

# NUCLEAR PROCESSES IN STELLAR EXPLOSIONS

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We know two kind of stellar explosion events; shock induced explosions of core collapsing massive stars known as type II supernovae, and accretion induced thermonuclear explosions such as type Ia supernovae, X-ray bursts, and novae in accreting binary systems. The type II supernova shock front causes rapid increase of density and temperature conditions in the stellar material initiating fast neutron or gamma induced nucleosynthesis processes such as the r-process and the p-process which contribute to the heavy element abundance distribution in our universe. Thermonuclear stellar explosions on the other hand are driven by nuclear ignition of dense stellar material at highly electron degenerate conditions. The ignition conditions are defined by the reaction rates of heavy ion fusion processes of stellar core material for type Ia supernovae, or by rapid nuclear fusion processes such as the hot CNO cycles or the rp-process in the stellar atmosphere of freshly accreted matter. This paper will provide a summary of the nucleosynthesis signatures of the rapid nucleosynthesis processes in stellar explosions and will highlight their impact on the associated energy release and the production of heavy elements as observed in our galaxy.

## 1. Nucleosynthesis in Stellar Explosions

### 1.1. *Seed abundances in stellar burning*

Explosive nucleosynthesis in stellar environments feeds on the ashes of previous nuclear burning processes. The abundance distribution in these ashes provide the seed for the ignition of explosive nucleosynthesis and the initial fuel for the build-up of a new abundance distribution of heavier elements. The seed abundance for the r-process in the early phase of the neutrino wind driven shock in type II core collapse supernovae is determined by the nucleosynthesis pattern of the  $\alpha$ -process<sup>1</sup> or the vp-process<sup>2</sup> reassembling the dissociated nuclear matter in the early moments of the shock, as well as by the neutron flux at the on-set of the r-process. The seed abundance for the shock front driven nucleosynthesis in the outer layers of the pre-supernova star has been built during the nucleosynthesis processes associated with the preceding stellar evolution processes. The seed abundance for type Ia supernova explosion is the white dwarf carbon oxygen abundance distribution as defined by the stellar helium

burning. Nova explosions are triggered by ignition of the hot CNO cycles burning on a fuel mixture of accreted hydrogen and the carbon oxygen (or even neon) enriched material at the surface of the accreting white dwarf <sup>3</sup>. For X-ray bursts in the atmosphere of an accreting neutron star, the seed for the rp-process is in the hydrogen, helium, and carbon rich abundance distribution of the accreted material, which is defined by spallation processes in the outer atmosphere of the neutron star <sup>4</sup>.

Stellar hydrogen, helium, and carbon burning are critical for establishing the seed distribution. Low mass stars,  $M \leq 4M_{\odot}$  end as white dwarfs with a predominantly  $^{16}\text{O}$ ,  $^{12}\text{C}$  abundance distribution defined by the  $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$  reaction in stellar helium burning <sup>5</sup>. White dwarfs emerging from more massive stars  $4M_{\odot} < M \leq 8M_{\odot}$  after core carbon burning have an abundance distribution which is characterized by a  $^{16}\text{O}$ ,  $^{20}\text{Ne}$ , and possibly  $^{24}\text{Mg}$  abundance distribution which is determined by the  $^{12}\text{C}+^{12}\text{C}$  fusion and the subsequent or parallel  $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ ,  $^{16}\text{O}(\alpha,\gamma)^{20}\text{Ne}$ ,  $^{20}\text{Ne}(\alpha,\gamma)^{24}\text{Mg}$ , and the  $^{24}\text{Mg}(\alpha,\gamma)^{28}\text{Si}$  alpha capture reactions <sup>5</sup>. Seed abundances for explosive nucleosynthesis processes such as the p-process in the outer layers of pre-supernova stars are determined by the s-process in shell helium burning and shell carbon burning <sup>6</sup>. The s-process abundance distribution again is closely associated with stellar neutron sources such as  $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$  in stellar helium and carbon burning with the  $^{22}\text{Ne}$  seed depending strongly on the slow  $^{14}\text{N}(p,\gamma)^{15}\text{O}$  reactions in the CNO cycles in the preceding hydrogen burning phase <sup>7</sup>. The interpretation and simulation of explosive nucleosynthesis processes can therefore not stand alone but relies heavily on a reliable understanding of the seed abundance distribution and its associated stellar nucleosynthesis processes.

## 1.2. *The r-process abundances*

The heavy elements above Fe are predominately produced in the s-process, the r-process, and to lesser extent by the p-process. The main s-process (slow neutron capture process) produces heavy elements up to the Pb, Bi region. It takes place in the hydrogen, helium inter-shell burning of AGB stars and the s-process reaction products are transported to the surface by dredge-up processes and ejected by stellar winds forming planetary nebulae <sup>8</sup>. The second, weak component of the s-process takes place in the helium core and/or carbon shell burning phases of massive stars producing s-process elements up the  $A=100$  range which are ejected in the subsequent type II supernovae explosion <sup>9</sup>.

The r-process (rapid neutron capture process) presumably takes place in the early phase of the supernova explosion, however present type II supernova

models still fail to reproduce the observed r-process abundance distribution. The solar or galactic r-process abundance distribution therefore is the critical signature for our interpretation of the r-process nucleosynthesis and the key signature for identifying the actual r-process site <sup>10</sup>. However, the galactic r-process abundances do not represent primary observables but are derived from subtracting the theoretically predicted s-process abundances from the observed solar abundance distribution of heavy elements <sup>11</sup>. These calculated s-process abundances rely sensitively on the actual model used for the s-process simulation and on the experimentally determined s-process reaction rates <sup>6</sup>. These measurements are therefore an extremely important ingredient for reliably unfolding the heavy element abundance distribution and for predicting the r-process abundance distributions.

Recent observations of old metal-poor halo stars have revealed a characteristic pattern for heavy element abundance distribution, which matches nearly perfectly the (scaled down) solar r-process abundance distribution. The only deviation seems to appear at the lower mass range of the abundance distribution <sup>12</sup>. This match between the solar and the r-process abundance distribution of very old stars has been interpreted as clear indication that the r-process takes place in a single site and not at a variety of different explosive scenarios. An interesting observation is that subtracting the scaled solar r-process abundance distribution for the abundance distribution of the old metal-poor stars results in an excess of light elements up to the mass  $A \approx 100$  range. This indicated the possibility of an additional not yet identified nucleosynthesis process for these elements associated with nucleosynthesis in early star generations. This process has been tentatively named LEPP (Light Element Production Process) <sup>13</sup> and a number of possible interpretations have been forwarded, ranging from the weak s-process in early stars <sup>14</sup> to the vp-process in the supernova shock before reaching r-process conditions <sup>2</sup>. The evidence and details of the LEPP will be discussed in another paper in this volume.

### 1.3. *The p-process abundances*

The p-process is responsible for the production of the neutron deficient stable isotopes in the mass range 60 to 200, which are called the p-nuclei. These isotopes are particularly rare, between 0.01% and 1% of the elemental abundance except for the Mo and Ru isotopes with an abundance fraction of up to 15%. There is a variety of proposed p-process scenarios <sup>15</sup>, but the presently most favored model is the photo-dissociation of the pre-existing seed abundance distribution in the type II supernova shock front traversing the O-Ne burning shell region of the pre-supernova star. Most of the p-nuclei abundances are well reproduced in the framework of this model, except for the light p-nuclei in the

Mo to In range <sup>16</sup>. No satisfying explanation has been found yet. A recent analysis of possible nuclear reaction and reaction flow patterns have confirmed the deficiencies in the abundance predictions <sup>17</sup> and point towards a solution associated with the seed abundance distribution or the site conditions for the p-process. It was proposed that the s-process seed abundance distribution can be altered substantially if the  $^{22}\text{Ne}(\alpha, n)$  neutron production rate is substantially enhanced <sup>18</sup>, however, the experimental data are not sufficient enough to support such a claim <sup>7</sup>. Alternative p-process sites have been frequently discussed (for a summary see <sup>16</sup>), in particular the ejected material from type I X-ray bursts may be enhanced in the mass 92 to 104 region feeding the light p-nuclei range. While this scenario may seem exotic, new model simulations actually support an enhanced ejection mechanism <sup>19</sup> which may feed the light p-nuclei.

## 2. Ignition of Stellar Explosions

### 2.1. Thermonuclear ignition of type Ia supernovae

Type Ia supernovae have recently attracted large attention, since they serve as standard candles for cosmological distance measurements. This however relies on the assumption that the explosion mechanism and conditions are not affected by the change in abundance distribution through the age of the universe. Type Ia supernovae are generally considered to be thermonuclear explosions of C/O white dwarfs that have increased in mass to just below the critical Chandrasekhar limit by accretion from a younger companion star <sup>20</sup>. While there are a number of uncertainties with the actual hydrodynamical components for the explosion mechanism, I will focus on the nuclear physics uncertainties associated with type Ia supernovae. The ignition of type Ia supernovae explosions is triggered by the  $^{12}\text{C}+^{12}\text{C}$  fusion reaction near the core of accreting white dwarfs which turns into a thermonuclear runaway at the highly electron degenerate conditions in the white dwarf material. Most of the initial fuel in the white dwarf matter is produced during the preceding CNO burning and the subsequent helium burning history of the pre-white dwarf phase of the star <sup>21</sup>. The ignition depends therefore critically on the abundance of  $^{12}\text{C}$  fuel, which is determined by the  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  reaction rate in stellar helium burning <sup>5</sup>. Another critical fuel component is  $^{22}\text{Ne}$ , which is produced by alpha capture reactions in helium burning on  $^{14}\text{N}$  as main product of the preceding CNO burning cycles <sup>7</sup>. It was shown that high abundances of  $^{22}\text{Ne}$  seem to accelerate the burning mechanism <sup>22</sup> through additional energy production through neutron induced reactions which were made available by the  $^{22}\text{Ne}(\alpha, n)$  process. The overall abundance of these fuel

components depends on the enrichment of CNO material during the evolution of the universe which may affect the ignition and incineration rate of white dwarf material <sup>21</sup>.

A major component in the nuclear physics uncertainty of type Ia ignition is the actual reaction rate for the  $^{12}\text{C}+^{12}\text{C}$  fusion process at the typical range of ignition temperature of 0.9 to 1.0 GK <sup>23</sup>. At the high density conditions the thermonuclear fusion rate is considerably enhanced through electron screening which needs to be properly calculated <sup>24</sup>. However, besides the uncertainties associated with screening, there are also substantial uncertainties in our understanding of the low energy fusion cross section. Traditionally, the experimental cross section for the fusion reactions between  $^{12}\text{C}$  and  $^{16}\text{O}$  isotopes, have been extrapolated towards stellar energies by using a simple potential model approach. Recent calculations of the low energy S-factor using the "Sao Paulo" potential to determine the stellar fusion rates indeed showed good agreements with previous estimates <sup>25</sup>. Systematic studies of how heavy ion fusion reactions do however indicate a sub-barrier decline of the cross section <sup>26</sup>, if compared to the predicted energy dependence. A phenomenological description of this phenomenon can be obtained by introducing a fusion hindrance term into the potential, which is associated with the incompressibility of nuclear matter <sup>27</sup>. Recent experimental efforts all have confirmed this sub-barrier fusion pattern and it has been argued that a similar behavior can also be expected for  $^{12}\text{C}+^{12}\text{C}$ ,  $^{12}\text{C}+^{16}\text{O}$ , or  $^{16}\text{O}+^{16}\text{O}$  fusion processes <sup>28</sup>. While no predictions exists on the basis of the phenomenological hindrance model, empirical fits of the existing data seem to support this claim and suggest a drastic decline of the low energy S-factor values while previous calculations suggested a more-less constant S-factor towards low energies <sup>28,29</sup>. This translates into a substantially lower reaction rate for these fusion processes which affects the ignition conditions for heavy ion burning in white dwarf matter.

The direct impact of the change of reaction rate still needs consistent simulations in the framework of a type Ia supernova explosion model. However, there are a number of different and rather complex models available which often differ substantially in their approach to simulate the explosion. The proposed change in fusion rate will substantially increase the required temperature and density conditions for the onset of carbon burning in the interior of white dwarfs <sup>29</sup>. Since the release of protons and alpha particles for subsequent capture reactions will be slowed down extending the simmering period between ignition and the on-set of the actual thermonuclear runaway. The impact of this will need to be considered within the framework of the models to draw more specific conclusions about the overall impact on the supernova event itself.

## 2.2. Thermonuclear ignition of type I X-ray bursts

Type I X-ray bursts are interpreted as thermonuclear runaways in the atmosphere of accreting neutron stars. Due to spallation of the accreted matter in the outer atmosphere <sup>4</sup>, the abundance distribution is expected to be dominated by hydrogen, helium and CNO material. Ignition takes place through the hot CNO cycles which heat the atmosphere for a simmering period until a thermonuclear runaway occurs through ignition of the rp-process <sup>30</sup>. The onset of the rp-process is determined by an interplay between the triple alpha process which enhances the CNO fuel and therefore the hot CNO energy release, and the  $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$  reaction which has been identified as the first break-out reaction from the hot CNO cycles feeding the rp-process <sup>31</sup>. The rp-process will rapidly convert the initial light CNO isotope abundance distribution of the accreted material into the Fe, Ni range or even beyond to the Sn to Sb range by a sequence of rapid proton capture reactions and fast  $\beta$  decays along the proton drip line <sup>30,32</sup>. The released amount of nuclear energy is sufficient to explain the observed luminosity of an X-ray burst <sup>32</sup>. The reaction rate for  $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$  is determined by the contributions of a single resonance which corresponds to the  $3/2^-$  state at 4.03 MeV in the compound nucleus  $^{19}\text{Ne}$ . It has been demonstrated before that possible E2 direct capture contributions to the reaction rate are negligible <sup>33</sup>. The strength of the critical  $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$  resonance level has recently been determined experimentally, albeit with large uncertainties <sup>34</sup>. The resulting reaction rate provides new constraints on the actual accretion rate for X-ray burst models <sup>35</sup>. It was also shown that the reaction rate impacts the periodicity of the burst sequence.

With the break-out from the hot CNO cycle the temperature increases, and a second break-out sequence  $^{14}\text{O}(\alpha,p)^{17}\text{F}(p,\gamma)^{18}\text{Ne}(\alpha,p)^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$  opens <sup>36</sup>, triggering the  $\alpha p$ -process up to the Ca region <sup>37</sup>. There has been substantial experimental effort in investigating and determining the associated reaction rates with low energy radioactive beams. While the proton capture rates are well determined, there are substantial uncertainties remaining with the  $^{14}\text{O}(\alpha,p)^{17}\text{F}$  and more so with the  $^{18}\text{Ne}(\alpha,p)^{21}\text{Na}$  rate <sup>36</sup>. New experimental effort is needed to remove the present uncertainties and determine the conditions for the second break-out. This sequence will open a continuous reaction flow from  $^4\text{He}$  up to  $^{38}\text{Ca}$  through the  $\alpha p$ -process, followed by the rp-process to  $^{56}\text{Ni}$  with rapidly increasing temperature and energy production. Beyond  $^{56}\text{Ni}$ , an equilibrium with inverse photo disintegration of the weakly bound  $^{57}\text{Cu}$ ,  $^{56}\text{Ni}(p,\gamma)^{57}\text{Cu}(\gamma,p)^{56}\text{Ni}$  halts the rapid energy release, initiating the subsequent cooling phase of the burst. The cooling period depends on the actual cooling mechanism, initially by convection triggered by the rapid increase of temperature, but mostly by radiative energy loss. The  $^{56}\text{Ni}(p,\gamma)^{57}\text{Cu}$  reaction falls out of equilibrium and nucleosynthesis ensues by an rp-process up to the  $^{100}\text{Sn}$  region. This process is

characterized by the long-lived waiting point nuclei  $^{64}\text{Ge}$ ,  $^{68}\text{Se}$ ,  $^{72}\text{Kr}$ , and possibly  $^{82}\text{Zr}$  which become highly enriched <sup>30</sup>. Depending on the actual cooling timescale the end-point of the rp-process is associated with the alpha unbound nuclei in the Te, Sb mass range near the proton drip line which cannot be bridged by rapid proton capture processes <sup>38</sup>. Proton and/or gamma induced  $\alpha$  emission triggers cyclic nucleosynthesis pattern in the Sn-Sb-Te range causing a substantial enrichment of  $A=104$  and  $A=106$  nuclei at the proton drip line. These Sb-Te cycles reduce rapidly the remaining hydrogen fuel, but produce fresh  $^4\text{He}$  and through the triple alpha process  $^{12}\text{C}$  material in the last phase of the burst.

### 3. From Thermonuclear to Pycnonuclear Burning

#### 3.1. *The fate of the rp-process ashes*

The reaction flow pattern described in the previous section defines the abundance distribution in the ashes of each rp-process driven burst. The low mass range is characterized by high abundance peaks for  $^4\text{He}$  and  $^{12}\text{C}$ , the main distribution is accumulated in the mass range from  $A=56$  to  $A=106$  <sup>32</sup>. The final abundances are concentrated along the proton-drip line; the distribution shows odd-even effects and peaks towards the  $A=104$ , and  $A=106$  region which demonstrates the impact of the Sb-Te cycle. After hydrogen burning has ceased, the proton rich isotopes decay by positron emission towards the line of stability, effectively delaying the cooling process by the release of decay energy. Freshly accreted material accumulates on top of the layer and compresses the ashes, causing a continuous increase in density <sup>39</sup>. The timescale for this gradual increase in density depends on the overall accretion rate in the binary system.

Superbursts are energetic long X-ray flares observed from accreting neutron stars (for a summary of observations, see <sup>40</sup>). It has been suggested that the increase in density triggers the so-called superbursts by explosive  $^{12}\text{C}+^{12}\text{C}$  ignition <sup>41</sup>. This explanation of superbursts is still under debate and depends critically on the ignition conditions for explosive carbon burning as discussed before <sup>29</sup>. In its present interpretation it also relies on taking into account the heat released from electron captures into excited states of daughter nuclei, with subsequent de-excitations of these nuclei. It produces additional heating of the crust which increases the crust temperature to a level necessary for ignition <sup>42</sup>.

The increasing density conditions lead to the on-set of electron capture which slowly shifts the abundance distribution towards the neutron drip line <sup>39</sup>. The time scale for this neutronization process is determined by the electron captures rates which depend on the rate of density increase. First simulations have shown that the drip-line is reached at a density of approximately  $10^{11} \text{ g/cm}^3$ . Further electron capture causes neutron emission which shifts the abundance distribution towards lower  $Z$  elements. This is accompanied by a rapid increase in free

neutrons and nuclear reaction pattern becomes very complex involving electron capture, neutron-emission, and neutron capture. Considering the strong impact of pairing near the neutron drip line the possibility of two-neutron or four-neutron emission even seems feasible. Only heavy nuclei that have even-even configurations will survive due to pairing. At densities of  $10^{12}$  g/cm<sup>3</sup> the abundance distribution shows free neutrons (and protons) and peaks in the Ne Mg range near the neutron drop line.

### 3.2. *Pycnonuclear reactions in the crust of neutron stars*

At densities in excess of  $10^{12}$  g/cm<sup>3</sup> nuclei are compressed forming a lattice structure<sup>43</sup>, the deflective Coulomb potential is neutralized by the free electrons in the lattice and depending on the distance between neighboring isotopes pycnonuclear fusion can occur. Pycnonuclear fusion of heavy isotopes increases rapidly with density but is relatively insensitive to the temperature of the stellar material. Pycnonuclear reactions are important for environments of extreme density such as expected for deeper layers of the neutron star crust. In a number of recent papers we have developed a formalism which describes consistently the transition from thermonuclear fusion processes in low density environments to screening enhanced fusion at high densities to pure pycnonuclear fusion in environments of extreme density conditions<sup>43</sup>. The pycnonuclear rate depends exponentially on a density dependent distance term between neighboring nuclei; they are also strongly correlated with the stoichiometry of the material and with the fusion probability of heavy neutron rich ions at low temperatures expressed by the astrophysical S-factor. The S-factor can be calculated using modified potential models<sup>25</sup> which take also into account the extended neutron halo for near drip-line nuclei. A systematic study of pycnonuclear fusion rates in the Z=6 to Z-12 has been completed and will be published shortly<sup>44</sup>. Previous studies of pycnonuclear reaction rates involved only fusion between identical particles<sup>39,45</sup>. In the framework of simplified models it was shown that pycnonuclear reactions may contribute as energy source to the heating of the deeper layers of accreting neutron stars in their transient phase. New calculations are in preparation to follow the nucleosynthesis processes in an environment of increasing density such as described here.

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## References

1. S. E. Woosley and R. D. Hoffman, *Astrophys. J.* **395**, 202 (1992).
2. C. Fröhlich, G. Martínez-Pinedo, M. Liebendörfer, F.-K. Thielemann, E. Bravo, W. R. Hix, K. Langanke, and N. T. Zinner, *Phys. Rev. Lett.* **96**, 142502 (2006).
3. J. Jose, M. Hernanz, and C. Iliadis, *Nucl. Phys.* **A777**, 550 (2006).
4. L. Bildsten, E. Sapeter, and I. Wasserman, *Astrophys. J.* **384**, 143 (1992).
5. L. R. Buchmann, C. A. Barnes, *Nucl. Phys.* **A777**, 254 (2006).
6. F. Käppeler and A. Mengoni, *Nucl. Phys.* **A777**, 291 (2006).
7. A. Karakas, M. Lugaro, M. Wiescher, J. Görres, and C. Ugalde, *Astrophys. J.* **643**, 471 (2006).
8. M. Busso, R. Gallino, G. J. Wasserburg, *Ann. Rev. Astr. Astrophys.* **37**, 239 (1999).
9. L.-S. The, M. El Eid, B. S. Meyer, *Astrophys. J.* **655**, 1058 (2007).
10. S. Wanajo and Y. Ishimaru, *Nucl. Phys.* **A777**, 676 (2006).
11. F. Käppeler, H. Beer, K. Wisshak, D. D. Clayton, R. L. Macklin, and R. A. Ward, *Astrophys. J.* **257**, 821 (1982).
12. C. Sneden, J. J. Cowan, J. E. Lawler, I. I. Ivans, S. Burles, T. C. Beers, F. Primas, V. Hill, J. W. Truran, G. M. Fuller, B. Pfeiffer, and K.-L. Kratz, *Astrophys. J.* **591**, 936 (2003).
13. F. Montes, T. C. Beers, J. Cowan, T. Elliot, K. Farouqi, R. Gallino, M. Heil, K.-L. Kratz, B. Pfeiffer, M. Pignatari, and H. Schatz, *Astrophys. J.* **671**, 1685 (2007).
14. C. Travaglio, R. Gallino, E. Arnone, J. Cowan, F. Jordan, and C. Sneden, *Astrophys. J.* **601**, 864 (2004).
15. M. Arnould, S. Goriely, K. Takahashi, *Phys. Rep.* **450**, 97 (2007)
16. D. Lambert, *Astron. & Astrophys. Rev.* **3**, 201 (1992).
17. W. Rapp, J. Görres, M. Wiescher, H. Schatz, and F. Käppeler, *Astrophys. J.* **653**, 474 (2006).
18. V. Costa, M. Rayet, R. A. Zappalà, R. M. Arnould, *Astron. & Astrophys.* **358**, L67 (2000).
19. N. N. Weinberg, L. Bildsten, and H. Schatz, *Astrophys. J.* **639**, 1018 (2006).
20. W. Hillebrandt and J. C. Niemeyer, *Ann. Rev. Astr. Astrophys.* **38**, 191 (2000).
21. I. Dominguez, P. Höflich, O. Straniero, *Astrophys. J.* **557**, 279 (2001).
22. D. A. Chamulak, E. F. Brown, F. X. Timmes, *Astrophys. J.* **655**, L93 (2006).
23. C. A. Barnes, *Essays in Nuclear Astrophysics*, edited by C. A. Barnes, D. D. Clayton, and D. N. Schramm (Cambridge University, Cambridge, 1982), p. 193.
24. L. R. Gasques, A. V. Afanasjev, E. F. Aguilera, M. Beard, L. C. Chamon, P. Ring, M. Wiescher, and D. G. Yakovlev, *Phys. Rev.* **C72**, 025806 (2005).

25. L. R. Gasques, A. V. Afanasjev, M. Beard, J. Lubian, T. Neff, M. Wiescher, and D. G. Yakovlev, *Phys. Rev.* **C76**, 045802 (2007).
26. C. L. Jiang, B. B. Back, H. Esbensen, R. V. F. Janssens, and K. E. Rehm, *Phys. Rev.* **C 73**, 014613 (2006).
27. Ş. Mişicu and H. Esbensen, *Phys. Rev. Lett.* **96**, 112701 (2006).
28. C. L. Jiang, K. E. Rehm, B. B. Back, and R. V. F. Janssens, *Phys. Rev.* **C 75**, 015803 (2007).
29. L. R. Gasques, E. F. Brown, A. Chieffi, C. L. Jiang, M. Limongi, C. Rolfs, M. Wiescher, and D. G. Yakovlev, *Phys. Rev.* **C76**, 035802 (2007).
30. H. Schatz, A. Aprahamian, J. Görres, M. Wiescher, T. Rauscher, J. F. Rembges, F.-K. Thielemann, B. Pfeiffer, P. Moeller, K.-L. Kratz, H. Herndl, B. A. Brown, H. Rebel, *Phys. Rep.* **294**, 167 (1998).
31. M. Wiescher, J. Görres, H. Schatz, *J. Phys.* **G25**, R133 (1999).
32. S. E. Woosley, A. Heger, A. Cumming, R. D. Hoffman, J. Pruet, T. Rauscher, J. L. Fisker, H. Schatz, B. A. Brown, M. Wiescher, *Astrophys. J. Suppl.* **151**, 75 (2004).
33. K. Langanke, M. Wiescher, W.A. Fowler, J. Görres, *Astrophys. J.* **301**, 301 (1986).
34. W. P. Tan, J. L. Fisker, J. Görres, M. Couder, and M. Wiescher, *Phys. Rev. Lett.* **98**, 242503 (2007).
35. J. L. Fisker, W. Tan, J. Görres, M. Wiescher, R. L. Cooper, *Astrophys. J.* **665**, 637 (2007).
36. M. Wiescher, G. P. A. Berg, M. Couder, J. L. Fisker, Y. Fujita, J. Görres, M. N. Harakeh, K. Hatanaka, A. Matic, W. Tan, A. M. van den Berg, *Prog. Part. Nucl. Phys.* **59**, 51 (2007).
37. J. L. Fisker, F.-K. Thielemann, M. Wiescher, *Astrophys. J.* **608**, L61 (2004)
38. H. Schatz, A. Aprahamian, V. Barnard, L. Bildsten, A. Cumming, M. Ouellette, T. Rauscher, F.-K. Thielemann, and M. Wiescher, *Phys. Rev. Lett.* **86**, 3471 (2001).
39. P. Haensel and J. L. Zdunik, *Astron. & Astrophys.* **404**, L33 (2003).
40. E. Kuulkers, *Nucl. Phys.* **B132**, 466 (2004).
41. A. Cumming, and L. Bildsten, *Astrophys. J.* **559**, L127 (2001).
42. S. Gupta, E. F. Brown, H. Schatz, P. Möller, and K.-L. Kratz, *Astrophys. J.* **662**, 1188 (2007).
43. D. G. Yakovlev, L. R. Gasques, A. V. Afanasjev, M. Beard, and M. Wiescher, *Phys. Rev.* **C74**, 035803 (2006).
44. M. Beard, A. V. Afanasjev, L. C. Chamon, L. R. Gasques, M. Wiescher, and D. G. Yakovlev, *At. Nucl. Dat. Tab.*, in preparation.
45. D. G. Yakovlev, L. Gasques, M. Wiescher, *Mon. Not. .Roy. Astr. Soc.* **371**, 1322 (2006).