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Nucleosynthesis during the rapid hydrogen burning process and the abundances of $^{92}$Mo and $^{94}$Mo

Hencheck, Michael, Ph.D.
The Ohio State University, 1994
Nucleosynthesis during the Rapid Hydrogen Burning Process and the Abundances of $^{92}$Mo and $^{94}$Mo

Dissertation

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

Michael Hencheck, B.S.

* * * * *

The Ohio State University

1994

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for Elizabeth with hope and love
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CHAPTER I

Current Theories Regarding Elemental Abundances

Much of the work done in Astrophysics has been motivated by the desire to explain the observed abundances of the elements. In fact, this could be considered the purpose of the sub-field of Nuclear Astrophysics. The Standard Model of the Big Bang \cite{27} predicts that the initially very dense, hot universe proceeds to a state in which it is primarily composed of hydrogen (77\% by mass) and helium (23\% by mass) with only trace amounts of other light elements. We are, however, intimately aware of a multitude of heavier elements. It would be pleasing to be able to offer an explanation as to their origins.

1.1 Stellar Nucleosynthesis

The origins of many of the elements can be explained using the currently accepted model of the life cycle of stars \cite{6}. In this model, a star begins its life as a cloud of hydrogen and helium, with trace amounts of a few other elements. This cloud begins to fall in upon itself under the mutual gravitational attraction of the individual atoms.
Table 1: The Proton-proton chains

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<td>$p + p \rightarrow d + e^+ + \nu_e$</td>
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As the potential energy of the infalling nuclei is converted to kinetic energy, the gas heats up. If the original gas cloud is large enough, the temperature in the inner core will rise to the point where there is a significant chance that two hydrogen nuclei can overcome the mutual coulomb repulsion between them and collide to form a deuterium nucleus through the reaction $p + p \rightarrow d + e^+ + \nu_e$. This deuterium nucleus is then converted to helium through one of the three p-p chains (see table 1).

The energy released in these reactions increases the pressure within the gas. Eventually a dynamic equilibrium is reached wherein the gravitational collapse of the cloud is balanced by the pressure provided by the energy released in these exothermic nuclear reactions. We call this type of hydrogen cloud a main sequence star.

In 1914, Hertzsprung and Russell plotted the luminosities of many stars in several clusters against their surface temperatures [18]. What they found was that the stars are not spread uniformly throughout this diagram, but form a definite pattern (see figure 1). We now know that in this figure, the stars are grouped according to the
type of burning taking place in the core. Stars that are in the hydrogen burning stage of their lives fall in the shaded region of figure 1 labeled "Main Sequence". Since stars spend by far the largest portions of their lives in this stage, the vast majority of stars that we see lie on the main sequence. Our sun is one such star.

After a time, most of the hydrogen in the core is converted to helium. The nuclear reactions then cease, and the star begins to collapse again. As the star collapses, its temperature rises still further until the core of the star is hot enough to allow helium burning to take place. In helium burning, two $^4$He nuclei combine to form $^8$Be which lives for $10^{-16}$ seconds before decaying back into two $^4$He nuclei. This lifetime is actually long compared to the transit time of two $\alpha$-particles in our stellar environment ($\sim 10^{-19}$ s). So, an equilibrium concentration of $^8$Be is built up ($\sim$ one $^9$Be per $10^9$ $^4$He). Occasionally, before the decay takes place, the $^8$Be is struck by another $^4$He nucleus. In this case, there is a small possibility that a $^{12}$C nucleus will

Figure 1: The Hertzsprung-Russell Diagram
be formed [19]. The probability of such a three-body collision may seem unreasonably low. However, the rate of the process is significantly enhanced by the existence of an s-wave resonance corresponding to a state in $^{12}\text{C}$ near the $^{8}\text{Be} + ^{4}\text{He}$ threshold. In fact, before this resonance was discovered, Hoyle [11] predicted its existence based on the observed abundance of $^{12}\text{C}$. The energy released in this process increases the pressure in the star and halts the gravitational collapse.

While helium burning is taking place in the core, the base of the hydrogen envelope heats up enough to allow hydrogen burning to begin in the shell surrounding the core. This raises the temperature of the envelope and decreases the amount of energy from the core that can leave the star. This, in turn, increases the pressure within the envelope, causing it to expand. We call this type of star a red giant or a super giant (see figure 1). Eventually the helium in the core is depleted, nuclear reactions cease, and the star begins to collapse again raising its temperature. When the temperature in the core is high enough, carbon burning will take place.

If the star is so massive (about eight solar masses) that it can continue to raise its temperature sufficiently through gravitational collapse after each burning phase, this process of collapse followed by dynamic equilibrium continues as long as the core of the star contains nuclei which can be fused together to release energy. In this case, the process will continue until the core has been converted to $^{56}\text{Ni}$. Since mass 56 nuclei are the most tightly bound nuclei, no additional energy can be released through reactions involving the fusion or fission of these nuclei. The gravitational collapse of the star then continues until the core becomes so dense that it can not be
compressed any further (roughly the density of nuclear matter). The huge amount of energy released when this happens ejects the outer envelopes of the star into the interstellar medium in a giant explosion we know as a supernova. The core is left behind as either a neutron star or possibly a black hole, depending on the initial mass of the star.

This explanation of the life cycle of massive stars, while certainly very impressive, leaves us with a certain difficulty. It does not account for nuclei heavier than mass 56. Yet, we know such nuclei exist. The existence of most of these nuclei can be explained through neutron capture processes known as the s-process and the r-process.

1.2 The Nucleosynthesis of Elements Beyond Iron

If the nuclei produced through stellar nucleosynthesis are exposed to a flux of neutrons, new nuclei can be produced through neutron capture. Since neutrons are unaffected by the coulomb barrier, very heavy nuclei can be produced through such a neutron capture process. This process can proceed in two distinct ways. If the neutron density is very large (~ $10^{20}$ neutrons/cm$^3$), then neutron capture will proceed much more quickly than the rate at which beta decay typically proceeds. In this case, the process is referred to as the r-process (for rapid). If, on the other hand, the neutron density is relatively small (~ $10^6$ neutrons/cm$^3$), the rate for neutron capture will tend to be less than that for beta decay. Then the process proceeds along the neutron-rich side of the valley of stability and is referred to as the s-process (for slow). As we shall see, both processes are needed to explain the abundances of all the nuclei.
1.2.1 The S-process

If the neutron density in a given environment is on the order of $10^6$ neutrons/cm$^3$ or less, then nucleosynthesis proceeds through the s-process. In the s-process, a neutron collides with a stable nucleus, producing a nucleus of the same element but with a mass number one greater than the original. If this new nucleus is stable, then it can be struck with another neutron producing yet another isotope of the same element. If, however, this new nucleus is unstable, then, since the neutron flux is so low, the nucleus will usually beta decay before it can collide with another neutron, producing a new element. If the daughter nucleus is stable, then it can collide with a neutron, otherwise it will also decay. A typical path through which nuclei can be produced in the s-process is shown in figure 2.

Notice in figure 2, starting with $^{116}$Sn, that neutron capture proceeds until $^{121}$Sn is created. The half-life against $\beta^-$ decay for $^{121}$Sn is 27 hours. However, the typical
capture lifetime if \( N_n = 10^6 \) neutrons/cm\(^3\) is on the order of 1000 years. So, \(^{121}\text{Sn}\) will usually beta decay forming \(^{121}\text{Sb}\) before neutron capture can take place.

It has been suggested that the s-process may take place during the helium burning stage of a second generation star. [7] The neutrons would be produced by the reaction \( ^{14}\text{N}(\alpha,\gamma)^{18}\text{F}(e^+,\nu)^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne}(\alpha,\pi)^{25}\text{Mg} \). Since this is a second generation star, these neutrons can then be captured by the nuclei produced during the lifetime of a first generation star.

1.2.2 The R-process

Inspection of figure 2 reveals that since \(^{121}\text{Sn}\) will tend to \(\beta^-\) decay before capturing a neutron, very little \(^{122}\text{Sn}\) can be produced by the s-process. In order to explain its existence and the existence of other nuclei like it, we must turn to the r-process. If the nuclei produced through stellar nucleosynthesis are exposed to a neutron density on the order of \(10^{20}\) neutrons/cm\(^3\), then unstable nuclei will not have time to decay before capturing another neutron. In this case nuclei will be driven towards the neutron drip line, where the isotope one neutron richer is unbound. At this point, it will be impossible to add another neutron, and abundances of very neutron rich, unstable nuclei will be built up. When the neutron capture process is over, these nuclei decay back toward the valley of stability (entering from the lower righthand corner of figure 2). We can see that while \(^{122}\text{Sn}\) cannot be produced through the s-process since \(^{121}\text{Sn}\) is unstable, an abundance of it should be built up through the r-process as nuclei at the neutron drip line decay back towards the valley of stability.
Since such a large neutron flux is required for the r-process, it is not a trivial matter to come up with a site for the process. The most popular theory presently is that the r-process must take place during a supernova, where it is conceivable that large amounts of neutrons are present. However, the details of the r-process site remain an object of continuing research.

1.2.3 The P-process

Referring once again to figure 2, we see that $^{120}$Te cannot be produced by either the s-process or the r-process. Since it lies on the proton rich side of the valley of stability, it is blocked from both the s and r-processes. This nucleus must be produced by yet another mechanism, referred to as the p-process. The p-process is the least well understood of the three processes. It is this process which must be responsible for the production of $^{92}$Mo and $^{94}$Mo and other nuclei on the proton rich side of the valley of stability. Current theories regarding the p-process are discussed in section 1.4.

1.3 Determining Abundances in Stellar Environments

Before we go on to look at the p-process in more detail, it may be useful to examine the formalism behind the determination of nuclear abundances in a given environment. In order to calculate how the abundances of nuclei progress with time, we must know the rates of the various nuclear reactions which can take place in that environment. For reasons which will become clear in section 1.4, we will be concerned only with
stellar environments.

Suppose, in our stellar environment, we have $N_1$ particles/cm$^3$ of type 1 and $N_2$ particles/cm$^3$ of type 2 with relative velocity $v$. If we consider nuclei of type 1 to be the projectiles and nuclei of type 2 to be the targets, then the reaction area presented to the projectiles is $\sigma(v)N_2$. The flux of projectiles is $N_1v$. So, the reaction rate is $N_1N_2v\sigma(v)$. However, since we are in a stellar environment, we have a Boltzmann distribution of velocities, and $v\sigma(v)$ must be integrated over this distribution. The result is written $\langle \sigma v \rangle$ and the reaction rate is $N_1N_2\langle \sigma v \rangle$. The mathematical form of $\langle \sigma v \rangle$ is given by equation 2.5.

The rate of change of the abundance of a particular nucleus, then, is equal to the rates for the reactions which create the nucleus minus the rates for the reactions which destroy the nucleus. For example, if we are in a situation such that nuclei can only experience proton capture, the rate of change in abundance of $^{84}$Rb is given by

$$\frac{dN_{Rb}}{dt} = N_{Kr}N_p\langle \sigma v \rangle_{Kr,p} - N_{Rb}N_p\langle \sigma v \rangle_{Rb,p} - \frac{N_{Rb}}{\tau_{Rb}} + \frac{N_{Sr}}{\tau_{Sr}},$$

(1.1)

where $N_{Kr}$ represents the abundance of $^{83}$Kr, $N_{Sr}$ represents the abundance of $^{84}$Sr, and $\tau_{Rb}$ and $\tau_{Sr}$ are the mean lifetimes against $\beta^+$ decay for $^{84}$Rb and $^{84}$Sr respectively. Such an equation can be set up for every nucleus in a network. A computer program is then written to solve the set of coupled differential equations.
1.4 Theories regarding the P-process

Theories concerning the p-process are faced with a challenge not presented to theories involving the s and r-processes. To create new nuclei on the neutron rich side of the valley of stability, we can simply add neutrons to existing nuclei with no regard for the charge of the nucleus or the energy of the incident neutron. However, if we wish to add a proton to an existing nucleus, first we must coax it to tunnel through the coulomb barrier presented by protons already in the nucleus. The transmission coefficient is given by [14]

\[ T = \exp \left( \frac{-2\pi Z_n e^2}{\hbar v} \right), \]

or equivalently,

\[ T = \exp \left( \frac{-(2\mu)^{1/2} \pi Z_n e^2}{\hbar E^{1/2}} \right), \]

where \( Z_n \) is the atomic number of the nucleus and \( E \) is the center of mass energy. Notice in equation 1.3, that as \( Z_n \) increases, the probability that the proton will reach the nucleus decreases exponentially. Our only recourse to compensate for this is to increase the value for \( E \) in the denominator. So, high energies are needed. In fact, we will see that temperatures on the order of \( 10^9 \) K will be needed in order to produce a significant build-up of p-process nuclei. Unfortunately, environments which contain such high temperatures have usually already depleted themselves of hydrogen. So, it is difficult to find a place in the universe where significant proton capture on heavy nuclei can take place.

Fortunately, there are two ways to create a proton rich nucleus. We can either add protons to lighter nuclei, or we can remove neutrons from heavier nuclei though photo-
neutron dissociation. While it still requires very high temperatures for significant photo-neutron dissociation to take place, we are no longer required to have protons coexisting with these high temperatures. This provides much greater freedom in choosing a site for the p-process. It is this mechanism that Woosley and Howard proposed [33] is responsible for creating the p-process nuclei.

1.4.1 The Woosley-Howard Model for the P-process

In an attempt to find a region which fulfills the necessary conditions of high temperatures and a supply of heavy seed nuclei, Woosley and Howard looked to type-II supernovae. Suppose a second generation star of about eight solar masses proceeds through its life. Since this is a second generation star, by the time it reaches the end of its life cycle, its nuclei will probably have already experienced both s and r-processing as discussed in sections 1.2.1 and 1.2.2. When the star explodes, these nuclei will be exposed to a hot photon bath. Woosley and Howard suggest that these photons cause the s and r-process nuclei to photodissociate down into the p-process nuclei.

As we will see in section 2.1.2, due to time-reversal invariance, the cross-section for photodissociation is proportional to the cross-section for the inverse capture reaction. The rate for the reaction \(1 + 2 \rightarrow 3 + \gamma\) is given by

\[
N_\gamma(\sigma\nu)_{3\gamma} = \left(\frac{\mu kT}{2\pi\hbar^2}\right)^{3/2} \frac{(2J_1 + 1)(2J_2 + 1)}{(2J_3 + 1)} e^{-Q/kT}(\sigma\nu)_{12}, \tag{1.4}
\]

where \(Q\) is the energy liberated when \(1 + 2 \rightarrow 3\) and the \(J\)'s represent the spins of
the particles [17]. Notice that the rate depends on both \( \langle \sigma v \rangle \) for the inverse reaction and \( Q \). When photodissociation begins, it will initially be easier for the seed nuclei to eject a neutron over a charged particle since \( \langle \sigma v \rangle \) for the inverse reaction is not hindered by the coulomb barrier. However, as each neutron is removed, the \( Q \)-value in equation 1.4 for the next photo-neutron dissociation tends to increase. (i.e., the next neutron is more tightly bound.) This decreases the photodissociation rate exponentially. Eventually, \( Q \) becomes large enough that the ejection of a charged particle is energetically preferred over the ejection of a neutron despite the coulomb barrier. These nuclei are referred to as branching points. Notice that, since the photodissociation rate decreases with each neutron emission, the longest photo-lifetimes tend to occur at branching points. Thus branching points are also waiting points where abundances tend to build up. If these nuclei are unstable, then after the high temperature processing phase is over, they will \( \beta^+ \) decay back towards the valley of stability. An example of how the p-process nuclei can be built up in this model is shown in figure 3.

The Woosley-Howard model gets good results for most of the p-process nuclei. There are, however, at least two notable exceptions to the success of this model. It is unable to produce significant amounts of either \(^{92}\text{Mo}\) or \(^{94}\text{Mo}\) under any circumstances. The reason for this seems to be that there are simply insufficient heavy seed nuclei available to produce the surprisingly large abundances of \(^{92}\text{Mo}\) and \(^{94}\text{Mo}\). The Woosley-Howard Model generates an average overabundance on the order of 260 for the p-process nuclei [33]. This means that the abundances built up for most nuclei
through this process are about 260 times the solar abundances. But, even if all of the nuclei with $A > 95$ were converted to $^{92}\text{Mo}$ and $^{94}\text{Mo}$, this would give an overproduction of only about 40 times the solar abundances for these two nuclei, and of course, would mean that no other p-process nuclei would be produced. It seems clear that some other mechanism must be responsible for the production of $^{92}\text{Mo}$ and $^{94}\text{Mo}$. One possibility is that these nuclei are built up through proton capture on more abundant lighter nuclei rather than through photodissociation of heavier nuclei.

1.4.2 The $\nu$-process

Before proceeding to discuss the subtleties particular to the production of $^{92}\text{Mo}$ and $^{94}\text{Mo}$, it would only be proper to discuss an additional process which may have some bearing on the p-process nuclei, the $\nu$-process [32]. When a large star ends its life in a supernova event as discussed in section 1.1, a large amount of energy is carried away by the vast number of neutrinos created as the core is converted into either
a neutron star or a black hole. As these neutrinos pass through the star, they can inelastically scatter off of nuclei, possibly exciting these nuclei into particle unbound states. While the cross-section for such neutral current scattering is rather low, the entire mass of the star acts as a target, greatly increasing the chances for such an event. The excited nuclei decay primarily through either neutron, proton or alpha emission. Through this process new nuclei can be created.

It was originally hoped that this process may liberate enough neutrons to account for the neutron densities needed for the r-process [9]. However, calculations carried out by Woosley et. al [32], seem to indicate that it is unlikely that sufficient neutrons are produced through neutrino scattering to account for the r-process. But, these same calculations also showed that the \( \nu \)-process was able to generate an over-abundance of many of the proton-rich nuclei below the iron group, and that it was capable of producing overabundances of two of the most mysterious isotopes above the iron group, \(^{138}\text{La}\) and \(^{180}\text{Ta}\). These isotopes cannot be appreciably produced in the Woosley-Howard Model (see section 1.4.1), since both \(^{138}\text{La}\) and \(^{180}\text{Ta}\) have an odd number of neutrons. Recall that in this model, it is at branching points that abundances are built up. Neither of these nuclei can lie at branching points since neutron emission will always be preferred over charged particle emission for these odd-\( n \) nuclei. It is also impossible to build these nuclei up through rapid proton capture. A rapid proton capture process would proceed by building abundances up at the proton drip line (see section 1.4.3) and then allowing the nuclei to \( \beta^+ \) decay back toward the valley of stability. Both \(^{138}\text{La}\) and \(^{180}\text{Ta}\) are shielded from the proton drip
line by stable nuclei ($^{138}\text{Ba}$ and $^{180}\text{W}$).

The $\nu$-process, however, can produce these nuclei by exciting the comparatively abundant nuclei $^{139}\text{La}$ and $^{181}\text{Ta}$ through inelastic neutrino scattering. The excited nuclei then decay through neutron emission producing the desired isotopes. This alone is a major achievement for the $\nu$-process.

1.4.3 Proposed Model for the Production of $^{92}\text{Mo}$ and $^{94}\text{Mo}$

As was seen in section 1.4.1, any model which proposes to create $^{92}\text{Mo}$ and $^{94}\text{Mo}$ will probably have to rely on proton capture. The difficulty, then, as discussed in section 1.4, is finding an environment which exists at a high enough temperature to allow proton capture to take place on heavy elements and still has protons present. One such environment may be the surface of a collapsed star. In a binary star system, one of the stars is usually more massive than the other. This more massive star will go through its life cycle more quickly. If it has a mass of at least eight solar masses, it will end its life in the cataclysmic event known as a supernova as discussed in section 1.1, transforming itself in most cases into a neutron star. When the less massive star later enters its helium burning stage, it will expand into a “red giant”. After it expands, matter on the surface of the less massive star will begin accreting onto the surface of the neutron star. This accreting matter will heat up as it falls into the potential well provided by the neutron star. Eventually, the surface of the neutron star becomes so hot that thermonuclear reactions begin, leading to a thermonuclear runaway. It is conceivable when this takes place, the material from the hydrogen
envelope could reach temperatures on the order of $10^9$ K [28].

If, in our previous example, the more massive star has a mass less than about 8 $M_\odot$, at some point it will be unable to generate a high enough temperature through gravitational collapse to begin the next burning stage. It will collapse until the weight of the star is supported by electron degeneracy. This is a white dwarf. As before, when the less massive star enters its helium burning stage, matter in its hydrogen envelope will begin accreting onto the surface of the white dwarf. Present models suggest that the surface of an accreting white dwarf is able to reach temperatures no higher than $0.8 \times 10^9$ K [22]. In section 2.2, we will find that temperatures of at least $0.9 \times 10^9$ K are needed to produce significant amounts of $^{92}$Mo and $^{94}$Mo on reasonable timescales. However, presently, the nova models are one dimensional, more detailed models could lead to new results.

Another possible site for rapid proton capture results if a neutron star's orbit around the less evolved partner begins to decay, and it spirals into the center of the companion star. This could happen if the accreting material begins to pile up around the neutron star, slowing it down [25]. The resulting star is referred to as a Thorne-Żytkow object. As the neutron star rests in the center of its companion, it pulls matter out of the envelope of the less massive star. It is believed that this material would be heated to temperatures reaching above $10^9$ K [3, 8]. The Thorne-Żytkow object is unique among these three scenarios in that it accretes matter from inside the companion star instead of from a position outside. As discussed in chapter IV, this could have a profound effect on the results of our study.
In all of these cases, we have protons and high temperatures coexisting. So, it should be possible to build up abundances of proton rich nuclei through proton capture. Beginning with solar abundances, the proton initiated reactions serve to add more and more protons to the existing nuclei driving them toward the proton drip line in a way analogous to the r-process (see section 1.2.2). After the process is over, the unstable nuclei $\beta^+$ decay back towards the valley of stability, giving us an overabundance of the p-process nuclei $^{92}\text{Mo}$ and $^{94}\text{Mo}$. Figure 4 shows the pathways responsible for producing $^{92}\text{Mo}$ and $^{94}\text{Mo}$ in this model.

During the high temperature phase, protons are added to the existing nuclei, driving them rapidly toward the proton drip line. After the process ends, the subsequent $\beta^+$ decays or electron captures back towards stability ultimately produce the p-process nuclei. Nuclei from $^{80}\text{Se}$ to $^{84}\text{Sr}$ are swept up the $N=46$ chain mostly to $^{92}\text{Pd}$, and the $N=48$ nuclei from $^{84}\text{Kr}$ to $^{86}\text{Sr}$ to $^{94}\text{Pd}$. At this point, if $^{93}\text{Ag}$ and $^{95}\text{Ag}$ are unbound, the process will halt, and large abundances of $^{92}\text{Pd}$ and $^{94}\text{Pd}$ will be built up, eventually to decay back to $^{92}\text{Mo}$ and $^{94}\text{Mo}$. If we neglect weak flows out of $N=46$ and $N=48$, we find overproduction factors $O(^{92}\text{Mo})=68$ and $O(^{94}\text{Mo})=84$. Mass calculations [12] suggest that even if $^{93}\text{Ag}$ is bound, it is so loosely bound that photodissociation of $^{93}\text{Ag}$ back to $^{92}\text{Pd}$ will dominate over proton capture on $^{92}\text{Pd}$. However, the half-life for $^{92}\text{Pd}$ against $\beta^+$ decay is estimated to be only about 0.9 s [24]. So, we must expect significant leakage out of the $N=46$ column. If $^{95}\text{Ag}$ is unbound, this will lead to a disparity between the amounts of $^{92}\text{Mo}$ and $^{94}\text{Mo}$ produced — too much $^{94}\text{Mo}$ will be created relative to $^{92}\text{Mo}$. If, however, $^{95}\text{Ag}$ is bound, leakage
Figure 4: Proton capture pathway producing $^{92}$Mo and $^{94}$Mo
from $^{94}\text{Pd}$ to $^{95}\text{Ag}$ through proton capture can compensate for leakage out of $^{92}\text{Pd}$ through $\beta^+$ decay. We will see in section 2.2 that we require that $^{95}\text{Ag}$ be bound in order to produce overabundances of $^{92}\text{Mo}$ and $^{94}\text{Mo}$ which can explain their relative solar abundances.

Therefore, in order for this hypothesis to be taken seriously:

1. It must be shown that abundances of $^{92}\text{Pd}$ and $^{94}\text{Pd}$ can be built up at appropriate temperatures and time intervals.

2. It must be shown that $^{95}\text{Ag}$ is bound.
CHAPTER II

Computer Analysis of Proposed Model

As discussed in section 1.3, in order to calculate how the abundances of the nuclei in a high temperature, proton-rich environment will change with time, it is necessary to write a differential equation similar to equation 1.1 for each of the nuclei in the environment. The solution to this coupled set of differential equations for a given time interval can then be found through computer numerical analysis.

2.1 Setup of Network Code

The network code written to calculate the change in abundances during the high temperature phase includes the nuclei from iron through indium that are either stable or on the proton rich side of the valley of stability. These nuclei are shown in appendix A. The nuclei were considered to initially possess solar abundances. Most of the characteristics attributed to these nuclei (mass, spin, halflife, etc.) were acquired from Tuli [26]. Those masses that were not indicated in Tuli [26] were derived using the mass formula of Jänecke and Masson [12]. In order to correct somewhat for the possibility that the masses so obtained for the very proton-rich nuclei are not as
accurate as those for nuclei nearer to the valley of stability, masses were also derived
from the Jänecke & Masson mass formula for proton-rich nuclei of known mass. The
differences between these results and the known masses were then noted, and the
derived masses were shifted by these amounts (See table 2).

Some of the halflives not listed in Tuli [26] have been measured by Winger et al. [29] or calculated by Biehle and Vogel [5]; these were used when possible. The
remaining halflives were taken from Takahashi, Yamanda and Kondoh [24]. The
characteristics attributed to the nuclei in the network are included in appendix B.

In determining the rate of change of the abundances, three processes were consid-
ered, (1) Proton capture, (2) Photo-proton dissociation, and (3) Radioactive decay.

Photo-neutron dissociation was not included because, for the proton-rich nuclei
with which we are dealing, the reaction rate for neutron emission is much less than
that for emission of a proton. For example, at a temperature of 1.1 ×10^9 K, the
reaction rate for $^{93}$Pd(γ,p)$^{92}$Rh is on the order of 10⁻¹¹ s⁻¹ while the reaction rate
for $^{93}$Pd(γ,n)$^{92}$Pd is zero to over 30 decimal places. In addition, neutron capture
processes were not included because as we have just seen, very few neutrons are
produced through photodissociation, and the few neutrons produced by (α,n) or (p,n)
reactions are typically captured quickly on the more abundant nuclei with masses
lower than A≈70. Also, α-induced processes were ignored because, due to their
higher charge, the coulomb barrier is sufficiently large that these will proceed much
more slowly than those initiated by protons.
Table 2: Estimated masses for very proton rich nuclei

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Mass Excess</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jänecke/Masson</td>
<td>This work</td>
</tr>
<tr>
<td>61Ge</td>
<td>-34.23</td>
</tr>
<tr>
<td>63Ge</td>
<td>-42.48</td>
</tr>
<tr>
<td>72Sr</td>
<td>-46.57</td>
</tr>
<tr>
<td>72Sr</td>
<td>-55.14</td>
</tr>
<tr>
<td>78Y</td>
<td>-52.67</td>
</tr>
<tr>
<td>80Zr</td>
<td>-55.49</td>
</tr>
<tr>
<td>82Nb</td>
<td>-52.84</td>
</tr>
<tr>
<td>83Nb</td>
<td>-58.49</td>
</tr>
<tr>
<td>84Mo</td>
<td>-55.74</td>
</tr>
<tr>
<td>85Mo</td>
<td>-58.64</td>
</tr>
<tr>
<td>86Tc</td>
<td>-52.88</td>
</tr>
<tr>
<td>87Tc</td>
<td>-59.12</td>
</tr>
<tr>
<td>88Ru</td>
<td>-55.98</td>
</tr>
<tr>
<td>89Ru</td>
<td>-59.34</td>
</tr>
<tr>
<td>90Rh</td>
<td>-53.37</td>
</tr>
<tr>
<td>91Rh</td>
<td>-59.34</td>
</tr>
<tr>
<td>92Pd</td>
<td>-55.52</td>
</tr>
<tr>
<td>93Pd</td>
<td>-59.36</td>
</tr>
<tr>
<td>94Ag</td>
<td>-52.16</td>
</tr>
<tr>
<td>95Ag</td>
<td>-59.50</td>
</tr>
<tr>
<td>98Cd</td>
<td>-60.04</td>
</tr>
<tr>
<td>99In</td>
<td>-60.41</td>
</tr>
</tbody>
</table>
2.1.1 Calculation of the \((p,\gamma)\) Reaction Rate

In order to create an equation like 1.1 for each of the nuclei in the network, the \((p,\gamma)\) reaction rate, \(N_p(\sigma v)\), must be determined for each isotope, where \(N_p\) is the number density of protons (i.e., stripped hydrogen nuclei) available in the star. Since the initial abundances were assumed to be solar, there are far more protons around than the sum of the rest of the nuclei in the network. Therefore, the change in \(N_p\) is a negligible fraction of its initial value, and it has been considered to be a constant. It is now left to determine \(\langle \sigma v \rangle\). As mentioned in section 1.3, \(\langle \sigma v \rangle\) refers to the product \(\sigma v\) integrated over a Boltzmann distribution of velocities. In other words,

\[
\langle \sigma v \rangle = \int_0^\infty \int_0^\infty \phi(v_n)\phi(v_p)\sigma(v)vdv_ndv_p,
\]

where \(v_n\) is the velocity of the nucleus, \(v_p\) is the velocity of the proton, \(v\) is the relative velocity between the two, and

\[
\phi(v_p) = 4\pi v^2 \left(\frac{m_p}{2\pi kT}\right)^{3/2} \exp\left(-\frac{m_pv^2}{2kT}\right),
\]

If we now substitute \(\mu\) as the reduced mass, \(M\) as the total mass and \(V\) as the center of mass velocity, we can write

\[
\langle \sigma v \rangle = \int_0^\infty \int_0^\infty \phi(V)\phi(v)\sigma(v)vdvdv.
\]

The integral over \(V\) yields 1. So,

\[
\langle \sigma v \rangle = 4\pi \left(\frac{\mu}{2\pi kT}\right)^{3/2} \int_0^\infty v^2 \exp\left(-\frac{\mu v^2}{2kT}\right)\sigma(v)vdv.
\]

Now, substituting in \(E = \frac{1}{2}\mu v^2\),

\[
\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty E\sigma(E)e^{-E/kT}dE.
\]
Our problem has now simplified to finding $\sigma(E)$ for the proton capture reaction. To do this, the target nucleus and the proton were assumed to form a compound nucleus in an excited state which then decays to the ground state through photon emission. Also, in finding the total $(p,\gamma)$ cross section, the spins of the particles were ignored. This approach will be valid as long as (1) the target nucleus is heavy so that there is a high level density in the compound nucleus at the interaction energy of interest, and (2) the reaction energies are less than about 10 MeV ($T < 10^{11} K$) so that direct and semi-direct reactions are negligible.

Figure 5 shows a proton approaching a target nucleus. The orbital angular momentum associated with the collision depicted in figure 5 is $L = bp = bh/\lambda$, where $p$ is the momentum of the proton. But, in the semiclassical limit $L = \ell \hbar$. So, $bh/\lambda = \ell \hbar$, or $b = \ell \lambda$. The maximum cross section for a given $\ell$ is given by the geometric cross-sectional area corresponding to that $\ell$:

$$\sigma_{\ell,max} = \pi b_{\ell+1}^2 - \pi b_{\ell}^2 = \pi \lambda^2 (2\ell + 1).$$  \hfill (2.6)
Table 3: Values for the proton channel of a Woods-Saxon potential and an equivalent square well.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_0$</td>
<td>Radius of Woods-Saxon potential</td>
</tr>
<tr>
<td>$R_1$</td>
<td>Radius of equivalent square well</td>
</tr>
<tr>
<td>$V_0$</td>
<td>Depth of Woods-Saxon potential</td>
</tr>
<tr>
<td>$V_1$</td>
<td>Depth of equivalent square well</td>
</tr>
<tr>
<td>$f$</td>
<td>Reflection factor for equivalent well</td>
</tr>
</tbody>
</table>

The total cross section then is

$$\sigma_{\text{tot}} = \pi \lambda^2 \sum_{\ell} (2\ell + 1) T_{\ell},$$

(2.7)

where $T_{\ell}$ is the transmission function for forming a state with angular momentum $\ell$. If we adopt a square well representation of a Woods-Saxon potential (see figure 6), then [31]

$$T_{\ell} = \frac{4\pi f}{\pi(1 + V_0 R_0^2 / R_1^2 E)^{1/2}} \frac{1}{F_{\ell}^2(\eta, \rho) + G_{\ell}^2(\eta, \rho)},$$

(2.8)

where $F_{\ell}$ and $G_{\ell}$ are the irregular and regular coulomb wave functions, respectively.

In this equation, $V_0 \left( \frac{R_0}{R_1} \right)^2$ represents the depth of the equivalent square well, and, considering only the proton channel, $\eta = (0.15748)Z \sqrt{\frac{\mu}{E}}$, and $\rho = (0.2187)R_1 \sqrt{\mu E}$. The values of $f$, $V_0$, $R_0$, and $R_1$ for the proton channel are shown in table 3.

Plugging equation 2.8 into equation 2.7:

$$\sigma_{\text{tot}} = \frac{4\pi f}{\pi(1 + V_0 R_0^2 / R_1^2 E)^{1/2}} \pi \lambda^2 \sum_{\ell} \frac{(2\ell + 1)}{F_{\ell}^2(\eta, \rho) + G_{\ell}^2(\eta, \rho)}.$$

(2.9)
Figure 6: The Woods-Saxon potential and an equivalent square well

For our target nuclei and interaction energies $\eta \gg \rho$, since $E \ll 0.72Z/R_1$. In this case [1],

$$\sum_{l} \frac{(2l + 1)}{P_2^2(\eta, \rho) + G_2^2(\eta, \rho)} \simeq \eta \exp \left( -2\pi\eta + 4(1 - \rho/12\eta)\sqrt{2\eta}\rho \right). \quad (2.10)$$

So,

$$\sigma_{tot} \simeq 4\pi f \lambda^2 \left( \frac{R_1^2 E}{V_0 R_0^2} \right)^{1/2} \eta \exp \left( -2\pi\eta + 4(1 - \rho/12\eta)\sqrt{2\eta}\rho \right). \quad (2.11)$$

If we use $\pi \lambda^2 = 0.6566/\mu E$ barns (with $E$ in MeV) [17], and make the following substitutions:

$$x = 4\sqrt{\frac{\eta\rho}{2}}, \quad \alpha = \frac{\sqrt{2} \rho^{3/2}}{3E \eta^{1/2}} \text{MeV}^{-1}, \quad \kappa = 0.4136 \frac{f R_1}{V_0^{1/2} R_0}, \quad (2.12)$$
then the dependence on \( E \) can be displayed explicitly,

\[
\sigma_{\text{tot}} \simeq \frac{\kappa Z}{\mu^{1/2} E} \exp \left( 2x - \alpha E - 2\pi(0.15748)Z \sqrt{\frac{\mu}{E}} \right). \tag{2.13}
\]

Plugging this into equation 2.5 yields

\[
\langle \sigma v \rangle \simeq \left( \frac{8}{\pi \mu} \right)^{1/2} \frac{e^{2x}}{(kT)^{3/2}} \frac{\kappa Z}{\mu^{1/2}} \int_0^\infty e^{- \left( \alpha E + 2\pi(0.15748)Z \sqrt{\mu/E} + E/kT \right)} dE. \tag{2.14}
\]

In its present form, equation 2.14, would be very difficult to solve. All is not lost, however. The shape of the integrand in equation 2.14 is shown in figure 7. We can approximate this shape with a gaussian. This process will be less messy if we make the following substitutions:

\[
a = \left( \alpha + \frac{1}{kT} \right) \quad \text{and} \quad b = 2\pi(0.15748)Z \mu^{1/2}. \tag{2.15}
\]

![Figure 7: The integrand of Equation 2.14](image)
Then, our integrand becomes

$$\exp \left[ - \left( aE + b/E^{1/2} \right) \right]. \quad (2.16)$$

The energy at which the integrand has its maximum value ($E_0$ in figure 7) can be found by setting the first derivative of the integrand to zero:

$$E_0 = \left( \frac{b}{2a} \right)^{2/3}. \quad (2.17)$$

Plugging $E_0$ into the integrand, we find its maximum value:

$$I_{\text{max}} = \exp(-3aE_0) \quad (2.18)$$

Now, we want to approximate the integrand by a gaussian:

$$\exp \left( -aE - \frac{b}{E^{1/2}} \right) \simeq I_{\text{max}} \exp \left[ - \left( \frac{E - E_0}{\Delta/2} \right)^2 \right]. \quad (2.19)$$

To find $\Delta$, we match the second derivatives of both sides of this equation at $E_0$. This gives

$$\Delta = \frac{4}{3^{1/2}} \left( \frac{E_0}{a} \right)^{1/2}. \quad (2.20)$$

Replacing the integrand in equation 2.14 by our gaussian, we find

$$\langle \sigma v \rangle \simeq \left( \frac{8}{\pi \mu} \right)^{1/2} \frac{e^{2\kappa Z}}{(kT)^{3/2} \mu^{1/2}} I_{\text{max}} \int_0^\infty e^{-\left( \frac{b-E}{2a} \right)^2} dE. \quad (2.21)$$

Carrying out the integration and substituting for $I_{\text{max}}$, $E_0$ and $\Delta$ leads to

$$\langle \sigma v \rangle \simeq \left( \frac{8}{\pi \mu} \right)^{1/2} \frac{e^{2\kappa Z}}{(kT)^{3/2} \mu^{1/2}} e^{-3a(b/2a)^{2/3}} \left( \frac{\pi}{3a} \right)^{1/2} \left( \frac{b}{2a} \right)^{1/3}. \quad (2.22)$$
Finally, substituting back in for $a$ and $b$ provides

$$\langle \sigma v \rangle \approx 1.301 \times 10^{-14} \frac{\kappa Z^{4/3}}{\mu^{5/6} T_9^{2/3}(1 + \alpha kT)^{5/6}} \times$$

$$\exp\left(2x - 4.2487 \left[\frac{Z^2 \mu (1 + \alpha kT)}{T_9}\right]^{1/3}\right) \frac{\text{cm}^3}{\text{S}} \quad (2.23)$$

### 2.1.2 Calculation of the ($\gamma$,p) Reaction Rate

Now that the ($p,\gamma$) reaction rate has been determined, we need to determine the ($\gamma$,p) reaction rate in order to complete the development of equation 1.1. Since the laws governing reactions do not change when the direction of the reaction is reversed (referred to as detailed balance), the cross section for $1 + p \rightarrow 2 + \gamma$ ($\sigma_{1p}$) and the cross section for $2 + \gamma \rightarrow 1 + p$ ($\sigma_{2\gamma}$) are intimately related. With this in mind, I would like to re-examine the cross section for proton capture investigated in section 2.1.1.

Equation 2.7 states that for proton capture

$$\sigma_{1p} = \pi \lambda_{1p}^2 \sum \ell (2\ell + 1) T_\ell. \quad (2.24)$$

But, in arriving at this equation, we ignored the spins of the participants. In this section, we can no longer ignore the spins, so we must replace the $(2\ell + 1)$ term by a statistical factor which takes the spins into account. Further, the $T_\ell$ term is no longer sufficient. To arrive at an acceptable statistical factor, we must sum over the final states and average over the initial states. If we call $J$ the spin of the compound nucleus, then there are $2J + 1$ possible final states. Also, there are $(2J_1 + 1)(2J_p + 1)$
possible initial states. So, our statistical factor is
\[
\frac{(2J + 1)}{(2J_1 + 1)(2J_2 + 1)}.
\] (2.25)

And,
\[
\sigma_{1p} = \pi \lambda_{1p}^2 \frac{(2J + 1)}{(2J_1 + 1)(2J_2 + 1)} |H|^2,
\] (2.26)

where \(H\) replaces \(T_t\) from equation 2.7 and contains the matrix elements governing the transition through the compound state to the final result. Similarly, the cross section for the inverse photo-proton dissociation reaction is given by
\[
\sigma_{2\gamma} = \pi \lambda_{2\gamma}^2 \frac{(2J + 1)}{(2J_2 + 1)} |H'|^2,
\] (2.27)

where \(H'\) contains the matrix elements governing this inverse reaction. Due to detailed balance, \(|H|^2 = |H'|^2\). So, we can write
\[
\frac{\sigma_{1p}}{\sigma_{2\gamma}} = \frac{\lambda_{1p}(2J_2 + 1)}{\lambda_{2\gamma}(2J_1 + 1)(2J_2 + 1)}.
\] (2.28)

Since all photons have a velocity of \(c\), \(\langle \sigma v \rangle_{2\gamma}\) is simply equal to \(\sigma(E)_{2\gamma}c\) integrated over the photon phase space:
\[
\langle \sigma v \rangle_{2\gamma} = \frac{c}{N_\gamma h^3} \int_0^\infty 4\pi \left(\frac{E}{c}\right)^2 \sigma(E)_{2\gamma} e^{-E/kT} \frac{dE}{c}
\] (2.29)

The total number of photons per unit volume is given by
\[
N_\gamma = \frac{8\pi^4}{13c^3 h^3 (kT)^3}.
\] (2.30)

Combining this with equations 2.5, 2.28 and 2.29 yields
\[
\frac{\langle \sigma v \rangle_{2\gamma}}{\langle \sigma v \rangle_{1p}} = \frac{13}{(8\pi^5)^{1/2}} \frac{(2J_1 + 1)(2J_2 + 1)}{(2J_2 + 1)^2} \left(\frac{\mu c^2}{kT}\right)^{3/2} \exp \left(-\frac{Q}{kT}\right).
\] (2.31)
So, finally,

\[ N_x(\sigma v)_{2\gamma} = \left( \frac{\mu kT}{2\pi \hbar^2} \right)^{3/2} \frac{(2J_1 + 1)(2J_p + 1)}{(2J_2 + 1)} \exp \left( -\frac{Q}{kT} \right)(\sigma v)_{1p}. \] (2.32)

2.2 Results of Analysis

Once the reaction rates were determined, the set of coupled differential equations was solved using fourth order Runge-Kutta [16]. The network code was written in FORTRAN and is shown in appendix C. The network was run at 71 temperatures equally spaced in \(0.01 \times 10^9\) K steps from \(0.7 \times 10^9\) to \(1.4 \times 10^9\).

The results of the analysis are shown in figures 8 – 13. The density of the hydrogen envelope was assumed to be \(10^4\) g/cm\(^3\) for these calculations. However, since the rate at which any reaction occurs scales with the density, times given in our figures will scale inversely with density. The temperature shown on the ordinate may be interpreted essentially as the highest reached during the proton capture process, since the processing that occurs at the maximum temperature will proceed at a faster rate than that at any other temperature and, thus, will tend to dominate. The abscissa indicates the length of time the proton capture process remains at this peak temperature.

Figures 8 and 10 show the overproduction factors achieved for \(^{92}\)Mo and \(^{94}\)Mo if \(^{95}\)Ag is proton unbound. The overproduction factor is defined as the abundance produced divided by the solar abundance observed for a particular isotope. If our model produces vastly different overproduction factors for \(^{92}\)Mo and \(^{94}\)Mo, then we
will have to abandon it, since it would not lead to the relative solar abundances which we observe. Figures 9 and 11 represent the results if $^{95}\text{Ag}$ is proton bound by 1.5 MeV. As can be seen in these figures, for high temperatures or long processing times, the abundances achieved for $^{94}\text{Mo}$ are significantly different if $^{95}\text{Ag}$ is proton bound than if $^{95}\text{Ag}$ is proton unbound.

Figures 12 and 13 show the fractional difference in overproduction factors for $^{92}\text{Mo}$ and $^{94}\text{Mo}$. For example, for a temperature of $1.1 \times 10^9$ K and a processing time of 0.7 seconds, the overproduction factors for these two isotopes are within a factor of 0.1 of each other. This point, then, represents a combination of temperature and processing time which leads to the proper relative solar abundances of $^{92}\text{Mo}$ and $^{94}\text{Mo}$.

Notice that the parameter space for which $^{92}\text{Mo}$ and $^{94}\text{Mo}$ are produced in roughly the same ratio as their solar abundances is much greater if $^{95}\text{Ag}$ is bound than if $^{95}\text{Ag}$ is unbound. This is consistent with our expectations as expressed in section 1.4.3.

In figures 12 and 13, contours are not shown unless both $^{92}\text{Mo}$ and $^{94}\text{Mo}$ have an overproduction factor of at least 20. This is because after the rp-process is over, the isotopes produced will be dispersed throughout the interstellar medium. We expect the sites for this rapid hydrogen burning process to be relatively rare. So, in order to explain the observed abundances of the Mo isotopes, considerably more nuclei must be produced in these sites than we observe in our solar system. As can be seen in figures 8 through 11, we find we are capable of producing overproduction factors of up to 70 for both Mo isotopes. We will see in chapter IV that for Thorne-Żytkow objects, much higher overproduction factors could be expected.
Figure 8: Overproduction factors for $^{92}\text{Mo}$ if $^{95}\text{Ag}$ is unbound

Figure 9: Overproduction factors for $^{92}\text{Mo}$ if $^{95}\text{Ag}$ is bound by 1.5 MeV
Figure 10: Overproduction factors for $^{94}\text{Mo}$ if $^{95}\text{Ag}$ is unbound

Figure 11: Overproduction factors for $^{94}\text{Mo}$ if $^{96}\text{Ag}$ is bound by 1.5 MeV
Figure 12: Fractional difference in overproduction factors for $^{92}\text{Mo}$ and $^{94}\text{Mo}$ if $^{96}\text{Ag}$ is unbound
Figure 13: Fractional difference in overproduction factors for $^{92}\text{Mo}$ and $^{94}\text{Mo}$ if $^{96}\text{Ag}$ is bound by 1.5 MeV
The first of our tasks seems to be completed. It has been shown that, if $^{95}\text{Ag}$ is bound, a rapid hydrogen burning process can produce large abundances of $^{92}\text{Mo}$ and $^{94}\text{Mo}$ in ratios that lead to the observed relative solar abundances. It now must determined if indeed $^{95}\text{Ag}$ is proton bound.

### 2.3 Additional Considerations

The results discussed in section 2.2 tend to be sensitive to changes in the unknown masses of some of the nuclei. In particular, our results for $^{92}\text{Mo}$ and $^{94}\text{Mo}$ are sensitive to the mass difference between $^{94}\text{Pd}$ and $^{95}\text{Ag}$. Our mass estimate gives a Q-value for $^{94}\text{Pd} + p \rightarrow ^{95}\text{Ag}$ of about 1.0 MeV. At this Q-value, photodissociation of $^{95}\text{Ag}$ leads to a fairly tightly constrained region of temperature and processing time for which comparable amounts of $^{92}\text{Mo}$ and $^{94}\text{Mo}$ occur. However, a increase in this Q-value of as little as 0.25 MeV greatly increases that range of temperature-time space, with the maximum occurring for a increase in Q of about 0.5 MeV. At $Q = 1.75$, the range of temperatures and processing times is not quite as broad as of that for $Q = 1.5$, and subsequent increases in Q have little effect as photodissociation of $^{95}\text{Ag}$ no longer competes with proton capture on $^{94}\text{Pd}$. Thus, the mass difference between $^{94}\text{Pd}$ and $^{95}\text{Ag}$ emerges as an important quantity to be determined.

Any rapid proton capture process has interesting ramifications for other p-process nuclides. For example, in a proton capture process, nuclei in the N=50 neutron column will be driven toward the proton drip line until $^{98}\text{Cd}$ is reached. Since $^{99}\text{In}$ seems to be very loosely bound [12], a large amount of $^{98}\text{Cd}$ will be built up for
processing temperatures of about $1.1 \times 10^9$ or greater. These nuclei might be expected ultimately to $\beta^+$ decay to $^{98}$Ru, greatly overproducing $^{98}$Ru, which has a very small solar abundance [26]. Some mass calculations suggest, however, that $^{98}$Ag may decay through some process other than simple $\beta^+$ decay, e.g. $\beta^+p$ decay. This would prevent excessive overproduction of $^{98}$Ru by the high temperature rp-process. Instead of decaying to $^{98}$Ru the nuclei at $^{98}$Cd would proceed to $^{97}$Mo, which is a factor of 10 more abundant than $^{98}$Ru. Therefore, the decay mode of $^{98}$Cd emerges as an important test of the present model. Similarly, $^{96}$Ru seems to be overproduced due to a build-up of material at $^{96}$Cd. However, it is likely that $^{96}$Cd would also undergo a $\beta^+p$ decay on its way to stability, proceeding to $^{95}$Mo, which is a factor of 6 more abundant than $^{96}$Ru.

Finally, using this model, it is potentially possible to build up large overabundances of lighter p-process nuclei (ie. $^{74}$Se, $^{78}$Kr and $^{84}$Sr) as well. Since some production of the light p-process nuclei may occur in other sites, this could present a problem for the model. Thus, the overabundance factors generated in the present model must be smaller for the lighter nuclei than for $^{92}$Mo and $^{94}$Mo. However, combinations of temperatures and times which correspond to acceptable ratios of $^{92}$Mo and $^{94}$Mo also tend to correspond to much smaller overproduction factors for these lighter p-process nuclei. Furthermore, as the high temperature region assumed in the present model cools, proton captures on the heaviest nuclei synthesized will cease, but any lighter nuclei that remain will continue to experience processing at these lower temperatures, further redistributing their abundances.
In order to determine if $^{95}$Ag is indeed bound, we traveled to the National Superconducting Cyclotron Laboratory at Michigan State University. There we hoped to use the A1200 fragment separator to search for $^{95}$Ag in the reaction products produced in a projectile fragmentation process.

### 3.1 Experimental Setup

At NSCL, an E/A = 60 MeV $^{106}$Cd beam produced by the K1200 cyclotron was used to bombard a 44.4 mg/cm$^2$ Ni target. The natural Ni target was fitted with a 9.4 mg/cm$^2$ $^9$Be backing which was used to increase the fraction of electrons stripped from the reaction products. The reaction products were separated and identified using the A1200 fragment separator. Figure 14 shows the schematic layout of the A1200, which consists of fourteen superconducting quadrupole and four superconducting dipole magnets. It has an angular acceptance of 4.3 msr, a momentum acceptance of 3%, and a maximum rigidity of 5.4 T m [20]. The experimental method employed closely follows that of Bazin et al. [2], Mohar et al. [15], and Yennello et al. [34].
A pair of position-sensitive parallel-plate avalanche detectors placed at Dispersive Image 2 were used to determine the radius of curvature ($\rho$) of the reaction products through the A1200. NMR measurements of the dipole fields provided a value for $B$, while thin plastic scintillators at Dispersive Image 1 and at the final image were used to measure the transit time through the device and, hence, the velocity ($\gamma$) of the reaction products. The products were deposited into a four element silicon telescope ($\Delta E_1, \Delta E_2, E_1, E_2$) where energy losses were measured. These values ($\rho$, $B$, $\gamma$, $\Delta E_1$, $\Delta E_2$, $E_1$, and $E_2$) provide all of the information necessary to uniquely identify the isotopes.
3.2 Data Analysis

The goal of the off-line data analysis was simply to identify the atomic number \((Z)\) and mass \((A)\) of each particle through the A1200. Observation then of a isotope with \(Z = 47\) and \(A = 95\) would tell us that \(^{95}\text{Ag}\) is proton bound.

3.2.1 \(Z\) Identification

The atomic number of each fragment was determined using the Bethe formula:

\[
Z^2 \approx \frac{K.E. \times \Delta E}{A}, \tag{3.1}
\]

where \(K.E.\) is the total kinetic energy of the particle. Recalling the relativistic expression \(K.E. = mc^2(\gamma - 1)\) and the fact that \(A \propto mc^2\), we find

\[
Z \propto \sqrt{\Delta E(\gamma - 1)}. \tag{3.2}
\]

The telescope described in section 3.1 provided two energy-loss measurements before stopping the particle. This allowed redundant nuclear charge \((Z)\) determinations. Expression 3.2, however, only gives the variation of \(Z\), not the absolute values. In order to arrive at absolute values, a linear fit must be made using known values of \(Z\):

\[
Z = a + b\sqrt{\Delta E_i(\gamma - 1)}. \tag{3.3}
\]

In order to calibrate \(Z\), the isotopes were observed in a \(\Delta E\) versus TOF graph (fig. 15). Here the cadmium beam was clearly visible (upper left-hand corner of fig
15) and was used to identify the $Z = 48$ peak in the $Z$ spectrum for each of the $\Delta E$ detectors. The calibrated spectrum are shown in figures 16 and 17.

### 3.2.2 A Identification

The magnetic force on a fragment travelling through the A1200 is $F_B = QBv$. This must be equal to the centripetal acceleration, $\frac{mv^2}{\rho}$. So,

$$\frac{mv^2}{\rho} = QBv,$$

and the momentum of the particle is given by

$$mv = QB\rho.$$
Figure 16: $Z$ spectrum calculated from $\Delta E_1$

Figure 17: $Z$ spectrum calculated from $\Delta E_2$
Our fragments, however, are relativistic, so the momentum in this expression must be replaced by the relativistic momentum ($\gamma mv$):

$$\gamma mc\beta = QB\rho. \tag{3.6}$$

Or,

$$\beta\gamma(3.1077)A = QB\rho. \tag{3.7}$$

So,

$$A = \frac{QB\rho}{(3.1077)\beta\gamma}. \tag{3.8}$$

We see that in order to calculate $A$ for each nucleus, we need to first identify its charge state ($Q$). To do so, we recall once again that $K.E. = mc^2(\gamma - 1)$. So, $K.E. = (931.5)A(\gamma - 1)$. Substituting for $A$ in 3.7 we find

$$Q = \frac{(3.1077) \times K.E. \times \beta\gamma}{(931.5)B\rho(\gamma - 1)}. \tag{3.9}$$

We can find the total kinetic energy ($K.E.$) of each fragment by summing the energies deposited in each of the silicon detectors: $K.E. = \Delta E_1 + \Delta E_2 + E_1 + E_2 \equiv E_{tot}$. Then the $Q$ of each element is given by

$$Q = \frac{3.1077 \times E_{tot} \times \beta\gamma}{931.5 \times B\rho(\gamma - 1)}. \tag{3.10}$$

Unfortunately, the fragments lose energy as the travel through the various devices along their paths before they reach the silicon telescope. Therefore, $E_{tot}$ does not represent the total kinetic energy as we require for formula 3.10. For this reason, the $Q$ spectrum must also be calibrated to known values.
Using the *Intensity* program written by Winger and Sherrill [30], it was found that we should expect the charge state distribution shown in table 4 for cadmium. In creating the *Intensity* program, Winger and Sherrill used data compiled by Shima et al. [21], Hofmann et al. [10] and Steinhof et al. [23] to create a phenomenological parameterization for the mean charge ($q_{\text{eff}}$) and the sigma width ($\sigma_q$) of the charge distribution as the beam leaves a degrading material. Ignoring shell effects so that a smooth distribution over several shells may be obtained, the charge state distributions are given by [30]

$$F(q) = \left[2^{\nu/2} \Gamma(\nu/2)\right]^{-1} t^{\nu/2-1} e^{-t/2}, \quad (3.11)$$

where $F(q)$ is the fraction of the beam in the $q$ charge state, and

$$t = c(Z_i + 2 - q) \quad (3.12)$$

$$\nu = c(Z_i + 2 - q_{\text{eff}}) \quad (3.13)$$

$$c = 2(Z_i + 2 - q_{\text{eff}})/\sigma_q^2. \quad (3.14)$$

This program has proven to be in good agreement with experiment for the beam energy at which our experiment takes place.

The most important point here is that we expect a strong peak for the $Q = Z$ state. So, it was possible by gating individually on the elements and observing the $Q$ spectra to identify the $Q = Z$ peak in each spectrum (fig 18). Since $Z$ had already been calibrated, this process allowed accurate calibration of $Q$. The calibrated $Q$-spectrum is shown in figure 19.
Table 4: Charge state distribution for $^{106}$Cd

<table>
<thead>
<tr>
<th>Charge State</th>
<th>Percent Produced</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48+}$</td>
<td>42.7 %</td>
</tr>
<tr>
<td>$^{47+}$</td>
<td>50.5 %</td>
</tr>
<tr>
<td>$^{46+}$</td>
<td>6.6 %</td>
</tr>
<tr>
<td>$^{45+}$</td>
<td>0.3 %</td>
</tr>
<tr>
<td>$^{44+}$</td>
<td>&lt;0.01 %</td>
</tr>
</tbody>
</table>

Figure 18: Sample $Q$ spectrum for Ag
Once $Q$ has been calibrated, $A$ should follow from equation 3.8. However, this equation relies on the assumption that $\beta$ (and, hence, $\gamma$) have been properly calibrated. It would be reassuring if we could verify that this was the case.

Since $Q$ and $Z$ have been identified we can create a $\Delta E$ vs. TOF spectrum for fully stripped nuclei and known values of $Z$ (fig. 15). From equation 3.8, we see that for a given $B\rho$ setting, $\text{TOF} \propto A/Q$. Therefore, the "columns" shown in figure 15 correspond to specific values for $N - Q$. Examining this all a little more closely, we see that for fully stripped nuclei,

$$\text{TOF} \propto A/Z.$$ \hspace{1cm} (3.15)

$$\text{TOF} = C_1 + C_2 \frac{(N + Z)}{Z}.$$ \hspace{1cm} (3.16)
If we plot TOF vs $1/Z$ for the nuclei in a given column, then, we find a straight line of slope $k_1 = C_2(N - Z)_{1}$. We expect a straight line because $(N - Z)_{1}$ is constant for all nuclei in that column. Now, if we do this for the nuclei in the column immediately to the left of the first, we get a straight line of slope $k_2 = C_2(N - Z)_{2}$, where $(N - Z)_{2} = (N - Z)_{1} + 1$. So,

$$k_2 - k_1 = C_2(N - Z)_{2} - C_2(N - Z)_{1} = C_2 [(N - Z)_{1} + 1 - (N - Z)_{1}] = C_2. \quad (3.19)$$

And

$$\frac{k_1}{k_2 - k_1} = (N - Z)_{1}. \quad (3.20)$$

Since $Z$ is known, this provides identification of $N$ and, hence, $A$. The $A$ spectrum can then be calibrated using these known values. The calibrated $A$ spectrum is shown in figure 20.

In summary, the analysis consists of three basic steps.

1. Calibrate $Z$ by identifying the beam in a $\Delta E$ vs TOF spectrum.

2. Calibrate $Q$ by identifying the $Q = Z$ peak in the various $Z$ spectra.

3. Identify $A$ for each isotope in the $\Delta E$ vs TOF spectrum by investigating the relationship between successive “columns”.

\[
\text{TOF} = C_1 + C_2 \frac{(2Z + N - Z)}{Z}. \quad (3.17)
\]

\[
\text{TOF} = (C_1 + 2C_2) + C_2 \frac{(N - Z)}{Z}. \quad (3.18)
\]
3.3 Results

The mass spectra in Figures 21 - 24 show the identification and production rates of the new nuclei produced: $^{88}$Ru, $^{90,91}$Rh, $^{92,93}$Pd, and $^{94,95}$Ag.

As can be seen in the figures, the mass resolution is sufficient to clearly separate the isotopes. A few events corresponding to $^{87}$Ru, $^{91}$Pd, and $^{93}$Ag are also observed; however, it is difficult to conclude from such a small number of events whether these nuclei were in fact identified or whether these were misidentified events. The data shown represent approximately 19 hours of data collection at a beam current of $\approx 0.2$ pnA. The observation of an isotope in this experiment implies that the ion has a lifetime longer than its flight time through the A1200 separator, which is on the
Figure 21: Mass spectrum for Ag

Figure 22: Mass spectrum for Pd
Figure 23: Mass spectrum for Rh

Figure 24: Mass spectrum for Ru
order of 150 ns.

The presence of the peak at $A=95$ in the spectrum for Ag indicating that $^{96}\text{Ag}$ is indeed bound tells us what we need to know for this work. Figure 13 represents the expected results regarding $^{92}\text{Mo}$ and $^{94}\text{Mo}$ due to the rapid hydrogen burning process, providing a reasonable range of temperatures and processing times for which acceptable rations of these isotopes are produced.
CHAPTER IV

Conclusions

The p-process nuclei are typically 100 times less abundant than their s- and r-process neighbors. This, however, is not the case for $^{92}$Mo and $^{94}$Mo which comprise a surprising 15% and 9% of natural Mo. This has presented a challenge to Nuclear Astrophysicists who wish to explain the observed solar abundances of the elements. While the $\gamma$-process has been successful at explaining the abundances of many of the p-process nuclei, it inevitably underproduces $^{92}$Mo and $^{94}$Mo simply because there are so many more of these nuclei than is typical for proton rich isotopes. With this in mind, we have investigated the feasibility of producing $^{92}$Mo and $^{94}$Mo through a rapid proton capture process.

The results are favorable. For all temperatures and processing times we investigated, the overproduction factors for $^{92}$Mo and $^{94}$Mo are equal to within a factor of three. However, for temperatures less than $0.9 \times 10^9$ K or very short times, the overproduction factors are less than 10, which is probably too small to account for the solar abundances of these nuclei. For a considerable range of temperatures and processing times, the overproduction factors differ by less than 50% and are at least of magnitude 20 (see figure 13). An overproduction of 20 would mean that 5% of the
galaxy would have had to experience p-processing in order to produce the amounts of $^{92}$Mo and $^{94}$Mo we see around us. That's a lot.

Initially, this difficulty concerning the actual amounts of $^{92}$Mo and $^{94}$Mo produced seems rather intimidating. However, the solution may exist in Thorne-Żytkow objects. As alluded to in section 1.4.3, Thorne-Żytkow objects are unique in that the accreted material is not taken from the outer surface of the star, but pulled from the inner surface of the envelope. Thus, we expect that the material processed in the high temperature region near the surface of the neutron star could have experienced helium burning and, hence, prior s-processing. Lamb et al. [13] have estimated that the resulting enhancement of nuclei in the A=60-90 region due to s-processing should be about a factor of 50. This would produce a net overproduction for $^{92}$Mo and $^{94}$Mo on the order of 1,000 - 3500, thus requiring only about 0.1% to 0.03% of the mass of the galaxy need have been processed in a Thorne-Żytkow environment in order to produce the observed $^{92,94}$Mo abundances. Therefore, Thorne-Żytkow objects emerge as the most favorable site for the production of $^{92}$Mo and $^{94}$Mo through rapid proton capture. In fact, some models suggest that Thorne-Żytkow objects are actually supported through proton captures on nuclei lighter than iron [3]. The only trouble is that, at this time, we have no observational verification that Thorne-Żytkow objects really exist. Externally, they should look like ordinary red giants and supergiants, although their lifetimes should be about 10 times longer [25]. Fortunately, it should be possible to distinguish Thorne-Żytkow objects from ordinary red giants and supergiants by observing the elements at the surface of the star. It is believed that the envelope
would be almost entirely convective [4], so products from the rp-process should be carried to the surface of the star. Biehle [4] has estimated that there should be an abnormally large amount of metals heavier than Fe, especially Br, Rb, Y, Nb, and Mo, at the surface of a Thorne-Zytkow object. The observation of these elements through absorption spectroscopy would not only indicate that the observed star is a Thorne-Zytkow object, but also that Thorne-Zytkow objects are indeed supported through the rp-process.

There is still much work to be done concerning the rapid hydrogen burning process. We have found that the masses of the nuclei near the drip line can have a profound affect on the results of the rp-process (see section 2.3). Also, the halflives and decay modes of nuclei at the proton-drip line will certainly effect the overproductions achieved. As discussed in section 2.3, the decay modes of $^{96}$Cd and $^{98}$Ag are particularly significant. If these nuclei decay by simple $\beta^+$ emission, then for most combinations of temperatures and processing times, too much $^{96}$Ru and $^{98}$Ru will be produced relative to $^{92}$Mo and $^{94}$Mo. A radioactive nuclear beam facility (such as NSCL at Michigan State, for example) would be ideal for testing the decay modes. A $^{98}$Ag beam could be created through fragmentation and then stopped in a silicon detector. By surrounding the detector with scintillator it should be possible to detect the positrons emitted as the Cadmium decays. The detection of a coincidence proton in the silicon detector would then indicate that $^{98}$Cd decayed through $\beta^+p$ rather than simple $\beta^+$ emission.
Thus, we have seen that the rapid hydrogen burning process is capable of producing large overabundances of $^{92}\text{Mo}$ and $^{94}\text{Mo}$ and can produce them in ratios that lead to the observed solar abundances. Further, Thorne-Żytkow objects would provide an ideal site for this process. However, experimental data concerning the attributes of the nuclei at the proton-drip line as well as observational information concerning Thorne-Żytkow objects will be of great help in determining the exact nature of the production of $^{92}\text{Mo}$ and $^{94}\text{Mo}$ as well as the other $p$-process nuclei.
Appendix A

Network of Nuclei
Appendix B

Characteristics of Nuclei

<table>
<thead>
<tr>
<th>Nuclei</th>
<th>Spin</th>
<th>Mass</th>
<th>Halflife</th>
<th>Abundance</th>
<th>Decay(s)</th>
<th>Branching</th>
</tr>
</thead>
<tbody>
<tr>
<td>48Fe</td>
<td>0.0</td>
<td>-18.130</td>
<td>0.3500E+02 mS</td>
<td>0.000E+00</td>
<td>E</td>
<td>0 %</td>
</tr>
<tr>
<td>49Fe</td>
<td>3.5</td>
<td>-24.580</td>
<td>0.7500E+02 mS</td>
<td>0.000E+00</td>
<td>E</td>
<td>0 %</td>
</tr>
<tr>
<td>50Fe</td>
<td>0.0</td>
<td>-34.470</td>
<td>0.1500E+03 mS</td>
<td>0.000E+00</td>
<td>E</td>
<td>0 %</td>
</tr>
<tr>
<td>51Fe</td>
<td>2.5</td>
<td>-40.217</td>
<td>0.3100E+03 mS</td>
<td>0.000E+00</td>
<td>E</td>
<td>0 %</td>
</tr>
<tr>
<td>52Fe</td>
<td>0.0</td>
<td>-48.331</td>
<td>0.8275E+01 h</td>
<td>0.000E+00</td>
<td>E</td>
<td>0 %</td>
</tr>
<tr>
<td>53Fe</td>
<td>3.5</td>
<td>-50.943</td>
<td>0.8510E+01 m</td>
<td>0.000E+00</td>
<td>E</td>
<td>0 %</td>
</tr>
<tr>
<td>54Fe</td>
<td>0.0</td>
<td>-56.250</td>
<td>0.0000E+00</td>
<td>0.524E+05</td>
<td>E</td>
<td>0 %</td>
</tr>
<tr>
<td>55Fe</td>
<td>1.5</td>
<td>-57.476</td>
<td>0.2730E+01 y</td>
<td>0.000E+00</td>
<td>E</td>
<td>0 %</td>
</tr>
<tr>
<td>56Fe</td>
<td>0.0</td>
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<td>0.0000E+00</td>
<td>0.825E+06</td>
<td>E</td>
<td>0 %</td>
</tr>
<tr>
<td>57Fe</td>
<td>0.5</td>
<td>-60.178</td>
<td>0.0000E+00</td>
<td>0.197E+05</td>
<td>E</td>
<td>0 %</td>
</tr>
<tr>
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<td>0.0</td>
<td>-62.151</td>
<td>0.0000E+00</td>
<td>0.287E+04</td>
<td>E</td>
<td>0 %</td>
</tr>
<tr>
<td>50Co</td>
<td>4.0</td>
<td>-17.980</td>
<td>0.1000E+02 mS</td>
<td>0.000E+00</td>
<td>E</td>
<td>0 %</td>
</tr>
<tr>
<td>51Co</td>
<td>3.5</td>
<td>-27.420</td>
<td>0.4000E+02 mS</td>
<td>0.000E+00</td>
<td>E</td>
<td>0 %</td>
</tr>
<tr>
<td>52Co</td>
<td>0.0</td>
<td>-34.287</td>
<td>0.5000E+02 mS</td>
<td>0.000E+00</td>
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<td>0 %</td>
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<tr>
<td>53Co</td>
<td>3.5</td>
<td>-42.639</td>
<td>0.2400E+03 mS</td>
<td>0.000E+00</td>
<td>E</td>
<td>0 %</td>
</tr>
<tr>
<td>54Co</td>
<td>0.0</td>
<td>-48.010</td>
<td>0.1932E+03 mS</td>
<td>0.000E+00</td>
<td>E</td>
<td>0 %</td>
</tr>
<tr>
<td>55Co</td>
<td>3.5</td>
<td>-54.025</td>
<td>0.1753E+02 h</td>
<td>0.000E+00</td>
<td>E</td>
<td>0 %</td>
</tr>
<tr>
<td>56Co</td>
<td>4.0</td>
<td>-56.037</td>
<td>0.7712E+02 d</td>
<td>0.000E+00</td>
<td>E</td>
<td>0 %</td>
</tr>
<tr>
<td>57Co</td>
<td>3.5</td>
<td>-59.342</td>
<td>0.2718E+03 d</td>
<td>0.000E+00</td>
<td>E</td>
<td>0 %</td>
</tr>
<tr>
<td>58Co</td>
<td>2.0</td>
<td>-59.844</td>
<td>0.7082E+02 d</td>
<td>0.000E+00</td>
<td>E</td>
<td>0 %</td>
</tr>
<tr>
<td>59Co</td>
<td>3.5</td>
<td>-62.226</td>
<td>0.0000E+00</td>
<td>0.220E+04</td>
<td>E</td>
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</tr>
<tr>
<td>51Ni</td>
<td>3.5</td>
<td>-12.010</td>
<td>0.2000E+02 mS</td>
<td>0.000E+00</td>
<td>E</td>
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</tr>
<tr>
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<td>0.2000E+02 mS</td>
<td>0.000E+00</td>
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<td>E</td>
<td>0 %</td>
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"B" ⇒ β⁻ decay
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<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>Element</td>
<td>Charge</td>
<td>Energy (eV)</td>
<td>Cross-Section ( barns)</td>
<td>Lifet ime (s)</td>
<td>Decay Mode</td>
</tr>
<tr>
<td>---------</td>
<td>--------</td>
<td>-------------</td>
<td>------------------------</td>
<td>--------------</td>
<td>------------</td>
</tr>
<tr>
<td>93Ru</td>
<td>4.5</td>
<td>-77.270</td>
<td>0.5970E+02 S</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>94Ru</td>
<td>0.0</td>
<td>-82.569</td>
<td>0.5180E+02 m</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>95Ru</td>
<td>2.5</td>
<td>-83.451</td>
<td>0.1640E+01 h</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>96Ru</td>
<td>0.0</td>
<td>-86.073</td>
<td>0.0000E+00</td>
<td>0.105E+00</td>
<td>---</td>
</tr>
<tr>
<td>97Ru</td>
<td>2.5</td>
<td>-86.113</td>
<td>0.2900E+01 d</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>98Ru</td>
<td>0.0</td>
<td>-88.225</td>
<td>0.0000E+00</td>
<td>0.355E-01</td>
<td>---</td>
</tr>
<tr>
<td>90Rh</td>
<td>5.0</td>
<td>-53.240</td>
<td>0.2000E+03 mS</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>91Rh</td>
<td>4.5</td>
<td>-59.470</td>
<td>0.6000E+03 mS</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>92Rh</td>
<td>8.0</td>
<td>-63.140</td>
<td>0.7000E+03 mS</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>93Rh</td>
<td>4.5</td>
<td>-69.110</td>
<td>0.5000E+01 S</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>94Rh</td>
<td>8.0</td>
<td>-72.710</td>
<td>0.9412E+01 S</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>95Rh</td>
<td>4.5</td>
<td>-78.340</td>
<td>0.6020E+01 m</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>96Rh</td>
<td>5.0</td>
<td>-79.626</td>
<td>0.9600E+01 m</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>97Rh</td>
<td>4.5</td>
<td>-82.590</td>
<td>0.3110E+02 m</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>98Rh</td>
<td>2.0</td>
<td>-83.168</td>
<td>0.8700E+01 m</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>99Rh</td>
<td>0.5</td>
<td>-85.519</td>
<td>0.1610E+02 d</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>92Pd</td>
<td>0.0</td>
<td>-55.810</td>
<td>0.9000E+03 mS</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>93Pd</td>
<td>4.5</td>
<td>-59.650</td>
<td>0.8000E+03 mS</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>94Pd</td>
<td>0.0</td>
<td>-66.270</td>
<td>0.9000E+01 S</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>95Pd</td>
<td>2.5</td>
<td>-70.120</td>
<td>0.4000E+01 S</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>96Pd</td>
<td>0.0</td>
<td>-76.150</td>
<td>0.2030E+01 m</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>97Pd</td>
<td>2.5</td>
<td>-77.800</td>
<td>0.3100E+01 m</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>98Pd</td>
<td>0.0</td>
<td>-81.301</td>
<td>0.1770E+02 m</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>99Pd</td>
<td>2.5</td>
<td>-82.193</td>
<td>0.2140E+02 m</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>100Pd</td>
<td>0.0</td>
<td>-85.221</td>
<td>0.3630E+01 d</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>94Ag</td>
<td>1.0</td>
<td>-52.640</td>
<td>0.8000E+03 mS</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>95Ag</td>
<td>4.5</td>
<td>-60.480</td>
<td>0.1700E+01 S</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>96Ag</td>
<td>8.0</td>
<td>-64.430</td>
<td>0.5100E+01 S</td>
<td>0.000E+00</td>
<td>E EP</td>
</tr>
<tr>
<td>97Ag</td>
<td>4.5</td>
<td>-70.790</td>
<td>0.2100E+02 S</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>98Ag</td>
<td>7.0</td>
<td>-73.000</td>
<td>0.4700E+02 S</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>99Ag</td>
<td>4.5</td>
<td>-76.780</td>
<td>0.2067E+01 m</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>100Ag</td>
<td>5.0</td>
<td>-78.170</td>
<td>0.2010E+01 m</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>101Ag</td>
<td>4.5</td>
<td>-81.190</td>
<td>0.1110E+02 m</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>96Cd</td>
<td>0.0</td>
<td>-55.880</td>
<td>0.5000E+03 mS</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>97Cd</td>
<td>2.5</td>
<td>-60.690</td>
<td>0.4000E+03 mS</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>98Cd</td>
<td>0.0</td>
<td>-67.900</td>
<td>0.8000E+01 S</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>99Cd</td>
<td>2.5</td>
<td>-69.890</td>
<td>0.1600E+02 S</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>100Cd</td>
<td>0.0</td>
<td>-74.320</td>
<td>0.4910E+02 S</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>101Cd</td>
<td>2.5</td>
<td>-75.660</td>
<td>0.1200E+01 m</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>102Cd</td>
<td>0.0</td>
<td>-79.720</td>
<td>0.5500E+01 m</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>99In</td>
<td>4.5</td>
<td>-62.130</td>
<td>0.8000E+01 S</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>100In</td>
<td>5.0</td>
<td>-63.870</td>
<td>0.4000E+01 S</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>101In</td>
<td>4.5</td>
<td>-68.360</td>
<td>0.1000E+02 S</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>Element</td>
<td>Charge</td>
<td>Energy (eV)</td>
<td>Atomic Number</td>
<td>Spin</td>
<td>Polarization (%)</td>
</tr>
<tr>
<td>---------</td>
<td>--------</td>
<td>-------------</td>
<td>----------------</td>
<td>------</td>
<td>------------------</td>
</tr>
<tr>
<td>102In</td>
<td>5.0</td>
<td>-70.580</td>
<td>0.2300E+02</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>103In</td>
<td>4.5</td>
<td>-74.607</td>
<td>0.1083E+01</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
<tr>
<td>100Sn</td>
<td>0.0</td>
<td>-55.820</td>
<td>0.1300E+02</td>
<td>0.000E+00</td>
<td>E ---</td>
</tr>
</tbody>
</table>
Appendix C

Programs used to Calculate Abundances

PARAM.DEF
PARAMETER NP=50
PARAMETER NN=80
PARAMETER ZMIN=34
PARAMETER TOTN=3.46646E+10
SUBROUTINE TRR(T, PG)

INCLUDE 'PARAM.DEF'

INTEGER Z, N, P, NMIN(NP), NMAX(NP), NJ, ZJ, TYPE, AT
REAL*8 EXCESS(NN, NP), T, AJ, K, RO, R1, AI, A, R, ALPHA, X, T9, TAU, RATE
REAL*8 PG(NN, NP)

1 FORMAT (I)
2 FORMAT (F)
3 FORMAT (E)
4 FORMAT (I, I)

OPEN (UNIT=31, FILE='RANGE.DAT', STATUS='OLD')
OPEN (UNIT=32, FILE='MASS.DAT', STATUS='OLD')

DO Z=1, NP
   READ (31, 4) NMIN(Z), NMAX(Z)
   DO P=NMIN(Z)+1, NMAX(Z)+1
      READ (32, 2) EXCESS(P, Z)
   ENDDO
ENDDO

CLOSE (31)
CLOSE (32)

TYPE=1
IF (TYPE.EQ.1) THEN
   AT=1
   AJ=1.0+EXCESS(1,1)/931.5
   ZJ=1
   RO=1.25
   R1=0.1
   K=0.20
ELSE
   AT=4
   AJ=4.0+EXCESS(3,2)/931.5
   ZJ=2
   RO=1.09
   R1=0.07
   K=0.32
ENDIF

DO Z=1, NP
   DO N=NMIN(Z), NMAX(Z)
      P=N+1
      AI=Z+N+EXCESS(P, Z)/931.5
      A=(AI*AJ)/(AI+AJ)
      R=RO*(AI**0.3333333)+R1
      ALPHA=A*(R**3.0)/(Z*ZJ)
      ALPHA=0.1215*(ALPHA**0.5)
      X=0.52495*((A*Z*ZJ*R)**0.5)
      T9=T/(1.0+0.08617*ALPHA*T)
      TAU=4.2487*(Z*ZJ+ZJ**0.3333333)
      RATE=(7.833E+9)*K*((Z*ZJ)**1.3333333)*T9**0.833333
      RATE=RATE/(A**0.8333333)*(T**1.5)
      RATE=RATE*EXP(2.0*X- TAU/(T9**0.3333333))/6.022E+23 ! CC/(#SEC)
      IF (AI+AJ.LT.N+Z+AT+EXCESS(P+AT-ZJ, ZJ)/931.5) THEN
         RATE=0.0
   END DO
ENDDO
ENDIF
IF (N+AT-ZJ.LT.MIN(Z+ZJ)) THEN
  RATE=0.0
ENDIF
PG(P,Z)=RATE
ENDDO
ENDDO
END
SUBROUTINE PHOTO(T,G)

INCLUDE 'PARAM.DEF'

REAL*8 T,EXCESS(NN,NP),M(NN,NP),SP(NN,NP),MJ,MT,RM,PI,K,H
REAL*8 DISS,Q
REAL*8 GP(NN,NP)
INTEGER N,Z,P,NMIN(NP),NMAX(NP),TYPE,NJ,ZJ

PI=3.141592654
K =1.38062E-16 ! CGS UNITS
H =1.0546E-27 ! CGS UNITS

1 FORMAT (I)
2 FORMAT (P)
3 FORMAT (E)
4 FORMAT (1,1)

OPEN (UNIT=41,FILE='RANGE.DAT',STATUS='OLD')
OPEN (UNIT=43, FILE='MASS.DAT', STATUS='OLD')
OPEN (UNIT=44,FILE='SPIN.DAT',STATUS='OLD')

T=T*1.0E+9
DO Z=1,NP
   READ (41,4) NMIN(Z),NMAX(Z)
   DO P=NMIN(Z)+1,NMAX(Z)+1
      READ (43,3) EXCESS(P,Z)
      READ (44,2) SP(P,Z)
   ENDDO
ENDDO

CLOSE (41)
CLOSE (43)
CLOSE (44)

TYPE=1

IF (TYPE.EQ.1) THEN
   ! JUST DOING PHOTO-PROTON FOR NOW
   NJ=0
   ZJ=1
ELSE
   NJ=2
   ZJ=2
ENDIF

MJ=(EXCESS(NJ+1,ZJ)+EXCESS(N-JJ+1,Z-ZJ)-EXCESS(P,Z))*1.60218E-6

MT=(EXCESS(P,Z)/931.5)+N+Z

RN=1.66056E-24*(MT*MJ)/(MT+MJ)

IF (N-NJ.LT.NMIN(Z-ZJ).OR.N-JJ.GT.NMAX(Z-ZJ).OR.Z-ZJ.LT.1 & .OR.EXCESS(P,Z).EQ.0.0.OR.EXCESS(N-JJ+1,Z-ZJ).EQ.0.0) THEN
   DISS=0.0
ELSE
   DISS=((RN/(2*H)*K/(PI*H)*T)**1.5)*EXP(-Q/(K*T))*
       & (2*SP(NJ+1,ZJ)+1)*(2*SP(N-JJ+1,Z-ZJ)+1)/(2*SP(P,Z)+1)
ENDIF
ELSE
DISS=0.0
ENDIF
GP(P,Z)=DISS
ENDDO
ENDDO
ENDDO
END
MAIN PROGRAM

INCLUDE 'PARAM.DEF'

INTEGER NMIN(NP),NMAX(NP),GN(NN,NP),GZ(NN,NP)
INTEGER GN2(NN,NP),GZ2(NN,NP),BR(NN,NP),NSTEP
REAL*8 AB(NN,NP),HL(NN,NP),PG(NN,NP),DENSITY
REAL*8 DTDID, DTNEXT, ERS, NU8(NN,NP), SPACE, H, LIGHT
REAL*8 NU(NN,NP), DNU(NN,NP), GP(NN,NP), PYET, IYET
INTEGER I, COUNT, N, Z, P, TI, FI(11), CONTOUR, PCONTOUR
REAL*8 LENGTH, FINISH, LEFT, DT, ORI2, ORI4, ORI3, ORI5, YET
REAL*8 OP52, OP54, LESSER, DIFFER, T, SUCCESS, FAIL

SUCCESS=10.0 !minimum op
FAIL=0.5 !max differ mo

1 FORMAT (I)
2 FORMAT (F)
3 FORMAT (E)
4 FORMAT (I,I)
5 FORMAT (E,I,I,I,I,I)
6 FORMAT (E,' ',E12.6)
9 FORMAT (E10.4,' ','E10.4', E10.4)
10 FORMAT (21F7.3)

OPEN (UNIT=1,FILE='RANGE.DAT', STATUS='OLD')
OPEN (UNIT=3,FILE='AB.DAT', STATUS='OLD')
OPEN (UNIT=4,FILE='DENSITY.DAT', STATUS='OLD')
OPEN (UNIT=5,FILE='NSTEP.DAT', STATUS='OLD')
OPEN (UNIT=6,FILE='ERR.DAT', STATUS='OLD')
OPEN (UNIT=7,FILE='LENGTH.DAT', STATUS='OLD')

READ (4,2) DENSITY
READ (8,2) ERS
READ (7,1) NSTEP
READ (11,2) LENGTH

DO Z=1,NP
READ (1,4) NMIN(Z), NMAX(Z)
NMIN(Z)=NMIN(Z)+1
NMAX(Z)=NMAX(Z)+1
DO P=NMIN(Z), NMAX(Z)
READ (3,3) AB(P,Z)
IF(HL(P,Z).NE.0.) THEN
   HL(P,Z)=1000*LOG(2.)/HL(P,Z)
ELSE
   HL(P,Z)=0.0
ENDIF
ENDDO
ENDDO
CLOSE (1)
CLOSE (3)
CLOSE (4)
CLOSE (7)
CLOSE (8)
CLOSE (9)
CLOSE (11)

OPEN (UNIT=9, FILE='923D.OUT', STATUS='UNKNOWN')
OPEN (UNIT=19, FILE='RP2D.10', STATUS='UNKNOWN')
OPEN (UNIT=29, FILE='943D.OUT', STATUS='UNKNOWN')
OPEN (UNIT=39, FILE='RP3D.OUT', STATUS='UNKNOWN')
OPEN (UNIT=11, FILE='RP2D.10', STATUS='UNKNOWN')
OPEN (UNIT=12, FILE='RP2D.20', STATUS='UNKNOWN')
OPEN (UNIT=13, FILE='RP2D.30', STATUS='UNKNOWN')
OPEN (UNIT=14, FILE='RP2D.40', STATUS='UNKNOWN')
OPEN (UNIT=15, FILE='RP2D.50', STATUS='UNKNOWN')

DO TI=90,140,1
  T=TI/100.
  CALL TRR(T,P)
  T=TI/100.
  CALL PHOTO(T,GP)
  H=(AB(1,1)*DENSITY)*((6.022E+23/TOTM)) ! No alphas !
  DO Z=1,NP
    DO P=NMIN(Z),NMAX(Z)
      IF (GP(P,Z)>H*10.) THEN
        GP(P,Z)=0.0
        PG(P,Z-1)=0.0
      ENDIF
      IF (Z.LT.ZMIN) THEN
        NU(P,Z)=0.0
      ELSE
        NU(P,Z)=(AB(P,Z)*DENSITY)*((6.022E+23/TOTM)) ! units = #/cc
      ENDIF
    ENDDO
  ENDDO
  NU(1,1)=(AB(1,1)*DENSITY)*((6.022E+23/TOTM)) ! No alphas !

LEFT=LENGTH
YET=0.0
PYET=0
ORI2=NU(51,42)
ORI4=NU(53,42)
ORI1=NU(41,34)
ORI3=NU(43,36)
ORI5=NU(47,38)
ORI6=NU(53,44)
ORI7=NU(55,44)

DT=1.0/NSTEP
PCONTOUR=278

DO WHILE (LEFT.GT.0.0)
  CALL DERIVE(NU,DNU,NMIN,NMAX,P,Y,HL,GN,GZ,BR,GN2,GZ2)
  CALL STEPPER(NU,DNU,DT,DTDID,DTNEXT,ERS,NMIN,NMAX,P,Y,
               & HL,GN,GZ,BR,GN2,GZ2)
  CALL FIX_NEG(NU,NMIN,NMAX,P,Y,HL,GN,GZ,BR,GN2,GZ2)
  YET=YET+DTDID
  LEFT=LENGTH-YET
IF (DTNEXT.GT.LEFT) THEN
  DT=LEFT
ELSE
  DT=DTNEXT
ENDIF

IF(YET.LE.0.1) THEN
  SPACE=100.
ELSE
  IF(YET.LE.1.0) THEN
    SPACE=10.
    ELSE
    SPACE=1.
  ENDIF
ENDIF

OP52=(NU(51,42)+NU(50,43)+NU(49,44)+NU(48,45)+NU(47,46))/ORI2
OP54=(NU(54,41)+NU(53,42)+NU(52,43)+NU(51,44)+NU(50,45)
    & NU(49,46))/ORI4

LESSER=MIN(OP52,OP54)
DIFFER=ABS(OP54-OP52)/LESSER

IF(LESSER.GE.SUCCESS.AND.DIFFER.LT.FAIL+.15
    & .AND.OP74.LE.LESSER*LIGHT.AND.OP78.LE.LESSER*LIGHT
    & .AND.OP84.LE.LESSER*LIGHT) THEN

  IF(DIFFER.GE.FAIL+0.1) THEN
    CONTOUR=INT(FAIL*10)+11
  ELSE
    CONTOUR=INT(DIFFER*10)+10
  ENDIF
  IF (CONTOUR.NE.PCONTOUR) THEN
    PCONTOUR=CONTOUR
    WRITE (CONTOUR,6) YET,T/1.0E+9
    IF(CONTOUR.EQ.11) THEN
      WRITE (19,9) YET,LESSER,T/1.0E+9
    ENDIF
  ENDIF
ENDIF

IYET=INT(YET*SPACE)/SPACE
IF (IYET.GT.PYET) THEN
  PYET=IYET
  IF(LESSER.GE.SUCCESS) THEN
    WRITE (39,9) IYET,T/1.0E+9,DIFFER
  ENDIF
ENDIF
ENDDO
WRITE (6,*)T/1.0E+9
WRITE (39,*)
ENDDO
CLOSE (11)
CLOSE (12)
CLOSE (13)
CLOSE (14)
CLOSE (15)
CLOSE (9)
CLOSE (19)
CLOSE (29)
CLOSE (39)
END
SUBROUTINE STEPPER(NU,DNU,DT,DTDID,DTNEXT,ERS,NMIN,NMAX,PG,GP, 
& HL,GN,GZ,BR,GN2,GZ2)

INCLUDE 'PARAM.DEF'

INTEGER NMIN(NP),NMAX(NP),GN(NN,NP),GZ(NN,NP)
INTEGER GN2(NN,NP),GZ2(NN,NP),BR(NN,NP)
REAL*8 HL(NN,NP),PG(NN,NP)
REAL*8 DTDID,DTNEXT,ERS
REAL*8 NU(NN,NP),DNU(NN,NP),GP(NN,NP)
REAL*8 NUSAVE(NN,NP),NUT(NN,NP),DNUSAVE(NN,NP)
REAL*8 DT2,DT,ERRMAX,ER
INTEGER N,Z,P

DO Z=ZMIN,NP
  DO P=NMIN(Z),NMAX(Z)
    NUSAVE(P,Z)=NU(P,Z)
    DNUSAVE(P,Z)=DNU(P,Z)
  ENDDO
ENDDO

NUSAVE(1,1)=NU(1,1)

ERRMAX=1.0

DO WHILE (ERRMAX.GT.1.0)
  DT2=DT/2.0
  CALL RK4(NUSAVE,DNUSAVE,DT,NUT,NMIN,NMAX,PG,GP,HL,GN,GZ,BR,GN2,GZ2)
  CALL RK4(NUSAVE,DNUSAVE,DT2,NU,NMIN,NMAX,PG,GP,HL,GN,GZ,BR,GN2,GZ2)
  CALL DERIVE(NU,DNU,NMIN,NMAX,PG,GP,HL,GN,GZ,BR,GN2,GZ2)
  CALL RK4(NU,DNU,DT2,NU,NMIN,NMAX,PG,GP,HL,GN,GZ,BR,GN2,GZ2)
  ERRMAX=0.0
  DO Z=ZMIN,NP
    DO P=NMIN(Z),NMAX(Z)
      NUT(P,Z)=NU(P,Z)-NUT(P,Z)
      IF (ABS(NUSAVE(P,Z)).LT.1.0) THEN
        ER=0.0
      ELSE
        ER=ABS(NUT(P,Z)/NUSAVE(P,Z))
      ENDIF
      ERRMAX=MAX(ERRMAX,ER)
    ENDDO
  ENDDO
  ERRMAX=ERRMAX/ERS
  IF (ERRMAX.GT.1.0) THEN
    DT=0.9*DT*ERRMAX**(-0.25)
  ENDIF
ENDDO

DTDID=DT

IF (ERRMAX.GT.6.E-4) THEN
  DTDID=DT
ELSE
  DTDID=DT
ENDIF

DO Z=ZMIN,NP
  DO P=NMIN(Z),NMAX(Z)
    NU(P,Z)=NU(P,Z)+NUT(P,Z)/15.0
  ENDDO
ENDDO
SUBROUTINE RK4(NU, DNU, DT, NUOUT, NMIN, NMAX, PG, GP, HL, & GN, GZ, BR, GN2, GZ2)

INCLUDE 'PARAM.DEF'

INTEGER NMIN(NP), NMAX(NP), GN(NN, NP), GZ(NN, NP)
INTEGER GN2(NN, NP), GZ2(NN, NP), BR(NN, NP)
REAL*8 HL(NN, NP), PG(NN, NP), DT
REAL*8 NU(NN, NP), DNU(NN, NP), GP(NN, NP)
REAL*8 NUOUT(NN, NP), NUOUT(NN, NP), DNUN(NN, NP), DNUM(NN, NP)
INTEGER N, Z, P

DO Z = ZMIN, NP
  DO P = NMIN(Z), NMAX(Z)
    NUOUT(P, Z) = NU(P, Z) + DNU(P, Z) * DT / 2.0
  ENDDO
ENDDO

CALL DERIVE(NUOUT, DNUN, NMIN, NMAX, PG, GP, HL, GN, GZ, BR, GN2, GZ2)
DO Z = ZMIN, NP
  DO P = NMIN(Z), NMAX(Z)
    NUOUT(P, Z) = NU(P, Z) + DNUN(P, Z) * DT / 2.0
  ENDDO
ENDDO

CALL DERIVE(NUOUT, DNUM, NMIN, NMAX, PG, GP, HL, GN, GZ, BR, GN2, GZ2)
DO Z = ZMIN, NP
  DO P = NMIN(Z), NMAX(Z)
    DNUN(P, Z) = DNUN(P, Z) + DNUM(P, Z)
  ENDDO
ENDDO

CALL DERIVE(NUOUT, DNUN, NMIN, NMAX, PG, GP, HL, GN, GZ, BR, GN2, GZ2)
DO Z = ZMIN, NP
  DO P = NMIN(Z), NMAX(Z)
    NUOUT(P, Z) = NU(P, Z) + (DNU(P, Z) + 2 * DNUM(P, Z) + DNUN(P, Z)) * DT / 6.0
  ENDDO
ENDDO

NUOUT(1,1) = NU(1,1)
END
SUBROUTINE DERIVE(NU,DNU,NMIN,NMAX,PG,GP,HL,GN,GZ,BR,GN2,GZ2)
INCLUDE 'PARAM.DEF'
REAL*8 LNL(NN,NP),NL2(NN,NP),PG2(NN,NP)
REAL*8 DTDID,DTNEXT,ERS
REAL*8 NU(NN,NP),DNU(NN,NP),GP(NN,NP)
REAL*8 CRE(NN,NP)
INTEGER N,Z,P
DO Z=ZMIN,NP
  DO P=NMIN(Z),NMAX(Z)
    CRE(P,Z)=0.0
  ENDDO
ENDDO
DO Z=ZMIN,NP
  DO P=NMIN(Z),NMAX(Z)
    IF (HL(P,Z).NE.0.0.AND.NU(P,Z).NE.0.0) THEN
      CRE(GN(P,Z)+1,GZ(P,Z))=CRE(GN(P,Z)+1,GZ(P,Z))+(NU(P,Z)/100.0)
    ELSE
      CRE(GN2(P,Z)+1,GZ2(P,Z))=CRE(GN2(P,Z)+1,GZ2(P,Z))+(NU(P,Z)/100.0)
    ENDIF
  ENDDO
ENDDO
DO Z=ZMIN,NP
  DO P=NMIN(Z),NMAX(Z)
    DNU(P,Z)=NU(1,1)*NU(P,Z-1)*PG(P,Z-1)+CRE(P,Z)
      & -NU(1,1)*NU(P,Z)*PG(P,Z)-NU(P,Z)*HL(P,Z)
      & +GP(P,Z)
  ENDDO
ENDDO
END
SUBROUTINE FIX_NEG(NU, NMIN, NMAX, PG, GP, HL, GN, GZ, BR, GN2, GZ2)

INCLUDE 'PARAM.DEF'

INTEGER NMIN(NP), NMAX(NP), GN(NN,NP), GZ(NN,NP)
INTEGER GN2(NN,NP), GZ2(NN,NP), BR(NN,NP)
REAL*8 HL(NN,NP), PG(NN,NP)
REAL*8 NU(NN,NP), GP(NN,NP), NUT(NN,NP)

REAL*8 CHANGE
INTEGER N,Z,P

DO Z=ZMIN,NP
   DO P=NMIN(Z),NMAX(Z)
      NUT(P,Z)=NU(P,Z)
   ENDDO
ENDDO

DO Z=NP,ZMIN,-1
   DO P=NMIN(Z),NMAX(Z)
      IF(NU(P,Z).LT.0.0) THEN
         CHANGE=NU(P,Z)/(NU(1,1)*PG(P,Z)+HL(P,Z)+PG(P,Z-1)*GP(P,Z))
         IF(GZ(P,Z).LT.0.AND.GZ2(P,Z).LT.Z) THEN
            NU(GN(P,Z)+1,GZ(P,Z))=NU(GN(P,Z)+1,GZ(P,Z))+
            & HL(P,Z)*(1-BR(P,Z)*0.01)*CHANGE
         ENDIF
         IF(GZ2(P,Z).LT.0.AND.GZ2(P,Z).LT.Z) THEN
            NU(GN2(P,Z)+1,GZ2(P,Z))=NU(GN2(P,Z)+1,GZ2(P,Z))+
            & HL(P,Z)*(1-BR(P,Z)*0.01)*CHANGE
         ENDIF
      ELSE
         NU(P,Z)=NU(P,Z)-PG(P,Z)*NU(1,1)*CHANGE
      ENDIF
   ENDDO
ENDDO

DO Z=ZMIN,NP
   DO P=NMIN(Z),NMAX(Z)
      IF(NU(P,Z).LT.0.0) THEN
         CHANGE=NU(P,Z)/(NU(1,1)*PG(P,Z)+HL(P,Z)+PG(P,Z-1)*GP(P,Z))
         IF(GZ(P,Z).NE.0.AND.GZ(P,Z).GT.Z) THEN
            NU(GN(P,Z)+1,GZ(P,Z))=NU(GN(P,Z)+1,GZ(P,Z))+
            & HL(P,Z)*(1-BR(P,Z)*0.01)*CHANGE
         ENDIF
         IF(GZ2(P,Z).NE.0.AND.GZ2(P,Z).GT.Z) THEN
            NU(GN2(P,Z)+1,GZ2(P,Z))=NU(GN2(P,Z)+1,GZ2(P,Z))+
            & HL(P,Z)*(1-BR(P,Z)*0.01)*CHANGE
         ENDIF
      ELSE
         NU(P,Z)=NU(P,Z)-PG(P,Z)*NU(1,1)*CHANGE
      ENDIF
   ENDDO
ENDDO

DO Z=NP,ZMIN,-1
   DO P=NMIN(Z),NMAX(Z)
      IF(NU(P,Z).LT.0.0) THEN
         CHANGE=NU(P,Z)/(NU(1,1)*PG(P,Z)+HL(P,Z)+PG(P,Z-1)*GP(P,Z))
         IF(GZ(P,Z).NE.0.AND.GZ(P,Z).LT.Z) THEN
            NU(GN(P,Z)+1,GZ(P,Z))=NU(GN(P,Z)+1,GZ(P,Z))+
            & HL(P,Z)*(1-BR(P,Z)*0.01)*CHANGE
         ENDIF
         IF(GZ2(P,Z).NE.0.AND.GZ2(P,Z).LT.Z) THEN
            NU(GN2(P,Z)+1,GZ2(P,Z))=NU(GN2(P,Z)+1,GZ2(P,Z))+
            & HL(P,Z)*(1-BR(P,Z)*0.01)*CHANGE
         ENDIF
      ELSE
         NU(P,Z-1)=NU(P,Z-1)+PG(P,Z-1)*GP(P,Z)*CHANGE
         NUT(P,Z-1)=NUT(P,Z-1)+PG(P,Z-1)*GP(P,Z)*CHANGE
      ENDIF
   ENDDO
ENDDO
\[ \text{NU}(p,z) = 0.0 \]
ENDIF
ENDDO
ENDDO
END
BIBLIOGRAPHY


