</td>
<td>5.52</td>
<td>152Gd</td>
<td>64</td>
<td>6.6·10^{-4}</td>
<td>0.2</td>
</tr>
<tr>
<td>98Ru</td>
<td>44</td>
<td>3.50·10^{-2}</td>
<td>1.88</td>
<td>156Dy</td>
<td>66</td>
<td>2.21·10^{-4}</td>
<td>0.06</td>
</tr>
<tr>
<td>102Pd</td>
<td>46</td>
<td>1.42·10^{-2}</td>
<td>1.02</td>
<td>158Dy</td>
<td>66</td>
<td>3.78·10^{-4}</td>
<td>0.10</td>
</tr>
<tr>
<td>106Cd</td>
<td>48</td>
<td>2.01·10^{-2}</td>
<td>1.25</td>
<td>162Er</td>
<td>68</td>
<td>3.51·10^{-4}</td>
<td>0.14</td>
</tr>
<tr>
<td>108Cd</td>
<td>48</td>
<td>1.43·10^{-2}</td>
<td>0.89</td>
<td>164Er</td>
<td>68</td>
<td>4.04·10^{-3}</td>
<td>1.61</td>
</tr>
<tr>
<td>113In</td>
<td>49</td>
<td>7.90·10^{-3}</td>
<td>4.30</td>
<td>168Yb</td>
<td>70</td>
<td>3.22·10^{-4}</td>
<td>0.13</td>
</tr>
<tr>
<td>112Sn</td>
<td>50</td>
<td>3.72·10^{-2}</td>
<td>0.97</td>
<td>174Hf</td>
<td>72</td>
<td>2.49·10^{-4}</td>
<td>0.16</td>
</tr>
<tr>
<td>114Sn</td>
<td>50</td>
<td>2.52·10^{-2}</td>
<td>0.66</td>
<td>180Ta</td>
<td>73</td>
<td>2.48·10^{-6}</td>
<td>0.01</td>
</tr>
<tr>
<td>115Sn</td>
<td>50</td>
<td>1.29·10^{-2}</td>
<td>0.34</td>
<td>180W</td>
<td>74</td>
<td>1.73·10^{-4}</td>
<td>0.13</td>
</tr>
<tr>
<td>120Te</td>
<td>52</td>
<td>4.30·10^{-3}</td>
<td>0.09</td>
<td>184Os</td>
<td>76</td>
<td>1.22·10^{-4}</td>
<td>0.02</td>
</tr>
<tr>
<td>124Xe</td>
<td>54</td>
<td>5.71·10^{-3}</td>
<td>0.12</td>
<td>190Pt</td>
<td>78</td>
<td>1.7·10^{-4}</td>
<td>0.01</td>
</tr>
<tr>
<td>126Xe</td>
<td>54</td>
<td>5.09·10^{-3}</td>
<td>0.11</td>
<td>196Hg</td>
<td>80</td>
<td>5.2·10^{-4}</td>
<td>0.15</td>
</tr>
<tr>
<td>138Ba</td>
<td>56</td>
<td>4.76·10^{-3}</td>
<td>0.11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source (Anders and Grevesse, 1989; Wallerstein et al., 1997)

Photodisintegration

Another important method of producing proton rich nuclei is the photodisintegration (photo-dissociation), which is responsible for producing much of the heavy (> 100 nucleons) proton rich isotopes. During a core-collapse supernova explosion,
temperature can reach extreme values up to $2 \times 10^9$ to $3 \times 10^9$ K. This high temperature environment can result in a black-body radiation which produces a bath of high energy photons. These photons or the gamma rays can disintegrate the heavy, stable neutron rich seed nuclei created by s-process or the r-process. Removal of neutrons will increase the proton/neutron ratio of the resulting nucleus. The two most important reactions for this process are neutron-photo dissociation ($\gamma,n$) and alpha-photo dissociation ($\gamma,\alpha$) (Rayet et al., 1995; Woosley and Howard, 1978; Woosley and Howard, 1990). Additionally, photodissociation maintains the abundance of p-process nuclei by maintaining the $(p,\gamma)\rightarrow(\gamma,p)$ equilibrium (Schatz, 2006).

**Aim of the Research**

Astrophysical models are powerful and useful tools to study nucleosynthesis. Various such models are being extensively used by the scientific community to predict many stellar scenarios. As an example, for a particular stellar reaction, theoretically determined reaction cross sections are available for the calculation of s-factors, reaction rates, etc. However, there are occasions where some disagreements exist between the theoretically obtained value and the actual observation. These disagreements suggest that theoretical models need modifications and improvements for the better interpretation of experimental results with lesser uncertainty (Famiano et al., 2008).

The bulk of the data available today on the synthesis of proton-rich nuclei is from theory alone. Most of the proton-capture cross sections or reaction rates have not been tested experimentally and are heavily depending on statistical model calculations such as Hauser-Feshbach formalism (Hauser and Feshbach, 1952). A detailed description about
the Hauser-Feshbach calculation is given in chapter 5. A main reason for lack of experimental data is the difficulty of achieving relevant stellar conditions in terrestrial laboratories. On the other hand, the reaction cross sections appear to be extremely small in these stellar environments, making the data acquisition further difficult. Therefore the investigation of nuclear reactions relevant to astrophysical energies has become an indispensable aspect of nuclear astrophysics research.

This dissertation describes an attempt to investigate the radiative proton capture reactions of four different nuclei. The nuclei investigated are, namely, $^{46}$Ti, $^{64}$Zn, $^{114}$Sn and $^{116}$Sn. Proton capture cross sections were measured at a wide energy range relevant to astrophysical conditions. Calculated experimental results were compared with predictions from statistical codes based on Hauser-Feshbach approach. Two such particular codes, MOST (Goriely, 2005) and NON-SMOKER (Rauscher and Thielemann, 2000; Rauscher, Thielemann, and Oberhummer, 1995) were used for the comparisons. As a continuation of the project, cross sections and reaction rates results were applied to a network reaction code for further analysis.
CHAPTER II

EXPERIMENTAL PROCEDURE

An experiment was designed to measure the radiative proton capture cross sections of four particular nuclides. Proton captures on these target nuclides; $^{46}$Ti, $^{64}$Zn, $^{114}$Sn and $^{116}$Sn have astrophysical importance, as discussed in the previous chapter. Targets were irradiated with a mono-energetic proton beam produced by the Van de Graaff Accelerator at the Western Michigan University. De-excitation photon emissions resulting from the activated were detected at a separate detector station. Reaction cross sections, astrophysical S-factors and reaction rates were calculated from gamma detection analysis.

Target Characteristics

The four target nuclides; $^{46}$Ti, $^{64}$Zn, $^{114}$Sn and $^{116}$Sn used in the experiment were in the form of self supporting metal foils. Table 2 shows the target properties; weight, isotopic abundances, daughter nuclides resulted from the proton capture reactions and decay half lives of the daughters. These data were provided from the Oak Ridge National Laboratory and the target isotopic abundances were obtained with a spark-source mass spectrometer (Famiano et al., 2008). Each target foil was carefully attached to an aluminum frame which can be promptly mounted to the irradiation chamber during the
Table 2

The targets, their composition, proton captured daughters and half-lives.

<table>
<thead>
<tr>
<th>Target</th>
<th>Thickness (mg/cm²)</th>
<th>Isotope</th>
<th>Atomic percent</th>
<th>Daughter</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>⁴⁶Ti</td>
<td>0.52</td>
<td>⁴⁶Ti</td>
<td>81.20</td>
<td>⁴⁷V</td>
<td>32.6 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>⁴⁷Ti</td>
<td>2.10</td>
<td>⁴⁸V</td>
<td>15.98 d</td>
</tr>
<tr>
<td></td>
<td></td>
<td>⁴⁸Ti</td>
<td>14.50</td>
<td>⁴⁹V</td>
<td>331 d</td>
</tr>
<tr>
<td></td>
<td></td>
<td>⁴⁹Ti</td>
<td>1.10</td>
<td>⁵⁰V</td>
<td>1.4×10⁷ y</td>
</tr>
<tr>
<td></td>
<td></td>
<td>⁵⁰Ti</td>
<td>8.11</td>
<td>⁵¹V</td>
<td>Stable</td>
</tr>
<tr>
<td>⁶⁴Zn</td>
<td>1.04</td>
<td>⁶⁴Zn</td>
<td>99.85</td>
<td>⁶⁵Ga</td>
<td>15.2 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>⁶⁶Zn</td>
<td>0.14</td>
<td>⁶⁷Ga</td>
<td>3.261 d</td>
</tr>
<tr>
<td></td>
<td></td>
<td>⁶⁸Zn</td>
<td>0.01</td>
<td>⁶⁹Ga</td>
<td>Stable</td>
</tr>
<tr>
<td>¹¹⁴Sn</td>
<td>0.05</td>
<td>¹¹²Sn</td>
<td>0.27</td>
<td>¹¹³Sb</td>
<td>6.7 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>¹¹⁴Sn</td>
<td>71.10</td>
<td>¹¹⁵Sb</td>
<td>32.1 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>¹¹⁵Sn</td>
<td>0.77</td>
<td>¹¹⁶Sb</td>
<td>1 h, 16 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>¹¹⁶Sn</td>
<td>10.23</td>
<td>¹¹⁷Sb</td>
<td>2.8 h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>¹¹⁷Sn</td>
<td>2.45</td>
<td>¹¹⁸Sb</td>
<td>5 h, 3.6 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>¹¹⁸Sn</td>
<td>6.30</td>
<td>¹¹⁹Sb</td>
<td>38.1 h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>¹¹⁹Sn</td>
<td>1.76</td>
<td>¹²⁰Sb</td>
<td>5.7 d, 15.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>¹²⁰Sn</td>
<td>5.89</td>
<td>¹²¹Sb</td>
<td>Stable</td>
</tr>
<tr>
<td></td>
<td></td>
<td>¹²²Sn</td>
<td>0.60</td>
<td>¹²³Sb</td>
<td>Stable</td>
</tr>
<tr>
<td></td>
<td></td>
<td>¹²⁴Sn</td>
<td>0.61</td>
<td>¹²⁵Sb</td>
<td>2.758 y</td>
</tr>
<tr>
<td>¹¹⁶Sn</td>
<td>2.21</td>
<td>¹¹²Sn</td>
<td>0.01</td>
<td>¹¹³Sb</td>
<td>6.7 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>¹¹⁴Sn</td>
<td>0.03</td>
<td>¹¹⁵Sb</td>
<td>32.1 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>¹¹⁵Sn</td>
<td>0.08</td>
<td>¹¹⁶Sb</td>
<td>1 h, 16 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>¹¹⁶Sn</td>
<td>95.60</td>
<td>¹¹⁷Sb</td>
<td>2.8 h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>¹¹⁷Sn</td>
<td>1.63</td>
<td>¹¹⁸Sb</td>
<td>5 h, 3.6 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>¹¹⁸Sn</td>
<td>1.48</td>
<td>¹¹⁹Sb</td>
<td>38.1 h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>¹¹⁹Sn</td>
<td>0.27</td>
<td>¹²⁰Sb</td>
<td>5.7 d, 15.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>¹²⁰Sn</td>
<td>0.63</td>
<td>¹²¹Sb</td>
<td>Stable</td>
</tr>
<tr>
<td></td>
<td></td>
<td>¹²²Sn</td>
<td>0.11</td>
<td>¹²³Sb</td>
<td>Stable</td>
</tr>
<tr>
<td></td>
<td></td>
<td>¹²⁴Sn</td>
<td>0.16</td>
<td>¹²⁵Sb</td>
<td>2.758 y</td>
</tr>
</tbody>
</table>

Note. The isotope of interest in each target is in bold letters.
experiment. Each frame has a square shaped window with sides 15.8mm of length. This allowed the beam to irradiate the target without interacting with frame.

Proton Beam Production

The Accelerator

All the experiments were conducted at the Western Michigan University 6 million Volts tandem Van de Graaff Accelerator Facility. Beam production was initiated at the negative-ion source, also known as the duo-plasmatron. A sketch of the accelerator is shown in figure 9.

![Diagram of the Van de Graaff Accelerator](image_url)

Figure 9. A sketch of the Van de Graaff Accelerator at Western Michigan University.

A beam of positive ions is produced at the duo-plasmatron and enters the exchange canal. A charge exchange process takes place at the exchange canal. Produced
negative ions get accelerated by an extraction voltage and are isolated by the inflection magnet. This negative ion beam which contains $H^-$ ions goes through a secondary charge exchange inside the pressure tank and immerses as a proton beam. Produced proton beam receives a final acceleration inside the pressure tank and passes a series of focusing and selection processes before entering the irradiation chamber.

The Negative-ion Source

Ion beam production initializes at the Negative-ion Source, which contains the duo-plasmatron and a charge exchange mechanism. Figure 10 shows important details of the beam production. When a proton beam is required to be produced, $H_2$ is used as the source gas. Through a needle valve, source gas is leaked into the source area containing the filament. Electrons emitted from the hot tungsten filament are repelled towards the grounded aperture due to negative bias of the filament.

![Figure 10. Schematics of the negative-ion source.](image-url)
The magnetic field inside probe makes the electrons travel in spiral paths, which in turn increase their probability of colliding with the molecules of the source gas. These collisions remove additional electrons from hydrogen molecules and increase the electron density of the beam. Hydrogen gas contained between the aperture and probe tip is ionized by this free electron beam producing a dense plasma of positive ions. Since there is a dilute plasma inside the probe and a dense plasma near the aperture, the apparatus gets the name ‘duo-plasmatron’. Positive ions (H\(^+\), H\(_2\)^+ or H\(_3\)^+) in the plasma get extracted by negatively charged extraction electrode near the aperture. Afterward these positive ions travel through an exchange canal where they collide again with hydrogen gas which acts as an exchange gas. During these collisions between H\(_2\) and positive ions, some positive ions capture electrons and leave the exchange canal as a negative beam of ions mostly consisting H\(^-\) ions. When progressing through consecutive regions of negative potentials beyond the exchange canal, H\(^-\) ions get accelerated and acquire energy of about 60keV per ion. This pre-accelerated negative ion beam then enters a secondary charge exchange and an acceleration phase at the pressure tank. The resulting well-focused proton beam is mono-energetic and can be set to a desired energy level depending on experimental requirements.

Irradiation Process

Technical Details

A diagram of the irradiation chamber with a target mounting set-up is shown in figure 11. Positioning and aligning of the target was done by irradiating the beam on a
‘dummy’ target and observing the beam spot by a video feed. A diffusion pump and a turbo pump were used to create the vacuum inside the chamber.

Figure 11. Schematics of the irradiation chamber.

During the irradiation, beam intensity was measured with a Faraday cup downstream of the target. A focusing cathode in front of the Faraday cup was used to deflect electrons. Because target scattering could reduce the beam current on the cup, cup measurements were taken with the target out immediately before and after every run, and measurements were normalized to those with the target out. The $^{116}$Sn target was irradiated by proton beams of energies 2.3, 2.7, 3.0, 3.3, and 3.7MeV. For the other targets energy range used was from 1MeV to 3.7MeV and the beam energy was increased by steps of 300keV. The beam current was monitored with an Ortec current digitizer and logged with a Fluke-189 logging multimeter. Both devices were in excellent agreement. Current stability was monitored continuously, and the average beam current was recorded
in 300 s intervals. In this way, the beam current could be integrated over small segments even for a slowly changing beam intensity. It was found, however, that the beam intensity was extremely stable even over several hours. It was estimated that $2.5 - 5.3 \times 10^{15}$ protons struck through each target per energy level. The beam spot size on the target was 2mm in diameter.

Irradiation Results

During the irradiation process, protons were captured by the nuclei in the target. This capture mechanism is described in equation 1.1. For the particular nuclides used in the experiment, these radiative proton capture reactions are listed below (proton numbers were omitted for simplicity).

\[ ^{46}\text{Ti} + p \rightarrow ^{47}\text{V} + \gamma \]  
\[ ^{64}\text{Zn} + p \rightarrow ^{65}\text{Ga} + \gamma \]  
\[ ^{114}\text{Sn} + p \rightarrow ^{115}\text{Sb} + \gamma \]  
\[ ^{116}\text{Sn} + p \rightarrow ^{117}\text{Sb} + \gamma \]

Targets were irradiated for approximately 2.5 times the half-life of their daughter products in order to obtain the best possible reaction yield. Gamma emissions from the reactions were not detected at this stage of the experiment. After the irradiation each target was transferred to a separate gamma detection station while recording the transfer time.
Gamma Detection

The nuclei produced by the proton capture; $^{47}$V, $^{65}$Ga, $^{115}$Sb and $^{117}$Sb are unstable. They decay back to new isotopes of the respective previous parent nuclei. The decay half-life associated with each nuclide is given in the table 2.

![Decay scheme of $^{47}$V.](image)

Figure 12. Decay scheme of $^{47}$V.

As shown in figure 12, a $^{47}$V nucleus decays to the states of $^{47}$Ti via $\beta^+$ decay, where a weak interaction transforms a proton in the $^{47}$V nucleus into a neutron while emitting a positron and an electron neutrino. These excited states in $^{47}$Ti then de-excite to the ground state while releasing energy by gamma emission. Energies of the most noticeable states are shown in the figure along with the respective de-excitation photons. The percentage values in brackets indicate the decay branching ratio of each state. The decay of $^{65}$Ga, $^{115}$Sb and $^{117}$Sb occur via electron captures where an atomic electron is
captured by a proton in the nucleus and produces a neutron and an electron neutrino. Due to the higher electron densities, electron capture is the dominant decay mechanism for these isotopes compared to beta decay. The respective decay products, $^{65}\text{Zn}$, $^{115}\text{Sn}$ and $^{117}\text{Sn}$ are shown in figures 13, 14 and 15 along with excited states, photons of interest and decay branching ratios.

Technical Details

A sketch of the counting station is shown in figure 16. Two HPGe (Hyper Pure Germanium) coaxial detectors (Ortec GMX-23200-S, and Canberra GC3518) were used to detect the gamma radiation emitting from the targets. HPGe detectors were specifically used in this experiment due to their excellent energy resolution in gamma ray spectroscopy and high efficiency (Knoll, 2000).

![Decay scheme of $^{65}\text{Ga}$](image)

Figure 13. Decay scheme of $^{65}\text{Ga}$.
Figure 14. Decay scheme of $^{115}$Sb.

Figure 15. Decay scheme of $^{117}$Sb.
In the experimental arrangement, the detectors were placed opposite each other and the irradiated target was placed between the detector faces. The Ortec and Canberra detectors had crystal diameters of 55.9mm and 62mm, respectively. The spacing between the aluminum faces of each detector was kept small so that the target frame was firmly constrained.

The entire detection area was shielded on all sides with 10cm thick lead bricks to reduce the background radiation. The target could be conveniently inserted and removed from the detector arrangement through an opening at the top of the lead shield, which was covered during the experiment. Furthermore, six plastic scintillators were placed on the top of the lead shield as an active shield. This allowed correlating cosmic rays in the HPGe detectors with a specific scintillation detector. During the entire experiment, the detectors were kept at cryogenic temperatures by a constant supply of liquid nitrogen (LN$_2$).

![Diagram of gamma counting station](image)

Figure 16. A sketch of the gamma counting station.
The total detection efficiency of a detector constitutes from its geometric detection efficiency and the absolute detection efficiency. The geometric efficiency \( e_{\text{geo}} \) depends on the physical arrangement of the target and the detector system whereas the absolute efficiency \( e_{\text{abs}} \) depends on intrinsic properties of the detector. The total efficiency \( e_{\text{tot}} \) can be obtained as

\[
e_{\text{tot}} = e_{\text{geo}} \cdot e_{\text{abs}}
\]  \hspace{1cm} (2.5)

When an irradiated target placed between the two detectors, it creates a solid angle \( \Omega \) on the surface of the each detector as shown in figure 17. The de-excitation photons from the irradiated target can be emitted in every direction but only the photons that were emitted within the angle \( \Omega \) can be detected by the detector. Therefore the geometric efficiency of the detector is defined as

\[
e_{\text{geo}} = \frac{\Omega}{4\pi}
\]  \hspace{1cm} (2.6)

and

\[
\Omega = 2\pi \int_0^{\theta_m} \sin\theta d\theta,
\]  \hspace{1cm} (2.7)

\[
\Omega = 2\pi(1 - \cos\theta_m)
\]  \hspace{1cm} (2.8)

where \( \theta_m \) is the maximum angle created by the target on the face of the detector. If the radius of the detector surface \( R \) and the distance from target to the detector surface \( d \) are known, \( \theta_m \) can be calculated as follows.

\[
\theta_m = \tan^{-1}\left(\frac{R}{d}\right)
\]  \hspace{1cm} (2.9)
The absolute efficiency is defined as the ratio of number of pulses recorded to the number of radiation quanta incident on the detector. Intrinsic factors such as the detector material, the energy of the incoming photons and the physical thickness crystal mainly determine the absolute efficiency of a detector (Knoll, 2000).

Detector Calibration and Uncertainties

Standard gamma test sources; $^{60}$Co, $^{22}$Na, $^{137}$Cs and $^{133}$Ba used for the energy and efficiency calibration are listed in table 3 along with their photons of interest. In addition to test sources, 1.461MeV characteristic gamma radiation of $^{40}$K was also used for the calibration purpose. This particular radiation emits from potassium traces in building construction materials in the laboratory.

The geometric efficiency of both detectors was calculated using the above described methodology and the results are shown in table 4. Uncertainties in the target placement were found to be 2mm in the longitudinal direction and 3mm in the radial direction.
Table 3

Test sources and the photons of interest.

<table>
<thead>
<tr>
<th>Test Source</th>
<th>Photons of interest (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{60}$Co</td>
<td>1.173, 1.333</td>
</tr>
<tr>
<td>$^{22}$Na</td>
<td>0.511 (Annihilation), 1.275</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>0.662</td>
</tr>
<tr>
<td>$^{133}$Ba</td>
<td>0.081, 0.356</td>
</tr>
</tbody>
</table>

The absolute detection efficiency curves for the Canberra and Ortec detectors are shown in figure 18 and figure 19 respectively. Another significant uncertainty arose from the variations in the beam intensity. Although the intensity of the proton beam was reasonably constant, fluctuations were observed over time.

Table 4

Geometric efficiency calculations.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Calibration</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Canberra</td>
<td>Ortec</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Canberra</td>
</tr>
<tr>
<td>$d$(mm)</td>
<td>11.3±2.0</td>
<td>9.3±2.0</td>
</tr>
<tr>
<td>$R$(mm)</td>
<td>31.0±3.0</td>
<td>27.9±3.0</td>
</tr>
<tr>
<td>$\theta$(°)</td>
<td>69.89±3.66</td>
<td>71.5±3.66</td>
</tr>
<tr>
<td>$\Omega$(Jordan, Gupta, and Meyer, 2003)</td>
<td>4.12±0.38</td>
<td>4.29±0.38</td>
</tr>
<tr>
<td>$\epsilon_{geo}$</td>
<td>0.33±0.03</td>
<td>0.34±0.03</td>
</tr>
</tbody>
</table>
This was corrected by measuring the beam intensity within small time intervals and integrating it over the entire irradiation period. For all the experimental measurements, a standard beam intensity uncertainty of 5% was assumed. Much smaller uncertainties were observed in the measurements of target thickness and abundance, standard source activities, the beam energy and the data acquisition live time. However the total contribution from all of these uncertainty factors found to be less than 1% and did not affect the experiment significantly.

![Canberra Detector](image)

**Figure 18.** Absolute detection efficiency of Canberra detector.

Data Acquisition Electronics

The DAQ was responsible for isolating data signals from a broad output spectrum of the detectors, signal amplification, digitizing analog voltage signals and storing data for further analysis. The figure 20 shows the main components of the DAQ system in a block diagram.
Each germanium detector was biased to a level of negative 2000V by a high voltage power supply. The output of each detector was an analog voltage pulse with magnitude proportional to the energy deposited by an incident gamma ray. This signal was amplified first by a preamplifier attached to the detector and the preamplifier output from each HPGe detector was routed to an Ortec NIM shaping module. The shaped signal was then routed to an Ortec NIM amplifier which functioned as the main amplifier. The amplified signal was then routed to a CAEN V785 VME ADC and the digitized output was fed to the data processing computer.

A secondary output from the preamplifier was routed to a Tennelec Constant Fraction Discriminator (CFD) and then routed to a Fan Input/Output (Fan I/O) module. Three parallel outputs from the Fan I/O were routed to Gate and Delay Generators (GDG) and three 'gate signals' with different delays were generated. Two of these gate signals were used to gate the ADC and to trigger the computer. The third gate signal was used as
the start command to a latch circuit where the stop command was provided from the data acquisition computer. The timing diagrams of these gate signals and the veto signal generated by the latch module are shown in figure 21.

Figure 20. A block diagram of the data acquisition electronics.

A parallel output from the CFD was routed to a LRS2551 VME scaler in order to register the number of gamma detections occur during the experiment. The system dead time was measured and found to be in the order of 20μs. The veto signal from the latch was used to inhibit the CFD and the scaler during the data acquisition dead time. A major contribution to the dead time comes from the computer together with minor contributions
from the other signal processing modules. However, when compared to the events rate, the dead time correction was always near 0% and was assumed negligible.

Figure 21. Timing diagram for the gate signals.
Important nuclear physics concepts relevant to the current experiment are presented in this chapter. A methodology was implemented to extract reaction cross sections from gamma emission results. The significance of reaction cross sections, thermonuclear reaction rates, astrophysical S-factors and Gamow window for the reactions are discussed with an astrophysical viewpoint. Fitting of statistical model based S-factors to the experimental results in order to derive experimental thermonuclear reaction rates were discussed at the end.

Reaction Cross Sections

The cross section is an important aspect in nuclear reaction studies. It gives the likelihood or the relative probability of the occurrence of a reaction between interacting agents. Consider a binary reaction of the type $A(x,y)B$ where $A$ and $x$ are the target and projectile respectively and $y$ and $B$ are the reaction products. If a beam of incoming projectiles incident on a stationary target, the cross section ($\sigma$) for the reaction can be written as

$$\sigma = \frac{r_B}{I_x N},$$

(3.1)
where $I_x$ is the number of incident projectiles per unit time, $N$ is the number of target nuclei per unit area and $r_B$ is the rate of production of the particle $B$. In this definition, cross section has the dimension of area per nucleus. The standard unit for cross section is the ‘barn’ (b) where a barn is equal to $10^{-28} \text{m}^2$ or $10^{-24} \text{cm}^2$.

![Figure 22. Schematics of a reaction cross section. Shown here are the target, the incident beam of projectiles and the direction of outgoing particles.](image)

In practice a detector will not be detecting all the outgoing particles from a reaction. As shown in figure 22, it will cover only a solid angle $d\Omega$, and therefore only a fraction of the reaction result ($dr_B$) will be detected. In general the distribution of outgoing particles is function of $\theta$ and $\phi$ and therefore can be expressed as

$$dr_B = r(\theta, \phi) \frac{d\Omega}{4\pi}$$ (3.2)

Therefore the deduced cross section ($d\sigma$) is a fraction of the total cross section and can be written as

$$\frac{d\sigma}{d\Omega} = \frac{r(\theta, \phi)}{4\pi I_x N}$$ (3.3)
where the quantity \( \frac{d\sigma}{d\Omega} \) is known as the differential cross section. By integrating over all the angles, the total reaction cross section \( \sigma \) can be found.

Photon spectra from the activated targets were analyzed in order to calculate the proton capture cross sections. During the irradiation, nuclei in a target capture protons and become unstable. These unstable target nuclei then decay by beta decays or by electron captures in to their respective daughter products.

These newly produced daughter nuclei are in their excited states and tend to de-excite by photon emissions. As described in chapter 2, these de-excitation spectrums have characteristic photon peaks belonging to the gamma region. One can determine the number of nuclei produced during the irradiation by measuring the detected gamma rays and correcting for the decay branching ratios (Famiano et al., 2008; Ozkan et al., 2002). The procedure for calculating the number of nuclei produced and hence the proton capture cross section of the reaction is illustrated below.

The total number of nuclei produced \( N_T \), during an irradiation time \( t_{irr} \) is:

\[
N_T = n\sigma \int_0^{t_{irr}} I(t) e^{-\lambda(t_{irr}-t)} dt, \tag{3.4}
\]

where \( \lambda \) is the decay rate of produced nuclei, \( I(t) \) is the beam intensity, \( \sigma \) is the proton capture cross section, and \( n \) is the areal number density of target nuclei.

In practice, fluctuations can be occurred in the proton beam intensity. During each experimental run, beam intensity was monitored over discrete time intervals. If the total irradiation time period is divided into segments that are sufficiently small, then the beam intensity can be assumed constant over each segment.
Then, during any time segment $i$, the number of daughter nuclei produced $n_i$ is:

$$n_i = \frac{l_i \sigma n}{\lambda} (1 - e^{-\lambda \Delta t_i}),$$

(3.5)

where $\lambda$ is the decay rate of the produced nuclei, $l_i$ is the beam intensity for interval $i$, and $\Delta t_i$ is the length of time interval $i$. The number of nuclei produced during the $i^{th}$ interval and left after the total irradiation, $N_i$, is:

$$N_i = n_i e^{-\lambda (\eta - i) \Delta t_i},$$

(3.6)

where $\eta$ is the total number of intervals in the irradiation period. By substituting equation (3.5) to equation (3.6), $N_i$ can be expressed as:

$$N_i = \frac{l_i \sigma n}{\lambda} (1 - e^{-\lambda \Delta t_i}) e^{-\lambda (\eta - i) \Delta t_i}$$

(3.7)

By summing all the irradiation intervals, the total number of nuclei left at the end of the irradiation period $N_T$ can be obtained.

$$N_T = \sum_{i=1}^{\eta} N_i$$

(3.8)

Substituting equation (3.7) to equation (3.8);

$$N_T = \sum_{i=1}^{\eta} \frac{l_i \sigma n}{\lambda} (1 - e^{-\lambda \Delta t_i}) e^{-\lambda (\eta - i) \Delta t_i}$$

(3.9)

The equation (3.9) is the total number of daughter nuclei left on the target at the end of an irradiation cycle. The target was then transferred to the counting station and the transfer time was recorded as $t_{tr}$. 

41
The total number of nuclei at the beginning of the counting process, $N_{ci}$,

$$N_{ci} = N_T e^{-\lambda t_{tr}} \quad (3.10)$$

By substituting equation (3.9) to equation (3.10);

$$N_{ci} = \sum_{i=1}^{n} \frac{I_i \sigma n}{\lambda} (1 - e^{-\lambda \Delta t_i}) e^{-\lambda (\eta - i) \Delta t_i} e^{-\lambda t_{tr}} \quad (3.11)$$

The irradiated target was kept at the counting station and gamma emission was detected for a time period of $t_c$. The number of daughter nuclei left in the target at the end of the counting period, $N_{cf}$:

$$N_{cf} = N_{ci} e^{-\lambda t_c} \quad (3.12)$$

Substituting equation (3.11) to equation (3.12),

$$N_{cf} = \sum_{i=1}^{n} \frac{I_i \sigma n}{\lambda} (1 - e^{-\lambda \Delta t_i}) e^{-\lambda (\eta - i) \Delta t_i} e^{-\lambda t_{tr}} e^{-\lambda t_c} \quad (3.13)$$

Therefore the total number of decays during counting, $N_d$ is the numerical difference between equation (3.11) and equation (3.13).

$$N_d = N_{ci} - N_{cf} \quad (3.14)$$

By substituting equation (3.11) and equation (3.113) to equation (3.14) and simplifying,
\[ N_d = \sum_{i=1}^{\eta} \frac{l_i \sigma n}{\lambda} (1 - e^{-\lambda \Delta t_i}) e^{-\lambda (\eta - i) \Delta t_i} e^{-\lambda t_{tr}} - \sum_{i=1}^{\eta} \frac{l_i \sigma n}{\lambda} (1 - e^{-\lambda \Delta t_i}) e^{-\lambda (\eta - i) \Delta t} e^{-\lambda t_{tr}} e^{-\lambda t_c} \]  

(3.15)

\[ N_d = \frac{\sigma n}{\lambda} e^{-\lambda t_{tr}} (1 - e^{-\lambda t_c}) \sum_{i=1}^{\eta} l_i (1 - e^{-\lambda \Delta t_i}) e^{-\lambda (\eta - i) \Delta t} \]  

(3.16)

Equation (3.16) gives the actual number of decays occurred during the counting period.

When a radioactive parent nucleus decays, it often can decay in several ways. The probability that it decays in to a particular mode is known as its branching ratio for that decay mode (Krane, 1987). Knowing the branching ratios of specific decay modes that have associated gamma ray emissions, the total number of gamma emissions can be obtained. However the actual number of gamma rays registered by the detector system differs from the total number of emissions due to the limited detection efficiency of the detectors. Knowing the efficiency of detection and branching ratios, the number of gamma rays detected \( (N_\gamma) \) can be related to the number of nuclei decayed as follows.

\[ N_\gamma = N_d \varepsilon_{tot} f, \]  

(3.17)

where \( \varepsilon_{tot} \) is the total detection efficiency and \( f \) is the branching ratio of the particular decay branch. Substituting equation (3.17) with equation (3.16) gives;

\[ N_\gamma = \frac{\sigma n}{\lambda} e^{-\lambda t_{tr}} (1 - e^{-\lambda t_c}) \sum_{i=1}^{\eta} l_i (1 - e^{-\lambda \Delta t_i}) e^{-\lambda (\eta - i) \Delta t} \varepsilon_{tot} f \]  

(3.18)
where the reaction cross section ($\sigma$) is the only unknown quantity. A simple modification to the equation (3.18) gives a final expression to obtain the cross section.

$$
\sigma = \frac{N \lambda}{n \varepsilon_{tot}} \left( e^{-\lambda t_f} \left( 1 - e^{-\lambda t_c} \right) \sum_{i=1}^{\eta} I_i \left( 1 - e^{-\lambda \Delta t_i} \right) e^{-\lambda (\eta-i) \Delta t} \right)^{-1} 
$$

(3.19)

Proton capture cross sections can be calculated for each irradiation period using equation (3.19). All the terms in the right hand side can be obtained from experimental measurements and literature.

**Thermonuclear Reaction Rates**

The thermonuclear reaction rate (TRR) is also an important factor in astrophysical models which determines the rate of interaction between particles. Rate of a nuclear reaction depends on the energy of the reacting particles, the particle flux and the reaction cross section. In astrophysical calculations, the energy dependence of the nuclear cross section can be represented as velocity dependence, and can be written as follows.

$$
\sigma = \sigma(v),
$$

(3.20)

where $v$ represents the relative velocity between the target and the projectile. Now consider a stellar gas containing only two types (type $a$ and type $b$) of particles. Assume that the number densities for these particles in the gas are $N_a$ cm$^{-3}$ for type $a$ and $N_b$ cm$^{-3}$ for type $b$. If the nuclei of type $a$ were arbitrarily chosen as the stationary targets and the nuclei of type $b$ were chosen as the projectiles moving with relative velocity $v$, the reaction rate ($\dot{r}$) between these nuclei can be expressed as
\[ r = N_a N_b v \sigma(v), \quad (3.21) \]

where \( r \) has the units reactions per cubic centimeter per second. The velocity of particles in a gaseous medium spreads over a wide range of values and can be represented as a probability distribution

\[ \int_0^\infty \varphi(v) dv = 1, \quad (3.22) \]

where \( \varphi(v) \) is a function of probability. By combining the equation (3.22) and the term \( v \sigma(v) \) in equation (3.21), the reaction rate per particle pair \(< \sigma v >\) can be expressed as follows.

\[ < \sigma v > = \int_0^\infty \varphi(v) v \sigma(v) dv \quad (3.23) \]

Then the total reaction rate is

\[ r = N_a N_b < \sigma v > \quad (3.24) \]

In a stellar gas the velocity of particles spread over a wide range of values. These velocities are non-relativistic and can be represented by a normalized Maxwell-Boltzmann velocity distribution \( \Phi(v) \) as follows.

\[ \Phi(v) = 4 \pi v^2 \left( \frac{\mu}{2\pi kT} \right)^{3/2} \exp \left( -\frac{\mu v^2}{2kT} \right) \quad (3.25) \]

Here \( \mu \) represents the reduced mass of a two particle system of nuclides of interest, \( k \) is the Boltzmann constant and \( T \) is the stellar temperature.

By inserting equation (3.25) into equation (3.23), the reaction rate per particle pair can be obtained as
\[ <\sigma v> = 4\pi \left(\frac{\mu}{2\pi kT}\right)^\frac{3}{2} \int_0^\infty \nu^3 \sigma(\nu) \exp\left(-\frac{\mu\nu^2}{2kT}\right) d\nu \]  

(3.26)

Finally by using the center-of-mass energy of the target and projectile system \( E = \frac{1}{2} \mu v^2 \), equation (3.26) can be rewritten in terms of energy.

\[ <\sigma v> = \left(\frac{8}{\pi \mu}\right)^\frac{1}{2} \frac{1}{(kT)^\frac{3}{2}} \int_0^\infty \sigma(E) E \exp\left(-\frac{E}{kT}\right) dE \]  

(3.27)

Astrophysical S-factors

In charged-particle-induced reactions, the occurrence of a reaction is possible, if the incident projectile has enough energy that there is a non-zero probability of the projectile tunneling through the Coulomb barrier of the target nucleus. The tunneling probability \( p \) is given as;

\[ p = \exp(-2\pi\eta), \]  

(3.28)

where \( \eta \), known as the Sommerfeld parameter, is a measure of the total nuclear charge between interacting particles.

\[ \eta = \frac{Z_1 Z_2 e^2}{\hbar\nu} \]  

(3.29)

Here \( Z_1 \) and \( Z_2 \) are the charge numbers of the target and the projectile respectively and \( e \) the charge of an electron.

In proton-induced reactions, for proton energies below the target's Coulomb barrier, cross section decreases rapidly and it is proportional to the tunneling probability through the barrier. Therefore, in the low energy region;
\[ \sigma(E) \propto \exp(-2\pi\eta) \quad (3.30) \]

For projectiles with higher energies, variation of cross section is directly proportional to the De Broglie wavelength and hence inversely proportional to the energy, as shown in equation (3.19).

\[ \sigma(E) \propto \pi\lambda^2 \propto \frac{1}{E} \quad (3.31) \]

Combining both expressions, cross section can be expressed as;

\[ \sigma(E) = \frac{1}{E} \exp(-2\pi\eta) S(E) \quad (3.32) \]

where the function \( S(E) \) is known as the ‘astrophysical S-factor’ and has the units ‘keV-barn’. For non-resonant reactions, \( S(E) \) is a smoothly varying function of energy and has a less energy dependence compared to the nuclear cross section. Therefore, the S-factor is preferred over the cross section when extrapolating experimental results to astrophysical energies (Rolfs and Rodney, 1988).

The previous expression for reaction rate, equation (3.27), can now be modified by substituting the S-factors instead of the cross sections. Then, the reaction rate becomes

\[ \langle \sigma v \rangle = \left( \frac{8}{\pi\mu} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) \exp \left( -\frac{E}{kT} - \frac{b}{E^{1/2}} \right) dE \quad (3.33) \]

Here the factor \( b \) is given by

\[ b = \frac{\sqrt{2\mu e^2 Z_1 Z_2}}{\hbar} \quad (3.34) \]

and has the units of MeV\(^{1/2}\). The square of \( b \) is referred as the ‘Gamow energy’.
For non-resonant reactions, astrophysical S-factors have a smooth variation with the energy. Therefore, in equation (3.27) the energy dependence of the reaction rate is determined mostly by the exponential term. At lower energies, the term $\exp(-b/E^{1/2})$ which describes probability of a charged particle penetrating the Coulomb barrier, becomes very small. On the other hand, at higher energies, the term $\exp(-E/kT)$ that corresponds to a Maxwell-Boltzmann distribution, becomes insignificant. This situation is represented in figure 23 showing two curves corresponding to the two terms inside the exponent. The superposition of the two curves leads to a ‘probability peak’ which is also known as the ‘Gamow peak’ occurs at energy $E_0$.

Figure 23. The energy dependence of the probability of a reaction taking place. The region with maximum possibility is the Gamow window (Rolfs and Rodney, 1988).
For a given stellar temperature, a nuclear reaction occurs with a maximum reaction rate within a narrow energy window $E_0 \pm \Delta/2$, where $\Delta$ is the effective width of this energy region which is also known as the ‘Gamow window’ for the reaction (Rolfs and Rodney, 1988). Therefore, when performing an experiment, it is common in practice to set the projectile energy within the Gamow window to obtain maximum reaction rates.

Statistical Model Approach

Stellar nucleosynthesis involves a large number of nuclear reactions where protons, neutrons and alpha particles interact with each other as well as other heavier nuclei. In order to understand the properties of such stellar environments, a detailed knowledge in nuclear masses, excitation energies, reaction cross sections and reaction rates is required. As the number of nuclei involved in these reactions increases, the complexity of the reactions also increases making the analysis difficult and time consuming. The lack of experimental data forces the researcher to depend on theoretical predictions. Therefore nuclear reaction model codes based on statistical models play a vital role in astrophysical studies. In this dissertation study, experimentally determined proton capture cross sections and thermonuclear reaction rates were compared with the theoretical predictions from two particular statistical model codes, MOST and NON-SMOKER. Both of these codes are based on the Hauser-Feshbach statistical reaction model (Descouvemont and Rauscher, 2006; Hauser and Feshbach, 1952). In general, for nuclei above the mass region $A\sim 25$, stellar nucleosynthesis occurs predominantly via the formation of an intermediate compound nucleus state. Direct reactions are much less significant in this particular mass-energy region.
Let’s consider a nuclear reaction in usual notation $A(x,y)B$. The basis of the Hauser-Feshbach formalism is the assumption that nuclear reactions are propagating through a compound nucleus state. Here the cross section ($\sigma$) is treated as an energy dependent quantity and expressed as an energy-averaged cross section, $\sigma(E)$. A nuclear reaction is considered as a two step process where the first step is the formation of the intermediate compound nucleus. The second step is the decay of this short-lived compound state into one of the many possible pairs of reaction products. Therefore the energy-averaged cross section is expressed as

$$\sigma(E) = \sigma_1(x + A) \frac{\Gamma(y+B)}{\Gamma_{tot}},$$

(3.35)

Here $\sigma_1(x+A)$ is the cross section of the first step where the compound state is formed. In the second term of the equation, the decay of the compound state is represented as a branching ratio where $\Gamma(y+B)$ is the partial width of decaying to that particular final state and the $\Gamma_{tot}$ is the total width of all the possible final states available.

The maximum value of the cross section of formation is $\sigma_{max}$ and is expressed as an energy dependent quantity.

$$\sigma_1(x + A) = \sigma_{max} = \pi \lambda^2 \omega,$$

(3.36)

where $\lambda$ is the De Broglie wavelength that reflects the quantum mechanical nature of the cross section and $\omega$ is a statistical factor accounts for the spins and parities of the projectile and the target (Rolfs and Rodney, 1988). For a reaction between a projectile with a mass $m_p$ and a target nucleus with a mass $m_t$, $\lambda$ can be expressed as:

$$\lambda = \frac{m_p m_t}{m_t} \frac{h}{(2m_p E_i)^{1/2}},$$

(3.37)
where $h$ is the Planck’s constant and $E_i$ is the laboratory energy of the incident projectile.

For nuclear reactions involving charged particles such as protons, the model replaces partial and total widths with transmission functions. Therefore the cross section can be expressed as

$$\sigma(E) = \pi \lambda^2 \omega \frac{T_x(l)T_y(l)}{\sum_i T_i(l)},$$  \hspace{1cm} (3.38)

where the transmission functions $T_x$ and $T_y$ represent the formation and the dissociation of compound state. The total widths in equation 3.35 are also replaced by the summation of all the possible transmission functions available.

In order to find the total reaction cross section, one has to consider all the resonance states in the compound nucleus and find the summation. If the angular momentum ($J$) and the parity ($\pi$) of these states are known, the Hauser-Feshbach cross section can be expressed as

$$\sigma(E) = \frac{\pi \lambda^2}{(2j_p + 1)(2j_t + 1)\sum_{j,\pi} \frac{T_x(J,\pi)T_y(J,\pi)}{\sum_i T_i(J,\pi)}},$$ \hspace{1cm} (3.39)

where $j_p$ and $j_t$ are the spins of the projectile and target.
CHAPTER IV

PROTON CAPTURE REACTIONS

Results of the proton capture analysis are presented in this chapter. Photon spectra from activated targets were analyzed for characteristic gamma emission peaks as well as annihilation photons. Contaminations in the spectra resulting from target impurities were measured and cross sections were calculated. For the $^{116}$Sn target, current experimental results were compared with previously published data to conform the accuracy and reproducibility of the experimental technique. Astrophysical S-factors derived from cross section results were graphed against the projectile energies along with predictions from the statistical model codes. Theoretical S-factors were scaled to fit the experimental results in order to derive experimentally based thermonuclear reactions rates.

$^{116}$Sn(p,$\gamma$)$^{117}$Sb Reaction

Proton capture reactions on $^{116}$Sn target were studied first and results were compared with previous results from Ozkan et al (Ozkan et al., 2002) to assess the accuracy and the reproducibility of the experimental method. The $^{117}$Sb nucleus produced by $^{116}$Sn(p,$\gamma$)$^{117}$Sb reaction, decays to states in the $^{117}$Sn nucleus with a decay half life of 2.8 hours. As shown in figure 15, these excited states of $^{117}$Sn nucleus de-excites by emitting photons of energies 158, 846, 1005 and 1020keV together with 511keV annihilation photons. The resulting decay spectrum obtained is shown in figure 24.
The 511keV photons occur due to the beta decays of the $^{117}$Sb nuclei. A positron emitted from $\beta^+$ decay, combines with an electron in the absorbing medium of the detector creating an electron-positron annihilation. The result is the production of two gamma rays, each having an amount of energy equal to the rest mass energy of an electron (Knoll, 2000).

Cross sections were calculated from the gamma emission data according to the procedure described in chapter 3. At beam energies below 3MeV, cross sections were sufficiently low that only 511keV photons were useful for calculations. For these calculations, the proton's effective center-of-mass energy ($E$) was defined as

$$
\int_{E_{CM} - \Delta}^{E} \sigma(E) dE = \int_{E}^{E_{CM}} \sigma(E) dE, \quad (4.1)
$$

where $E_{CM}$ is the absolute center-of-mass proton beam energy impinging on the target.
and $\Delta$ is the energy width of the target. Annihilation radiation resulting from the contaminants in the target was also examined. Only $^{117}\text{Sn}$ and $^{118}\text{Sn}$ isotopes were the noticeable contaminants as the target mass fractions of other isotopes were minute. $^{117}\text{Sn}$ captures a proton and produces an $^{118}\text{Sb}$ nucleus which then beta decays to $^{118}\text{Sn}$. Its contribution to the 511keV photons was measured by looking at the de-excitation photons of $^{118}\text{Sn}$, such as the 1229keV photon. The other possibility is the decay of $^{119}\text{Sb}$ which was produced by proton captures on $^{118}\text{Sn}$. However there is no contribution to the 511keV peak as $^{119}\text{Sb}$ completely decays via electron capture.

Astrophysical S-factors derived from cross sections are shown in figure 25 for proton effective center-of-mass energies ranging from 2.21MeV to 3.59MeV. The results were compared with previous results from (Ozkan et al., 2002) and found to be in good agreement, verifying the accuracy of the experimental technique. In addition, the energy range of the measured cross sections and resulting S-factors were extended to lower energies. Additionally, results from NON-SMOKER statistical code are also shown in figure 25.

At lower energies, higher deviations exist between experimental data and NON-SMOKER predictions while better agreements can be seen towards higher proton energies. Results from the NON-SMOKER code were scaled to fit the experimental data according to the approach described in (Ozkan et al., 2002). A scaling function $f(E)$, was used to correlate the experimental S-factors $S(E)$, to the statistical model predictions. Scaling was done in such a way that $f(E)$ does not diverge at infinity and never becomes negative. With the introduction of $f(E)$:

$$S'(E) = f(E)S(E), \quad (4.2)$$
where \( S'(E) \) represents the scaled astrophysical S-factors.

Scaling was necessary since it allowed experimental results to be integrated over the entire energy range in order to calculate thermonuclear reaction rates. Also it enabled predicting results beyond the limited energy range where experimental data was taken.

The scaling function \( f(E) \) of equation (4.2) which used to make this conversion was chosen as \( f(E) = 25.15/E - 4.418 \). The scaled S-factors are also shown in figure 25. Experimental thermonuclear reaction rates (TRRs) were derived from scaled S-factors according to the methodology described in chapter 3. The uncertainties in the reaction rates were also calculated by considering the uncertainties in the S-factor results. These results are shown in figure 26 as functions of temperature. Experimental TRRs were

![Graph showing S-factors and reaction rates](image-url)
compared to theoretical results from NON-SMOKER and MOST codes and are shown in figure 27. The ratios of experimental results to NON-SMOKER and experimental results to MOST are shown in figure 28.

Figure 26. Experimental reaction rate of the $^{116}\text{Sn}(p,\gamma)^{117}\text{Sb}$ reaction. The broken lines indicate the uncertainty in the reaction rate.

Figure 27. Reaction rate comparisons for the $^{116}\text{Sn}(p,\gamma)^{117}\text{Sb}$ reaction. Experimental TRRs and predictions from NON-SMOKER and MOST codes are shown.
Figure 28. Reaction rate ratios for the $^{116}\text{Sn}(p,\gamma)^{117}\text{Sb}$ reaction.

$^{114}\text{Sn}(p,\gamma)^{115}\text{Sb}$ Reaction

Proton captures on $^{114}\text{Sn}$ nucleus produces an $^{115}\text{Sb}$ nucleus which decays to a $^{115}\text{Sn}$ with a half life of 32.16 minutes. The decay scheme is shown in figure 14 along with the photons of interest and the decay branching ratios. The gamma ray spectrum from the de-excitations of $^{115}\text{Sb}$ nuclei is shown in figure 29, where the 497keV gamma peak, 511keV annihilation peak and 1008keV sum peak (497keV + 511keV) were used to identify and quantify the amount of $^{115}\text{Sb}$ produced in the target.

Contribution to the annihilation peak from impurities in the $^{114}\text{Sn}$ target was investigated. It was assumed that the beta decay of $^{117}\text{Sb}$ which was produced by proton captures on $^{116}\text{Sn}$ may have the largest contribution to the 511 peak. However the decay rate of $^{117}\text{Sb}$ is comparably smaller than the decay rate of $^{115}\text{Sb}$ and the characteristic 158keV gamma peak from the decay of $^{117}\text{Sb}$ was never observed. Therefore it was determined that the contamination from $^{116}\text{Sn}$ is negligible.
The other possible contributors presented in the target were isotopes ranging from $^{118}\text{Sb}$ to $^{125}\text{Sb}$. Contamination from $^{118}\text{Sb}$, $^{120}\text{Sb}$ and $^{125}\text{Sb}$ was determined insignificant because there were no characteristic photons observed from their decay spectrums. All of these isotopes have very long half lives compared to the $^{115}\text{Sb}$ and their abundances in the target were also small. Likewise the contribution from other remaining isotopes was not a concern since $^{119}\text{Sb}$, $^{122}\text{Sb}$ and $^{124}\text{Sb}$ do not have $\beta^+$ decay branches while both $^{121}\text{Sb}$ and $^{123}\text{Sb}$ isotopes are stable.

Astrophysical S-factors derived from the cross section results are shown in figure 30 for proton effective center-of-mass energies ranging from 2.11MeV to 3.62MeV. NON-SMOKER results for the same energy range are also shown in the figure. Statistical model results were scaled using a scaling function $f(E) = 12.359/E - 1.709$ for the purpose of calculating TRRs. Experimentally derived TRRs and their uncertainties are shown in figure 31. Experimental reaction rates for the $^{114}\text{Sn}(p,\gamma)^{115}\text{Sb}$ reaction were compared to the MOST and NON-SMOKER theoretical predictions and results are
shown in figure 32. The ratios of the experimentally determined TRRs to those from the statistical model calculations are shown in figure 33.

![Graph showing S-factors for the $^{114}$Sn(p,γ)$^{115}$Sb reaction. NON-SMOKER predictions and scaled NON-SMOKER rates are also shown.](image)

Figure 30. Experimental S-factors for the $^{114}$Sn(p,γ)$^{115}$Sb reaction. NON-SMOKER predictions and scaled NON-SMOKER rates are also shown.

$^{64}$Zn(p,γ)$^{65}$Ga Reaction

The broad decay spectrum of $^{65}$Ga includes photons of energies 61, 115, 153, 206, 660, 752, 769, 867, 910, 932, and 1047keV in addition to the 511keV annihilation photons. Selected photons of interest are shown in figure 13 along with decay branching ratios. Two magnified regions of the resulted gamma spectrum is shown in figure 34 where the upper portion of the figure shows peaks with energy less than 660keV. The bottom portion of the figure 34 shows higher energy peaks. Due to the availability of multiple photon peaks, the accuracy of cross section calculation increases.
Figure 31. Experimental TRRs and the uncertainties for the $^{114}\text{Sn}(p,\gamma)^{115}\text{Sb}$ reaction.

Figure 32. Reaction rate comparisons for the $^{114}\text{Sn}(p,\gamma)^{115}\text{Sb}$ reaction.
Because of the $^{64}$Zn target was extremely pure, contamination in the 511keV peak was insignificant. In fact the decay of $^{67}$Ga which produced by proton captures on $^{66}$Zn, does not make any contribution as $^{67}$Ga decays by electron capture. The only remaining contaminant produced by proton captures, $^{69}$Ga is a stable isotope. Astrophysical S-factors derived from the cross section results are shown in figure 35 for proton effective center-of-mass energies ranging from 2.12MeV to 3.61MeV. NON-SMOKER results for this reaction shows a much better agreement compared to the Sn targets. The scaling function $f(E) = 1.365/E^3 - 3.29405/E^2 + 2.997/E - 0.095$ was used to correlate statistical model predictions to the experimental results.

![Graph showing reaction rate ratios for the $^{114}$Sn(p,$\gamma$)$^{115}$Sb reaction.](image)

Figure 33. Reaction rate ratios for the $^{114}$Sn(p,$\gamma$)$^{115}$Sb reaction.

Experimental TRRs for the proton captures on $^{64}$Zn are shown in figure 36 along with the uncertainties in the reaction rates. Rate comparisons between the experimental
results and the MOST and NON-SMOKER results are shown in figure 37. Ratios of the experimental results to the statistical model predictions are given in figure 38.

![Graph showing decay spectrum](image)

**Figure 34.** Decay spectrum of the $^{64}$Zn(p,$\gamma$)$^{65}$Ga reaction. Source (Famiano et al., 2008)

![Graph showing astrophysical S-factors](image)

**Figure 35.** Astrophysical S-factors for the $^{64}$Zn(p,$\gamma$)$^{65}$Ga reaction. Also shown are the NON-SMOKER predictions and scaled NON-SMOKER rates.

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Proton captures on $^{46}$Ti target produces $^{47}$V which then $\beta^+$ decays with a 100% branching ratio to states of $^{47}$Ti. A typical photon spectrum of $^{47}$Ti is shown in figure 39, where the 511keV annihilation peak is the major contributor in cross section calculations. A smaller contribution to calculations comes from the 1390, 1550, 1794, and 2163keV peaks at higher proton energies.

Contamination in the 511 peak mainly comes from the decay of $^{48}$V which produced by proton captures on $^{47}$Ti isotopes. However its contribution was removed by examining the 983keV and 1312keV peaks in the spectrum.

There was no contribution from other impurities in the target since $^{49}$V and $^{50}$V do not have $\beta^+$ decay branches. The other significant contaminant, $^{51}$V is a stable isotope.

Figure 36. Experimental TRRs and uncertainties for the $^{64}$Zn(p,$\gamma$)$^{65}$Ga reaction.
Astrophysical S-factors derived from the cross section results are shown in figure 40 for proton effective center-of-mass energies ranging from 0.88MeV to 3.23MeV. Also shown are the predicted results and scaled results from NON-SMOKER.

Figure 37. Reaction rate comparisons for the $^{64}$Zn(p,$\gamma$)$^{65}$Ga reaction.

Figure 38. Reaction rate ratios for the $^{64}$Zn(p,$\gamma$)$^{65}$Ga reaction.
Figure 39. Decay spectrum of the $^{46}\text{Ti}(p,\gamma)^{47}\text{V}$ reaction. The inset is a magnified region with some of the much less dominant 1390, 1550, 1794, and 2163keV peaks (Famiano et al., 2008).

In this case the particular behavior of statistical model which predicted an exponent at energies below 1MeV and a varying exponential behavior at higher energies, made it difficult to scale the results. To correlate the experimental results to theoretical predictions in order to derive the thermonuclear reaction rates, the scaling function $f(E) = 0.27\exp(-0.001E^{2.25}) + 47.58\exp(-0.538E^{2.9}) - 46.80\exp(-0.57E^{3})$ was used. Experimental TRRs for proton capture on $^{46}\text{Ti}$ derived from scaled S-factors are shown in figure 41 along with the uncertainties. As in the previous sections, experimental results were compared with theoretical predictions from MOST and NON-SMOKER codes and ratios were calculated. These results are shown in figures 42 and 43 respectively.
Figure 40. Astrophysical S-factors for the $^{46}$Ti(p,γ)$^{47}$V reaction. Also shown are the predictions from NON-SMOKER calculations along with the scaled NON-SMOKER rates.

Figure 41. Experimental reaction rates of the $^{46}$Ti(p,γ)$^{47}$V reaction.
Figure 42. Reaction rate comparisons for the $^{46}\text{Ti}(p,\gamma)^{47}\text{V}$ reaction.

Figure 43. Reaction rate ratios for the $^{46}\text{Ti}(p,\gamma)^{47}\text{V}$ reaction.
CHAPTER V

NETWORK CALCULATIONS

Experimentally derived thermonuclear reaction rates (TRRs) were compared with the theory and discussed. A computer model was used to simulate the rp-process network and the input parameters to the model were modified with experimental results. Abundance distributions of nuclides of interest are presented and discussed. As an extension to this work, a photonuclear (photodisintegration) reaction network relevant to synthesizing proton rich nuclides was simulated using inverse reactions.

Analysis on rp-process

The rp-process contributes to the nucleosynthesis by producing some of the lighter mass proton rich nuclei. The stellar environments and conditions favoring the process were discussed in chapter 1. Below the A=20 mass region, rp-process can be considered as a continuation of the hot CNO cycle (HCNO) with limited number of reactions. However, the analysis becomes much more difficult beyond A>20 mass region due to the involvement of a large number of nuclear reactions and decay chains. Therefore it is necessary to simulate the synthesis process with an adequate computer model for a detailed analysis (Iliadis et al., 1999; Rembges et al., 1997). Often there can be as many as thousands of nuclei involved in capture reactions, photo-dissociations, radioactive decay processes etc, making the network complicated and difficult to analyze.
Modeling the Nucleosynthesis

A nucleosynthesis process consists of a complex network of nuclear reactions which consists of a large number of nuclei and many different nuclear reactions among them. Often there can be as many as thousands of nuclei involved in capture reactions, photo-dissociations, radioactive decay processes etc, making the network difficult to analyze. Although each individual reaction contributes to the elemental production with some degree of significance, the net outcome of such a synthesis process depends on the collective behavior of the entire network.

Computer models play an important role in astrophysical network calculations by making it possible to handle vast amounts of data efficiently with high computational accuracy. The outcome of a network analysis contains elemental abundance distribution, energy and temperature profiles, etc. Although nuclear-astrophysical experiments have improved significantly over the past decades, still most of the widely used models depend on theoretical predictions as their prime source of reaction data. Therefore it has become an important aspect of nuclear astrophysics research to improve such models with experimental inputs.

The GAMBLER Network Code

In this dissertation research, the network code GAMBLER (General Abundance Manipulator Based on Local Evolution of Reactions) was used to study the details of the proton capture reactions. GAMBLER is a widely used network code in stellar nucleosynthesis studies and is much appropriate for rp-process and photodisintegration analysis. The primary purpose of the code is to find the change in abundance of all the
nuclei participated in the network. In the following section, the implementation of the code will be discussed briefly.

The abundance of a nucleus of type $i$ ($Y_i$), is a dimensionless quantity and is defined as

$$Y_i = \frac{X_i}{A_i},$$  \hspace{1cm} (5.1)

where $X_i$ is the mass fraction and $A_i$ is the mass number of the nucleus. It is important to notice that only the abundances of the ground state nuclei are considered in this implementation. The number density (Famiano et al., 2008) of the nucleus can be written as

$$n_i = \frac{X_i \rho}{m_i},$$  \hspace{1cm} (5.2)

where $\rho$ represents the mass density of the element and $m_i$ is the mass. An approximation to the mass, $m_i$ can be obtained as

$$m_i = A_i m_\mu = \frac{A_i}{N_A},$$  \hspace{1cm} (5.3)

where $m_\mu$ is the atomic mass unit in CGS units and $N_A$ is the Avogadro’s number. Then the equation (5.2) can be modified and the number density becomes

$$n_i = Y_i \rho N_A$$  \hspace{1cm} (5.4)

By considering a nuclear reaction of type $i(j,k)l$ where $i$ and $j$ are reactants while $k$ and $l$ are the reaction results, the change in abundance of nuclei $i$, ($Y_i$) can be written as
\[
\frac{dY_i}{dt} = -Y_i \gamma j \rho N_A <\sigma v>_{ij,kl},
\]

where the minus sign indicates that \( Y_i \) is decreasing in the network. Here \(<\sigma v>\) is the reaction rate per particle pair which was derived in chapter 3.

When executing a reaction network, the code starts with initial abundances of all the available elements and moves forward to calculate the abundances at a future time. For the simplification of analysis, let's consider the abundance of an arbitrary element and denote the right hand side of equation (5.5) by the function \( f(Y) \).

\[
\dot{Y} = f(Y)
\]

By the semi-implicit Euler method, the abundance of a future time can be written as

\[
y_{n+1} = y_n + hf(y_{n+1}),
\]

where \( h \) is a small time step. By expanding \( f(y_{n+1}) \) about \( f(y_n) \), the above expression can be linearized.

\[
f(y_{n+1}) = f(y_n) + \left[ \frac{\partial f}{\partial y} \right]_{y_n} (y_{n+1} - y_n)
\]

By substituting equation (5.8) in equation (5.7);

\[
y_{n+1} = y_n + h \left[ 1 - h \frac{\partial f}{\partial y} \right]^{-1} f(y_n)
\]

For simplicity of calculations let's define;

\[
\Delta = h \left[ 1 - h \frac{\partial f}{\partial y} \right]^{-1} f(y_n)
\]
Then the equation (5.9) takes the form

\[ y_{n+1} = y_n + \Delta \]  

(5.11)

Also a set of matrices were defined as

\[ \hat{A} = (I - h\hat{J}), \]  

(5.12)

where \( \hat{J} \) is the Jacobian matrix which is defined as

\[ \hat{J} = \frac{\partial f}{\partial y} \]  

(5.13)

Then by solving a set of equations of the form

\[ \hat{A} \cdot \Delta = hf(y_n) \]  

(5.14)

The value of \( \Delta \) can be found and hence equation (5.11) can be solved.

The reacting nuclides in the network are contained in a Jacobian matrix which represents the flow of the synthesis process in nuclei per second. Starting from protons and neutrons the network contains elements up to xenon, and for each element it includes isotopes from stability to the proton drip line. This makes a total number of 686 nuclei in the network and it executes 7635 reactions between these nuclei.

The Jacobian matrix shown in figure 44 is made up of all the elements in the network and each matrix element represents a possible reaction between two reacting agents. Although all the elements in the Jacobian should have non-zero values in principle, most of the reactions can be excluded from calculations due to their very low contributions to the synthesis process (Wallace, 2005). As a result the matrix is 98.4% sparse and almost all the significant matrix elements found along the diagonal.
In GAMBLER, inputs for reaction rate calculations are contained in separate files for different synthesizing mechanisms. For charged particle capture reactions, such as rp-process, inputs have been calculated assuming that each reaction proceeds through a direct reaction or a compound nuclear (CN) intermediate state. Most of the rates in the network were theoretical predictions from the Hauser-Feshbach code NON-SMOKER while actual experimental results have been included whenever available.

When executing a network calculation, GAMBLER starts with initial elemental abundances, which are stored in libraries. Initial stellar conditions such as temperature, gravity, pressure and density can be selected according to the synthesis process considered. Once all the initial inputs were stated, the program calculates the elemental abundance at a future time by progressing through finite small steps. In addition to the abundance, information regarding density, temperature and the energy production can be obtained.
The input data file of the rp-process contains reaction information on (p,γ), (p,α), (n,γ), (n,p), (n,α) and (α, γ) reactions along with their inverse reaction data. These reaction rates have been obtained from the REACLIB database which contains a comprehensive collection of nuclear reaction rates. Based on Caughlan and Fowler compilation (1988), reaction rates in REACLIB are presented in a characteristic seven parameter format which make them convenient to use in astrophysical model calculations.

Reaction Rate Comparisons

Aim of the analysis was to compare the experimental reaction rates with theoretical data and observe how these experimental results influence the rp-process. For each target used in the experiment, experimental TRRs were derived from S-factor results. Methodology for these derivations was explained in the third chapter with results shown in the fourth chapter. TRR results were then plotted against the temperature, and on the same graphical area, respective theoretical results were plotted for the comparison. These plots are shown in figures 45, 46, 47 and 48. In all of these figures the vertical axis represents the reaction rate and the horizontal axis represents the temperature in $10^9$K units.

It was observed that in the low temperature region (< 1 GK) theoretical predictions agree well with the experimental results for all the four targets. In general, beyond the 2GK region, deviations can be seen for the Ti and Zn targets. For the two Sn targets, deviations occur approximately after the 3GK temperature region.
Abundance Calculations

Updating Reaction Rates

In order to investigate the influence of experimental results on the rp-process network calculations, the reaction rate file of GAMBLER needed to be updated with experimental data. In REACLIB, the nuclear reaction rate ($\lambda$) is represented as an exponential function of the temperature with seven parameters ($a_0$ to $a_6$).

$$\lambda = \exp\left[ a_0 + \frac{a_1}{T_9} + \frac{a_2}{(T_9)^{1/3}} + a_3(T_9)^{1/3} + a_4T_9 + a_5(T_9)^{5/3} + a_6\log(T_9) \right],$$  \hspace{1cm} (5.15)

where above expression can be rewritten as

Figure 45. Experimental and theoretical TRRs for the $^{46}$Ti target.
\[ \lambda = \exp \left[ a_0 + \sum_{i=1}^{5} a_i T_i^{2i-5/3} + a_6 \ln T_9 \right] \tag{5.16} \]

In this representation, \( T_9 \) stands for the temperature in the units of \( 10^9 \) Kelvin. In order to update the GAMBLER's reaction rates, experimental reaction rate results were transformed into the same seven-parameter format following the instructions given in (Cyburt et al., 2010).

Figure 46. Experimental and theoretical TRRs for the \(^{64}\text{Zn}\) target.

The REACLIB rates in parametric format were fit to the experimental curves, while observing the changes in parameters. Getting the best possible fit is important as it changes the theoretically defined values of the parameters into new values. The fitting was executed manually until a smooth overlap between the two curves was visible. When assigning values to the rate parameters, in the case of a non resonant charged particle
reaction, following constrains from (Bildsten and Rutledge, 2000) were used as guidelines.

Figure 47. Experimental and theoretical TRRs for the $^{114}$Sn target.

Figure 48. Experimental and theoretical TRRs for the $^{116}$Sn target.
In table 5, $Z_1$ and $Z_2$ are the proton numbers of projectile and the target, $A$ is the reduced mass of the projectile in atomic mass units, $S(0)$ is the astrophysical S-factor in MeV-barn at zero energy and $B$ is a constant with a value of $7.8318 \times 10^9$ cm$^3$ s$^{-1}$ mole$^{-1}$ MeV$^{-1}$ barn$^{-1}$. Numerical values for $a_3$, $a_4$ and $a_5$ can be varied in order to get fittings at higher temperatures.

With modified rate parameters, the reaction rate library of GAMBLER was updated. Network calculations were performed to investigate the influence of experimental findings on the rp-process. Comparisons were made between results from the original reaction rate values and the modified ones. Attention was given to investigate the abundance distributions resulting from reactions in the neighborhoods of modified reactions. Similar comparisons were made between results obtained for different initial burning conditions.

### Table 5

Fitting rules for non resonant, charged particle induced reaction rates.

<table>
<thead>
<tr>
<th>Rate parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0 = \ln \left[ B \left( \frac{Z_1 Z_2}{A} \right)^{1/3} S(0) \right]$</td>
</tr>
<tr>
<td>$a_1 = 0$</td>
</tr>
<tr>
<td>$a_2 = -4.2486 (Z_1^2 Z_2^2 A)^{1/3}$</td>
</tr>
<tr>
<td>$a_3 = \text{float}$</td>
</tr>
</tbody>
</table>

Source (Cyburt et al., 2010)
Results

A network calculation was performed to simulate the rp-process occurs on a surface of an accreting neutron star. Presence of rp-process is commonly identified by the associated X-ray burst, which shows a rapid increase in luminosity with a peak that lasts for about 20 seconds before decaying gradually. The emission spectrum of an X-ray burst shows its highest intensity in the X-ray region of the electromagnetic spectrum (Bildsten, 1995; Bildsten and Rutledge, 2000; Joss, 1977). Table 6 shows the stellar environmental parameters used in the simulation.

Table 6

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Value</th>
<th>Element</th>
<th>Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial temperature</td>
<td>0.2 GK</td>
<td>$^1\text{H}$</td>
<td>0.66</td>
</tr>
<tr>
<td>Density</td>
<td>$4.8\times10^3\text{ kg/cm}^3$</td>
<td>$^4\text{He}$</td>
<td>0.339</td>
</tr>
<tr>
<td>Pressure</td>
<td>$7.4\times10^{22}\text{ N/m}^2$</td>
<td>$^{14}\text{O}$</td>
<td>0.000352</td>
</tr>
<tr>
<td>Local gravity</td>
<td>$1.9\times10^{12}\text{ m/s}^2$</td>
<td>$^{15}\text{O}$</td>
<td>0.000648</td>
</tr>
</tbody>
</table>

Figure 49 shows the change in temperature with time during a typical X-ray burst. The sudden rise of the temperature shows the peak of the X-ray burst which is characteristic to such an explosive event. Temperature profiles obtained with original reaction rates and experimental rates were compared and found to be identical. It is because the shape of the temperature peak is mainly determined by the amount of hydrogen in the network and it did not altered by experimental modifications.
At first, a network calculation was executed with theoretical reaction data from the REACLIB data base. Then a second calculation was carried out after modifying the reaction rates of targets of interest with respective experimental results. The change in abundance was plotted in terms of mass fraction. Figures 50 to 57 show these experimental and theoretical results. Table 7 shows a summary of these capture reactions and daughter products along with respective figure numbers.

Figure 50 shows the production of $^{47}$V from the reaction $^{46}$Ti(p,$\gamma$)$^{47}$V. It is interesting to note that the abundance of $^{47}$V increases rapidly with time at the beginning of the network and reduces in a similar rate. Being an unstable isotope, it completely beta decays to $^{47}$Ti.

Figure 49. Change in temperature during the X-ray burst simulation.

Mass fraction distribution of $^{47}$Ti (figure 51) becomes stable over time after reaching a peak. Synthesis of $^{65}$Ga due to the reaction $^{64}$Zn(p,$\gamma$)$^{65}$Ga is shown in figure
52. Similar to the production of $^{47}$V, this also shows a rapid increase in abundance followed by a gradual decay. Figure 53 shows that the abundance of $^{65}$Zn is reaching equilibrium. However $^{65}$Zn is also an unstable nucleus which decays to $^{65}$Cu with a half-life of 244 days. Therefore it will be interesting to execute the network for a longer period of time to observe the behavior of $^{65}$Zn.

Table 7

The reactions studied, reaction results and figure numbers.

<table>
<thead>
<tr>
<th>Target</th>
<th>Proton capture reaction</th>
<th>Daughter (Unstable)</th>
<th>Figure No.</th>
<th>Decay of daughter</th>
<th>Figure No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{46}$Ti</td>
<td>$^{46}$Ti(p,γ)$^{47}$V</td>
<td>$^{47}$V</td>
<td>50</td>
<td>$^{47}$Ti</td>
<td>51</td>
</tr>
<tr>
<td>$^{64}$Zn</td>
<td>$^{64}$Zn(p,γ)$^{65}$Ga</td>
<td>$^{65}$Ga</td>
<td>52</td>
<td>$^{65}$Zn</td>
<td>53</td>
</tr>
<tr>
<td>$^{114}$Sn</td>
<td>$^{114}$Sn(p,γ)$^{115}$Sb</td>
<td>$^{115}$Sb</td>
<td>54</td>
<td>$^{115}$Sn</td>
<td>55</td>
</tr>
<tr>
<td>$^{116}$Sn</td>
<td>$^{116}$Sn(p,γ)$^{117}$Sb</td>
<td>$^{117}$Sb</td>
<td>56</td>
<td>$^{117}$Sn</td>
<td>57</td>
</tr>
</tbody>
</table>

The change in abundance of $^{115}$Sb which produced by the radiative proton captures on $^{114}$Sn target is shown in figure 54. It can be seen that the abundance predicted by the theory is slightly lower than the experimental results. As an unstable isotope $^{115}$Sb decays back to stable $^{115}$Sn via electron capture and beta decays, thus decreasing the abundance of $^{115}$Sb over time. The abundance of $^{115}$Sn reaches a peak within few hundreds of seconds and remains closer to the peak as shown in figure 55. Much similar to the $^{115}$Sb, the abundance of $^{117}$Sb also increases rapidly and decreases with a gradual decay (figure 56). In this case theory seems to predict the mass fraction of $^{117}$Sb very
accurately at the beginning of the network while a slight deviation appears as the network
proceeds. The decay of $^{117}$Sb produces stable $^{117}$Sn which shows a stable level of
abundance over time.

Figure 50. Change in abundance of $^{47}$V during an X-ray burst.

Figure 51. Change in abundance of $^{47}$Ti during an X-ray burst.

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Figure 52. Change in abundance of $^{65}\text{Ga}$ during an X-ray burst.

Analysis on Inverse Reactions

As discussed previously, the unstable parent nuclei $^{47}\text{V}$, $^{65}\text{Ga}$, $^{115}\text{Sb}$ and $^{117}\text{Sb}$ decay to the respective daughter products $^{47}\text{Ti}$, $^{65}\text{Zn}$, $^{115}\text{Sn}$ and $^{117}\text{Sn}$ via β-decay and electron capture. However, at very high stellar temperatures, typically in the 2GK−3GK region, photonuclear (photodisintegration) reactions can also contribute to the decay of above nuclides. As a continuation of the present work, an attempt was made to study these disintegration processes.

High Temperature Photodisintegrations

During the later phases of a stellar evolution, due to the extreme temperature of the environment, high energy photons can interact with previously produced heavy nuclides. These energetic photons, mainly in the form of γ-rays, can disintegrate elements
Figure 53. Change in abundance of $^{65}$Zn during an X-ray burst.

Figure 54. Change in abundance of $^{115}$Sb during an X-ray burst.
synthesized by s-, r- or rp-process. Although the affect of photodisintegration on nucleosynthesis is minute at lower temperatures, its contribution increases significantly at higher stellar temperatures. The reactions \((\gamma,p)\), \((\gamma,n)\) and \((\gamma,a)\) can be considered as the predominant photodisintegration reactions that contributes to the production of elements (Woosley and Howard, 1978; Woosley and Howard, 1990).

![Graph](image)

Figure 55. Change in abundance of \(^{115}\text{Sn}\) during an X-ray burst.

It is rather difficult and sometimes impossible to study this process experimentally due to the lack of gamma-ray photon beams with sufficient energy. Efforts have been made in laboratories to measure photodisintegration cross sections using high energy tunable \(\gamma\)-ray lasers, focusing mainly on the lighter elements in the chart of nuclides (Weller, and Ahmed, 2003). Unavailability of intense and monochromatic photon beams has limited the experimental data for photodisintegration.
Figure 56. Change in abundance of $^{117}$Sb during an X-ray burst.

Figure 57. Change in abundance of $^{117}$Sn during an X-ray burst.
of most of the heavy nuclides. However, an indirect method to measure the photodisintegration cross section is to measure the cross section of the inverse reaction and then use the detailed balance principle to find the cross section of interest.

Inverse Reactions and Detailed Balance Principle

Temperature is a key factor which governs the direction of a nuclear reaction. At low stellar temperatures, reactions with positive Q-values occur predominantly compared to the reactions with negative Q-values. Consider the following example where a nuclear reaction between two participants labeled as 1 and 2 forms the new products 3 and 4.

\[ l + 2 \rightarrow 3 + 4, \quad Q > 0 \]  

(5.17)

At low temperatures, the inverse of above is insignificant since the reactants 3 and 4 do not have enough energy to initiate a reaction. However, if the temperature increases sufficiently, number of particles with energy higher than Q increases and the inverse reaction becomes significant.

\[ 3 + 4 \rightarrow 1 + 2, \quad Q < 0 \]  

(5.18)

For such a pair of reactions, the ratio of forward and inverse reaction cross sections \( \frac{\sigma_{12}}{\sigma_{34}} \) can be obtained using the detailed balance principle.

\[
\frac{\sigma_{12}}{\sigma_{34}} = \frac{m_3m_4E_{34}(2J_3 + 1)(2J_4 + 1)(1 + \delta_{12})}{m_1m_2E_{12}(2J_1 + 1)(2J_2 + 1)(1 + \delta_{34})}
\]  

(5.19)

Here \( m \) stands for the masses of reacting particles, \( E \) stands for center of mass energies and \( J \) stands for the spins of the particles. The purpose of the term \( \delta \) is to double the cross section, in the case of identical particles. By using the eq. 3.33 which discussed
in third chapter and the relation \( E_{34} = E_{12} + Q \) \((Q>0)\), the ratio of reaction rates per particle pair \((\langle \sigma v \rangle_{34}/\langle \sigma v \rangle_{12})\) can be obtained.

\[
\frac{\langle \sigma v \rangle_{34}}{\langle \sigma v \rangle_{12}} = \frac{(2J_1 + 1)(2J_2 + 1)(1 + \delta_{34})}{(2J_3 + 1)(2J_4 + 1)(1 + \delta_{12})} \left(\frac{\mu_{12}}{\mu_{34}}\right)^{3/2} \exp\left(-\frac{Q}{kT}\right)
\] (5.20)

Here \( \mu \) is the reduced mass of the particles, \( k \) is the Boltzmann constant and \( T \) is the temperature. In order to derive photodisintegration reactions relevant to radiative proton capture reactions, above equation needs modifications including replacing the particle labeled as '4' with a gamma ray photon (\( \gamma \)).

\[
\frac{\langle \sigma v \rangle_{3\gamma}}{\langle \sigma v \rangle_{12}} = \left(\frac{169}{8\pi^5}\right)^{1/2} \frac{(2J_1 + 1)(2J_2 + 1)}{(2J_3 + 1)} \left(\frac{\mu c^2}{kT}\right)^{3/2} \exp\left(-\frac{Q}{kT}\right)
\] (5.21)

Here \( c \) represents the speed of light. Comprehensive explanations on the detailed balance principle and its application to nuclear reactions can be found in Rolfs and Rodney (1988) and Pagel (2009).

**Reaction Rate Comparisons**

Following the above described methodology, photodisintegration reaction rates on \( ^{47}\text{V} \), \( ^{65}\text{Ga} \), \( ^{115}\text{Sb} \) and \( ^{117}\text{Sb} \) were derived. These experimental results are shown in figures 58 to 61 along with the respective rate predictions from REACLIB data base. The inverse reactions of interest and their forward counterparts are shown in table 8.

As discussed previously, it is evident that the inverse reaction rates at low temperature range are extremely small and can be excluded from abundance calculation. Rates increase noticeably beyond (2-3) GK region and become much significant for
calculations. A good agreement can be seen between the experimental results and the theoretical predictions for low stellar temperatures. However with increasing temperature, disagreements can be seen for all the four reactions studied.

Table 8

<table>
<thead>
<tr>
<th>Forward reaction</th>
<th>Inverse reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{46}\text{Ti} + p \rightarrow ^{47}\text{V} + \gamma$</td>
<td>$^{47}\text{V} + \gamma \rightarrow ^{46}\text{Ti} + p$</td>
</tr>
<tr>
<td>$^{64}\text{Zn} + p \rightarrow ^{65}\text{Ga} + \gamma$</td>
<td>$^{65}\text{Ga} + \gamma \rightarrow ^{64}\text{Zn} + p$</td>
</tr>
<tr>
<td>$^{114}\text{Sn} + p \rightarrow ^{115}\text{Sb} + \gamma$</td>
<td>$^{115}\text{Sb} + \gamma \rightarrow ^{114}\text{Sn} + p$</td>
</tr>
<tr>
<td>$^{116}\text{Sn} + p \rightarrow ^{117}\text{Sb} + \gamma$</td>
<td>$^{117}\text{Sb} + \gamma \rightarrow ^{116}\text{Sn} + p$</td>
</tr>
</tbody>
</table>

Abundance Calculations

Updating Reaction Rates

Photodisintegration reactions occur in environments where the temperature is high enough (typically 2GK–3GK) and pre-synthesized heavy elements are abundant. Therefore, type 1 and type 11 supernova explosions and accretion on to a neutron star can be considered as possible stellar sites favoring the process (Howard, Meyer, and Woosley, 1991).

In order to simulate a photodisintegration site, the initial temperature was set to 2GK and the surface gravity was set to $7 \cdot 10^{12}\text{m/s}^2$. The density was chosen as $1 \cdot 10^{17}\text{kg/m}^3$. The theoretical rates obtained from the network calculation were then fitted to the experimental data in order to derive the experimental rate parameters. A procedure
similar to which followed with proton capture (forward) reactions, was used for the derivation.

Figure 58. Photodisintegration reaction rates for $^{47}\text{V}(\gamma,p)^{46}\text{Ti}$ reaction.

Figure 59. Photodisintegration reaction rates for $^{65}\text{Ga}(\gamma,p)^{64}\text{Zn}$ reaction.
Figure 60. Photodisintegration reaction rates for $^{115}\text{Sb} (\gamma, p)^{114}\text{Sn}$ reaction.

Figure 61. Photodisintegration reaction rates for $^{117}\text{Sb} (\gamma, p)^{116}\text{Sn}$ reaction.
Photodisintegrations synthesize new elements by destroying the previously synthesized heavier nuclides. In general, these heavier nuclides are the ones that were synthesized by s-process and the r-process. In order to simulate a photodisintegration reaction network, GAMBLER requires initial abundances of the elements in the network as an input. Therefore, for each element between hydrogen and xenon, the abundance of the most abundant isotope was added to the network. These abundance data was obtained from Anders and Grevesse (1989) (Anders and Grevesse, 1989).

Results

Figures 62, 63, 64 and 65 show results of the network calculation as comparisons between theoretical and experimental predictions. For all the figures, vertical axis represents the abundance in terms of mass fraction and horizontal axis represents the time in seconds. The broken curves in the figures show the theoretically predicted distribution of abundance for each reaction. Experimental results for same reactions are shown by the solid curves.

For the $^{47}\text{V} + \gamma \rightarrow ^{46}\text{Ti} + \text{p}$ reaction (figure 62), it can be seen that $^{47}\text{V}$ has been destroyed in the network as time elapse. Abundance of $^{47}\text{V}$ comes to a peak during its production by proton captures and it decays by beta decay and photodisintegrations. This result also agrees with the conclusions of previous proton capture reactions (figure 50) which predicts a decrease of abundance with time.

$^{65}\text{Ga}$ is destroyed in the network by capturing electrons to form $^{65}\text{Zn}$ and also by the $^{65}\text{Ga} + \gamma \rightarrow ^{64}\text{Zn} + \text{p}$ reaction. Abundance prediction from theory is very close to the
experimental results in the beginning of the network but an overproduction of $^{65}$Ga can be seen as time elapses.

Figure 62. Change in abundance of $^{47}$V in the network.

Figure 63. Change in abundance of $^{65}$Ga in the network.
Mass fraction of $^{115}\text{Sb}$ increases rapidly to a peak and then decreases gradually. Decay could occur due to electron capture or beta decay of $^{115}\text{Sb}$ or by the photodisintegration reaction $^{115}\text{Sb} + \gamma \rightarrow ^{114}\text{Sn} + \text{p}$. The abundance distribution curves of $^{117}\text{Sb}$ show a closely similar pattern to those of the $^{115}\text{Sb}$ isotope.

Figure 64. Change in abundance of $^{115}\text{Sb}$ in the network.
Figure 65. Change in abundance of $^{117}\text{Sb}$ in the network.
CHAPTER VI

DISCUSSION AND CONCLUSIONS

Radiative proton capture reactions on $^{46}$Ti, $^{64}$Zn, $^{114}$Sn and $^{116}$Sn targets were investigated at the Van de Graaff accelerator facility at Western Michigan University. A monoenergetic proton beam with proton center-of-mass energies ranging from 1MeV to 4MeV was used for the irradiation.

Proton capture cross sections and S-factors of $^{116}$Sn target were studied first to confirm the accuracy and the reproducibility experiment. In the case of the $^{116}$Sn target, comparisons proved a good agreement between current measurements and previous experimental results. In addition, cross sections in the lower proton energy region were also investigated for $^{116}$Sn covering a larger Gamow window.

For the $^{114}$Sn target, the $^{114}$Sn$(p,\gamma)^{115}$Sb reaction was investigated for the first time in this particular proton energy region. Being a p-process nuclide, a proton capture study on $^{114}$Sn target has an additional significance. For the Sn nuclei, S-factor results predicted by NON-SMOKER are in better agreement in the higher energies. This may be a result of shell closure effects in the Sn nuclei affecting the proton captures at lower proton energies (Rauscher, Thielemann, and Kratz, 1997). It is worthwhile to explore this matter further as it might suggest improvements to the NON-SMOKER code.

On the other hand, statistical model predictions show a better agreement with the experimental cross sections and the S-factors for the $^{46}$Ti and $^{64}$Zn targets. Although $^{64}$Zn is believed to be produced by an $\alpha$-process in a type II supernova, it is suggested that the
synthesis of $^{64}$Zn has a small p-process contribution (Hoffman et al., 1996; Hoffman, Woosley, and Qian, 1997; Woosley and Heger, 2004). In the case of $^{46}$Ti, a small portion of the rp-process is believed to be passing through this particular nuclide (Wiescher et al., 2002).

Scaling the theoretical S-factors from NON-SMOKER was essential to derive experimental reaction rates. Thermonuclear reaction rates were derived by integrating the S-factors over the entire energy range, where the individual S-factors needed to be interpolated reliably. Scaling provides a distribution of S-factors covering the entire energy range which made the integration possible. It is noted that for the proton capture on $^{46}$Ti, a more complicated scaling function was required due to the particular shape of the S-factor distribution. The uncertainties in the experimental cross sections were occurred mainly due to fluctuations in the beam and geometric reasons. Affect of uncertainty on S-factor calculations and reaction rates was estimated and found to be less than 5% in overall. It was observed that for all the four reactions, the reaction rate uncertainties increase slightly with temperature.

Comparisons between experimental and theoretical reaction rates were useful to evaluate the reliability of statistical models. For all the four reactions studied, NON-SMOKER seemed to have the upper hand in predicting results closer to the experiment. Especially in the case of the $^{46}$Ti target, the reaction rate ratio of experimental results to the NON-SMOKER is much close to the unity throughout most of the temperature range, proving the reliability of the code. On the other hand, MOST code seemed to predict slightly higher reaction rates for all the four reactions studied. Network simulations were carried out with the focus of investigating elemental abundance distributions important to
the p-process. Two major constituents of the p-process, the rp-process and the high
temperature photodisintegrations were simulated. One aspect of the study was to evaluate
the accuracy of the predictions given by theoretical network reaction models in nuclear
astrophysics. In general the input data for such networks largely depends on theoretical
calculations. Therefore it is essential to test these predictions experimentally, in order to
increase the reliability and accuracy of the network calculations.

The rp-process network was conducted simulating a X-ray burst condition. The
experimental mass fractions results of $^{47}$V, $^{47}$Ti, $^{65}$Ga, $^{65}$Zn, $^{115}$Sb, $^{115}$Sn, $^{117}$Sb and $^{117}$Sn
were compared with theoretical predictions and found good agreements in general.
Except for $^{47}$V, comparisons revealed a better agreement between the theory and
experiment at the beginning of the network. Over time, a slight overestimation of the
theoretical mass fraction could be observed. In the case of $^{47}$V, a slightly lower
experimental mass fraction was observed in the beginning where better agreements were
visible near the end of the network. For all the four experiments, the maximum ratio of
theoretical mass fractions to the experimental mass fractions was found to be in the order
of 1.15.

Photodisintegration reactions appear as a significant contributor in
nucleosynthesis at higher stellar temperatures. In this study, a special attention was given
to investigate the role of ($\gamma$,p) reactions on the production of nuclides in the proton rich
side. The aim of the second network analysis was to investigate the influence of such
reactions on the targets of interest. The photodisintegration reaction rates were derived by
the inverse reactions of proton capture experimental results. Using the same methodology
that followed with forward reactions, GAMBLER’s theoretical rates were updated with
experimental data and results were compared. It was observed in the study that, at lower stellar temperatures, typically beyond 1GK, photodisintegration reaction rates are extremely small and their influence on elemental abundance is insignificant. For the two Sb nuclei and the $^{65}$Ga nucleus, the general shape of the abundance distribution is much similar to that obtain from proton capture reactions. However, for the $^{47}$V nucleus, the shape of the abundance distribution curve is slightly different from the previous forward reaction. It is probable that the rapid decrease of the abundance over time may be due to the increased activity of the photodisintegrations. Also for the $^{47}$V, it is interesting to notice that there is a better agreement between the theory and experimental results exists in the beginning of the network. For all the four reactions considered here, it can be concluded that the network code is reliable in predicting results close to the experiment. The visible differences between theoretical and experimental curves suggest some overproductions being predicted by the theory.
REFERENCES


