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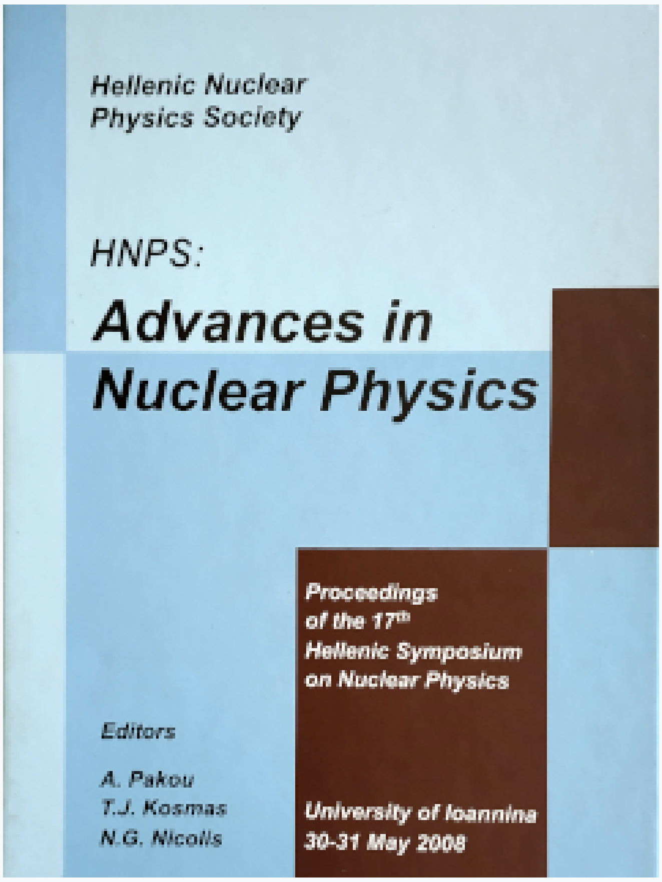

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Nucleosynthesis by accelerated particles in a bipolar Supernova explosion

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Abstract

The most spectacular final phase of an evolved star, is the supernova explosion. It has been suggested by observations that such an event might not be spherically symmetric. This asphericity could be explained by the formation of jets of accelerated particles by the explosion, which could interact with the stellar matter and give rise to a possible nucleosynthesis. Such a nucleosynthesis is studied. The final abundance pattern is shown to depend on the values of the model parameters adopted, especially the energy spectrum of the accelerated particles.

1 Introduction

According to the theory of nucleosynthesis, it is believed that the majority of the nuclei with $A \geq 12$ has been produced in the interiors of stars. The conditions of temperature and density in the central regions of a star can lead to nuclear reactions, resulting in an energy output, necessary to sustain the luminosity of the star and in the production of heavier nuclei. These fusion reactions can explain the production of nuclei up to the region of iron ($A \simeq 56$). Charged-particle fusion reactions cannot lead to heavier species and thus, special mechanisms have to be invoked. The most successful ones are the s-, r- and p- processes (2),(3). It is often met during the final stages of the evolved massive stars, that the supplied conditions are favourable for the operation of these processes. The nature of nucleosynthesis is deeply connected to the stellar evolution. A typical massive star ($M \simeq 25 M_{\odot}$) will go through a succession of nuclear burning phases and it will develop a Fe core, which will become dynamically unstable and implode. Through a quite complicated chain of physical events, this implosion will lead to a catastrophical explosion. This Supernova explosion will eject the matter of the star, some of it nuclearly processed, and leave behind a neutron star or a black hole as a remnant. Based on observations, the essential idea of asphericity in such an explosion has been suggested (4). A new class of supernovae, called hypernovae, which have distinctly larger energies, could demonstrate this feature. In combination with other properties of these explosions, deviations from spherical symmetry can be inferred (for a more thorough discussion see (4)). It is believed that these characteristics of hypernovae can be justified by the assumption that they are bipolar explosions. The nature of the central energy generating object is quite complicated and it contains physics that is not fully understood yet. As matter falls onto the central residue, an accretion disc is formed. Instead of falling in the central region, a part of this matter will most likely escape from the disc. This current of escaping particles appears collimated around the axis of rotation forming a jet of particles. Nucleosynthesis in this kind of systems has been examined so far in two locations, the materials heated by the jets and the materials in the jets themselves. However, a different approach is adopted in the present study. The bombardment of matter in the stellar mantle by the acccelerated particles in the jets may cause spallation reactions. The scope is to examine the possible nucleosynthesis of heavy elements ($Z \geq 60$), produced by spallation reactions induced by energetic particles located in the jets of a bipolar supernova explosion. The treatment of this problem follows the approach of (1).

2 Model description

The changes in the abundances of the nuclei, which are exposed to an incoming energetic particle flux, are described by a nuclear reaction network including all reactions of relevance. All nuclei with $0 \leq Z \leq 102$, which are located between the proton drip-line and the neutron-rich region, are included. The nuclei in the chosen region are then coupled by a system of differential equations. Each term in this system of equations corresponds to a specific reaction affecting the nucleus, mainly proton, α and neutron captures, $\beta^{\pm}$ and α -decays, as well as spontaneous and induced fission. The rate of change of the molar fraction $Y_{(Z,A)}$ of a nucleus (Z,A) with charge number Z and mass number A can be written as

$$\begin{aligned}\frac{dY_{(Z,A)}}{dt} = & -Y_{(Z,A)}\Phi_p\langle\sigma\rangle_p && + \sum_k Y_k \Phi_p \langle\sigma\rangle_{p,k}^{(Z,A)} \\ & - Y_{(Z,A)}\Phi_\alpha\langle\sigma\rangle_\alpha && + \sum_k Y_k \Phi_\alpha \langle\sigma\rangle_{\alpha,k}^{(Z,A)} \\ & - Y_n \rho N_\alpha \langle\sigma v\rangle_n^{(Z,A)} Y_{(Z,A)} && + \sum_k Y_n \rho N_\alpha \langle\sigma v\rangle_{(n,k)}^{(Z,A)} Y_k\end{aligned}$$

$$
\begin{aligned}
&- \lambda_{\beta^-}^{(Z,A)} Y_{(Z,A)} && - \lambda_{\beta^+}^{(Z,A)} Y_{(Z,A)} \\
&+ \lambda_{\beta^-}^{(Z-1,A)} Y_{(Z-1,A)} && + \lambda_{\beta^+}^{(Z+1,A)} Y_{(Z+1,A)} \\
&- \lambda_{\alpha}^{(Z,A)} Y_{(Z,A)} && + \lambda_{\alpha}^{(Z+2,A+4)} Y_{(Z+2,A+4)} \\
&- \lambda_{sf}^{(Z,A)} Y_{(Z,A)} && + \sum_k \lambda_{sf,k}^{(Z,A)} Y_k
\end{aligned}
\qquad (1)
$$

where $\lambda_\beta^\pm$, λ_α and λ_{sf} are the $\beta^\pm$, α and fission decay rates respectively. The quantities $\langle\sigma\rangle_p$ and $\langle\sigma\rangle_\alpha$ are the total effective cross sections for proton and α captures, averaged over the energy distribution $\Phi(E)$, i.e. for the proton case $\langle\sigma\rangle_p = \frac{1}{\Phi_p}\int_0^\infty \Phi(E)\sigma_p(E)dE$ where $\sigma_p(E)$ is the E-dependent total proton capture cross section and $\Phi_p = \int_0^\infty \Phi(E)dE$ the proton flux amplitude. The proton and α capture reaction cross sections are either taken by experiments, especially for lighter species (5), or calculated by the nuclear reaction code TALYS (6). The calculation includes single-particle (nucleons,alpha) as well as mutli-particle emissions and fission. Due to the large number of open channels at high energies, typically about 30 different (p or $\alpha, xn\ yp\ z\alpha$) reaction types corresponding to the emission of x neutrons, y protons and z α-particles, need to be taken into account per target nucleus. In total we are dealing with about 5000 nuclei and 250000 proton, neutron and α capture reactions. In all cases the particle flux is assumed to be constant in time during the irradiation period τ_{irr}. We will restrict ourselves to two types of energy spectra, namely a constant energy distribution in the range $E_{min} \le E \le E_{max}$ and the traditional power law introduced by Clayton et al. (7) and defined by

$$\Phi(E) = kE^{-\gamma} \ . \qquad (2)$$

In the present work, special attention is paid to the role played by the neutrons emitted during the spallation process. We assume that neutrons produced in this way are thermalized on timescales much shorter than the typical capture timescales. Neutron capture rates $\langle\sigma v\rangle_n$ are estimated by the Hauser-Feshbach reaction code MOST (8).

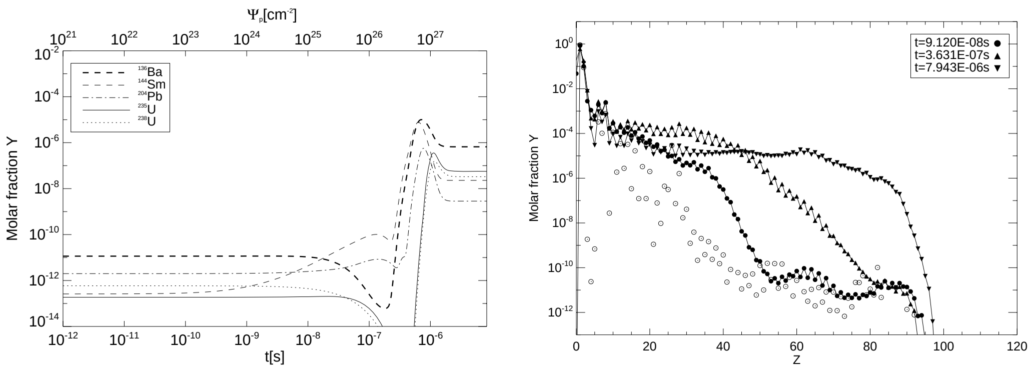
3 Results and analysis

The energetic particles in the jets, as they appear in the central region of the star, can interact with the surrounding stellar mantle via spallation reactions. It would be of interest to examine the magnitude of heavy element nucleosynthesis ($Z \ge 56$) induced by such non-thermal mechanisms. The precise conditions met in a bipolar explosion and the characteristics of the jets, are far from being put on a firm quantitative basis. In particular, as it was mentioned, the nature of the central energy generating object is complicated and a number of parameters is used to examine its energy outcome. The initial composition of the particles in the jets has not been determined yet and it has to wait for a detailed study of the flow of the material around the central residue (4). We regard the material in the jets to be consisted mainly of protons and alpha particles. Another free parameter is the particle energy spectrum. It depends on the still-uncertain mechanism behind the acceleration. A purely parametric approach is followed, taking as free parameters the properties of the accelerated protons and α-particles. Based on simulations (4), at a radius of 4000 km from the center, the flux intensity can reach values up to 10^{14} mb^{-1}s^{-1} approximately, with energies ranging between 2 and 14 MeV/nucleon. However, it should be clearly stated here that the present study has an exploratory character. This means that the parameters are going to be approximated in orders of magnitude and they will be regarded constants in time. All the irradiation times considered will be $\tau_{irr} \leq 10^{-4}$ s. If a star terminates its life by a hypernova explosion, this means that it will have a mass of about $20 - 25 M_{\odot}$ and it will have experienced all the nuclear burning phases. As the jets emerge at the central region and propagate through the star, they will meet layers of different composition, i.e. the ashes of each nuclear burning phase. The outermost hydrogen layer of the star will be examined here for two reasons: first, it is the simplest case, in agreement with the exploratory nature of our study and second, the materials in this layer are most likely to be ejected by the explosion and the resulting nucleosynthesis products could enrich the interstellar medium. The hydrogen shell composition is assumed to be the solar one (9).

3.1 Power-law spectrum

First we examine the case of a power-law energy distribution for the accelerated particles (Eq. 2). For the gamma exponent we adopt values between 2 and 4 as commonly used (10), (12), (11) and we limit ourselves to a lower energy limit of $E_{min} = 1$ MeV/nucleon and to an upper energy limit of $E_{max} = 15$ MeV/nucleon. A typical case with $\Phi_p = 10^6$ mb^{-1} s^{-1}, $\Phi_\alpha/\Phi_p = 0.5$ and a power law with $\gamma = 2$ is analyzed in detail. Fig. 1a shows the corresponding evolution of the abundances of five heavy nuclei, over time, or equivalently, over the total proton fluence $\Psi_p = \int_0^t \Phi_p dt$, up to that time. Interestingly enough, we observe a significant rise in the abundances of the heavy elements for times greater than 5×10^{-7} s, or for fluxes greater than 5×10^{26} cm^{-2}. At this point, α-particle captures set in and drive the production to heavier species. This can be seen in Fig. 1b, where the full elemental abundance distribution is compared to the solar one, for three irradiation times. If fluences of the order of 10^{26-27} cm^{-2} can be achieved, then, the abundances of the elements heavier than iron can increase up to 5 orders of magnitude. These conditions are favourable for bridging the $N > 126$ α-unstable region between Bi and

Th, hence for producing actinides. This occurs mainly due to the particularly large neutron densities $N_n = 10^{23}$ cm^{-3} attained under these circumstances. Indeed, for such an energy spectrum, the dominant reactions are α-particle transfer reactions, with emission of one to three neutrons. For fluences larger than 10^{27} cm^{-2} a steady flow is achieved and the heavy element abundances do not change with time anymore. For large fluences the abundance pattern is rather flat, since spallation reactions already at a few MeV tend to smooth out all the nuclear structure effects. Obviously, the nucleosynthesis results as described above, is quite sensitive to the adopted values of the parameters of the accelerated particles. The role of the composition parameter Φ_α/Φ_p can be understood with the help of Fig. 2a, where we can see the effect of the alpha particle flux on the abundance pattern. A helium-rich flux seems to favour the late-time production of the heavier species. Similarly, if a steeper energy spectrum (i.e. a larger γ exponent) is adopted, then the contribution of the highly energetic alpha particles becomes smaller, which results in their captures being less efficient in the late-time production of heavy elements. Setting $\gamma = 4$, irradiation times 10 times greater are needed to achieve a flat abundance distribution, as seen in Fig. 2b. For different flux magnitudes, but with the same total fluence $\Psi = 10^{27}$ cm^{-2}, we get Fig. 2c. It is concluded , that for greater fluxes multi-particle transfer reactions dominate, due to the more intense presence of highly energetic particles, for the spectrum with $\gamma = 2$. As a result, more material is recycled back to lighter species. Longer irradiation times will be needed to reach a stable flow. Nevertheless, it is noted that this conclusion holds only for the present energy spectrum and proton

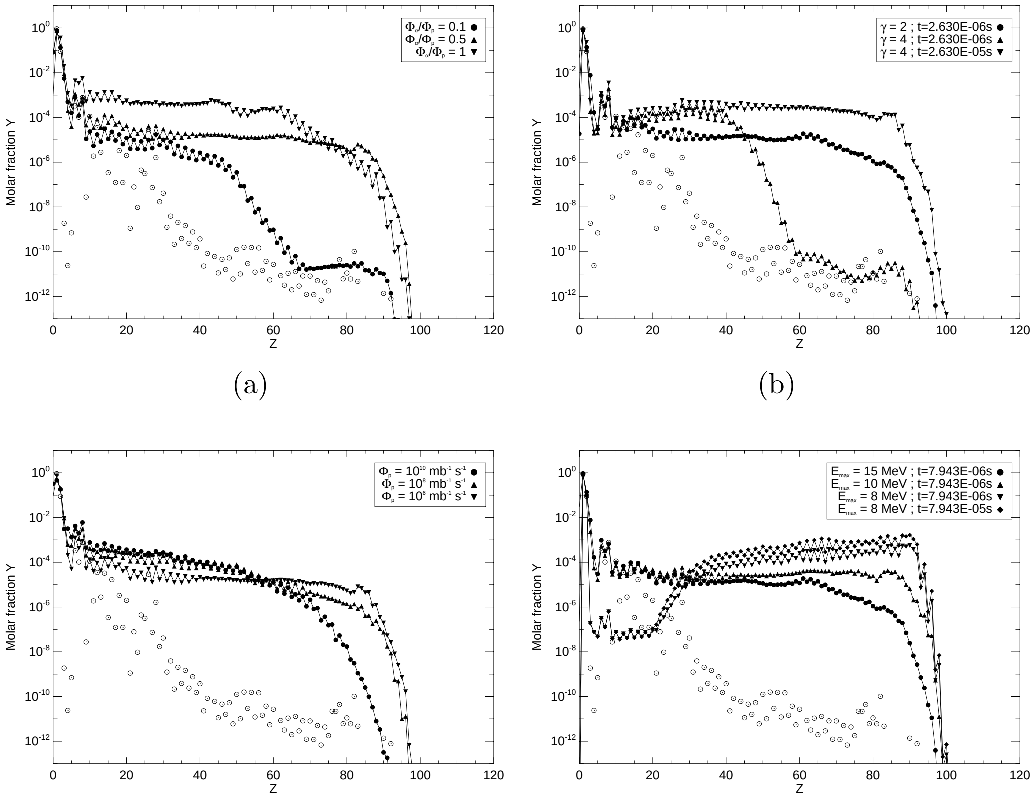


(a) (b)

Fig. 1.

(a) Evolution with time, or equivalently the total proton fluence Ψ_p, of five selected heavy nuclei. The values of the parameters of the accelerated particles in this case are $\Phi_p = 10^6$ mb^{-1} s^{-1}, $\Phi_\alpha/\Phi_p = 0.5$ and a power-law spectrum with $\gamma = 2$.

(b) Abundance distribution of the elements resulting from the spallation reactions with $\Phi_p = 10^6$ mb^{-1} s^{-1}, $\Phi_\alpha/\Phi_p = 0.5$ and a power-law spectrum with $\gamma = 2$, for three different irradiation times.



(a) (b) (c) (d)

Fig. 2.

(a) Elemental abundance distribution for $\Phi_p = 10^6$ mb^{-1} s^{-1}, $\tau_{irr} \approx 10^{-6}$ s, $\gamma = 2$ and three different values of Φ_α/Φ_p.

(b) Same as (a) $\Phi_p = 10^6$ mb^{-1} s^{-1}, $\Phi_\alpha/\Phi_p = 0.5$ and two values of the gamma exponent $\gamma = 2$ and 4. The last case is given for two irradiation times.

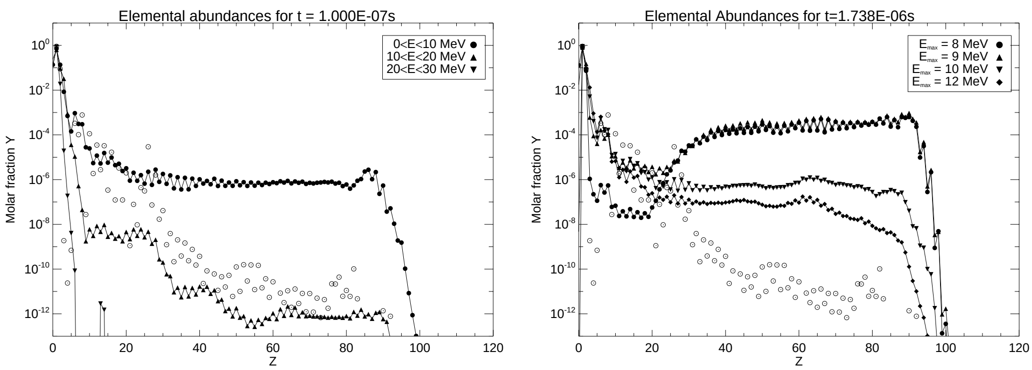
(c) Same as (a) for three different values of the magnitude of the proton flux Φ_p and $\Phi_\alpha/\Phi_p = 0.5$, $\gamma = 2$ for a total fluence of $\Psi_p = 10^{27}$ cm^{-2}.

(d) Same as (a) $\Phi_p = 10^6\ mb^{-1}s^{-1}$, $\Phi_\alpha/\Phi_p = 0.5$, $\gamma = 2$ and three different upper energy limits, $E_{max} = 15, 10$ and 8 MeV. The last case is given for two irradiation times.

to alpha particle flux ratio (Φ_α/Φ_p). As a last remark, we examine the effect of the upper energy limit, which we regarded to be 15 MeV for all the cases. It is expected that for a spectrum with lower E_{max}, spallation reactions with multi-particle emission will be less intense and thus heavy nuclei will not be destroyed easily. It can be seen in Fig. 2d that heavy elements are produced by about 2 orders of magnitude more for the cases with lower E_{max}.

3.2 Constant energy spectrum

Let us now turn to the scenario where the energy distribution of the particles is taken constant, in a small range of energies (typically 10 MeV). We initially concentrate on the $0 \leq E \leq 10$ MeV region, with $\Phi_p = 10^6$ mb^{-1} s^{-1} and $\Phi_\alpha/\Phi_p = 0.5$. The results are very similar to the power-law spectrum case. All the abundances are rising for total fluences of $\Psi_p = 10^{27}$ cm^{-2} and a flat elemental abundance pattern is reached in later irradiation times. The value of Φ_α/Φ_p has the same effects as in the previous spectrum. However, it seems that if a proton-rich flux can be maintained for great irradiation times, then spallation reactions tend to produce mainly protons and the heavier element molar fraction is seen to reduce. Actually, highly energetic protons destroy any heavy nucleus initially present in the material. Variations in the flux magnitude do not affect the final abundance pattern in a significant way. If we examine the energy regions $10 \leq E$ MeV ≤ 20 and $20 \leq E$ MeV ≤ 30, then the increasingly strong high energy component of the spectrum destroys the heavier nuclei and leads to a recycling of the material Fig. 3a. Finally, we examine different values of the upper energy limit, as seen in the legend of Fig. 3b. The higher the E_{max}, the more recycling of the nuclei occurs.



(a) (b)

Fig. 3.

(a) Elemental abundance distribution for $\Phi_p = 10^6$ mb^{-1} s^{-1}, $\Phi_\alpha/\Phi_p = 0.5$, $\tau_{irr} = 10^{-7}$ s and three constant energy spectra.

(b) Same as (a) for $\Phi_p = 10^6$ mb^{-1} s^{-1}, $\Phi_\alpha/\Phi_p = 0.5$, $\tau_{irr} = 1.7\ 10^{-6}$ s and a constant energy distribution with $E_{max} = 12,\ 10,\ 9$ or 8 MeV. For the last case, a larger irradiation time is adopted.

4 Summary and conclusions

The present study aimed at the examination of a possible heavy element nucleosynthesis by spallation reactions. Because of the unknown properties of the accelerated particles, which are held responsible for the reactions, a purely parametric approach is adopted. As free parameters we have taken the proton and α-particle flux, their energy distribution, the irradiation time and the composition of the accelerated material. We have shown that at least for the specific simulations presented here, heavy elements can be produced significantly. Obviously, more improvements to the parametric modelling are needed. In particular, a better description of the neutron capture rates at low energies would be desirable, as well as a full survey of the large parametric space characterizing the properties of the accelerated particles. In order to achieve this, detailed magneto-hydrodynamical simulations of the behaviour of the system and the relativistic flow in such a bipolar supernova explosion are needed.

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