Reducing Uncertainties in the Production of the Gamma-emitting Nuclei $^{26}\text{Al}$, $^{44}\text{Ti}$, and $^{60}\text{Fe}$ in Core-collapse Supernovae by Using Effective Helium Burning Rates

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Received 2016 November 16; revised 2017 March 18; accepted 2017 March 22; published 2017 April 10

Abstract

We have used effective reaction rates (ERRs) for the helium burning reactions to predict the yield of the gamma-emitting nuclei $^{26}\text{Al}$, $^{44}\text{Ti}$, and $^{60}\text{Fe}$ in core-collapse supernovae (SNe). The variations in the predicted yields for values of the reaction rates allowed by the ERR are much smaller than obtained previously, and smaller than other uncertainties. A “filter” for SN nucleosynthesis yields based on pre-SN structure was used to estimate the effect of failed SNe on the initial mass function averaged yields; this substantially reduced the yields of all these isotopes, but the predicted yield ratio $^{60}\text{Fe}/^{26}\text{Al}$ was little affected. The robustness of this ratio is promising for comparison with data, but it is larger than observed in nature; possible causes for this discrepancy are discussed.

Key words: galaxies: nuclei – Galaxy: abundances – nuclear reactions, nucleosynthesis, abundances

1. Introduction

Astronomical observations of gamma-rays from long-lived radioactive nuclei provide unique opportunities for nuclear astrophysics. The flux of gamma-rays from the decay of $^{26}\text{Al}$ can be used to infer the rate of supernovae (SNe) in the galaxy (Diehl 2013). And since $^{26}\text{Al}$ and $^{60}\text{Fe}$ are made in different radial shells of massive stars (e.g., Timmes et al. 1995), the ratio of their fluxes can provide a stringent test of massive star and SN models. Convincing conclusions, however, require reliable predictions of the production rate of these gamma emitters in SNe, and the current status is far from satisfactory.

An important problem is the large impact of uncertainties in the reaction rates $r_{3\alpha}$ and $r_{\alpha\gamma}$ of the helium burning reactions: $3\alpha$ and $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$. It was found (Tur et al. 2010) that over a range of $\pm 2\sigma$, where $\sigma$ is the experimental uncertainty in the helium burning rates, the production of $^{26}\text{Al}$ varies by about a factor of three. The production of $^{60}\text{Fe}$ and the ratio of $^{26}\text{Al}$ to $^{60}\text{Fe}$ vary by much larger factors. As a result, predictions of the yields of the gamma nuclei are not robust, and depend on the particular values of the helium burning rates chosen from within the allowed experimental ranges.

In this paper, we attempt to address this issue by using an effective reaction rate (ERR) for the helium burning reactions (West et al. 2013; Austin et al. 2014) to predict the yields of the gamma nuclei. Compared to the earlier calculations, this greatly reduces the predicted variation of their yields. With the helium burning rate problem then mainly under control, we examine some of the issues that remain. In particular, we examine the nature of the effects of failed SNe, by considering the model of O’Connor & Ott (2011). In this context, we conclude, tentatively, that the ratio of $^{60}\text{Fe}$ and $^{26}\text{Al}$ abundances is a robust observable. Whether this remains the case when more sophisticated models of these and related effects is considered appears to remain an unresolved question.

2. Method

This ERR had been determined by parameterizing the two helium burning rates and fixing the parameters by fitting the results of SN nucleosynthesis to the abundance pattern (Lodders 2010) of isotopes produced mainly in core-collapse SNe: the intermediate mass and $s$-only nuclei. This procedure simultaneously treats the uncertainties of the two reaction rates in the context of the KEPLER code as described in Rauscher et al. (2002). After scaling the rates relative to standard values, as done in Tur et al. (2007), we found that equivalently good matches occur along a line correlating the two rates: $r_{\alpha\gamma} = r_{3\alpha} + 0.35$ as shown in Figure 1 of Austin et al. (2014). The line samples the full $\pm 2\sigma$ range of $r_{3\alpha}$, but $r_{\alpha\gamma}$ is more constrained; we therefore plot the results below as a function of $r_{3\alpha}$. We had anticipated that the rates would be constrained in both $r_{\alpha\gamma}$ and $r_{3\alpha}$, but the fitted production rates did not lead to that constraint.

The yields of the gamma nuclei were obtained by West et al. (2013) using the KEPLER code (Weaver et al. 1978; Woosley & Weaver 1995; Rauscher et al. 2002; Woosley et al. 2002; Heger et al. 2005) to model the evolution of sets of 12 initial stellar masses (12, 13, 14, 15, 16, 17, 18, 20, 22, 25, 27, and $30\,M_{\odot}$) from central hydrogen burning to core collapse. A $1.2 \times 10^{51}\,\text{erg}$ explosion was then simulated using a piston placed at the base of the oxygen shell (Woosley & Heger 2007). For each mass, calculations were made for a rate matrix covering approximately $\pm 2\sigma$ for $r_{\alpha\gamma}$ and $r_{3\alpha}$, a total of 176 rate pairs. It is now known that not all massive stars explode (e.g., Smartt 2009). To get a rough idea of this effect on yields of the gamma nuclei, we applied a compactness parameter filter (O’Connor & Ott 2011; West et al. 2013; Sukhbold & Woosley 2014), namely, $\xi_2 < 0.25$, to account for these failed SNe. Stars with masses 22, 27, and $30\,M_{\odot}$ as well as a few $r_{\alpha\gamma}$, $r_{3\alpha}$ pairs at other masses did not satisfy this criterion, and were assumed not to explode.
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We then calculated the average yield \( Y \) for the initial mass function (IMF) using the usual formulae:

\[
Y_i(r) = \frac{m_{i+1} - m_i}{m_{i+1} - m_i} Y(m_i) + \frac{m - m_i}{m_{i+1} - m_i} Y(m_{i+1}),
\]

\[
Y = \left[ \sum_{i=1}^{N-1} \int_{m_i}^{m_{i+1}} Y(m) m^{-2.35} \, dm \right] / \int_{m_1}^{m_N} m^{-1.35} \, dm,
\]

where \( m_i \) and \( Y(m_i) \) are taken from the \( r_{\alpha,\gamma} \) versus \( r_{3\alpha} \) grid (West et al. 2013; Austin et al. 2014).

3. Results and Discussion

In Figure 1, we show the results of these calculations, expressed as an average over a Salpeter IMF with an exponent of \(-2.35\). The results are given for equally spaced (in \( r_{3\alpha} \)) points along the ERR line. For our standard case, labeled STD, we omit the explosive yields of the failed SNe, but include wind contributions since winds are mainly emitted before the onset of core collapse. To show the effects of the compactness parameter filter, we also give the results of the unfiltered calculations, including the yields for all calculated stars (labeled ALL). As expected, the IMF averages for the \( M_{\odot} \leq 20 \) subset of our grid (not shown) differ little from the STD case.

In this figure, the mass-to-mass variations arise mainly from binning effects; not all simulations were performed at points that lay precisely on the ERR line, and some interpolation was required.

There are two immediate conclusions from this figure. First, the yields display only small variations along the ERR line. This is true for both the STD and ALL results. In contrast, the variations corresponding to independent uncertainties in \( r_{3\alpha} \) and \( r_{\alpha,\gamma} \), as determined in Tur et al. (2010), are much larger as shown by the colored bars. Second, the effects of the simple compactness parameter filter are rather large, as shown by the differences of the STD and ALL results.

Given the importance of the compactness parameter filter, we show in Figure 2 how \( \xi_{2.5} \) depends on mass and reaction rates along the ERR line. Previously, there have only been estimates for variations in \( r_{\alpha,\gamma} \) (Sukhbold & Woosley 2014). The results for our grid indicate that if the rates are varied along the ERR line, variations of \( \xi_{2.5} \) are relatively small for most stars. The \( 20 M_{\odot} \) star shows larger fluctuations, perhaps related to its complex convection structure (Rauscher et al. 2002; Limongi & Chieffi 2006; Tur et al. 2010). See Sukhbold & Woosley (2014) for a detailed discussion.

Results for the Fe/Al production ratios are shown in Figure 3. Again, the use of the ERR significantly reduces the variations compared to those obtained earlier (Tur et al. 2010). The interpolation effects are relatively small, and the ratios are rather similar for the STD, AND, and 12–20 \( M_{\odot} \) cases.

All these values, however, are significantly larger than the values (\( \pm 1 \sigma \) range) of 0.20–0.46 inferred from the flux observations (Wang et al. 2007; Diehl 2013) by multiplying them by 60/26. A recent paper describing flux observations in detail (Bouchet et al. 2015) yields entirely consistent results with similar uncertainties.

The present predictions for this ratio and for the individual yields for given stellar masses are also larger than those of Limongi & Chieffi (2006, hereafter LC; see Tur et al. 2010). One might speculate that this is due to different treatments of convection and to other stellar model choices that affect the details of the convection structures of a star. Convective processes can, for example, carry nuclei to hotter regions of the star where their effective lifetime and survival probability are significantly reduced. These effects can be large for the gamma nuclei or other nuclei involved in their production (\(^{59}\)Ni, for example) as discussed in Tur et al. (2007, 2010). Alternatively, these differences may arise from different choices for the helium
burning rates, which can also affect the convection structure of the star. As noted above, these effects can be large.

It is encouraging that the more detailed approach of Sukhbold et al. (2016), apparently using the same rates for non-helium burning reactions as in this Letter, leads to a decrease in the Fe/Al ratio. However, Sukhbold et al. did not consider the effects of uncertainties in the two helium burning reactions discussed here and in Tur et al. (2010), so this conclusion is tentative.

Differences in other reaction rates also impact the Fe/Al ratio. The present simulations are part of an extended series of simulations (Tur et al. 2007, 2009, 2010; West et al. 2013) aimed at understanding the effects of uncertainties in the helium burning rates on various observables. For this purpose, we chose to use the default KEPLER rates for other reactions, even though some had been superseded. Woosley & Heger (2007, hereafter WH) and Brown & Woosley (2013, hereafter BW) discussed the effects of updating these rates and found that the ratio was reduced to about 1.0. These authors also discuss other changes in reaction rates, in explosion energies, and in stellar models that would produce further effects. The most important changes were to update the rates for the $^{26}$Al($p$, n)$^{27}$Mg and $^{28}$Al($\alpha$, $\alpha$)$^{32}$Al reactions, but a final resolution of these issues will probably require additional measurements (Iliadis et al. 2011). Changes in the opacities used in certain regions of the star were also important.

It is also possible that there are other sources of Fe or Al. The galactic mass of $^{26}$Al is 1.5–3.6 $M_\odot$ (Diehl 2013). Bennett et al. (2013) and C. Wrede (2014, personal communication) note that up to 0.6 $M_\odot$ of galactic $^{26}$Al could be produced by classical novae. This would increase the ratio in the contributions of massive stars, but not by enough to remove the discrepancy.

The LC, WH, and BW calculations include contributions from stellar masses above 30 $M_\odot$. It is not clear, however, to what extent these masses are relevant. The estimates of Sukhbold et al. (2016) indicate that most stars with $M > 30 M_\odot$ do not explode, although they may expel most or all of their envelope. Other newer simulations (Pejcha & Thompson 2015; Cote et al. 2016; Ertl et al. 2016; Muller et al. 2016; Sukhbold et al. 2016) also allow explosions for larger masses in some cases. Characterization of a complex phenomenon in terms of a single compactness parameter is a substantial approximation, and the newer simulations indicate that more complex criteria yield a sharper distinction between explosive and non-explosive scenarios. It seems a safe conclusion, however, that much remains to be done before this issue is settled.

There remains the issue of the ERR itself. Once one has determined such an effective rate, the principal test is that it reproduces a variety of observables not involved in its determination. So far, we have shown that using the ERR, rather than the central values of the rates with errors treated as independent, greatly reduces variations owing to uncertainties in the helium burning reaction rates for: the values of the central carbon fraction at the end of helium burning and of the remnant mass (West et al. 2013); the yields of the neutrino nuclei (Austin et al. 2014); and in this Letter, the yields of the gamma nuclei. This satisfies an important necessary condition, but there remains the question of whether the absolute values of the observables are reproduced. Since one does not know any of the observed or predicted values with the necessary accuracy, it is perhaps useful in this circumstance to estimate the yield changes owing to the uncertainty in our determination of the ERR.

One can obtain an estimate of the uncertainty in the location of the ERR line from the detailed discussion in West et al. (2013), where the location is specified by $r_{\alpha} = r_{\alpha_{0}} + b$ and $b = 0.35 \pm 0.2$; our calculations used $b = 0.35$. We have repeated the calculations for $b = 0.2$ and $b = 0.5$. We find that the average differences in yields, compared to those for the central value, are 18%, 7%, and 22% for $^{26}$Al, $^{44}$Ti, and $^{60}$Fe, respectively. For $^{26}$Al and $^{44}$Ti the deviations are largest toward $b = 0.5$ and for $^{60}$Fe toward $b = 0.2$.

It appears that uncertainties in the ERR for helium burning reactions introduce yield uncertainties that are smaller than those resulting from other uncertainties. The uncertainties arising from the determination of which stars explode are perhaps the largest.

4. Conclusions

We find that:

1. Using the ERR for the helium burning reactions, rather than treating the rates and their uncertainties as independent, results in much smaller variations in predicted $^{26}$Al and $^{60}$Fe

Figure 2. Compactness parameters. The heavy dark line at $\xi=0.25$ is the value assumed to divide stars that are likely to explode in the model of O’Connor & Ott (2011) from those that are not.
yields and their ratio in SNe, as is shown in Figures 1 and 3. The variations are smaller than other uncertainties.  

(2) The $^{60}$Fe/$^{26}$Al yield ratio may be the most robust observable involving the gamma nuclei. Systematic observational errors are smaller for the ratio than for individual yields. We have shown that predictions of the ratio do not depend strongly on the helium burning rates or on the sample of stars considered, or on which stars undergo successful explosions. Given the present uncertainty in this latter determination, this is an important advantage. Other mechanisms may eject part of the envelop in weak and/or failed SNe and lead to additional $^{26}$Al production; see Lovegrove & Woosley (2013) for a theoretical description and Adams et al. (2016) for observational evidence.

(3) Use of the ERR may provide a superior approach to reducing the uncertainties in nucleosynthesis yields due to uncertainties in convective structure and boundary mixing during core helium burning. The strong yield variations in the earlier results, especially for $^{60}$Fe, were ascribed to the sensitivity of the convection structure of the star to the helium burning rates (Rauscher et al. 2002; Tur et al. 2010).

(4) Unfortunately, we cannot at present take advantage of the transparency of the galaxy to high-energy gamma-rays and the accurate high-resolution observations from the SPI spectrometer on the INTEGRAL satellite (Diehl 2013). Other relevant reaction rates and simulation inputs need to be improved. In addition to the uncertainties in the fraction of SNe that explode, there remain, for example, questions on the effects of Wolf–Rayet winds on the production of $^{26}$Al, the effects of the explosion energy on explosive burning yields, changes arising when evolving stars are part of a binary system, and effects and uncertainties in the convection structure of evolving stars.

Figure 3. Ratio Fe/Al of the IMF averaged yields for the STD and ALL results of Figure 1 and for the range 12–20 $M_\odot$. The horizontal band covering ±18% gives an indication of the precision of the present results. The narrow vertical bar shows the variations found in previous calculations (Tur et al. 2010) for the Lodders (2003) abundances; the bar extends to 10.

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Research support from: US NSF; grants PHY08-22648 (JINA), PHY-1430152 (JINA-CEE), PHY11-02511; US DOE: contract DE-AC52-06NA25396, grants DE-FC02-01ER41176, FC02-09ER41618 (SciDAC), DE-FG02-87ER40328. A.H. was supported by an ARC Future Fellowship (FT120100363) and SMA by Michigan State University.