NUCLEAR PHYSICS ISSUES OF THE R-PROCESS *

F.-K. THIELEMANN, E. KOLBE, G. MARTINEZ-PINEDO, I.V. PANOV, T. RAUSCHER

Departement für Physik und Astronomie, Universität Basel, Switzerland
E-mail: http://quasar.physik.unibas.ch

K.-L. KRATZ, B. PFEIFFER

Institut für Kernchemie, Universität Mainz, D-55128 Mainz, Germany

S. ROSSWOG

Dept. of Physics & Astronomy, University of Leicester,
LE1 7RH Leicester, UK

The present paper aims at understanding r-process nucleosynthesis by addressing the nuclear physics involved, the necessary environment conditions in the (stellar) production sites, and the observational constraints.We also summarize the remaining challenges and uncertainties which need to be overcome for a full understanding of the nature of the r-process.

1. Introduction

The heavy elements in nature are made by neutron capture [74] and (at least) two types of different environments are required [7,8]. (i) A process with small neutron densities, experiencing long neutron capture timescales in comparison to β-decays ($\tau_\beta < \tau_{n,\gamma}$, slow neutron capture or the s-process), causing abundance peaks in the flow path at nuclei with small neutron capture cross sections, i.e. stable nuclei with closed shells at magic neutron numbers [26,2]. (ii) A process with high neutron densities and temperatures, experiencing rapid neutron captures and the reverse photodisintegrations with $\tau_{n,\gamma}, \tau_{\gamma,n} < \tau_\beta$, causing abundance peaks due to long β-decay half-lives where the flow path comes closest to stability (again at magic neutron numbers, but for unstable nuclei). In the latter rapid neutron-capture process

*This work is supported by the Swiss Nationalfonds

(r-process) it is possible that highly unstable nuclei with short half-lives are produced [27], leading also to the formation of the heaviest elements in nature like Th, U, and Pu. This involves nuclei near the neutron drip-line. Far from stability, neutron shell closures are encountered for smaller mass numbers A than in the valley of stability. Therefore, if r-process peaks are due to long β-decay half-lives of neutron-magic nuclei, the r-process abundance peaks are shifted in comparison to the s-process peaks (which occur for neutron shell closures at the stability line).

Besides this basic understanding, the history of r-process research has been quite diverse in suggested scenarios [72,11,84,27,59]. If starting with a seed distribution somewhere around A=50-80 before rapid neutron-capture sets in, the operation of an r-process requires 10 to 150 neutrons per seed nucleus to form all heavier r-nuclei. The question is which kind of environment can provide such a supply of neutrons to act before decaying with a 10 min half-life. The logical conclusion is that only explosive environments, producing or releasing these neutrons suddenly, can account for such conditions. Two astrophysical settings are suggested most frequently, related to two entropy options discussed in more detail in the following sections : (i) Type II supernovae (SNe II) with postulated high-entropy ejecta [87,77,16,52,85,81] and (ii) neutron star mergers or similar events (like axial jets in supernova explosions) which eject neutron star matter with low-entropies [34,42,14,69,17,71,70].

2. The Role of Nuclear Physics

The main aspects of an r-process are neutron captures, photodisintegrations, and β-decays. An $(n,\gamma)\rightleftharpoons(\gamma,n)$ equilibrium exists if neutron captures and photodisintegrations are fast in comparison to beta-decays between isotopic chains, leading to a distribution of abundances in each isotopic chain governed by a chemical equilibrium $\mu_n + \mu_{Z,A} = \mu_{Z,A+1}$ in a Boltzmann gas. This causes abundance ratios of neighboring isotopes $Y(Z,A+1)/Y(Z,A) = f(n_n,T,S_n)$ to depend only on neutron density n_n, temperature T, and the neutron separation energy S_n (or reaction Q-value for the appropriate neutron capture) [72,31]. The maximum in each isotopic chain occurs when $Y(Z,A+1)/Y(Z,A)$ changes from a rising to a declining ratio (i.e. from > 1 to < 1). A ratio of 1 defines a universal $S_{n,max}$ for all maxima, independent of the specific isotopic chain. Thus, the combination of a neutron density n_n and temperature T determines the r-process path (connecting the isotopes with the maximum abundance in each isotopic chain) located at the same neutron separation energy $S_{n,max}$. During an r-process event exotic nuclei with neutron separation energies of 4 MeV and less are important, up to S_n=0, i.e. the neutron drip-line. This underlines that the understanding of nuclear physics far from stability is a key ingredient and the knowledge of nuclear masses (S_n) [47,4,3,58] determines the r-process path and new Hartree-Fock(-Bogoliubov) or relativistic mean field approaches are addressing this question [10,13,68,5,20,53]. However, the FRDM model [47] still seems to provide the best predictions [20].

The β-decay rates $\lambda_\beta^{Z,A}$ are related to the half-lives of very neutron-rich nuclei via $\lambda_\beta = ln(2)/\tau_{1/2}$. The abundance flow from each isotopic chain to the next is governed by β-decays. We can introduce a total abundance in each isotopic chain $Y(Z)$=$\sum_A Y(Z,A)$. Process timescales in excess of β-decay half-lives lead to a steady-flow equilibrium $Y(Z)\lambda_\beta(Z)$ = const [31] shown most clearly in Fig. 2 of [16], where $\lambda_\beta(Z)$ is an abundance averaged half-life. Thus, in that case the knowledge of nuclear masses (S_n), determining the r-process path, and half-lives ($\tau_{1/2}$) [48,15,6,39], determining the relative abundances of each isotopic chain, would be sufficient to predict the whole set of abundances [59]. This seems to be the case in the regions between the r-process peaks (neutron magic numbers) and in the low-mass tails of the $A\simeq$130 and $A\simeq$195 peaks of the solar-system r-process abundances [31]. Nuclei in the r-process path with the longest half-lives of the order 0.2-0.3s, related to the abundance peaks themselves, do not fulfill the steady flow requirement. In this case the coupled set of differential equations $\dot{Y}(Z) = \lambda_\beta(Z-1)Y(Z-1) - \lambda_\beta(Z)Y(Z)$ has to be solved for all isotopic chains Z, if an $(n,\gamma)\rightleftharpoons(\gamma,n)$ equilibrium applies.

In the most general case of (astrophysical) environment conditions, one has to solve a full set of differential equations for all nuclei from stability to the neutron drip-line [11,84,16], including individual neutron captures [65,19,83,66,67], photodisintegrations, and beta-decays. However, from existing results one finds that an $(n,\gamma)\rightleftharpoons(\gamma,n)$ equilibrium is attained before the freeze-out of neutron abundances and photodisintegrations (for decreasing temperatures). For small β-decay half-lives, encountered in between magic numbers and for small Z's at magic numbers, also the steady-flow approximation seems applicable. The freeze-out from equilibrium can follow two extreme options: (i) an instantaneous freeze-out, just followed by the final decay back to stability, where also β-delayed properties (neutron emission and fission) are needed and can depend strongly on the beta strength-function [80,43,11,73,56]. (ii) In the more general case of a slow freeze-out also neutron captures can still affect the final abundance pattern [76,16]. If the

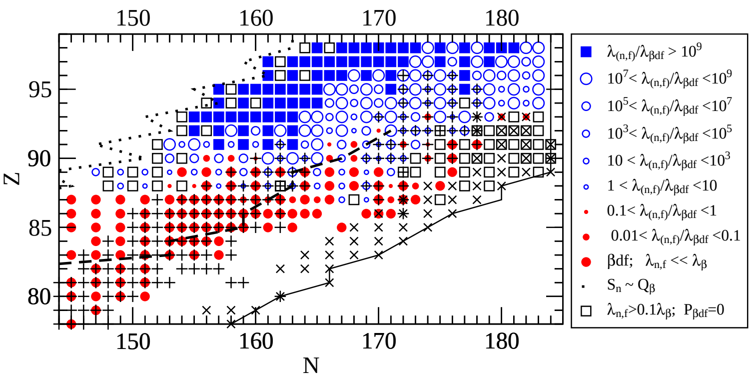

Figure 1. Ratios of neutron-induced to beta-delayed fission for nuclei of interest in r-process calculations. These exploratory results were obtained with the fission barriers by Howard & Möller [23]. Different barrier heights [50,38] will lead to different total fission rates. However, it was shown here that neutron-induced fission is a viable ingredient for r-process studies and should not be neglected in comparison to beta-delayed fission.

latter is the case, individual neutron capture cross sections are required [44,66,67].

Fission will set in during an r-process, when neutron-rich nuclei are produced at excitation energies beyond their fission barriers [80,11]. The role of β-delayed and neutron-induced fission has two aspects. For nuclei with neutron separation energies of the order 2 MeV, neutron capture will produce compound nuclei with much smaller excitation energies than those obtained in β-decay. However, the rates of neutron-induced processes (responsible also for the $(n,\gamma)\rightleftharpoons(\gamma,n)$ equilibrium) are orders of magnitude larger than beta-decay rates. Thus, it is possible that neutron-induced fission can compete with beta-delayed fission (see Fig. 1). Fission determines on the one hand the heaviest nuclei produced in an r-process [80,11,17,50,38] and on the other hand also the fission yields fed back to lighter nuclei [17,56,49].

In some environments, like e.g. in supernovae, a high neutrino flux of different flavors is available. This gives rise to neutral and charged current interactions with nucleons and nuclei, i.e. elastic/inelastic scattering or electron neutrino or antineutrino capture on nuclei, e.g. $\nu_e + (Z,A) \rightarrow (Z+1,A)+e^-$, (giving results similar to β transformations). During freeze-out the first mechanism redistributes abundances to nearby mass numbers [29,60,21] similar to spallation. Neutrino capture for high neutrino fluxes could mimic fast β^--decays, possibly accelerating an r-process to heavy elements [51,18,40,62,45,32]. The effects of exotic neutrino properties are discussed in [30,41,57].

Site-independent classical analyses [31,12], based on neutron number density n_n, temperature T, and duration time τ, as well as entropy based calculations with the parameters entropy S, Y_e, and expansion timescale τ [22,16] (to be discussed in the following section) have shown that the solar r-process can be fit by a continuous superposition of components with neutron separation energies at freeze-out in the range 4-1 MeV [12,16]. These are the regions of the nuclear chart (extending to the neutron drip-line) where nuclear structure, related to masses far from stability and beta-decay half-lifes [59] has to be investigated. They include predominantly nuclei not accessible in laboratory experiments to date but hopefully in the foreseeable future (RIKEN, RIA, GSI). In addition, expanding theoretical efforts with increasingly sophisticated means are required, addressing also neutrino-induced reactions [32,21] and fission properties [56,50,38]. The actual astrophysical realization of the relevant conditions will be discussed in the following sections.

3. Working of the r-Process and Required Environment Properties

The parameter which determines whether an r-process occurs is, the neutrons per seed ratio, see e.g. [16]. The r-process requirement of 10 to 150 neutrons per r-process seed (in the Fe-peak or somewhat beyond), permitting to produce nuclei with $A > 200$, can be translated into the parameters entropy S, Y_e and expansion timescale τ of a heated blob of material in astrophysical events, consisting of a net ratio of protons to neutrons (or total nucleons) with a given expansion history. At low entropies (without an alpha-rich freeze-out of charged-particle reactions) this is equivalent to $Y_e = \langle Z/A \rangle$=0.12-0.3. Such a high neutron excess is only possible for high densities in neutron stars under beta equilibrium ($e^- + p \leftrightarrow n + \nu$, $\mu_e + \mu_p = \mu_n$), based on the high electron Fermi energies which are comparable to the neutron-proton mass difference [42].

Deviations from this straightforward balance are only possible if one stores large amounts of mass in N=Z nuclei with small neutron capture cross sections (e.g. ^{4}He), leaving then all remaining neutrons for a few heavy seed nuclei. This phenomenon is known as an extremely α-rich freeze-out in complete Si-burning and corresponds to a weak link of reactions between the light nuclei (n, p, α) and heavier nuclei at low densities. The links across the particle-unstable A=5 and 8 gaps are only possible via the three-body reactions $\alpha\alpha\alpha$ and $\alpha\alpha n$ to ^{12}C and ^{9}Be, whose reaction rates show a quadratic density dependence. The entropy ($\propto T^3/\rho$ in radiation dominated matter) can be used as a measure of the ratio between the remaining He mass fraction and heavy nuclei. A well known case is the big bang where under extreme entropies essentially only ^{4}He is left as the heaviest nucleus available. Somewhat lower entropies permit the production of (still small) amounts of heavy seed nuclei. Then, even moderate values of Y_e=0.4-0.5 can lead to high ratios of neutrons to heavy nuclei for entropies in excess of 200 k$_B$ per baryon. and neutron captures can proceed to form the heaviest r-process nuclei [86,44,77,87,22,16].

These two environments represent a normal (low-entropy) and an α-rich (high-entropy) freeze-out from charged-particle reactions before the dominance of neutron-induced reactions. Towards low entropies the transition to a normal freeze-out occurs, leading to a negligible entropy dependence of the neutron to seed ratio.

4. r-Process Sites

4.1. *Type II Supernovae*

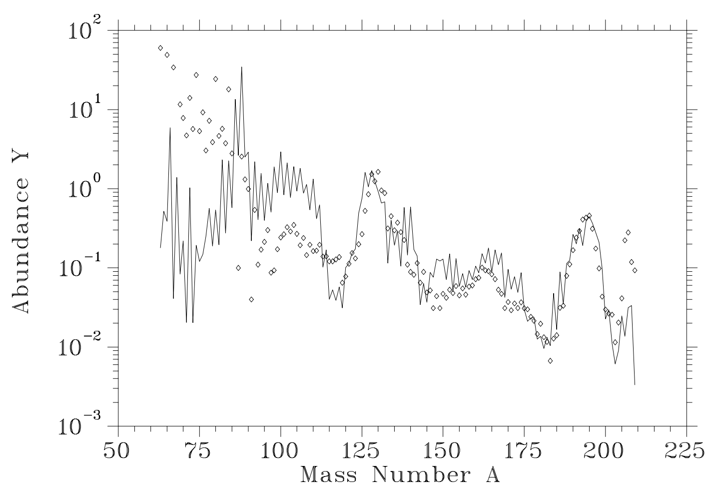

Figure 2. Fit to solar r-process abundances (open rhombus) with the ETFSI-1 mass formula [4], making use of a superposition of entropies. These calculations were performed with $Y_e = 0.45$, but similar results are obtained in the range $0.30 - 0.49$, only requiring a scaling of entropy. The trough below $A \simeq 130$ can be avoided by the changing of shell effects far from stability. The strong deficiencies in the abundance pattern below $A \simeq 110$ are due to an α-rich freeze-out where essentially no neutrons are left. This is related to the Y_e of the astrophysical scenario rather than to nuclear structure [16].

The apparently most promising mechanism for supernova explosions after Fe-core collapse of a massive star is based on neutrino heating beyond the hot proto-neutron star via the dominant processes $\nu_e + n \rightarrow p + e^-$ and $\bar{\nu}_e + p \rightarrow n + e^+$ with a (hopefully) about 1% efficiency in energy deposition. The neutrino heating efficiency depends on the neutrino luminosity, which in turn is affected by neutrino opacities. Aspects of the explosion mechanism are still uncertain and depend on Fe-core sizes from stellar evolution, electron capture rates of pf-shell nuclei [33], the supranuclear equation of state, as well as the details of neutrino transport and Newtonian vs. general relativistic calculations [64,46,35]. The present situation is that 1D spherically symmetric calculations without convective turnover (neither in the neutron star nor in the region of the neutrino sphere) do not show explosions. In order to evaluate properties of exploding models, tests with reduced neutrino-nucleon elastic scattering cross sections which are directly related to the neutrino luminosity [36] have been performed.

If SNe II are also responsible for the solar r-process abundances, given the galactic occurance frequency, they would need to eject about 10^{-5} M$_\odot$ of r-process elements per event (if all SNe II contribute equally). The scenario is based on the so-called "neutrino wind", i.e. a wind of matter from the neutron star surface (within seconds after a successful supernova explosion) is driven via neutrinos streaming out from the still hot neutron star [87,77,22,61,45,55].

This high entropy neutrino wind is expected to lead to a superposition of ejecta with varying entropies. If a sufficiently high entropy range is available, an abundance pattern as shown in Fig. 2 can be obtained [16]. However, the r-process by neutrino wind ejecta of SNe II faces two difficulties. (i) whether the required high entropies for reproducing heavy r-process nuclei can really be attained in supernova explosions has still to be verified [52,81]. Presently it seems that only (unrealistically?) large or compact neutron stars with masses in excess of 2 M$_\odot$ can provide the high entropies required. (ii) the mass region 80–110 experiences difficulties to be reproduced adequately [16,85], reflecting rather abundances determined by alpha separation energies after an alpha-rich freeze-out than neutron separation energies. It has to be seen whether the inclusion of non-standard neutrino properties [41] can cure both difficulties or lower Y_e zones can be ejected from SNe II, as recently claimed [75] from assumed prompt explosion calculations, lacking a proper neutrino transport. Present supernova models face the problem that the entropies required seem not yet attainable, unless ad hoc assumptions [79] can be verified.

4.2. *Neutron Star Mergers*

An alternative site for the heavy r-process nuclei are neutron-star ejecta, like e.g. in neutron star mergers [34,14,17]. The binary system, consisting of two neutron stars, looses energy and angular momentum through the emission of gravitational waves and merges finally. The measured orbital decay gave the first evidence for the existence of gravitational radiation [78,82,37] and indicates timescales of the order of 10^8y or less (dependent on the excentricity of the system). The rate of NS mergers has been estimated to be of the order $10^{-6} - 10^{-4}\mathrm{y}^{-1}$ per galaxy [14,28]. A merger of two NS can also lead to the ejection of neutron-rich material [25,69,71,70] of the order of $10^{-(2-3)}\mathrm{M}_\odot$ in Newtonian and relativistic calculations [54]. The decompression of cold neutron-star matter has been studied [34,42]; however, a hydrodynamical calculation coupled with a complete r-process calculation has not been undertaken, yet.

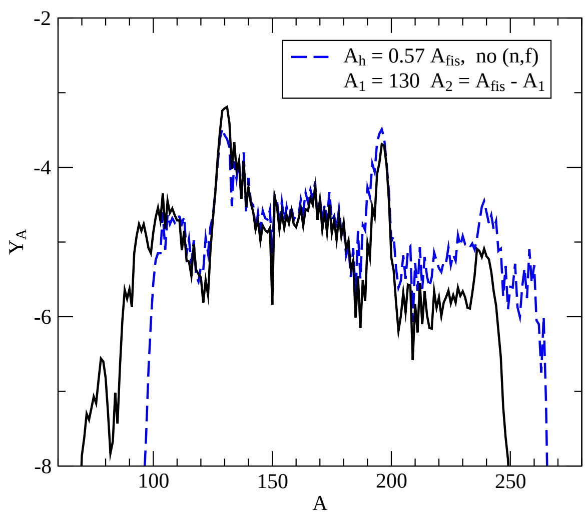

Figure 3. Composition of ejecta from a neutron star merger event (Σ mass fractions =1) with an average Y_e=0.10. Either only beta-delayed fission or both beta-delayed and neutron-induced fission were employed, varying also the fission yield distribution [56]. The effect of these different treatments is obviously seen for A>240, but more importantly for A<130 and underlines the impact of fission barriers and the fission yield distribution. These effects are directly related to all events with very high neutron densities, i.e. neutron star ejecta in mergers or jets where strong fission cycling takes place.

Fig. 3 shows the composition of ejecta from a NS merger [17,69,56]. It is seen that the large amount of free neutrons (up to $n_n \simeq 10^{32}$ cm^{-3}) available in such a scenario leads to the build-up of the heaviest elements and also to fission cycling within very short timescales, while the flow from the Fe-group to heavier elements "dries up". This leads to a composition void of abundances below the A$\simeq$130 peak, which is, however, dependent on detailed fission yield predictions [56].

5. Conclusions

At present, the suggested r-process sources, supernovae and neutron star mergers, did not yet prove to be "the" main-component r-process source without reasonable doubt. A discussion of the advantages and disadvantages of both possible r-process sources (SNe II vs. neutron star mergers) is given in refs. [63,70]. Self-consistent core collapse supernovae do not give explosions [64,46,35], yet, but parameter studies with neutrino opacities permit to "fit" the correct explosion behavior [36]. Thus, there is no way to predict whether the required entropies for an r-process can be obtained [85,81]. Neutron star merger calculations give the correct mass ejection [69], but relativistic calculations need to be followed up [54] and Y_e needs to be treated with weak interactions and neutrino transport included self-consistently.

The two possible sites discussed above (SNe II and neutron star mergers) have different occurance frequencies and different amounts of r-process ejecta, if a successful r-process actually occurs. These properties will enter into the enrichment pattern of r-process elements in galactic evolution. Inhomogeneous galactic evolution models in the very early phases of the Galaxy [24,1] will finally indicate that either one of the above mentioned sites or both in combination can meet the observational contraints from the r/Fe scatter as a function of metallicity.

Nuclear properties far from stable nuclei are of prime importance in the astrophysical r-process. Due to the (partial) equilibrium nature at high temperatures and neutron densities, the dominant influence is given by nuclear masses and β-decay properties (half-lives, delayed neutron emission and fission). Neutron-induced fission can play a competing role to beta-delayed fission. All these aspects need a better future understanding, including the role of neutrino-induced reactions, as they enter directly in the resulting r-process yields and abundance distributions.

References

1. D. Argast, D. et al., *A&A* **388**, 842 (2002).
2. C. Arlandini et al., *Ap. J.* **525**, 886 (1999).
3. G. Audi et al., *Nucl. Phys.* **A624**, 1 (1997).
4. Y. Aboussir et al., *At. Data Nucl. Data Tables* **61**, 127 (1995).
5. M. Bender et al., *Eur. Phys. J.* **A8**, 59 (2000).
6. I.N. Borzov and S. Goriely, *Phys. Rev.* **C62**, 5501 (2000).
7. E.M. Burbidge et al., *Rev. Mod. Phys.* **29**, 547 (1957).
8. A.G.W. Cameron, Atomic Energy of Canada, Ltd., CRL-41 (1957).
9. A.G.W. Cameron, *Nucl. Phys.* **A688**, 289 (2001).
10. B. Chen et al., *Phys. Lett.* **B355**, 37 (1995).
11. J.J. Cowan et al., *Phys. Rep.* **208**, 267 (1991).
12. J. J. Cowan et al., *Ap. J.* **521**, 194 (1999).
13. J. Dobaczewski, *Acta Phys. Pol.* **B30**, 1647 (1999).
14. D. Eichler et al., *Nature* **340**, 126 (1989).
15. J. Engel et al., *Phys. Rev.* **C60**, 4302 (1999).
16. C. Freiburghaus et al., *Ap. J.* **516**, 381 (1999).
17. C. Freiburghaus et al., *Ap. J.* **525**, L121 (1999).
18. G. Fuller and B.S. Meyer, *Ap. J.* **453**, 792 (1995), **464**, 521 (1996).
19. S. Goriely, E. Khan, *Nucl. Phys.* **A706**, 217 (2002).
20. S. Goriely et al., *Phys. Rev.* **C66**, 4326 (2002).
21. A. Hektor et al., *Phys. Rev.* **C61**, 5803 (2000).
22. R.D. Hoffman et al., *Ap. J.* **482**, 951 (1997).
23. W.M. Howard, P. Möller, *ADNDT* **25**, 219 (1980).
24. Y. Ishimaru et. al. *IAU SYMP* **187**, 117; MPA/P13, p.224 (2002).
25. H.T. Janka and M. Ruffert, *A&A* **307**, L33 (1996).
26. F. Käppeler et al., *Rep. Prog. Phys.* **52**, 945 (1989).
27. F. Käppeler et al., *Ann. Rev. Nucl. Part. Sci.* **48**, 175 (1998).
28. V. Kalogera et al., *Ap. J.* **556**, 340 (2001).
29. E. Kolbe et al., *Phys. Rep.* **227**, 37 (1993).
30. E. Kolbe et al., *Eur. J. Phys.* **A3**, 389 (1998).
31. K.-L. Kratz et al., *Ap. J.* **403**, 216 (1993).
32. K. Langanke, E. Kolbe, *ADNDT* **79**, 293 (2001).
33. K. Langanke, G. Martinez-Pinedo, *Rev. Mod. Phys.*, in press (2002).
34. J.M. Lattimer et al., *Ap. J.* **213**, 225 (1977).
35. M. Liebendörfer et al., *Phys. Rev.* **D63**, 3004 (2001).
36. M. Liebendörfer et al., MPA/P13, p.126 (2002).
37. D.R. Lorimer, *Living Reviews in Relativity*, in press (2002).
38. A. Mamdouh et al., *Nucl. Phys.* **A679**, 337 (2001).
39. G. Martinez-Pinedo and K. Langanke, *Phys. Rev. Lett.* **83**, 4502 (1999).
40. G. McLaughlin and G.M. Fuller, *Ap. J.* **464**, L143 (1996).
41. G.C. McLaughlin et al., *Phys. Rev.* **C59**, 2873 (1999); **489**, 766 (1997).
42. B.S. Meyer, *Ap. J.* **343**, 254 (1989).
43. B.S. Meyer et al., *Phys. Rev.* **C39**, 1876 (1989).
44. B.S. Meyer et al., *Ap. J.* **399**, 656 (1992).

45. B.S. Meyer et al., *Phys. Rev.* **C58**, 3696 (1998).
46. A. Mezzacappa et al., *Phys. Rev. Lett.* **86**, 1935 (2001).
47. P. Möller et al., *At. Data Nucl. Data Tables* **59**, 185 (1995).
48. P. Möller et al., *At. Data Nucl. Data Tables* **66**, 131 (1997).
49. P. Möller et al., *Nature* **409**, 785 (2001).
50. W.D. Myers, W.J. Swiatecki, *Phys. Rev.* **C60**, 4606 (1999).
51. D.K. Nadyozhin, I.V. Panov, WEIN-92, ed. T.D. Vylov, World Scientific (Singapore), p. 479 (1993).
52. S. Nagataki, K. Kohri, *Publ. Astron. Soc. Japan* **53**, 547 (2001).
53. T. Niksic et al., *Phys. Rev.* **C66**, 4306 (2002).
54. R. Oechslin et al., *Phys. Rev.* **D65**, 3005 (2002).
55. K. Otsuki et al., *Ap. J.* **533**, 424 (2000).
56. I. Panov et al., *Nucl. Phys.* **A688**, 587 (2001).
57. S. Pastor, G. Raffelt, *Phys. Rev. Lett.* **89**, 191101 (2002).
58. J.M. Pearson et al., *Phys. Lett.* **B387**, 455 (1996).
59. B. Pfeiffer et al., *Nucl. Phys.* **A693**, 282 (2001).
60. Y.-Z. Qian et al., *Phys. Rev.* **C55**, 1532 (1997).
61. Y.-Z. Qian and S.E. Woosley, *Ap. J.* **471**, 331 (1996).
62. Y.-Z. Qian et al., **Ap. J. 494**, 285 (1998).
63. Y.-Z. Qian, *Ap. J.* **534**, L67 (2000).
64. M. Rampp and H.T. Janka, *Ap. J.* **539**, L33 (2000).
65. T. Rauscher et al., *Phys. Rev.* **C57**, 2031 (1998).
66. T. Rauscher and F.-K. Thielemann, *At. Data Nucl. Data Tables* **75**, 1 (2000); **79**, 47 (2001).
67. T. Rauscher et al., *Nucl. Phys.* **A675**, 695 (2000).
68. P.G. Reinhard et al., *Hyperfine Interactions* **127**, 13 (2000).
69. S. Rosswog et al., *A&A* **341** 499 (1999); *A&A* **360** 171 (2000).
70. S. Rosswog, M.B. Davies, *Mon. Not. R Astron. Soc.* **334**, 481 (2002).
71. M. Ruffert and H.-T. Janka, *A&A* **380**, 544 (2001)
72. P.A. Seeger et al., *Ap. J. Suppl.* **97**, 121 (1965).
73. A. Staudt and H.V. Klapdor-Kleingrothaus, *Nucl. Phys.* **A549**, 254 (1992).
74. H.E. Suess and H.C. Urey, *Rev. Mod. Phys.* **28** 53 (1956).
75. K. Sumiyoshi et al., *Ap.J.* **562**, 880 (2001).
76. R. Surman et al., *Phys. Rev. Lett.* **79**, 1809 (1997).
77. K. Takahashi et al., *A&A* **286**, 857 (1994).
78. J. Taylor, *Rev. Mod. Phys.* **66**, 711 (1994).
79. M. Terasawa et al., *Ap.J.* **578**, L137 (2002).
80. F.-K. Thielemann et al., in *Fifty Years with Nuclear Fission*, ed. J.W. Behrens and A.D. Carlson, American Nuclear Society, p. 592 (1989).
81. T.A. Thompson et al., *Ap. J.* **562**, 887 (2001).
82. S.E. Thorsett, *Phys. Rev. Lett.* **77**, 1432 (1996).
83. D. Vretenar et al., *Phys. Rev.* **C63**, 7301 (2001).
84. G. Wallerstein et al., *Rev. Mod. Phys.* **69**, 995 (1997).
85. S. Wanajo et al., *Ap. J.* **554**, 578 (2001).
86. S.E. Woosley and R.D. Hoffman, *Ap. J.* **395**, 202 (2002).
87. S.E. Woosley et al., *Ap. J.* **433**, 229 (1994).