Nuclear Physics Constraints on the Characteristics of Astrophysical Thermonuclear Flashes

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Abstract. We review the nuclear physics that is associated with the outbursts of Type Ia
(thermonuclear) supernova explosions and with the thermonuclear runaway events that define
the outbursts of both classical novae and recurrent novae. We describe how distinguishing
characteristics of these two classes of astrophysical explosion are strongly dependent both
upon fuel ignition in degenerate matter and upon the rates of critical charged-particle reaction
rates and weak interaction rates. In this centennial celebration of the important contributions of
Rutherford and his collaborators to our understanding of the structure of the nucleus of an
atom, it is quite interesting to note the evolution of the $\alpha$-particle scattering experiments
described in Rutherford’s seminal paper (Rutherford 1911) to current studies of $\alpha$-particle
induced reactions and their defining roles in studies of stellar, nova, and supernova
nucleosynthesis. We identify and discuss for example: (1) the manner in which ($\alpha$, p) reactions
in proximity to the Z = N line carry the major flows from $^{12}$C and $^{16}$O to $^{56}$Ni in Type Ia
supernovae; and (2) the critical role of the $^{15}$O($\alpha$,γ)$^{19}$Ne reaction in possibly effecting
“breakout” of the Hot CNO cycles at the highest temperatures achievable in Classical Novae.
In this contribution, we first review the current status our understanding of Type Ia supernova
events and then that of Classical Novae.

1. Introduction
It is recognized that diverse astrophysical phenomena are consequences of thermonuclear runaways in
matter at high densities and high temperatures: classical novae are powered by runaways in accreted
hydrogen shells on white dwarfs; Type I X-ray bursts are powered by runaways in accreted
hydrogen/helium shells on neutron stars; and Type Ia supernovae are powered by the complete
incineration of carbon-oxygen white dwarfs to iron-peak nuclei. In all cases, it is generally accepted
that these events take place in close binary systems in which the occurrence of mass transfer from a
companion star is a contributing factor. Numerical simulations of these three classes of events have
identified critical nuclear physics constraints/behaviors that strongly impact the observed outburst
characteristics. Both novae and X-ray bursts are triggered by and powered by the Hot CNO Cycles, for
which the rate of energy generation is constrained by the slower rates of positron decays. For the case
of Type Ia supernovae, the critical nuclear physics consideration is that the incineration of the carbon-
oxogen (CO) white dwarf leading to synthesis of “iron-peak” isotopes occurs under neutron poor
conditions ($Y_e \approx 0.5$) in an approximate Nuclear Statistical Equilibrium. Such conditions are quite
naturally realized in the explosive burning of carbon-oxygen fuels in Type Ia events and yield $^{56}$Ni as
the dominant nucleosynthesis product. In the following sections we review, both for Type Ia supernovae and for classical novae, the nature of their outbursts, the critical roles played by nuclear physics in the determination of their outburst characteristics, and implications for explosive nucleosynthesis and the enrichment of Galactic matter.

2. Type Ia (Thermonuclear) Supernovae

We note in perspective that supernova explosions can be powered either by thermonuclear energy release (Type Ia) or by gravitational energy release (Type II). In this review we concentrate specifically on thermonuclear supernovae. Surveys indicate a rate of occurrence of these brightest of supernova events, in galaxies like our Milky Way, of approximately one event per century, but the last two such events seen in our Galaxy were those by Tycho Brahe (1572) and Johannes Kepler (1604). The standard model of for the outbursts of Type Ia supernova events involves the thermonuclear disruption (and effective incineration) of a white dwarf star of mass \( \sim 1.4 \, M_\odot \) composed of roughly equal mass fractions of \(^{12}\text{C}\) and \(^{16}\text{O}\) fuel. It is understood that mass transfer in close binary systems leads to growth of the white dwarf to the Chandrasekhar limiting mass. The dominant products of nucleosynthesis at the high temperatures and densities characteristic of such explosive burning are self-conjugate nuclei, with \(^{56}\text{Ni}\) being the most abundant nucleus in the iron-peak region. For a Chandrasekhar mass white dwarf, the energy release in the full incineration of equal masses of \(^{12}\text{C}\) and \(^{16}\text{O}\) to \(^{56}\text{Ni}\) exceeds \(10^{51}\) ergs, more than sufficient both to unbind the white dwarf and to account for the high velocity of the supernova ejecta. The more important consideration here, however, is the production of mass \(A=56\) nuclei as the unstable nucleus \(^{56}\text{Ni}\) (\(\tau = 8.5\) days), the decay of which through \(^{56}\text{Co}\) (\(\tau = 111.5\) days) to the stable \(^{56}\text{Fe}\) powers the light curves of SNeIa. In 1998, the use of SNeIa as effective ‘standard candles’ was found to provide strong evidence for an accelerating cosmic expansion \[1,2\]. The fact that the peak luminosity of such an event is approximately proportional to the \(^{56}\text{Ni}\) mass \[3\] emphasizes the significance of understanding the nuclear physics that dictates the production of nickel relative to “intermediate mass nuclei” (IMN), like those in the silicon-to-calcium mass region, in diverse Type Ia events. In the following discussions, we will explore the nature of \(^{56}\text{Ni}\) production in SNe Ia and predictions both for the nature of the observed diversity in supernova brightness and for nucleosyntheses.

The history of our understanding of iron production in supernovae reveals the sensitivity of such production to both the underlying nuclear physics and the conditions that prevail in the cores of the stellar progenitors. Hoyle \[4\] identified the site of the synthesis of iron-peak nuclei (viz. isotopes of Ti, V, Cr, Mn, Fe, Co, Ni, Cu, and Zn) with a “nuclear statistical equilibrium” (NSE) process that operates under these conditions. Hoyle and Fowler \[5\] identified SNe Ia with explosions of white dwarfs in which carbon and oxygen fuels were burned to iron peak nuclei. These authors’ were guided by the view that nuclei of mass \(A=56\) were formed as \(^{56}\text{Fe}\) \[6,7\]. Cameron \[8\] noted rather the strong dependence of iron-peak explosive nucleosynthesis products on neutron enrichment (\(Y_e\)), a feature that ultimately led to the recognition \[9\] that typical supernova conditions yield \(^{56}\text{Ni}\) as the principle product \(\textit{in situ}\). The first paper to incorporate the effects of \(^{56}\text{Ni}\) decay in a study of SNe Ia light curves was that of Colgate and McKee \[10\].

Why is \(^{56}\text{Ni}\) production characteristic of these explosive supernova environments? The answer to this question again reflects the complex interplay between nuclear physics and astrophysics. Pre-explosion compositions of both Type Ia and Type II supernovae both involve primarily self-conjugate nuclei, viz. \(^{12}\text{C}\), \(^{16}\text{O}\), and \(^{28}\text{Si}\). Explosive burning at temperatures exceeding \(\sim 4 \times 10^{9}\) K typically occurs on short/dynamic timescales of seconds or fractions thereof. Weak interactions (e.g. electron captures) here proceed too slowly to convert and significant fraction of protons to neutrons. It follows that the most abundant iron-peak products \(\textit{in situ}\) of nucleosynthesis in supernovae are proton-rich nuclei of \(Z \approx N\), viz. \(^{40}\text{Ca}\), \(^{44}\text{Ti}\), \(^{48}\text{Cr}\), \(^{52}\text{Fe}\), \(^{56}\text{Ni}\), \(^{60}\text{Zn}\), and \(^{64}\text{Ge}\). The nuclear build-up for \(Y_e \approx 0.5\) proceeds closely along the \(Z=N\) line through \(^{56}\text{Ni}\) and \(^{60}\text{Zn}\) via \((\alpha, p)\) followed by \((p, \gamma)\) reactions.
Strong supporting evidence for the conclusion that the iron-peak nuclei are formed under neutron-poor conditions is provided by scrutiny of the manner in which the isotopic patterns of the even-Z iron peak nuclei are formed in such events. For purposes of illustration, we note specifically: in the considered supernova environments $^{50}$Cr is formed directly as $^{50}$Cr, while $^{52}$Cr and $^{53}$Cr are decay products of $^{52}$Fe and $^{53}$Fe; $^{54}$Fe is synthesized as $^{54}$Fe, while $^{55}$Fe and $^{57}$Fe are decay products of $^{56}$Ni and $^{57}$Ni, respectively; and $^{58}$Ni is synthesized as $^{58}$Ni, while $^{60}$Ni, $^{61}$Ni, and $^{62}$Ni are decay products of $^{60}$Zn, $^{61}$Zn, and $^{62}$Zn – but the resulting isotopic patterns for the elements chromium, iron, and nickel are consistent with the isotopic composition of Solar System/Cosmic matter. The manner in which these patterns are generated strongly suggests that a neutron-poor environment is essential. This characteristic of the isotopic patterns of iron-peak nuclei formed in explosive nucleosynthesis is apparent in the figure below that identifies both the proton-rich nuclei along the alpha line and the stable isotopes in the iron peak regime to which they decay. This behavior again confirms that the iron-peak elements are indeed formed under neutron-poor ($Y_e \approx 0.5$) explosive burning conditions, for which $^{56}$Ni is the dominant product. In the figure below note that the decays of the isotopes $^{47}$V, $^{48}$Cr, $^{49}$Cr, $^{51}$Mn, $^{52}$Fe, $^{53}$Co, $^{55}$Ni, $^{56}$Cu, $^{60}$Zn, $^{61}$Zn, $^{62}$Zn, $^{63}$Ga, $^{64}$Ge, $^{65}$Ge, and $^{66}$Ge all proceed directly to stable isotopes of iron-peak nuclei for elements titanium to germanium. This behavior is indeed a forced consequence of explosive nucleosynthesis.

![Figure 1: The nuclear chart in the iron peak regime from calcium to krypton. Stable isotopes are shown in blue. Unstable isotopes in proximity to the Z=N line that constitute significant radiogenic decay parents of abundant stable isotopes of iron-peak nuclei are shown in yellow. This illustrates the character of the synthesis of iron-peak nuclei occurring under proton-poor burning conditions in explosive supernova environments, where the reaction flows follow closely the Z=N line.](image-url)
The significance of the production of \(^{56}\text{Ni}\) as a major product of explosive nucleosynthesis in Type Ia supernovae is clear: since most of the energy release in the burning of \(^{12}\text{C}\) and \(^{16}\text{O}\) to iron-peak nuclei is expended in unbinding the white dwarf and in powering the ejecta, it is in fact the decay of \(^{56}\text{Ni}\) to \(^{56}\text{Co}\) and \(^{56}\text{Fe}\) that powers their light curves. The mass ejected in the form of \(^{56}\text{Ni}\) (and neighboring iron-peak nuclei) is therefore known with reasonable accuracy. Since most of the remaining ejecta mass is in nuclei from oxygen to calcium (“intermediate mass elements”), we can hope to quantify the contributions from both Type Ia and Type II supernovae. Constraints on supernova explosion models can then be identified, if we can understand the factors that can influence the \(^{56}\text{Ni}\) mass and use both observations and theory to quantify their impact. We now appreciate that, while Type Ia supernovae are the only type of supernova event seen to occur in early type (elliptical) galaxies, they are also observed to occur in younger stellar populations. The view that SNe Ia can have short-lived progenitors (~ \(10^8\) years) was first emphasized many years ago by Oemler and Tinsley [11], based upon their recognition that the SNe Ia rate per unit mass is very high in irregular galaxies and roughly proportional to their present star formation rates in spiral galaxies. The observational support for both short lived and long lived progenitors for SNe Ia has been explored by a number of sources. The observed trends can be briefly summarized as follows: (1) A rather broad range of peak Type Ia supernova luminosities is observed quite independent of galaxy type (environment), that is both for young stellar populations (e.g. spiral and irregular galaxies) and for older stellar populations (e.g. elliptical or S0 galaxies). For spiral galaxies, the spread can be greater than a factor ~ 5, while for elliptical galaxies the spread is reduced by perhaps 20-30 percent. (2) The mean luminosities of SNe Ia observed in spiral galaxies are clearly higher than those of elliptical galaxies [13,14]. A significant feature here is the absence of the brightest SNe Ia in elliptical and S0 galaxies.

There are a number of factors that can impact the \(^{56}\text{Ni}\) mass (and associated variations in peak luminosities) that we can identify. These include: the degree of neutronization of particularly the innermost/denser regions of the core e.g. by electron captures during the outburst, the degree of pre-expansion occurring prior to ignition of detonation in deflagration-detonation transition (DDT) models, gravitationally confined detonation (GCD) models, or pulsationally delayed detonation models, the primordial composition of the progenitor star which is reflected in the post-helium burning abundance level of the neutron-rich isotope \(^{22}\text{Ne}\) [15], and the mass of the CO white dwarf in “sub-Chandrasekhar” models. Neutron enrichment (neutronization) arising either from \(^{22}\text{Ne}\) enrichments in the stellar progenitor or from electron captures over the course of the outburst favors higher abundances of \(N \geq Z\) nuclei relative to \(N = Z\) isotopes like \(^{56}\text{Ni}\). Lower densities arising either from the effects of pre-expansion or from the presence of higher mass white dwarfs as characterize all of the sub-Chandrasekhar models can constrain the burning temperatures to values lower than those that can drive build-up to \(^{56}\text{Ni}\).

The manner in which such factors conspire to influence peak supernova brightness is evident from some features of Figure 2 below, where the abundance pattern is that predicted for the “carbon deflagration” SNe Ia model of Thielemann et al. [15]. In this model, the slow early advance of the burning front allows expansion of the overlying regions (ahead of the front) such that the burning temperatures do not then reach those required to synthesize iron-peak nuclei. Note the high degree of neutron enrichment of the innermost layers (~ 0.2 solar masses) by means of electron captures, the broad region of mass (~0.8 solar masses) dominated by \(^{56}\text{Ni}\), and the ~ 0.4 solar masses of intermediate mass nuclei in the outermost regions. We should also note that a decrease in \(Y_e\) attributable to the presence of \(^{22}\text{Ne}\) in the region in which iron-peak nuclei are synthesized can moderate the \(^{56}\text{Ni}\) mass. It is with the use of models such as these, together with the knowledge that the peak brightness is correlated with the \(^{56}\text{Ni}\) mass, that we can identify stronger constraints both on SNeIa models and on their nucleosynthesis contributions.
Figure 2: The composition of the ejected matter predicted for the carbon-deflagration model of Thielemann, Nomoto, and Yokoi [16]. The velocity history of the ejecta began with low velocities that increased systematically as the burning front continued outward through the star, such that the velocities of the outermost ejecta reached values ~ 15,000 km s⁻¹, consistent with observations. (Figure courtesy F.-X. Timmes)

3. The Thermonuclear Outbursts of Classical Novae
The outbursts of classical novae are understood to be consequences of thermonuclear runaways proceeding in accreted hydrogen-rich shells on the surfaces of white dwarfs in close binary systems [17,18]. Because of the high rate of occurrence of novae in galaxies like our own Milky Way (~40 per year), these interesting objects have been a subject of both observational and theoretical research for many decades. Mass accumulation on the white dwarf components of these systems yields degenerate conditions at the base of the accreted hydrogen envelope, at pressures $P_{\text{crit}} \approx \text{few x } 10^{19} \text{ dyne cm}^{-2}$, and runaway ensues. In this context, classical nova explosions provide a virtually textbook example of the manner in which nuclear physics serves to define and constrain the characteristics of astrophysical phenomena. Here it is the ‘hot’ carbon-nitrogen-oxygen (CNO) cycle ($\beta^+$ decay limited) hydrogen-burning sequences [19,20]

$$^{12}\text{C}(p,\gamma)^{13}\text{N}(p,\gamma)^{14}\text{O}(\beta^+\nu)^{15}\text{O}(\beta^+\nu)^{15}\text{N}(p,\alpha)^{12}\text{C}$$

that dictate the energetics of the outbursts at temperatures above ~ 80 million K and constrain the nuclear energy release on a dynamic timescale. This is attributable to the fact that the lifetimes of the
positron decays of $^{14}$O and $^{15}$O are long compared to the dynamical timescale at the base of the accreted envelope ($\sim$ seconds). Under these conditions, the energy release is constrained to be that corresponding to the capture of one or two protons on every available CNO nucleus; this yields a total energy release $\sim 2 \times 10^{15}$ ergs g$^{-1}$, for matter of Solar composition. In contrast, the binding energy per gram at the surface of a representative solar mass ($M_\odot$) white dwarf is $\sim 2 \times 10^{17}$ ergs g$^{-1}$. This discrepancy led to the suggestion [21, 17] that significant envelope enrichments in the concentrations of CNO elements are demanded to allow us to understand the characteristics of the light curves and the observed masses of nova ejecta, particularly for the ‘fastest’ (most dynamic) novae. Since the representative temperatures achieved in the burning shells of novae are typically less than approximately 400 million K (such that ‘breakout from the conventional CNO cycles cannot occur [20]), this implies that the abundance enrichments are most likely attributable to “dredge-up” of matter from the underlying white dwarf.

The conclusion that the envelope enrichments are a result of dredge-up holds important further implications for both stellar evolution and novae. It implies that the composition of the enriched component of the nova ejecta reflects that of the outer regions of the core of the underlying white dwarf. Abundance studies of nova nebular ejecta [18, 22] reveal evidence for significant enrichments relative to Solar System concentrations of both carbon and oxygen (CO) and oxygen and neon (ONe) nuclei, confirming the presence of both CO and ONe white dwarfs in nova binary systems. How does this compare with expectations? Stellar evolution studies predict both that stars of initial mass less than approximately 10 solar masses will lose a significant fraction of their envelopes, eject a ‘planetary nebula’ shell, and evolve to white dwarfs of either carbon-oxygen or oxygen-neon composition. The masses of these white dwarf remnants lie in the range $M_{\text{CO}} \approx 0.5$-$1.2 M_\odot$ for CO dwarfs and $M_{\text{ONe}} > 1.1$-$1.2 M_\odot$ for ONe dwarfs. Since the stellar progenitors of the more massive (ONe) white dwarfs ($\sim$8-$10 M_\odot$) are fewer in number than those of the CO white dwarfs ($\sim$ 0.5-$8$) $M_\odot$, they should be relatively rare.

“Selection effects” associated with nova binary systems can however explain white dwarf masses for nova systems observed in outburst that are significantly higher than the mean white dwarf mass resulting from the normal evolution of single stars, which is of order 0.6 solar masses. This is a consequence of the fact that If we assume (1) a white dwarf mass distribution consistent with standard stellar evolution studies, (2) a critical pressure to ignite explosive hydrogen burning that is mass independent, and (3) an accretion rate that is approximately the same for all systems, then the expected (representative) mean properties of the white dwarf mass, white dwarf radius, and envelope mass) of the white dwarfs in observed nova systems are [23]:

$$M_{\text{WD}} \approx 1.2 M_\odot \quad R_{\text{WD}} \approx 4 \times 10^8 \text{ cm} \quad M_{\text{env}} \approx 2 \times 10^{-5} M_\odot$$

The selection effect arises from the fact that the envelope mass required to ignite runaway at the base of the accreted envelope ($P_{\text{crit}}$ is the critical pressure)

$$M_{\text{envl}} = \frac{4\pi}{G} P_{\text{crit}} \left(\frac{R_{\text{WD}}}{M_{\text{WD}}}\right)^3$$

decreases for a more massive white dwarf of smaller radius. The mean mass of the white dwarf population in nova systems observed in outburst is thus greater than that of the white dwarf population generated by the evolution of single stars and we can understand the frequency of ONe nova events.

Another interesting possible feature of classical novae for nuclear physical is the possibility that “breakout” from the hot CNO cycles can occur. We have seen that for normal nova systems evolving
with accretion rates of order $\sim 10^{-9}$ solar masses per year, the temperatures achieved at the peaks of their outbursts never exceed the level $\sim 400$ million K required for breakout. However, Townsley and Bildsten [24] have identified a population of massive nova white dwarfs accreting at rates $\sim 10^{-11}$ $M_\odot$ yr$^{-1}$, with central temperatures as low as $\sim 4 \times 10^6$ K. The combination of such low temperatures and low accretion rates can give rise to nova thermonuclear runaways involving massive white dwarfs and achieving exceptionally high peak burning temperatures. These conditions have been shown [25] to be sufficient to yield breakout; the critical reaction impacting this breakout is $^{15}$O($\alpha$,\gamma)$^{19}$Ne, the rate of which remains very uncertain. (This reaction is also important to considerations of X-ray bursts.) While this result does not negate the general demand for significant dredge-up of core matter from the underlying white dwarfs in nova systems in general, it may allow us better to understand both the massive envelopes for ‘neon (rich) novae’ like Nova 1974 Cyg 1992 and Nova V838 Her 1991) and the heavy element enriched compositions of their ejecta.

![Figure 3: Abundances of the elements in the reaction network as a function of the mass number A. Presented are both the initial (Solar) abundances and the final abundances (red curve) for the case of a 1.35 $M_\odot$ white dwarf. [26]](image)

4. Concluding Comments:
Our discussions in this paper have focused on the manner in which nuclear physics can help to define and to constrain the physics of both classical novae and Type Ia supernovae, but they have not addressed many of the other outstanding challenges. For Type Ia supernovae, in addition to outstanding questions concerning the physics of the outburst models, we have yet identified neither their progenitor systems nor the origin of the distinctions between these events as observed in elliptical and spiral galaxies. For novae, we must understand the effective mechanism of dredge-up and the long term evolution of these recurring events, and we need also to identify both the distinctions between nova and recurrent nova systems and their possible relation to the yet unidentified progenitors of SNe Ia. There is much left to learn, but it is clear that the furtherance of our understanding of their nuclear energetics and nucleosynthesis properties will remain of great importance to future progress.
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