GUSTAV-HERTZ-PREIS

Supernova evolution and nucleosynthesis

A new nucleosynthesis process might explain the abundancies of Molybdenum and Ruthenium isotopes in the solar system.

Gabriel Martínez-Pinedo

In massive stars a sequence of fusion reactions takes place, starting from the fusion of hydrogen to helium and proceeding through carbon, neon, oxygen, silicon up to iron. When the iron core becomes unstable and collapses to produce a neutron star, a core-collapse supernova explosion occurs. Since the energy liberated by the collapse is emitted mainly in neutrinos of all flavors, such a supernova is one of the few astrophysical events where the weak interaction produces effects of macroscopic scale. Whereas most of the nuclei heavier than iron are produced by neutron captures, the origin of the neutron-deficient isotopes Molybdenum and Ruthenium in our solar system has remained mysterious.

Stars with masses exceeding roughly 10 solar masses are the most efficient producers of the heavy elements. During their hydrostatic burning phases these stars are stabilized by the pressure generated by the energy released in the nuclear reactions. However, when the nuclear energy source ceases, massive stars eventually collapse and, if not too massive, bounce and explode in spectacular events known as core-collapse supernovae. In this way, most of the nuclear material bred in the interior of the star is ejected into space.

Supernovae are complex and physically diverse events in which all four known forces play an important role in extreme regimes and conditions. During the collapse matter reaches extreme densities and finally the collapse stops when densities larger than nuclear matter density (2.3×10^{17} kg m^{-3}) are reached. Since 1934, when Baade and Zwicky suggested that supernovae were due to the collapse of the core of massive stars to form neutron stars, the major challenge facing supernova theory has been how to convert the implosion of the core into an explosion. The detection of neutrinos emitted from the supernova explosion that took place on February 23rd, 1987 in the Large Magellanic Cloud confirmed the theoretical result that most of the energy liberated by the collapse of the core is emitted in the form of neutrinos. In fact, the neutrino densities are similar to matter densities, making supernovae one of the few astrophysical events where the weak interaction produces effects of macroscopic scale.


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The crab nebula is the remnant of a supernova that was observed on earth in 1054. This superimposed false-color image shows the emission in X-rays (blue-purple), optical (green) and infrared (red) light.

Neutrinos not only play an important role in the explosion dynamics, but also determine the conditions in which nucleosynthesis takes place in the inner regions of the star. Here, half of the elements heavier than iron are expected to be synthesized during the explosion. This article discusses the close interplay that exists between the explosion mechanism of massive stars and the resulting explosive nucleosynthesis. Our current picture of the evolution and explosion of massive stars is introduced together with the main processes governing the nucleosynthesis of heavy nuclei.

IN BRIEF

- The dynamics of the supernova collapse is greatly determined by weak-interaction processes like electron captures on nuclei.
- Electron neutrino and antineutrino absorptions determine the proton-to-neutron ratio of the ejected matter, which in turn decides the outcome of the explosive nucleosynthesis.
- At early times the ejected matter is proton-rich, constituting the site of a new nucleosynthesis process, denoted as the νp-process.
- At later times, the ejected matter becomes neutron-rich and might be the site for the r-process.

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1617-9437/08/0909-51

Massive star evolution and explosion

Stars are born from the collapse of giant clouds of gas. As the collapse proceeds the temperature increases and at some point becomes large enough to ignite hydrogen. The heat liberated by the fusion of four nuclei of hydrogen into a nucleus of helium creates enough pressure to temporarily stop the collapse. Fusion in the core continues until its hydrogen is exhausted. The core then contracts and as a result both the core and the surrounding material are heated. Hydrogen fusion then begins in the surrounding layers. Meanwhile, the core becomes hot enough to ignite the fusion of three nuclei of helium to form ^{12}C, in what is known as the triple alpha reaction. The successive evolution of the star follows a similar pattern. Each time a fuel runs out, the core contracts, heats up and then a new burning phase starts, where the fuel usually consists of the ashes of the previous burning stage. This way the star proceeds through carbon, neon, oxygen and finally silicon burning. Although the burning of hydrogen and helium takes millions of years, the later evolution is greatly accelerated with the last burning phase – silicon burning – lasting only two weeks for a 15 solar mass star.

Silicon burning results in the build up of a core made of iron group nuclei (**Fig. 1**). Later, silicon burning continues in the boundary between the iron core and the silicon shell, adding additional mass to the iron core. Iron nuclei have the largest binding energy per nucleon and constitute the final product of fusion reactions, as any additional fusion will not liberate energy. The iron core is just an inert sphere that has to sustain larger and larger pressure. With increasing density the electrons become degenerate and relativistic. Subrahmanyan Chandrasekhar showed that under these conditions both the gravitational energy and the electron kinetic energy are inversely proportional to the star radius. An equilibrium is only possible if the mass of the core is less than a critical value known as Chandrasekhar mass. This mass depends on the number of electrons present in the core and can be written as $M_{\mathrm{Ch}} = 1.44\,(2Y_e)^2\,M_\odot$, with Y_e the number of electrons per nucleon present in the core and $M_\odot$ the solar mass.

Around the same time that silicon burning starts, the electron Fermi energy reaches the MeV range, allowing for electron capture to occur in the just-produced iron group nuclei with energy thresholds of a few MeV. Electron capture is a process mediated by the weak interaction in which a nucleus with charge number Z and mass number A absorbs an electron and is transformed into a nucleus with charge Z–1 after emission of a neutrino. Electron capture is responsible for the reduction of the number of electrons present in the core of the star and consequently reduces the pressure support, accelerating the collapse.

As the atoms in the star core are completely ionized, electron capture denotes the absorption of an electron from the continuum. An accurate description of this process requires the determination of the transition strength to all possible final states. Experiments have shown the existence of a collective excitation, known

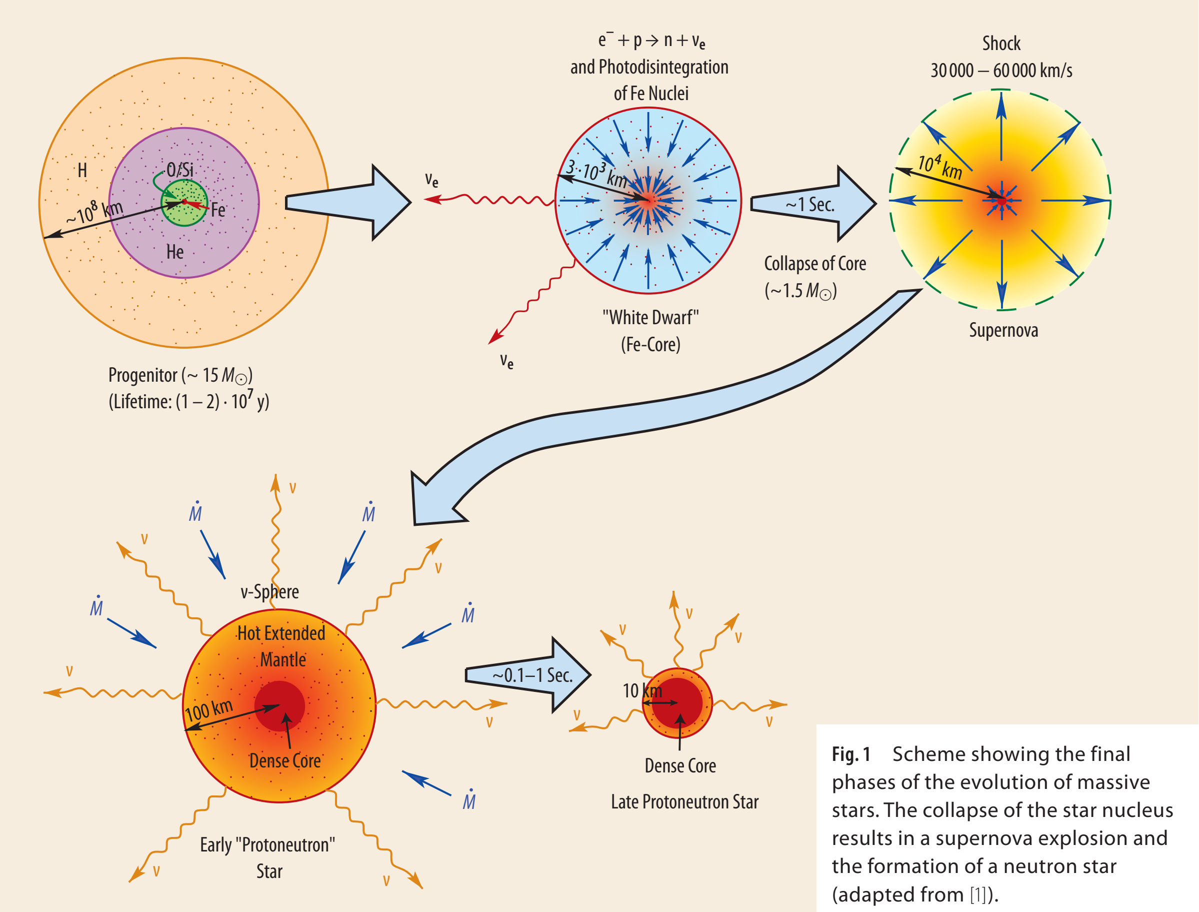

Fig. 1 Scheme showing the final phases of the evolution of massive stars. The collapse of the star nucleus results in a supernova explosion and the formation of a neutron star (adapted from [1]).

as Gamow-Teller resonance [2], located at an excitation energy of a few MeV in the final nucleus. Transitions to this resonance dominate the rate of electron capture for the conditions found in the star core. Consequently, experimental techniques have been developed for the measurements of many Gamow-Teller distributions on stable nuclei via charge-exchange reactions [3]. Future radioactive-ion-beam facilities and, in particular, FAIR [4] in Darmstadt will allow one to extend these measurements to unstable nuclei, using inverse kinematics techniques. These measurements will provide valuable information for the determination of the relevant electron capture rates; however, theoretical models will be necessary to account for finite temperature effects in the stellar medium. In recent years, progress in many-body techniques and computer capabilities has allowed one to routinely perform shell-model calculations in model spaces that reach 10 billion basic states [5], allowing for microscopic calculations of the relevant electron capture rates for iron group nuclei [6].

For a long time, it was assumed that as the nuclei present in star core become more and more neutron rich, the rate of electron captures in nuclei will be drastically reduced and electrons will only be captured in free protons. However, shell-model Monte Carlo calculations by Langanke et al. [7] have shown that once many-body correlations and finite temperature effects (the central temperature of the star is around 0.7 MeV) are considered, electron capture on nuclei dominates over capture in protons during the whole collapse. This results in important changes in the collapse evolution when comparing collapse models that consider only electron capture on protons with models that include both capture on protons and on nuclei [8]. The additional capture channel results in a faster decrease of the number of electrons present in the medium until densities around 10^{15} kg m^{-3} are reached. At these densities neutrinos are effectively trapped in the core, as the time they require to diffuse out becomes larger than the remaining collapse time (a few milliseconds). The inverse process to electron capture, neutrino absorption of either bound or free neutrons, becomes possible, reducing the decrease of Y_e. At this point, the ratio of electrons to nucleons reaches a value around 0.3, corresponding to a value of the Chandrasekhar mass of 0.5 solar masses. This is approximately the size of the inner region of the core that collapses until reaching densities above nuclear matter density, when finally the short-range repulsion of the nuclear force halts the collapse.

The sudden halt of the collapse of the inner core generates a shock wave (**Fig. 1**). Initially, it was thought that the shock wave would deposit energy in the outer layers of the core and eject the rest of the star with high velocities. However, now it is known that this is not the case. All recent computer simulations show that the shock wave stalls. Surrounding the inner core there is a region containing around 0.8 solar masses of iron group nuclei. As the shock wave moves through this region, matter is heated to such high temperatures that it is dissociated into protons and neutrons; in addition, electron capture can take place on the resulting free protons, producing a copious emission of neutrinos. The final result is that after a few milliseconds the shock wave stalls and the hot proto-neutron star (PNS) begins to accrete mass. If this accretion is not stopped a transition to a black hole will take place. However, the PNS emits a prodigious luminosity of neutrinos. Basically, the gravitational energy liberated during the collapse (3×10^{46} J) is emitted during a time of 10 seconds. If around 1 % of this energy is transferred to the matter surrounding the PNS it will be enough to explain the typical kinetic energy of the ejecta in a core-collapse supernova, $(1-2)\times 10^{44}$ J. The large difference in energies is due to the relatively small cross-section of the processes that govern the energy transfer ($\nu_e + n \rightarrow p + e^-$ and $\bar{\nu}_e + p \rightarrow n + e^+$, where n, p, e^+, e^-, ν_e, and $\bar{\nu}_e$ are the neutron, proton, positron, electron, electron neutrino and electron antineutrino, respectively) and the facts that part of the energy is radiated away by the inverse processes and that only a small amount of matter can absorb energy by interactions with the neutrinos. The efficiency of the absorption is affected by the existence of hydrodynamical instabilities in the forming neutron star and in the neutrino heating region. An accurate account of the energy transfer by neutrinos, consequently, requires multidimensional radiation-hydrodynamics simulations. Currently only two-dimensional calculations are possible (for reviews see [9–11]), but they show that we are finally getting closer to understanding how supernova explosions take place. On the way to a final solution, new physical ingredients could be necessary, including the effects of rotation and magnetic fields, improvements to the high-density nuclear equation of state and changes to neutrino physics. These ingredients could play different roles for stars of different masses, as the explosion mechanism could change with increasing stellar mass.

Our understanding of core-collapse supernovae will greatly improve with the observation of neutrinos emitted by a future galactic supernova. In the meantime, indirect information about the conditions achieved in the inner regions of the star can be obtained by looking at the resulting nucleosynthesis.

Explosive nucleosynthesis in supernovae

In the previous section we have seen that the series of fusion reactions that take place during the life of the star end when iron group nuclei are formed in the core. The production of heavier nuclei by fusion reactions is not possible as this process becomes endoergic. In addition, fusion is impeded by the growth of the Coulomb repulsion with increasing nuclear charge. Consequently, the easiest way of producing heavy nuclei is via neutron captures, provided that neutrons can be produced locally. Depending on the amount of neutrons produced, we can have two situations. If after a neutron capture the produced unstable nucleus has a beta decay half-life shorter than the time necessary for an additional neutron capture, we talk of the **s-process** or slow neutron capture process. The s-process is responsible for the production of half of the elements heavier than iron and is thought to occur in lower-mass stars during the asymptotic giant branch phase and in massive stars during the helium-burning phase. The other half of elements heavier than iron are produced by the **r-process**, rapid neutron capture, where the time between successive neutron captures is much shorter than the beta decay half-live of the produced nuclei. The large neutron densities, $N_n > 10^{32}$ m^{-3}, necessary for the r-process require explosive environments like supernovae.

There are 35 neutron-deficient nuclei, commonly known as p-nuclei, that cannot be produced by the s-process or the r-process. In their seminal work Burbidge, Burbidge, Fowler and Hoyle (BBFH) [12] suggested that these nuclei can be synthesized by a process that they denoted the **p-process**, in an environment with proton densities larger than 10^{31} m^{-3} and temperatures in the range of $(1-3)\times 10^9$ K. However, for a long time no astrophysical scenario was found with such large proton densities and temperatures. Consequently, it was suggested that these nuclei can be produced by photodissociation of heavy nuclei previously produced by the s- and r-processes. This process, sometimes known as the **γ-process**, can explain the solar abundances of most of the p-nuclei. However, it fails to reproduce the large abundances of ^{92,94}Mo and ^{96,98}Ru [13] in the solar system.

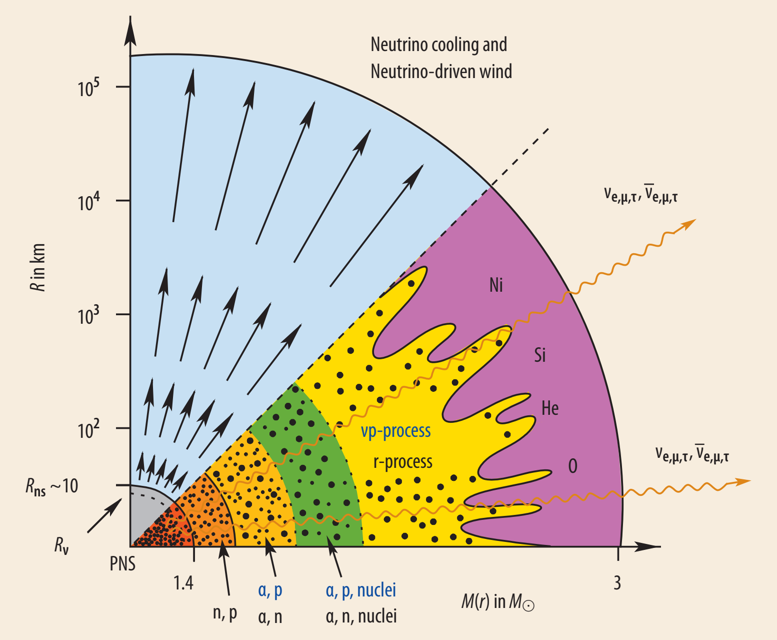

Fig. 2 Neutrinos emitted from the "neutrinosphere" (R_ν) drive a wind from the surface (R_{ns}) of the proto-neutron star (PNS). Initially the wind is very hot and composed of neutrons and protons in a ratio determined by the absorption of electron neutrinos and antineutrinos. As the matter expands and cools, nucleons recombine to form alpha particles with some remaining free protons (proton-rich ejecta) or neutrons (neutron-rich ejecta). Further cooling leads to the assembly of a few α-particles into nuclei in the iron group. As the temperature declines further two different nucleosynthesis processes can take place: the νp-process in proton-rich ejecta or the r-process in neutron-rich ejecta (adapted from [11]).

An alternative site for the production of these isotopes has been recently identified in the innermost ejecta of a supernova explosion. The newly-formed neutron star cools, emitting neutrinos and antineutrinos of all families. As the neutrinos stream out they interact with matter in the proto-neutron star atmosphere. Due to the continuous energy deposition, the matter becomes gravitationally unbound. This results in an outflow of matter, known as neutrino-driven wind, at such a high temperature that it is composed of radiation, electron-positron pairs and neutrons and protons. The neutron-to-proton ratio is determined by the competition between neutrino absorption on neutrons ($\nu_e + n \rightarrow p + e^-$) and antineutrino absorption on protons ($\bar{\nu}_e + p \rightarrow n + e^+$). The rate of each reaction depends on the neutrino flux and energy, as the cross-section for neutrino absorption is proportional to the neutrino energy squared. The fluxes of neutrinos and antineutrinos are almost identical, but antineutrinos have larger average energies because the outer layers of the neutron star are neutron-rich and, consequently, antineutrinos are emitted from deeper and hotter regions of the neutron star than neutrinos. During the early seconds after explosion, the ejecta are proton rich (containing more protons than neutrons), even if antineutrinos have larger energies, since protons are more strongly bound than neutrons. As the neutron star cools and contracts the outer layers become neutron-richer and the energy difference between antineutrinos and neutrinos increases. At some point the energy difference is large enough to allow for neutron-rich ejecta.

Once the ejected matter cools below temperatures of 10×10^9 K, the neutrons and protons begin to combine with each other forming ^{4}He nuclei, also known as α-particles. Each α-particle removes two neutrons and two protons from the wind and at some point the composition consists only of alpha particles and free protons (neutrons) for proton (neutron) rich ejecta. At temperatures around 5×10^9 K, α-particles assemble into heavier nuclei but the expansion of matter is so fast that only a few iron-group nuclei are formed (**Fig. 2**).

The proton-rich ejecta, at temperatures around 2×10^9 K, consist mostly of α-particles, protons and iron-group nuclei with $N \sim Z$. The proton densities are around 10^{33} m^{-3}. This environment fulfills the conditions suggested by BBFH; in addition, the nuclear structure of the nuclei present should also be considered. As proton captures build up heavy nuclei, ^{64}Ge is reached. This nucleus with 32 protons and 32 neutrons can now capture a proton or beta decay. The first process will produce ^{65}As that is unbound to proton emission and will decay instantaneously. The beta decay half-life of ^{64}Ge is 63.7 s. This time is much longer than the few seconds the matter spends in the temperature range of $(1-3)\times 10^9$ K where proton captures are possible. However, the ejecta are under strong fluxes of neutrinos and antineutrinos. The matter is practically inert to neutrino absorptions, as these reactions are endoergic for neutron-deficient nuclei. However, the situation is different for antineutrinos that can be captured on a time scale of seconds, both on protons and nuclei. As protons are much more abundant than heavy nuclei, antineutrino absorption occurs predominantly on protons, producing neutrons. These neutrons are immediately absorbed into the abundant neutron-deficient nuclei and, in particular, into ^{64}Ge, on a time scale of ∼ 0.2 seconds, which is much shorter than its beta-decay half-life. In this way, the matter flow can proceed to heavier nuclei and synthesize the problematic light p-nuclei, ^{92,94}Mo and ^{96,98}Ru (**Fig. 3**), by a series of (p,γ), β^+ and (n, p) reactions, with the neutrons produced by antineutrino absorptions on protons. These series of reactions have been denoted as the **νp-process** in reference [17]. The name emphasizes the important role played by antineutrinos and the fact that this "new" p-process has similar features to the p-process suggested by BBFH.

Let us consider now the situation in neutron-rich ejecta. In this case, once reactions involving α-particles end, the matter is composed of α-particles, neutrons and heavy nuclei. If the amount of free neutrons per heavy nucleus, the so-called neutron-to-seed ratio, is larger than 150 the heavier elements occurring in nature, U and Th, can be synthesized. However, current state-of-the-art hydrodynamical models [18] show that for temperatures $T > 3 \times 10^9$ K, at which α-capture reactions occur, the density of the matter is too large, resulting in the formation of too many nuclei. The neutron-to-seed ratios are around 50 and, consequently, only heavy nuclei with mass number below 130 are produced. There is hope, however, that the neutrino-driven wind will allow for the production of heavier nuclei, once the explosion mechanism is fully understood and the effects of rotation and of magnetic fields are included in the wind evolution. In addition, the poorly understood equation of state for matter at subnuclear densities, $\sim 10^{16}$ kg m^{-3}, determines the luminosities and energies of the emitted neutrinos.

The neutrino-driven wind is a primary nucleosynthesis site, meaning that the production of elements is independent of the initial composition of the star. The composition of the wind is mainly sensitive to the properties and evolution of the proto-neutron star. Consequently, similar abundance patterns will result from a neutron star produced in the early galaxy as from one produced today. This is consistent with observations of very old metal-poor stars [19], which show the same relative abundance of r-process elements as the ones observed in the sun. If we assume that each neutrino-driven wind consists of an early proton-rich phase (νp-process) and a later neutron-rich phase (r-process), it is expected that there will be a correlation between the abundances of ^{92,94}Mo and ^{96,98}Ru and the abundances of r-process elements observed in stars.

Independently of the astrophysical site, the r-process proceeds via a series of neutron captures that stops when the inverse (γ,n) reaction or the beta decay becomes competitive. After beta decay the proton number is increased by one unit, and in this way heavier elements are synthesized. The flow of matter is sensitive to the beta-decay rates. The nuclei participating in the r-process are so neutron rich that most of them have never been synthesized in the laboratory and, consequently, the properties relevant for the r-process (mass, neutron capture cross sections and beta-decay rate) are unknown. This situation will change drastically once the new radioactive-ion-beam facility FAIR is built [4]. There, many of the nuclei participating in the r-process will be studied. The r-process ends once the neutron-density is too low to sustain more neutron captures. If the neutron-to-seed ratio is large enough, nuclei with $Z > 90$ and $N > 184$ will be produced. These nuclei will decay by fission during the r-process producing new seeds and neutrons. Under these conditions, both fission probabilities and yields are necessary for a reliable determination of the resulting r-process abundances.

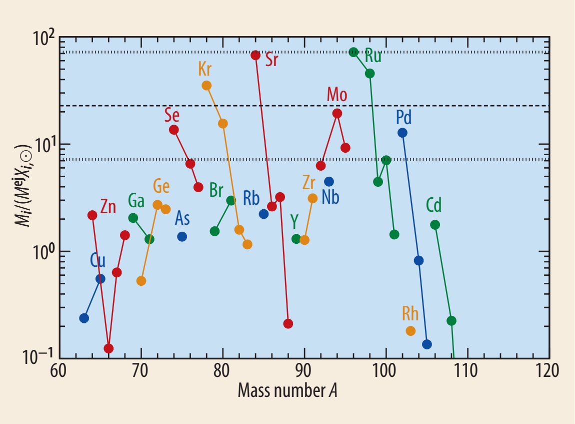

Fig. 3 Overproduction factors (defined as the ratio between the ejected mass of a nucleus, M_i, and the total mass of the ejecta, M^{ej}, normalized to the same ratio in the solar system, $X_{i,\odot}$), resulting from the νp-process occurring during the explosion of a 15 solar masses star, as modelled by the Garching group [14]. The horizontal lines indicate a band between the largest overproduction factor (^{96}Ru) and a factor 10 times smaller. This band accounts for possible uncertainties in the astrophysical conditions and nuclear input used. Similar results have been obtained in refs. [15,16].

Conclusions

In recent years, progress in supernova modeling and improvements in the description of the relevant microphysics input have led to a more reliable description of supernova dynamics. Future progress will require the development of multidimensional radiation-hydrodynamics codes to fully explore the role of hydrodynamical instabilities in the explosion and continuous improvements in the many-body models necessary for the description of the relevant, weak-interaction processes at supernova conditions. These models will benefit from the construction of next generation radioactive-ion-beam facilities, like FAIR [4]. These facilities will allow for the experimental study of many of the unstable nuclei that are essential in many explosive astrophysical scenarios, including core-collapse supernovae.

Independently of what is the exact explosion mechanism of core-collapse supernovae, the neutrinos emitted during the cooling of the proto-neutron star will determine the conditions under which explosive nucleosynthesis takes place. While radioactive ion-beam facilities will only indirectly contribute to the nuclear-physics input necessary to model supernova explosions, they will provide direct and essential data for nucleosynthesis studies. This will include precise mass measurements of heavy nuclei with $N \sim Z$, which are necessary for a reliable prediction of the nucleosynthesis yields of the νp-process. In addition, mass and half-life measurements of many r-process nuclei will become available, removing one of the largest uncertainties of r-process nucleosynthesis.

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I would like to thank Hans-Thomas Janka, Karlheinz Langanke, Matthias Liebendörfer and Friedrich-Karl Thielemann for many years of collaboration. This work is partly supported by SFB 634.

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