High-precision (p,t) reactions to determine reaction rates of explosive stellar processes
Matić, Andrija

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2007

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Chapter 1

Introduction

1.1 Explosive stellar scenarios

One of the goals of nuclear astrophysics is to explain the energy production in stars, and related to this, creation and abundance of the chemical elements. Since the discovery in 1952 by Merrill [1] of radioactive technetium in spectra of S-stars, it became clear that nuclear synthesis of heavier nuclei in a star’s interior does happen indeed. Furthermore, since technetium has a half-life of $10^5$ to $10^6$ years, which is a very short time period on a cosmological scale, this implies that nuclear synthesis also takes place in our present times.

According to the Big-Bang theory matter created shortly after the Big Bang consists predominantly of $^1$H and $^4$He. The heaviest created progenitor nucleus produced in significant abundance is $^7$Li, whereas all heavier nuclei are created in stars; see Ref. [2]. The so-called main-sequence stars, which encompass the majority of stars, fuse hydrogen into helium. After the exhaustion of hydrogen in the core of a star, the core will contract because of the gravitational force and consequently the temperature and the pressure in the core will rise. Under these conditions the helium burning process will start and carbon (C), and oxygen (O), will be produced. After the exhaustion of helium in the core, its contraction will resume, leading to the ignition of C and O burning processes through which heavier elements are created.

$^{22}$Na and $^{26}$Al are two long-living nuclei which eventually $\beta^+$ decay followed by subsequent $\gamma$-ray emission in the respective daughter nuclei. In case of explosive-burning scenarios, these nuclei can be ejected into the interstellar medium, and their subsequent $\gamma$-ray radiation can be detected with existing $\gamma$-ray observatories in outer space. Therefore, in this section we will discuss 4 explosive-burning scenarios for stars; these are novae, supernovae type I, supernovae type II, and X-ray bursts. Some nuclear processes which take place during the phases of explosive burning and which lead to the creation of heavier elements than C and O will be discussed as well. These explosive scenarios have to be taken into account in order to explain the isotopic abundances observed throughout the universe.
1.1.1 Supernovae type II

A typical star for which one can apply the supernova II model has a mass of more than about 8 \( M_{\odot} \) (mass of the Sun). These stars evolve much faster than most main-sequence stars, which have typical lifetimes of about \( 10^8 \) years. During its lifetime a star goes through many burning stages, starting with the cycles of hydrogen burning up to silicon burning, subsequently leading to the formation of a Fe-Ni core. Because the iron nuclei are most tightly bound, a star cannot produce energy by the fusion of nuclei using iron or nickel as seed. Endothermic nuclear reactions will continue at extremely high temperatures of about \( 4 \times 10^9 \) K. These reactions are \( \gamma \)-ray photo-disintegration of nuclei and electron capture on protons leading to the production of neutrons and escaping neutrinos. The stellar iron core loses energy through these two reactions, and consequently the pressure of the degenerate electrons in the core decreases. Subsequently, the core contracts under the gravitational force and the temperature increases by compression. This dynamical collapse is starting at a density of about \( 10^9 \) g cm\(^{-3}\) and goes on to nearly nuclear matter density (\( 10^{14} \) g cm\(^{-3}\)). At that moment, the density in the core can not be increased much further and the core collapse is stopped abruptly (in the order of a few milliseconds) leading to the collapsing material bouncing on the core.

The bounce of the stellar material is very hard. Consequently, this leads to an outward moving compression wave which has such a high speed that it creates a shock wave. If the shock wave is strong enough material can get such a high energy, leading to a velocity beyond that of the escape velocity. In this case a large part of the stellar mass is ejected and this is the supernovae phenomenon. If the mass of the progenitor star is between 8-20 \( M_{\odot} \), the stellar core will evolve to a neutron star. If the progenitor mass is above 20 \( M_{\odot} \), the stellar core evolves to a black hole.

1.1.2 Novae

In case of a so-called nova, one is dealing with a binary system. One of the stars is a white dwarf and the other one is a star near the main sequence or an aging star such as red giant. The white dwarf can be a star mainly consisting of carbon-oxygen (CO) or oxygen-neon-magnesium (ONeMg), formed after the helium-burning (He) or carbon-burning stages, respectively.

In low-mass main-sequence stars hot gaseous matter can be described by the ideal gas law. In these circumstances a velocity distribution of electrons and nuclei can be described by the Maxwell-Boltzmann velocity distribution. In case a star has consumed its nuclear fuel, it will collapse under the gravitational force with a huge increase in density. Under an enormous matter density the electron energy distribution is changed due to the Pauli exclusion principle. As the stellar material shrinks, its volume decreases and the number of states in a unit energy interval is reduced. Consequently, there will be less quantum states at
lower energies than is necessary for the Maxwell-Boltzmann distribution to apply and more electrons remain at higher energy than would be expected from Maxwell-Boltzmann. As the density continues to increase more and more electrons will remain with higher energy, up to the moment when almost all states up to the Fermi level are filled. At this moment the electrons form a degenerate gas which is under a huge pressure because of the electrons rapid motion. The high pressure provided by the electrons prevents further compression of the stellar material. In case of a white dwarf the electrons are pressed so tightly that further compression is not possible.

The Roche lobe is a space around a star in a binary system which contains all material bound to that star. If a star expands beyond its Roche lobe, material can fall onto the other member of the binary system. In case of a nova the latter is a white dwarf and a hydrogen-rich accretion envelope can be created around it. This results from material falling from the star near the main sequence onto its accompanying star, the white dwarf. Since more and more hydrogen-rich material is accreted on top of the white dwarf, the temperature of this envelope will rise up to the moment that the hydrogen burning process starts. This temperature is around 0.02 \( T_9 \). Because electrons are in a degenerate state, gas material can not expand or cool before the degeneracy is lifted, and hence a rapid rise of temperature under constant pressure and density will occur. Degeneracy is lifted when the local temperature reaches the Fermi temperature, causing a rapid expansion of the envelope material into the interstellar medium. The typical nova peak temperature is 0.2 - 0.3 \( T_9 \).

During a nova explosion the burning of hydrogen proceeds through the CNO cycles (see section 1.2). Under these circumstances, high temperatures can be achieved and the CNO cycles can be broken, leading to rapid proton-capture (\( rp \)) reactions. These \( rp \) reactions can produce nuclei with a mass higher than those taking part in the CNO cycles.

### 1.1.3 Supernovae type Ia

The model of a supernova type Ia is a binary system of a CO white dwarf and a companion star. Various types of companion stars have been assumed in different models. In the most common scenario, the white dwarf accretes material from a companion star up to the moment that its core mass reaches the Chandrasekhar mass [3]. At that moment the gravitational force is strong enough to overcome the pressure from the degenerate electron gas, leading to a collapse of the star. At these high pressures and temperatures carbon and oxygen ignite in the core of the white dwarf and the burning front propagates outwards.

During a supernova explosion, a sequence of runaway nuclear reactions occur in the core of the star. This is in contrast to regular nova explosions, where a thermonuclear runaway happens at the bottom of the accreted envelope. Furthermore, a supernova type Ia explosion releases a much greater amount of energy than a typical nova explosion. It is believed that a supernova type Ia is not an important contributor to nucleosynthesis beyond iron.
1.1.4 X-ray bursts

The standard model of an X-ray burst is based on a close binary system, where one member of this system is a neutron star and the other one a hydrogen-rich star. Neutrons in a neutron star are so densely packed that they form a degenerate gas. Because of the high density and the deep gravitational well of a neutron star, a freely falling proton will arrive at the surface of the neutron star with an energy greater than 100 MeV [4]. At the surface, the high-energy proton will lose its energy via emission of many X-rays, mostly with an energy range below 20 keV.

At the surface of the neutron star, the accumulated material becomes degenerate like in novae. Under high temperature hydrogen starts to burn via the hot CNO cycle (see section 1.2). This process is rapid and occurs under a constant pressure up to the moment when degeneracy of the neutron gas is lifted and it expands. When the cooling rate becomes equal to the energy production, X-ray bursters reach a peak-surface temperature of 2.5 $T_9$. At the end, most of the initial helium and most of the other isotopes are converted into heavy isotopes with mass heavier than $A=72$, up to $^{100}$Sn, see Ref. [5]. In these processes proton-rich isotopes beyond $^{56}$Fe can be produced.

1.2 CNO cycles

The cold CNO cycle is the fusion process of 4 hydrogen nuclei into helium with an energy production of 26.73 MeV per cycle. This process takes place in hot (above 0.16 $T_9$), hydrogen-rich environment where small amounts of heavier elements (C, N, O) act as catalysts, and thus their relative abundances remain unchanged during the process.

The cold and hot CNO cycles are presented in Fig. 1.1. The cold CNO cycle operates at temperatures below 0.2 $T_9$ and it is governed by the slowest reactions. These are the $\beta^+$ decays of $^{13}$N and $^{15}$O. When the stellar temperature reaches 0.2 $T_9$, proton capture on $^{13}$N is more probable than $\beta^+$ decay and the hot CNO cycle becomes operational. When the stellar temperature increases above 0.4 $T_9$, an additional hot CNO cycle becomes available via the ($\alpha$,p) reaction on $^{14}$O.

At stellar temperatures beyond 0.5 $T_9$ and 0.8 $T_9$, the $^{15}$O($\alpha$,\gamma)$^{19}$Ne and $^{18}$Ne($\alpha$,p)$^{21}$Na reactions become possible, respectively. These two reactions provide a break out from the CNO cycle into the NeNa cycle. Davids et al. [6] pointed out that there is no significant break out from the CNO cycle via the $^{15}$O($\alpha$,\gamma)$^{19}$Ne reaction.

The $^{18}$Ne($\alpha$,p)$^{21}$Na reaction proceeds, at the temperatures required for explosive burning of hydrogen in novae and X-ray bursts, through individual resonances above the $\alpha$-emission threshold in the compound nucleus $^{22}$Mg. Therefore, to calculate the rate for this reaction, one has to know the properties of these high-lying resonances.
1.3 NeNa and MgAl cycles

In hot stellar environments, where temperatures are higher than those for the stable CNO cycles, other cycles become operational where nuclei with a mass heavier than oxygen start to act as a catalyst. These are the NeNa and MgAl cycles, which form a sequence as presented in Fig. 1.2. These two cycles do not contribute significantly to the stellar energy production, because of the higher Coulomb barriers involved in the reactions presented in Fig. 1.2. But they are important for the production of elements between $^{20}$Ne and $^{27}$Al.

$^{22}$Na and $^{26}$Al are two long-lived nuclei with a half-life of 2.602 years and $7.2 \times 10^5$ years, respectively. Their decay is followed by $\gamma$-ray emission at 1.275 MeV and 1.809 MeV, respectively; see Fig. 1.3. Therefore, if these two isotopes can survive nova and X-ray burst explosions, their characteristic $\gamma$-ray emissions can be observed after the nova explosion. Weiss and Truran [7] concluded that a nova can be an important source of $^{26}$Al in the Galaxy, and that some nearby novae can produce amounts of $^{22}$Na which can be detected with $\gamma$-ray observatories.

The detection of the 1.275 MeV and 1.809 MeV $\gamma$-rays will provide an excellent bench-
mark for existing novae models. The 1.809 MeV γ-ray, associated with the $\beta^+$ decay of $^{26}$Al nucleus, has been observed by the COMPTEL γ-ray observatory based on board of the CGRO satellite [8]. The very same observatory could not detect any signal of the $^{22}$Na 1.275 MeV γ-ray [8]. However, the upper limit for the ejected amount of $^{22}$Na from observed novae could be determined.
1.4 **Astrophysical importance of $^{22}\text{Na}$ and $^{26}\text{Al}$**

### 1.4.1 $^{22}\text{Na}$

The cold NeNa cycle is presented in the left panel of Fig. 1.2. From this figure we can see that the production of $^{22}\text{Na}$ follows the

$$^{21}\text{Na} (\beta^+ \nu)^{21}\text{Ne} (p, \gamma)^{22}\text{Na}$$

reaction path. The proton capture reaction on $^{21}\text{Na}$ becomes more probable than its $\beta^+$-decay with rising stellar temperatures. Consequently, the

$$^{21}\text{Na} (p, \gamma)^{22}\text{Mg} (\beta^+ \nu)^{22}\text{Na}$$

reaction path may lead to the production of $^{22}\text{Na}$. Furthermore, proton capture can occur on $^{22}\text{Mg}$ ($t_{1/2}=3.87$ s) at these temperatures. Due to the low $Q$-value for the $^{22}\text{Mg} (p, \gamma)^{23}\text{Al}$ reaction, the majority of $^{23}\text{Al}$ nuclei will, however, be destroyed via the inverse $^{23}\text{Al} (\gamma, p)^{22}\text{Mg}$ reaction [9]. The lack of relevant data for the $^{21}\text{Na} (p, \gamma)^{22}\text{Mg}$ reaction is one of the main sources of uncertainty in calculations of the production of $^{22}\text{Na}$. Therefore, the study of the nuclear structure of $^{22}\text{Mg}$ has been subject of many recent experiments [10, 11, 12, 13, 14, 15, 16]. These studies together with the results from capture reactions using radioactive beams of $^{21}\text{Na}$ [17, 18, 19] have contributed to a better understanding of the production rate for $^{22}\text{Na}$ in stellar environments.

In Section 1.2 we mentioned that the $^{18}\text{Ne} (\alpha, p)^{21}\text{Na}$ reaction might provide a possible break-out from the hot CNO cycle to the NeNa cycle. This reaction proceeds at high temperatures, which can be found in explosive stellar environments, through individual resonances above the $\alpha$-emission threshold in the compound nucleus. Therefore, the $^{18}\text{Ne} (\alpha, p)^{21}\text{Na}$ reaction and the nuclear structure of $^{22}\text{Mg}$ have been the subject of several experimental investigations. Caggiano *et al.* [13] and Chen *et al.* [12] measured excitation energies in $^{22}\text{Mg}$ above the $\alpha$-emission threshold with an accuracy between 15 keV and 45 keV. Bradfield-Smith *et al.* [20] and Groombridge *et al.* [21] measured resonance strengths and the excitation energies of levels in $^{22}\text{Mg}$ above 10 MeV with an accuracy of 50 keV and 140 keV, respectively. However, the accuracy achieved in these 4 experiments for the determination of the excitation energy is not satisfactory for the astrophysical rate calculations. The errors in the excitation energies produce more than a 50% error in the calculated $^{18}\text{Ne} (\alpha, p)^{21}\text{Na}$ reaction rates. In the present work we measured excitation energies of levels in $^{22}\text{Mg}$ with an error less than 5 keV for levels below 10.5 MeV and approximately 20 keV for levels above 10.5 MeV.

### 1.4.2 $^{26}\text{Al}$

The 1.809 MeV $\gamma$-ray line was observed by the HEAO-C satellite $\gamma$-ray observatory in 1984 [22]. The discovery of $^{26}\text{Al}$ in the interstellar medium [23] demonstrated that indeed nucleosynthesis processes are ongoing in our present time. The half-life of $7.2 \times 10^5$ yr for
$^{26}\text{Al}$ is short compared to the time scale of the galactic chemical evolution. The production

$$^{25}\text{Al} \rightarrow ^{25}\text{Mg} \rightarrow ^{26}\text{Al}$$

Figure 1.4: $^{26}\text{Al}_{g.s.}$ and $^{26}\text{Al}^m$ production and $\beta^+$ decay schemes. Different nuclear reactions are marked with different arrow types.

mechanism for $^{26}\text{Al}$ depends on the stellar environment, the most promising production sites being Wolf-Rayet stars, AGB stars [24], novae, and supernovae explosions. The two $^{26}\text{Al}$ production mechanisms are presented in Fig. 1.4. The first one can occur at “lower” stellar temperatures above 0.035 T\textsubscript{9}, where $^{26}\text{Al}$ is produced via the reaction sequence:

$$^{25}\text{Al}(\beta^++\nu)\rightarrow ^{25}\text{Mg}(p,\gamma)\rightarrow ^{26}\text{Al}_{g.s.}(\beta^+\nu)\rightarrow ^{26}\text{Mg}^*(\gamma)\rightarrow ^{26}\text{Mg}_{g.s.}.$$ 

The half-life of the ground state of $^{26}\text{Al}$ is 7.2 $\times$ 10$^5$ yr. Its decay to the first-excited 2$^+$ state in $^{26}\text{Mg}$ is followed by $\gamma$-ray emission of 1.809 MeV. However, if proton capture on $^{25}\text{Al}$ is faster than $^{25}\text{Al}$ $\beta^+$ decay (which will occur at stellar temperatures higher than 0.4 T\textsubscript{9}), the reaction will follow the second path;

$$^{25}\text{Al}(p,\gamma)\rightarrow ^{26}\text{Si}(\beta^+\nu)\rightarrow ^{26}\text{Al}^*(\beta^+\nu)\rightarrow ^{26}\text{Mg}_{g.s.}.$$ 

In this path $^{26}\text{Si}$ decays into the isomeric, first-excited 0$^+$ state of $^{26}\text{Al}$ with a half-life of only 6.4 s, which subsequently decays to $^{26}\text{Mg}_{g.s.}$. Following this path there will be no 1.809 MeV $\gamma$-ray emission, and galactic production of $^{26}\text{Al}$ cannot be observed. Ward and Fowler [25] showed that for temperatures lower than 0.4 T\textsubscript{9} there is no thermal equilibrium between $^{26}\text{Al}_{g.s.}$ and the first-excited state and consequently, they can be treated like separate species.

The $^{25}\text{Al}(p,\gamma)$ $^{26}\text{Si}$ reaction has not been measured directly, yet. However, the nuclear structure of $^{26}\text{Si}$ has been the subject of several recent experimental studies [26, 27, 28,
In this context we also performed the $^{28}\text{Si}(p,t)^{26}\text{Si}$ measurements above the proton-emission threshold with an energy resolution of 13 keV.

At stellar temperatures above 0.3 $T_\odot$, energy production and nucleosynthesis in an explosive hydrogen-burning environment are determined by the $rp$-process and $\alpha p$-process. The proton-capture reaction rates are orders of magnitude faster than $\beta$-decay rates in the $rp$-process. The reaction path consists of a series of $(p,\gamma)$ reactions up to a nucleus where further proton capture is inhibited. The proton-capture reactions can be inhibited by the negative proton-capture $Q$-value, which is followed by proton decay, or by a small positive proton-capture $Q$-value, which is followed by a photodisintegration process. The reaction flow has to wait for the slow nucleus $\beta$-decay and that nucleus is denoted as a “waiting point”.

The $^{22}\text{Mg}$, $^{26}\text{Si}$, $^{30}\text{S}$, and $^{34}\text{Ar}$ isotopes are $\beta^+$ unstable and possible waiting points. These isotopes are important because most of the reaction flow is passing through them. Because of the small $(p,\gamma)$ $Q$-value for $^{22}\text{Mg}$, photodisintegration prevents a significant flow through a subsequent $^{23}\text{Al}(p,\gamma)$ reaction. However, this waiting point can be bridged by the $^{22}\text{Mg}(\alpha,p)^{25}\text{Al}$ reaction. This reaction is part of a chain

\[ ^{14}\text{O}(\alpha,p)(p,\gamma)^{18}\text{Ne}(\alpha,p)(p,\gamma)^{22}\text{Mg}(\alpha,p)(p,\gamma)^{26}\text{Si}(\alpha,p)(p,\gamma)^{30}\text{S}(\alpha,p)(p,\gamma)^{34}\text{Ar}(\alpha,p)(p,\gamma)^{38}\text{Ca} \]

and has been theoretically investigated by Fisker et al. [30]. These calculations were performed to explain bolometrically double-peaked type I X-ray bursts, see Refs. [31, 32, 33]. The $^{22}\text{Mg}(\alpha,p)^{25}\text{Al}$ reaction has not been experimentally investigated previously, because there are no $^{26}\text{Si}$ data above the $\alpha$-emission threshold which is located at 9.164 MeV. We performed the $^{28}\text{Si}(p,t)^{26}\text{Si}$ measurements and for the first time observed the nuclear structure above the $\alpha$-emission threshold in $^{26}\text{Si}$.

### 1.5 Outline of this work

In Chapter 2 the formalisms for the calculation of the nuclear reaction rates are given. The experimental set up used for our $(p,t)$ reaction studies is explained in Chapter 3. The momentum calibration for the obtained spectra is presented in Chapter 4, whereas the analysis of the data obtained for $^{22}\text{Mg}$ and $^{26}\text{Si}$ are explained in Chapters 5 and 6, respectively. In Chapter 7, the conclusions and an outlook of this work are given.