Nuclear Physics of Type Ia Supernovae: Diagnostics and Nucleosynthesis

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Overview: Supernova Nucleosynthesis

- Stellar evolution and supernova theory together with recent observations of metal deficient ([Fe/H] ≤ -1.5) stars have confirmed that the ejecta of SNe II are characterized by elevated ratios of α-elements (O to Ti) relative to iron: 
  \[
  \left(\frac{\alpha\text{-elements}}{\text{Fe}}\right) \approx +0.5
  \]

- This implies that the contributions of SNe Ia to $^{56}\text{Fe}$ (via $^{56}\text{Ni}$ and $^{56}\text{Co}$) comprise $\approx 2/3$ of Galactic iron.

- Given that SNe Ia produce $\approx 0.6 \, M_\odot$ per event while SNe II produce only $\approx 0.1 \, M_\odot$ per event, it follows that SNe II have been $\approx 3$ times more numerous averaged over Galactic history.

- Both SNe Ia and SNe II form mass 56 in a neutron-deficient environment primarily as $^{56}\text{Ni}$, and to the best of our knowledge their isotopic compositions of iron-group nuclei are the same.
α-Elements in Metal-Deficient Halo Stars

**Oxygen**

![Oxygen Diagram](image)

**Titanium**

![Titanium Diagram](image)

**Calcium**

![Calcium Diagram](image)

**DLA's: (Lu et al. 1996)**

![DLA Diagram](image)
Supernova Nucleosynthesis

SNe II Nucleosynthesis

(THEIEMANN, HOMOTO AND HASHIMOTO 1992)

SNe Ia Nucleosynthesis

Mass fractions of several major nuclei as they result from post-shock supernova processing.
Supernova Ia Nucleosynthesis

- Early studies of Type Ia models and associated nucleosynthesis focused on the “carbon detonation model” of Arnett (1969).

- We now recognize that this results in the burning of the entire core to $^{56}\text{Ni}$, in disagreement with recent spectroscopic studies of SNe Ia ejecta which reveal the presence of intermediate mass elements.

⇒ Not a Pure Detonation

(Arnett, Truran, and Woosley 1971)
Explosive Iron-Peak Nucleosynthesis in Supernovae

Figure 14. The detailed evolution for the exterior mass zone is traced through the expansion and cooling. The mass fractions of representative nuclei are plotted as a function of decreasing temperature.

PREDOMINANT COMPOSITION OF MATTER IN STATISTICAL EQUILIBRIUM

IRON PEAK

HELIUM
SNe Ia Nucleosynthesis Considerations

- $^{56}$Ni-dominated iron peak required:
  - Best fit to isotopic composition of the bulk of iron-peak nuclei.
  - Powering of SNe Ia light curve. Robustness of SNe Ia properties.

- $X(^{56}$Ni) constrained by neutronization:
  - Weak interactions in dense inner core drive neutronization yielding high levels of $^{54}$Fe, $^{58}$Ni, and even $^{56}$Fe.
  - Primordial heavy element abundance converted to $^{22}$Ne provides effective neutronization - reduced $Y_e$.
  - Equilibrium/frozen’ abundances both are sensitive to such neutronization.

- Late entry of SNe Ia iron in Galaxy.
- No evidence for possible differences in isotopic production by SNe Ia and II.
Explosive (T>4x10^9 K) supernova incineration of ^12C, ^16O, and ^28Si yields proton-rich iron-peak product nuclei of Z≈N (Y_e≈0.5), viz. ^44Ti, ^48Cr, ^52Fe, ^56Ni, ^60Zn, and ^64Ge (Truran, Arnett, and Cameron 1967; Arnett, Truran, and Woosley 1971).

Relatively small changes (decreases) in Y_e can, however, influence the emerging abundance patterns.

Such increases in N/Z (or decreases in Y_e) can be introduced by weak interactions at higher densities – or by the presence of the neutron rich isotope ^22Ne in the stellar matter.
$^{56}\text{Ni}$ Production in Explosive Nucleosynthesis
SNe Ia Nucleosynthesis Considerations

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Nickel Variations

- Nearly all one-dimensional Chandrasekhar mass models of Type Ia supernovae produce most of their $^{56}$Ni in a nuclear statistical equilibrium environment between mass shells 0.2 $M_\odot$ and 0.8 $M_\odot$.

- In this region weak reactions occur on long timescales and the degree of neutron enrichment is contained in the $^{22}$Ne abundance.

(Iwamoto et al. 1999)
Silicon Burning with Weak Interactions = f(T)

T = 3 \times 10^9 \; \text{K}
\rho = 2 \times 10^6 \; \text{g/cc}

Weak Interactions Included

T = 4 \times 10^9 \; \text{K}
\rho = 2 \times 10^7 \; \text{g/cc}

Weak Interactions Included
Explosive Oxygen Burning Nucleosynthesis

Fig. 9. Nucleosynthesis in a typical zone for explosive oxygen burning. The time coordinate gives the time after the deflagration front hits this specific mass zone.
SNe Ia Nucleosynthesis Considerations

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Nearly all one-dimensional Chandrasekhar mass models of Type Ia supernovae produce most of their $^{56}\text{Ni}$ in a nuclear statistical equilibrium environment between the mass shells $0.2\, M_{\text{sun}}$ and $0.8\, M_{\text{sun}}$. 
Hydrogen burning (CNO cycles): all initial CNO nuclei are converted to $^{14}$N

Helium burning: all $^{14}$N $\Rightarrow$ $^{22}$Ne via the reactions

$^{14}$N($\alpha$,\(\gamma\))$^{18}$F(e\(^+\),\(\nu\))$^{18}$O($\alpha$,\(\gamma\))$^{22}$Ne

The white dwarf progenitors of Type Ia supernovae have a composition of $^{12}$C, $^{16}$O, and approximately 2.5 percent $^{22}$Ne.

The scatter in CNO abundances in the ISM of our Galaxy (Edvardsson 1995) gives an effective range for $^{22}$Ne of 0.8 to 7.5 percent.
The iron-to-hydrogen ratio is a chronometer in that the accumulation of iron in the interstellar medium increases monotonically with time ⇒ an “age-metallicity” relation.
A scatter of a factor of 3 about the mean in the initial metallicity leads to a variation of about 30% (0.15 M_) in the mass of $^{56}$Ni ejected. An increased metallicity by a factor 3 - as in early type galaxies - reduces the peak brightness of SNe Ia by this factor.

The peak brightness variation caused by this variation in the mass of $^{56}$Ni ejected is $\Delta M_V \sim 0.3$ mag. which doesn’t account for all the observed variation.
High metallicity populations may be expected to exhibit lower peak Supernova Ia luminosities.

The range of metallicities characteristic of the stellar components of spiral galaxies can yield significant scatter in peak luminosities of their SNe Ia.

Early type galaxies - particularly those of higher mass - are characterized by abundances \( \approx 2-4 \, Z_\odot \) and may therefore both show less scatter in peak luminosity and have fewer of the brightest SNe Ia. (See, e.g., Hamuy et al. 2002; Garnavich 2004)
Possible Stellar Population Dependences

Fig. 1.—$B-V$ color (top) and morphological type (bottom) of the SN host galaxy vs. decline rate of the SN.

Fig. 2.—Decline rate of the SN (top) and $B-V$ color of the SN host galaxy (bottom) vs. absolute $V$ magnitude of the SN host galaxy.

(Hamuy et al. 2002)
Type Ia Simulations and Nucleosynthesis

- Detailed nucleosynthesis calculations for 2D and 3D hydrodynamic simulations are necessarily constrained to the use of small networks. A remedy has been to compute the isotopic yields and their velocity distribution with the use of massless tracer particles embedded in the star (e.g. Travaglio et al. 2004).

- Here the initial spacial distribution of these tracers is proportional to the mass density and the particles are advected using the interpolated fluid velocity, such that the particle ensemble provides a Lagrangian description of the explosion.

- We have performed such a calculation (Brown et al. 2004) in the context of a two-dimensional deflagration simulation. Along each particle trajectory in (ρ,T) space, we evolved a 214-isotope reaction network spanning the range from n, p, and α-particles to $^{70}$Zn. The reaction rates were taken from the REACLIB compilation (Rauscher & Thielemann 2000) and the weak interaction rates from Langanke & Martínez-Pinedo (2001).
Tracer particle temperatures after 2.0 seconds of evolution. (Brown et al. 2004) There are approximately 10,000 tracer particles, with an initial spacial distribution proportional to mass density.

These arise from a two dimensional simulation performed in cylindrical coordinates, at an equivalent resolution of 8 km. The white dwarf was initially cold, with $T=5\times10^7$ K, $M=1.38M_\odot$, and $R=2.13$ km.
Type Ia Simulations and Nucleosynthesis

Mass abundance of selected isotopes as a function of Lagrangian mass coordinate.

The summed mass fraction of isotopes produced in the numerical simulation.
We have explored as well the dependence of the $^{56}\text{Ni}$ abundance on the initial metallicity as reflected in $^{22}\text{Ne}$. We recomputed the nucleosynthesis for the cases $X(^{22}\text{Ne}) = 0.2$ and 0.6 and substantially reproduced the analytic results of Timmes et al. (2003).
Concluding Comments

- From observations of halo stars and damped Lyman-α systems, SNe II contribute \( \approx 1/3 \)rd Galactic iron. Taking ejected masses \( 0.1 M_{\odot} \) for SNe II’s and \( 0.6 M_{\odot} \) SNe Ia’s gives \( R_{\text{II}}/R_{\text{Ia}} = 3 \). (Dahlen et al: “Investigating the intrinsic ratio of exploding core collapse events to SNe Ia gives a ratio \( \approx 3 \)....”)

- First contributions from SNe Ia occur at \( \approx \) onset of disk activity at metallicity \([\text{Fe/H}] \approx -1\). (Dahlen et al: “We find characteristic delay times \( \tau > 2 \) Gyr are consistent with the data”)

- It follows that the frequency of SNe Ia at higher redshifts can be expected to decrease. (Dahlen et al. (2004) “identify a decrease in the SNe Ia rate over the range \( z = 1 \) to 1.6.”)

- Neutronization of inner core by electron captures less severe with new rates of Langanka and Martinez-Pinedo (2001).

- Elevated primordial enrichments contained in \(^{22}\text{Ne}\) can reduce the \(^{56}\text{Ni}\) mass produced in the critical \( 0.2 \) to \( 0.8 M_{\odot} \) range and thereby the peak luminosity.

- Detailed nucleosynthesis calculations in tandem with observations of SNe Ia ejecta as a function of velocity can substantially constrain and guide theoretical modeling.