SUPERNOVA NUCLEOSYNTHESIS AS A TOOL TO ANALYZE THE EXPLOSION MECHANISM

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Abstract

Type II supernovae (SNe II) are linked to the gravitational collapse of massive stars ($M>8M_{\odot}$) at the end of their hydrostatic evolution. The resulting central hot proto-neutron star cools via neutrino emission. Neutrino opacities and transport determine the neutrino emission luminosity, which, together with the neutrino heating effiency in adjacent layers, is responsible for the explosion and ejection of matter. This affects the nucleosynthesis products via two main uncertainties, (i) the locations of the mass cut between the ejecta and the remaining neutron star and (ii) the total explosion energy responsible for explosive nucleosynthesis. Thus, observations can constrain these quantities.

Type Ia supernovae (SNe Ia) are explained by exploding white dwarfs in binary stellar systems. The favored systems are accreting white dwarfs, approaching the (maximum stable) Chandrasekhar mass before contraction and central ignition. Their major uncertainties are related (i) to the the accretion rate in the binary system which determines the carbon ignition density and (ii) the flame speed after central ignition. We provide several new constraints to the "average" SNe Ia systems, representing the major source of Fe-group nuclei in the Galaxy.

1 Introduction

Many contributions to this conference were devoted to the essential nuclear input for astrophysical calculations, i.e. experimental cross sections in hydrostatic burning stages of stellar evolution, electron captures in late burning stages and in stellar collapse, the nuclear equation of state and its influence on the supernova core collapse, neutrino transport and opacities in dense nuclear matter, the precision of cross section predictions for explosive burning, the properties (e.g. masses and half-lives) of nuclei far from beta-stability and resulting effects on abundance features of heavy nuclei. These topics are also covered in the NuPECC report on nuclear and particle astrophysics [3] and a recent review concentrating on experimental approaches [18]. In this contribution we present applications of such nuclear properties to specific astrophysical sites and test how resulting abundance compositions from explosive burning can give clues to the detailed working of supernovae.

Nuclear burning can in general be classified into two categories: (1) hydrostatic burning stages on timescales dictated by stellar energy loss and (2) explosive burning due to hydrodynamics of the specific event. Both are of importance for supernovae. In SNe II the outer ejected layers are unprocessed and contain results of prior H-, He-, C-, and Ne-burning in stellar evolution. In general, the initial hydrostatic composition also influences the ejected yields of explosively processing layers. Hydrostatic burning stages are characterized by temperature thresholds, permitting Maxwell-Boltzmann distributions of (charged) particles (nuclei) to penetrate increasing Coulomb barriers: H-burning [conversion of ^{1}H into ^{4}He via pp-chains, initiated by ^{1}H$(p,e^+)^2$H, or the CNO cycle with the slowest reaction ^{14}N$(p,\gamma)^{15}$O] He-burning [^{4}He$(2\alpha,\gamma)^{12}$C (triple-alpha) and ^{12}C$(\alpha,\gamma)^{16}$O], C-burning [^{12}C(^{12}C, $\alpha)^{20}$Ne], and O-burning [^{16}O(^{16}O,$\alpha)^{28}$Si]. The alternative is that photodisintegrations start to play a role when 30kT$\approx$Q (the Q-value of the inverse capture reaction). This ensures sufficient photons with energies >Q in the Planck distribution and leads to Ne-Burning [^{20}Ne$(\gamma,\alpha)^{16}$O, ^{20}Ne$(\alpha,\gamma)^{24}$Mg] at $T>1.5\times10^9$K (preceding O-burning) due to a small Q-value of $\approx$4 MeV and Si-burning at temperatures in excess of 3×10^9K [initiated like Ne-burning by photodisintegrations]. The latter ends in a thermodynamic equilibrium with an abundance distribution around Fe (nuclear statistical equilibrium, NSE), as Q-values of 8-10 MeV along the valley of stability permit photodisintegrations at these temperatures as well the penetration of the corresponding Coulomb barriers.

In such an NSE the abundance of each nucleus Y$_{(Z,A)}$ with atomic weight A and charge Z, measured in mole per gram of matter, is only governed by chemical potentials and thus only dependent on temperature T, density ρ, its nuclear binding energy B, and partition function G(T), while fulfilling mass conservation $\sum_i A_iY_i = 1$ and charge conservation $\sum_i Z_iY_i = Y_e$ (the total number of protons equals the net number of electrons). Y_e is changed by weak interactions (beta-decays and electron captures) on longer timescales. While still approaching NSE, different nuclear mass regions, usually separated by closed shells and small Q-values, can already be in equlibrium with the background of free neutrons, protons and alphas, but such quasi-equilibrium (QSE) clusters have total abundances which are offset from their NSE values [39, 46, 41].

2 Explosive Burning

Many of the hydrostatic burning processes occur also under explosive conditions at higher temperatures and on shorter timescales, cases, but often the beta-decay half-lives of unstable products are longer than the timescales of the explosive processes under investigation. This requires in general the additional knowledge of nuclear cross sections for unstable nuclei [35, 41]. A recent reaction rate sensitivity analysis of explosive burning products [44], however, also noticed that due to equilibrium effects (NSE and QSE) the dependence on cross section uncertainties (in explosive burning) is strongly reduced. Extensive calculations of explosive C, Ne, O, and Si burning have been performed for many years [1]. The fuels for explosive nucleosynthesis consist mainly of N=Z nuclei like ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, or ^{28}Si, resulting in intermediate to heavy nuclei, again with N≈Z, unless densities are high enough to ensure substantial electron captures due to energetic, degenerate electrons.

We will concentrate here only on explosive Si-burning which differs strongly from its hydrostatic counterpart. Explosive Si-burning can be devided into three different regimes: (i) incomplete Si-burning and complete Si-burning with either (ii) a normal (high density, low entropy) or (iii) an alpha-rich (low density, high entropy) freeze-out of charged-particle reactions. At high temperatures or during a "normal" freeze-out, the abundances are in a full NSE. An alpha-rich freeze-out is caused by the inability of the triple-alpha reaction ^{4}He$(2\alpha,\gamma)^{12}$C, transforming ^{4}He into ^{12}C, and the ^{4}He$(\alpha n,\gamma)^9$Be reaction, to keep light nuclei like n, p, and ^{4}He, and intermediate mass nuclei beyond A=12 in an NSE during declining temperatures, when the densities are small. This causes a large alpha abundance after freeze-out, which shifts abundances in QSE groups to heavier nuclei, transforming e.g. ^{56}Ni, ^{57}Ni, and ^{58}Ni into ^{60}Zn, ^{61}Zn, and ^{62}Zn. It leads also to a slow supply of ^{12}C still during freeze-out, leaving traces of alpha nuclei, ^{32}S, ^{36}Ar, ^{40}Ca, ^{44}Ti, ^{48}Cr, and ^{52}Fe, which did not fully make their way up to ^{56}Ni. This effect, typical for SNe II, is a function of remaining alpha-particle mass fraction (or entropy).

We will omit here the discussion of r-process nucleosynthesis (rapid neutron capture) and just point out that it relates to subsets of explosive Si-burning, either with low or high entropies and thus experiencing a normal or alpha-rich freeze-out. The requirement of a neutron/seed ratio of 10 to 150 after charged particle freeze-out translates in a normal freeze-out into a $Y_e = <Z/A>$ as low as 0.12-0.3, as found in neutron star matter. Another option is an extremely alpha-rich freeze-out with a moderate $Y_e > 0.40$ [38, 47, 10].

3 Type II Supernova Explosions

All stars with main sequence masses M>8M$_\odot$ [11, 42] produce a collapsing core after the end of their hydrostatic evolution, which proceeds to nuclear densities. The total energy released, 2-3$\times 10^{53}$erg, equals the gravitational binding energy of a neutron star. Because neutrinos are the particles with the longest mean free path, they are able to carry away that energy in the fastest fashion as seen for SN1987A in the Kamiokande, IMB and Baksan experiments [5]. The most promising mechanism for supernova explosions 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 [37, 25, 19, 36, 8]. The explosion via neutrino heating is delayed after core collapse for a timescale of seconds or less. The exact delay time t_{de} depends on the neutrinos transport and convection entropy gradients [12, 17, 6, 26].

3.1 Induced Nucleosynthesis Calculations

The uncertainties of self-consistent models, suggests instead to make use of the fact that typical kinetic energies of 10^{51} erg are observed and light curve as well as explosive nucleosynthesis calculations can be performed by introducing a shock of appropriate energy in the pre-collapse stellar model [42, 46, 40, 29]. Present explosive nucleosynthesis calculations for SNe II are still based on such induced supernova explosions by either depositing thermal energy or invoking a piston with a given kinetik energy of the order 10^{51} erg. Induced calculations (lacking self-consistency) utilize the constraint of requiring ejected ^{56}Ni-masses from the innermost explosive Si-burning layers in agreement with supernova light curves, being powered by the decay chain ^{56}Ni-^{56}Co-^{56}Fe. This can also serve as guidance to the supernova mechanism with mass cuts, based on ^{56}Ni in the ejecta [40, 29].

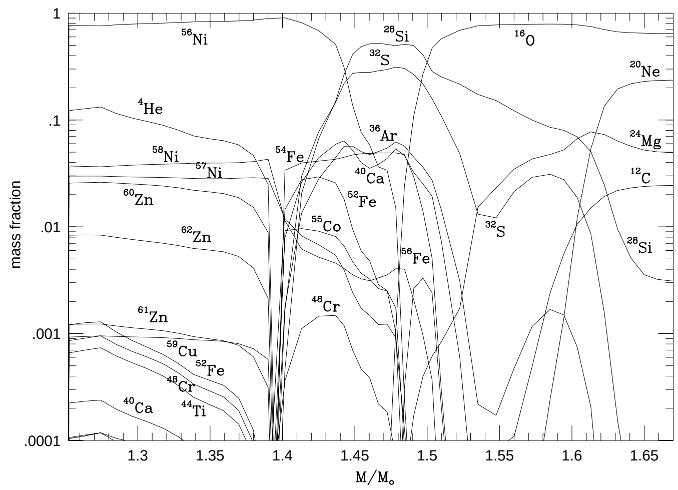

Figure 1: Isotopic composition of the ejecta for a core collapse supernova from a 13M$_\odot$ star (3.3M$_\odot$ He-core). The exact mass cut in $M(r)$ between neutron star and ejecta depends on the details of the delayed explosion mechanism.

Fig. 1 shows the composition after explosive processing for a constant Y_e=0.4989 in the inner ejcta, which experience incomplete and complete Si-burning. Huge changes in the Fe-group composition occur when this is changed to 0.4915 for mass zones below $M(r)$=1.5M$_\odot$. Then the abundances of ^{58}Ni and ^{56}Ni become comparable. All neutron-rich isotopes increase (^{57}Ni, ^{58}Ni, ^{59}Cu, ^{61}Zn, and ^{62}Zn), the even-mass isotopes (^{58}Ni and ^{62}Zn) show the strongest effect. One can also recognize the increase of ^{40}Ca, ^{44}Ti, ^{48}Cr, and ^{52}Fe with an increasing alpha-rich freeze-out.

In Fig. 2 we display the Y_e-distributions of a 20M$_\odot$ star and the position of the outer boundary of explosive Si-burning with complete Si exhaustion, where predominantly ^{56}Ni is produced. This changes as a function of the delay time t_{de} (here 0, 0.3, 0.5, 1, and 2s) between core bounce and explosion because matter is accreted onto the proto-neutron star. Observed ^{56}Ni ejecta indicate the corresponding neutron star masses. The upper mass limit of neutron stars, due to the nuclear equation of state [34], causes therefore also the upper mass limit of stars which undergo successful supernova explosions before the formation of central black holes set in. Different maximum stable masses between the initially hot and a cold neutron star, possibly related to kaon condensates [4, 34], could result in a supernova explosion *and* afterwards the formations of a central black hole.

Observational constraints for individual supernovae (e.g. SN1987A, SN1993J)

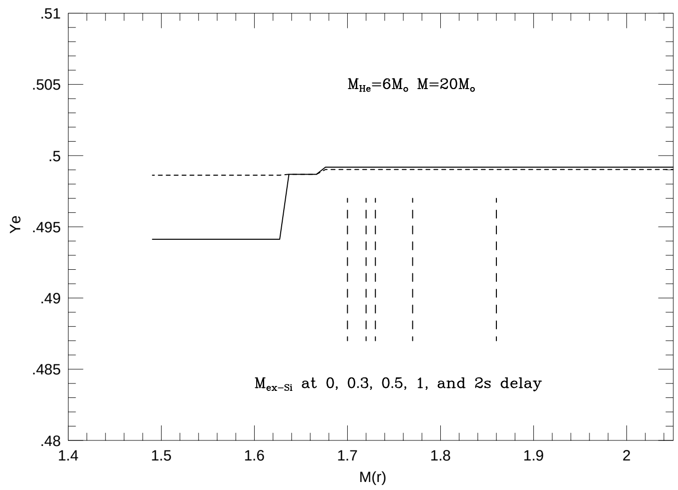

Figure 2: The Y_e-distributions in a 20$M_\odot$ star and the position of the outer boundary of complete Si-burning, as a function of the delay/accretion period t_{de}. A required amount of Ni-ejecta and the delay time t_{de} determine Y_e and the composition in the ejected material. The steep drop in Y_e corresponds to the edge of core O-burning.

and supernova remnants (e.g. Cas A, G292.0+1.8, N132D) give constraints on element abundances (like C, O, Si, Cl, Ar, Co, and Ni) and isotopic abundances (like ^{56}Ni, ^{57}Ni, ^{44}Ti, and ^{26}Al) from optical, UV, and X-ray spectra, supernova lightcurves, as well as gamma-ray lines following nuclear decay [40, 7], which constrain the products of hydrostatic burning stages like C, O, Ne and Mg and the composition close to the mass cut between the central neutron star and the supernova ejecta (^{56}Co, ^{57}Co, ^{44}Ti). They give a consistent picture for neutrino heating delay times of 0.3-0.5s, explosion energies of the order 10^{51}erg, and a mass cut close to or outside the O-burning shell with minute permitted admixtures of deeper layers so that only matter with $Y_e \geq 0.497$-0.498 is ejected. These constraints have to be met by self-consistent hydro calculations.

4 Type Ia Supernovae

There are strong observational and theoretical indications that SNe Ia are thermonuclear explosions of accreting white dwarfs [43, 13, 30]. Theoretically, both Chandrasekhar mass white dwarf models and sub-Chandrasekhar mass models have been considered [32, 9, 14]. These corresponds to a single degenerate scenario, i.e., accretion of H or He via mass transfer from a binary companion at a relatively high rate. In the case of He accretion at low rates, He detonates at the base of the accreted layer before the system reaches the Chandrasekhar mass [45, 24, 2]. A double degenerate scenario, i.e., the merging of two C+O white dwarfs in a binary system with a combined mass exceeding the Chandrasekhar mass limit [15] exists as well.

The Chandrasekhar vs. sub-Chandrasekhar mass issue has recently experienced some progress. Observational features of SNe Ia in early phases clearly indicate that Chandrasekhar models give a more consistent picture than the sub-Chandrasekhar models of helium detonations [13, 33]. On the other hand, late time spectra challenge the traditional model W7 [32] due to a too large ^{58}Ni content and too high central densities [23]. Thus, this model requires improvements (i) in terms of the Fe-group composition and (ii) the central ignition densities. The recent findings of supersoft X-ray sources, potential progenitors of SN Ia events with high accretion rates and low ignition densities [31, 22], leave hope also for late time spectra.

4.1 Ignition and Burning Front Propagation

For Chandrasekhar mass models carbon ignition in the central region leads to a thermonuclear runway. High accretion rates cause a higher central temperature and pressure, favoring lower ignition densities. A flame front then propagates at a subsonic speed as a *deflagration wave* due to heat transport across the front [32]. Here the most uncertain quantity is the flame speed which depends on the development of instabilities of various scales at the flame front. Multi-dimensional hydro simulations of the flame propagation have been attempted by several groups, though the results are still preliminary [21, 27, 28]. These simulations have suggested that a carbon deflagration wave might propagate at a speed $v_{\rm def}$ as slow as a few percent of the sound speed $v_{\rm s}$ in the central region of the white dwarf. Though the calculated flame speed is still very preliminary, due to the lack of a proper treatment of turbulence, it is useful to examine nucleosynthesis consequences of such a slow flame speed. After an initial deflagration in the central layers, the deflagration is assumed to turn into a detonation at lower densities [20, 45].

In the deflagration wave, electron captures enhance the neutron excess. The amount of electron capture depends on both $v_{\rm def}$ (influencing the time duration of matter at high temperatures, and with it the availability of free protons) and the central density of the white dwarf (increasing the electron chemical potential). The resultant nucleosynthesis in slow deflagrations [20] has some distinct features compared with faster deflagrations like W7 [32],

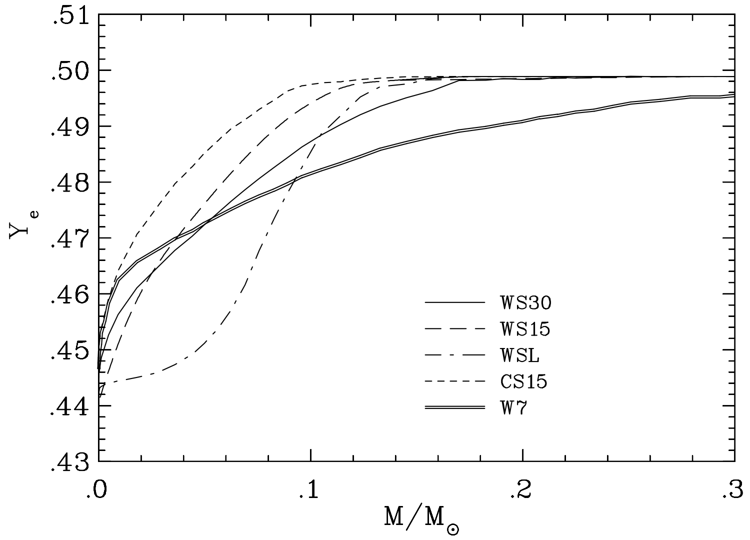

Figure 3: Y_e after freeze-out of nuclear reactions measures the electron captures on free protons and nuclei. Small burning front velocities lead to steep Y_e-gradients which flatten with increasing velocities (see the series of models WS15, WS30, and W7). Lower central ignition densities shift the curves up (CS15), but the gradient is the same for the same propagation speed. Only when the Y_e from electron captures is smaller than for stable Fe-group nuclei, subsequent β^--decays will reverse this effect(WSL).

thus providing important constraints on these two parameters. Initially slower deflagrations cause an earlier expansion of the outer layers with respect to the arrival of the burning front (as information of the central ignition propagates with sound speed and lead to lower densities for the outer deflagration and detonation layers. Here we want to concentrate on the main aim, which is to find the "average" SN Ia conditions responsible for their nucleosynthesis contribution to galactic evolution, i.e. especially the Fe-group composition.

4.2 The Fe-Group Composition in Slow Deflagrations

We adopt two models with central densities of ρ=1.37 (C) and 2.12$\times 10^9$ g cm^{-3} (W) at the onset of thermonuclear runaway and assume that a slow (S) deflagration propagates with speeds $v_{\rm def}/v_{\rm s}$ = 0.015 (WS15, CS15) and 0.03 (WS30) and consider also the extreme case of an initially laminar flame front (WSL). The central region undergoes electron captures on free protons and iron peak nuclei.

Fig. 3 summarizes the major options to change Y_e values in the central part of SNe Ia explosions are: (i) the burning front speed, determininig the Y_e gradient and (ii) the central ignition densities, being inversely proportional to

Y_e. These features hold true as long as Y_e values in explosive burning do not drop below 0.44, when competing β^--decays have also to be taken into account (case WSL). Such parameter studies can give important clues to v_{def} and $\rho_{c,ign}$. Y_e values of 0.47-0.485 lead to dominant abundances of ^{54}Fe and ^{58}Ni, values between 0.46 and 0.47 produce dominantly ^{56}Fe, values in the range of 0.45 and below are responsible for ^{58}Fe, ^{54}Cr, ^{50}Ti, ^{64}Ni, and values below 0.43-0.42 are responsible for ^{48}Ca.

For all cases discussed here (WSL, WS15, WS30, CS15) ^{58}Ni can be produced within the permitted uncertainty limits. ^{54}Cr is produced within these limits in CS15, but overproduced in WSL, WS15 and WS30, due to the too low central Y_e's. ^{50}Ti is produced close to solar values for CS15, well produced for WS30, and clearly overproduced in WSL and WS15 (for full details see [16]). From this exercise we see that this would make CS15 a better model than WS15, WS30 or WSL, in terms of avoiding overproduction of these elements, and would permit solar abundances in total. This interpretation is also in agreement with identifying the recently discovered supersoft X-ray sources as SN Ia progenitor systems. Their high accretion rates (close to $\dot{M}$=10^{-7}M$_\odot$) would be in agreement with such low ignition densities.

References

[1] Arnett, W.D. 1995, Ann. Rev. Astron. Astrophys. 33, 115

[2] Arnett, W.D. 1996, *Nucleosynthesis and Supernovae*, Princeton Univ. Press

[3] Baraffe, I. et al. 1997, *NuPECC Report on Nuclear and Particle Astrophysics*, http://quasar.physik.unibas.ch/nupecc

[4] Brown, G.E., Bethe, H.A. 1994, Ap. J. 423, 659

[5] Burrows, A. 1990, Ann. Rev. Nucl. Part. Sci. 40, 181

[6] Burrows, A., 1996, Nucl. Phys. A606, 151

[7] *Supernova Explosions: Their Causes and Consequences*, eds. A. Burrows, K. Nomoto, F.-K. Thielemann, http://www.itp.ucsb.edu/online/supernova/snovaetrans.html

[8] Burrows, A., Sawyer, R.F. 1998, Phys. Rev. D, submitted

[9] Canal, R., 1997, in *Thermonuclear Supernovae*, eds. P. Ruiz-Lapuente, R. Canal, J. Isern, Kluwer Academic Publishers, p. 257

[10] Freiburghaus, C. et al. 1997, Nucl. Phys. A621, 405c; 1998, Ap. J., in press

[11] Hashimoto, M., Iwamoto, K., Nomoto, K., 1993, Ap.J. 414, L105

[12] Herant, M. et al. 1994, Ap. J. 435, 339

[13] Höflich, P., Khokhlov, A. 1996, Ap. J., 457, 500
[14] Höflich, P., Wheeler, J.C., Thielemann, F.-K. 1998, Ap.J., in press
[15] Iben, I.Jr., Tutukov, A.V. 1984, Ap. J. Suppl. 54, 335
[16] Iwamoto, K. et al. 1998, Ap. J., submitted
[17] Janka, H.-T., Müller, E. 1996, Astron. Astrophys. 306, 167
[18] Käppeler, F., Wiescher, M., Thielemann, F.-K. 1998, Ann. Rev. Nucl. Part. Sci., in press
[19] Keil, W., Janka, H.-T. 1995, Astron. Astrophys. 296, 145
[20] Khokhlov, A.M. 1991, A&A 245, 114; 245, L25
[21] Khokhlov, A.M. 1995, Ap. J. 449, 695
[22] Li, X.D., van den Heuvel, E.P.J. 1997, Astron. Astrophys. 322, L9
[23] Liu, W.H., Jeffery, D.J., Schultz, D.R. 1997, Ap. J. 483, L107
[24] Livne, E., Arnett, W.D. 1995, Ap. J. 452, 62
[25] Mezzacappa, A., Bruenn, S.W. 1993, Ap. J. 405, 637
[26] Mezzacappa, A. et al. 1997, Ap. J., in press
[27] Niemeyer J.C., Hillebrandt W. 1995, Ap. J., 452, 769
[28] Niemeyer, J.C., Woosley, S.E. 1997, Ap. J. 475, 740
[29] Nomoto, K. et al. 1997, Nucl. Phys., A616, 79c
[30] Nomoto, K., Iwamoto, K., Kishimoto, N. 1997, Science 276, 1378
[31] Nomoto, K., Kondo, Y. 1991, Ap. J. 367, L19
[32] Nomoto, K., Thielemann, F.-K., Yokoi, K. 1984, Ap. J. 286, 644
[33] Nugent, P. et al. 1997, Ap. J. 485, 812
[34] Prakash, M. et al. 1997, Phys. Rep. 280, 1
[35] Rauscher, T., Thielemann, F.-K., Kratz, K.-L. 1997, Phys. Rev. C56, 1613
[36] Reddy, S., Prakash, M., Lattimer, J.M. 1997, Nucl. Phys. A, in press
[37] Schinder, P.J. 1990, Ap. J. Suppl. 74, 249
[38] Takahashi, K., Witti, J., Janka, H.-T. 1994, Astron. Astrophys. 286, 857
[39] Thielemann, F.-K., Arnett, W.D. 1985, Ap. J. 295, 604
[40] Thielemann, F.-K., Nomoto, K., Hashimoto, M. 1996, Ap. J. 460, 408
[41] Thielemann, F.-K. et al. 1997, in *Nuclear and Particle Astrophysics*, ed. J. Hirsch, Cambridge Univ. Press, in press (astro-ph/9802077)
[42] Weaver, T.A., Woosley, S.E. 1993, Phys. Rep. 227, 65
[43] Wheeler, J.C. et al. 1995, Phys. Rep., 53, 221
[44] Woosley, S.E. et al. 1997, Nucl. Phys. A621, 445c
[45] Woosley, S.E., Weaver, T.A. 1994, Ap. J., 423, 371
[46] Woosley, S.E., Weaver, T.A. 1995, Ap. J. Suppl. 101, 181
[47] Woosley, S. E. et al. 1994, Ap. J. 433, 229