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# Explosive nucleosynthesis in core-collapse supernovae and the titanium problem

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**Abstract.** Based on a new mechanism to drive spherically symmetric core-collapse supernovae, PUSH, we perform full network nucleosynthesis calculations for different progenitors. While the $^{56-58}$Ni yields match the observational data very well for certain progenitors, the ejected titanium masses in our calculations are lower than the values inferred from observations. We demonstrate the dependence of ejecta composition on the progenitor structure and the mass cut. Furthermore, we discuss possible solutions to the well-known problem of titanium underproduction.

## 1. Introduction

Recently, the PUSH method for triggering core-collapse supernovae in 1D has been presented ([1], Fröhlich et al., and Ebinger et al., this volume). In this approach, a fraction of the energy of the heavy flavour neutrinos is deposited in the gain region to artificially increase the neutrino heating efficiency in otherwise non-exploding spherically symmetric models. Apart from studying explosion characteristics for a broad range of progenitors, this method provides a good framework for nucleosynthesis studies in core-collapse supernovae.

One of the long-standing problems associated with explosive nucleosynthesis in core-collapse supernovae is the discrepancy in the amount of $^{44}$Ti ejected between observations and simulations, the latter usually being significantly lower than the former. While observations of SN 1987A have reported values between $(0.5 - 4) \times 10^{-4}$ M$_\odot$ [2, 3, 4, 5, 6, 7, 8], simulations (e.g., [9, 10]) typically predict around one order of magnitude less.

We give a short overview of our nucleosynthesis network and compare the composition of the ejecta from two different progenitors in our calculations with the observed values from SN 1987A in section 2. In section 3 we summarize the titanium underproduction problem and discuss possible solutions.

## 2. Composition of the ejecta

The PUSH method is calibrated on observables (explosion energy, $^{56-58}$Ni, and $^{44}$Ti yields) of SN 1987A. To that end, we explore the progenitor space between 18 M$_\odot$ and 21 M$_\odot$, as it is known that the progenitor of SN 1987A is in that mass bracket. After applying a fallback of 0.1 M$_\odot$, many progenitors in that mass range are found to reproduce the $^{56}$Ni yield from

SN 1987A well enough, however only about half of them also produce $^{57}$Ni and $^{58}$Ni to an amount that is needed to match the observational data. The reason can be found in the initial $Y_e$ profiles of the progenitors and the position of the cutoff mass in the supernova simulations. The ejecta composition is plotted against mass coordinates in Figure 1 for two of the progenitors we consider (18.0 $M_\odot$ and 20.6 $M_\odot$) [11]. For the 18.0 $M_\odot$ model, the cutoff mass is 1.56 $M_\odot$ and a large part of the silicon shell is ejected. In this shell, the initial matter composition is slightly neutron-rich (due to a small contribution from $^{56}$Fe) with $Y_e \simeq 0.498$ and the conditions for the production of $^{57}$Ni and $^{58}$Ni are favourable. The transition from silicon shell to oxygen shell for the 20.6 $M_\odot$ model happens around 1.74 $M_\odot$, i.e., inside the mass cut. Therefore, the matter ejected by this model is less neutron-rich and contains less $^{57}$Ni and $^{58}$Ni (see also [12]).

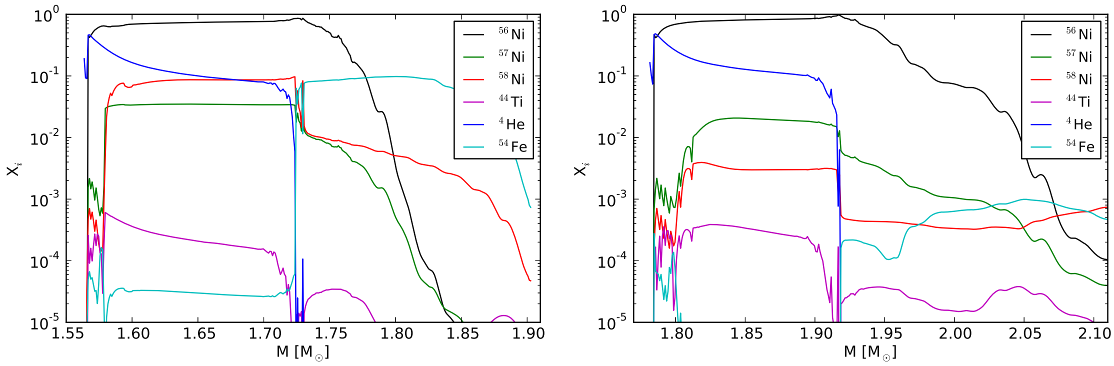


**Figure 1.** Ejecta composition of the 18.0 $M_\odot$ (left) and 20.6 $M_\odot$ (right) progenitors vs mass coordinates.

## 3. Titanium-44

With a fallback of 0.1 $M_\odot$ onto the proto-neutron star, the amount of $^{56-58}$Ni in the ejecta and the explosion energies agree very well with observations of SN 1987A for two of the progenitors we considered (18.0 $M_\odot$ and 19.4 $M_\odot$). However, the inclusion of fallback drastically reduces the ejected amount of $^{44}$Ti, as it is produced in the innermost part of the ejecta. In Figure 2 the ejected amounts of $^{44}$Ti (a) without and (b) with fallback are compared for four different progenitors and five different PUSH parameter sets, plotted against the respective explosion energies. The error box represents the observational values from Seitenzahl et al. (2014) [8].

Too low $^{44}$Ti yield predictions have been a long-standing problem in supernova nucleosynthesis calculations (e.g., [9, 10]). Several uncertainties are connected to the production, destruction, and ejection of $^{44}$Ti. First, ejecta in a supernova may be subject to convective overturn, which cannot be simulated in our 1D approach. To account for this, we can assume homogeneous mixing up to the outer boundary of the silicon shell before cutting off the fallback material (e.g., [13]). As a consequence, the ejected $^{44}$Ti mass for the 18.0 $M_\odot$ progenitor increases to $2.70 \times 10^{-5}$ $M_\odot$ compared to the previous yield of $1.04 \times 10^{-5}$ $M_\odot$. Moreover, there are uncertainties in the main nuclear reactions that are responsible for the production and destruction of $^{44}$Ti. The final amount of produced $^{44}$Ti depends mainly on two reactions: $^{40}$Ca($\alpha$,$\gamma$)$^{44}$Ti and $^{44}$Ti($\alpha$,$p$)$^{47}$V. Recent measurements of the $^{44}$Ti($\alpha$,$p$)$^{47}$V reaction rate concluded that it may be considerably smaller than previous theoretical predictions [14]. Using this smaller cross section, our yield of ejected $^{44}$Ti for the 18.0 $M_\odot$ progenitor rises to $1.49 \times 10^{-5}$ $M_\odot$ with fallback and $5.65 \times 10^{-5}$ $M_\odot$ without fallback (see Figure 3). If we include both the new cross section and homogeneous mixing (corresponding to the red line in Figure 3), the amount of $^{44}$Ti in the

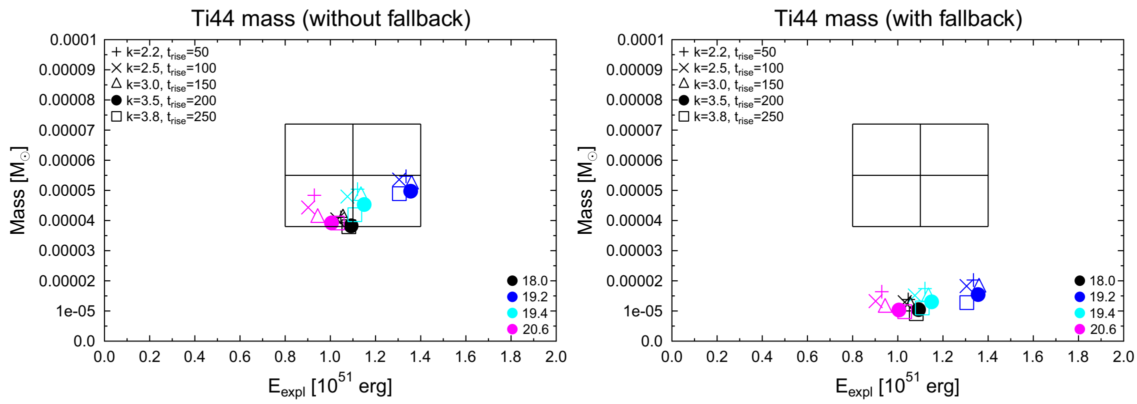


**Figure 2.** Ejected $^{44}$Ti masses for different progenitors and PUSH parameter sets (a) without and (b) with the inclusion of 0.1 $M_\odot$ fallback.

ejecta is $3.99 \times 10^{-5}$ $M_\odot$ including fallback, just within the error range of the observational value reported in Ref. [8].

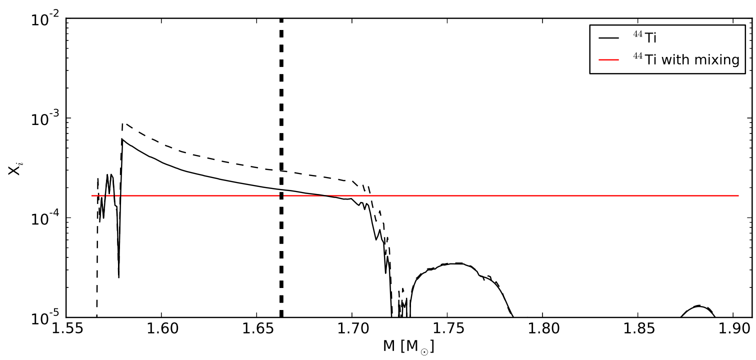


**Figure 3.** $^{44}$Ti yields of the ejecta for the 18 $M_\odot$ star as in Figure 1 (black solid line), and with an updated $^{44}$Ti($\alpha$,$p$)$^{47}$V rate (black dashed line). The red line represents the distribution when in addition to the updated rate homogeneous mixing is assumed. The dashed vertical line indicates the mass cut if 0.1 $M_\odot$ fallback is applied.

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