Nuclear Physics in Stellar Evolution and Nucleosynthesis
- evidence of nuclear physics behaviors
- energy generation in stars

Summer School in Nuclear Physics
Laurence Berkeley National Laboratory
June 6-10, 2005

Nuclear Astrophysics: Perspective

- The Universe emerged from the first three minutes of the cosmological Big Bang with a composition consisting of \(^1\)H, \(^2\)D, \(^3\)He, \(^4\)He, and \(^7\)Li, with only trace abundances of heavy elements.

- The synthesis of all elements heavier than \(^4\)He is then understood to occur in stars and supernova explosions over the history of the Galaxy.

- Thermonuclear reactions proceeding in stellar cores serve both to power stars over their lifetimes of billions of years and to synthesize the common elements with which we are familiar - from carbon to the actinide nuclei thorium, uranium, plutonium, etc.
Nuclear Astrophysics: Perspective

Onion-like structure of a presupernova star several million years after its birth:

- mass: $10 \ldots 10^2 \, M_\odot$
- radius: $50 \ldots 10^3 \, R_\odot$

- shells of different composition are separated by active thermonuclear burning shells
- core Si-burning leads to formation of central iron core
Nuclear Astrophysics: Perspective

- The need for nuclear energy to power stars was recognized not long after the earliest discoveries in nuclear physics in the last century.

- The gravitational energy available for the Sun is given by:
  \[ E_{\text{grav}} = \frac{3G M_{\odot}^2}{5R_{\odot}} \approx 2.4 \times 10^{48} \text{ ergs} \]
  which yields a possible burning lifetime (for a constant luminosity Sun):
  \[ \tau_{\text{grav}} = \frac{E_{\text{grav}}}{L_{\odot}} \approx 20 \text{ million years} \]

- In contrast, thermonuclear burning of approximately 10% of the Sun’s mass from hydrogen to helium (releasing \( \approx 7 \text{ MeV/nucleon} \)) yields approximately \( 10^{51} \) ergs and can thus provide the Sun’s luminosity of \( 3.9 \times 10^{33} \text{ erg s}^{-1} \) for a lifetime exceeding \( 10^{10} \) years.

Nuclear Astrophysics: Perspective

- Supernova energetics are tied to nuclear processes:

- Type Ia are understood to be pure thermonuclear supernovae, powered by energy release in the incineration of a \(^{12}\text{C}\) and \(^{16}\text{O}\) degenerate core of mass \(1.4 \text{ M}_{\odot}\):
  - The energy release in the conversion of one solar mass of a 50/50 mix of \(^{12}\text{C}\) and \(^{16}\text{O}\) to pure \(^{56}\text{Ni}\) is (with an increase in binding energy per nucleon of 0.8 MeV) approximately \(1.6 \times 10^{51}\) ergs.
  - This is sufficient both to unbind the white dwarf and to account for the observed kinetic energy of the ejecta.
  - The luminosity of a Type Ia supernova at maximum is then provided by the decay energy of the transition from \(^{56}\text{Ni}\) to \(^{56}\text{Fe}\) via \(^{56}\text{Ni} \rightarrow^{56}\text{Co} \rightarrow^{56}\text{Fe} \).
Radioactivity

- Isotopes of Ni and other elements
- Conversion of γ-rays and positrons into heat and optical photons

Diehl and Timmes (1998)

Type Ia Supernova: 1994D
Type II supernovae (or “core collapse” supernovae) are powered rather by the gravitational energy release in the formation of a neutron star.

The formation of a 1.4 M⊙ neutron star of radius 15 km releases: \[ E_{\text{grav}} = \frac{3GM_{\text{NS}}^2}{5R_{\text{NS}}} \approx 2.1 \times 10^{53} \text{ ergs} \]

Thermonuclear reactions here again play an important role in synthesizing nuclei from oxygen to zinc. Type II supernovae are indeed the main source of such nuclei in galaxies.

For the case of supernova 1987A, observations of gamma rays from \(^{56}\text{Co}\) decay to \(^{56}\text{Fe}\) confirmed the ejection of 0.07 M⊙ of mass A=56 in the form of \(^{56}\text{Fe}\), powering the tail of the light curve.

Type II Supernova: Crab (Nebular Remnant) 1054
The Astronomer’s Periodic Table of the Elements

“Cosmic” Abundances of the Elements
The “Cosmic” abundance patterns - which represent the integrated contributions from stars and supernovae in our Galaxy over some 14 billion years - clearly reflect nuclear systematics, e.g.:

- dominance of $\alpha$-particle nuclei: $^{12}$C through $^{40}$Ca
- dominance of unstable $\alpha$-nuclei products $^{44}$Ti, $^{48}$Ti, $^{52}$Fe, $^{56}$Ni, $^{60}$Zn, $^{64}$Ge, $^{68}$Se, $^{72}$Kr seen in decay products
- nuclear statistical equilibrium centered on $A=56$, first noted by Hoyle (1946)
- strong signatures of neutron shell structure in the abundance peaks in the heavy element region at magic numbers $N=50, 82, and 126$
- odd-even abundance trends
- existence of 4 stable odd-odd nuclei: $^2$D, $^6$Li, $^{10}$B, $^{14}$N

“Cosmic” Abundances of the Elements
Valley of Beta Stability

Core Temperature and Density Evolution in Stars
Nuclear Reactions and Energy Generation

- Thermonuclear reaction rates for hot stellar interiors are generally determined by averaging the product of the relative velocity of the two interacting particles times the cross section \( <\sigma v> \) over a Maxwellian distribution of relative velocities.

- For a particle of number density \( n_p \) interacting with target particles \( n_T \) of cross section \( \sigma \) and moving with velocity \( v \), the number of interactions per target nucleus per unit time is \( n_p \sigma v \) and the collision lifetime per target nucleus is \( \tau_C = (n_p \sigma v)^{-1} \) seconds.

- The number of collisions per unit volume per unit time is then \( r = n_p(v) n_T(v) \sigma(v) v \text{ cm}^{-3} \text{ s}^{-1} \).

Nuclear Reactions and Energy Generation

- The appropriate rate when averaged over a Maxwellian distribution of relative velocities is then \( r = n_p n_T <\sigma v> \), where the \( n_p \) and \( n_T \) are now the total number densities.

- The rate (where \( \mu \) is the reduced mass and \( v \) the velocity of relative motion) is given more generally by:

\[
r = n_p n_T \int_{-\infty}^{\infty} v \sigma(v) 4\pi (\mu/2\pi kT)^{3/2} \exp(-\mu v^2/2kT) v^2 dv
\]

- The Maxellian temperature dependence is as shown.
The Gamow ‘window’ identifies the energy range for which the cross section needs to be experimentally or theoretically known.

\[ E_0 = \left( \frac{b k T}{2} \right)^{1/2} = 0.122 \cdot \left( \frac{Z_1^2 Z_2^2 A}{T_9} \right)^{1/3} \text{ MeV} \]

\[ \Delta E = \frac{4}{\sqrt{3}} \sqrt{E_0 k T} = 0.2368 \cdot \left( \frac{Z_1^2 Z_2^2 A}{T_9} \right)^{1/6} T_9^{5/6} \text{ MeV} \]

It is common and useful in astrophysics to remove the dominant Coulomb barrier dependence and identify the astrophysical S factor.

\[ S(E) = \sigma \cdot e^{2 \pi \cdot \eta} \]

Where:

\[ 2 \pi \cdot \eta = \frac{2 \pi \cdot Z_1^2 \cdot Z_2^2 \cdot e^2}{\hbar \sqrt{\frac{2 \cdot E_{cm}}{\mu}}} \]

With the Coulomb barrier dependence thus removed, the residual factor S(E) is significantly less energy dependent. Note representative cases:
The choice of nuclear fuel as a stellar energy choice is dictated largely by two factors:

- **Charge**: The Coulomb barrier energy is typically significantly higher than the thermal energy of the constituent particles.
  
  \[ B_C = 1.44 \frac{Z_1Z_2}{R} \text{ MeV} \approx \frac{Z_1Z_2}{A^{1/3}} \text{ MeV} \]
  
  \[ E_{\text{thermal}} = kT \approx 0.86 \text{ MeV} \left(T/10^9 K\right) \]

- **Abundance**: The earliest phases of energy generation involve hydrogen and helium, the dominant BBN products. The initial composition of the Sun involved less than 2% elements heavier than helium.
### Nuclear Reactions and Energy Generation

**Representative Optimum Bombarding Energies**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$B_C$(MeV)</th>
<th>$E_0$(keV)</th>
<th>$\Delta E_0$(keV)</th>
<th>$T$(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^2\text{D(p,}\gamma)^3\text{He}$</td>
<td>0.83</td>
<td>5.7</td>
<td>4.3</td>
<td>$10^7$</td>
</tr>
<tr>
<td>$^6\text{Li(p,}\alpha)^3\text{He}$</td>
<td>1.9</td>
<td>12</td>
<td>6.2</td>
<td>$10^7$</td>
</tr>
<tr>
<td>$^{10}\text{B(p,}\alpha)^7\text{Be}$</td>
<td>2.7</td>
<td>17</td>
<td>7.3</td>
<td>$10^7$</td>
</tr>
<tr>
<td>$^{12}\text{C(}\alpha, \gamma)^{16}\text{O}$</td>
<td>4.8</td>
<td>300</td>
<td>180</td>
<td>$2\times10^8$</td>
</tr>
<tr>
<td>$^{12}\text{C} + ^{12}\text{C}$</td>
<td>12.5</td>
<td>2.4 MeV</td>
<td>1 MeV</td>
<td>$10^9$</td>
</tr>
</tbody>
</table>

### Nuclear Reactions and Energy Generation

**Hydrogen Burning Phase of Stellar Evolution**

[Diagram showing energy generation and CNO cycles]
Nuclear Reactions and Energy Generation

Proton-Proton Hydrogen Burning Reactions

The pp-chains

pp-1: $^1\text{H}(p,e^+\nu)^2\text{H}$
      $^2\text{H}(p,\gamma)^3\text{He}$
      $^3\text{He}(^3\text{He},2\text{p})^4\text{He}$  84.7%

pp-2: $^3\text{He}(\alpha,\gamma)^7\text{Be}$
      $^7\text{Be}(e^-,\nu)^7\text{Li}$
      $^7\text{Li}(p,\alpha)^4\text{He}$

pp-3: $^7\text{Be}(p,\gamma)^8\text{B}$
      $^8\text{B}(\beta^+,\nu)^7\text{He}$

fusion of $4^1\text{H} \rightarrow 4\text{He} + 2\text{e}^+ + 2\text{ve} + 26.7$ MeV energy release

Nuclear Reactions and Energy Generation

Network for the pp-chain I

\[
\frac{d^3\text{H}}{dt} = -2 \cdot \frac{1}{2} Y_{\text{He}} \cdot Y_{\text{H}} \cdot \rho \cdot N_A \langle \sigma \nu \rangle_{\text{H}(p,\gamma)} + 2 \cdot \frac{1}{2} Y_{\text{He}} \cdot Y_{\text{He}} \cdot \rho \cdot N_A \langle \sigma \nu \rangle_{\text{He}(^3\text{He},2\text{p})}
\]

\[
\frac{d^2\text{He}}{dt} = -2 \cdot \frac{1}{2} Y_{\text{He}} \cdot Y_{\text{H}} \cdot \rho \cdot N_A \langle \sigma \nu \rangle_{\text{H}(p,\gamma)} + \frac{1}{2} Y_{\text{He}} \cdot Y_{\text{He}} \cdot \rho \cdot N_A \langle \sigma \nu \rangle_{\text{He}(p,\gamma)}
\]

\[
\frac{d^3\text{He}}{dt} = -2 \cdot \frac{1}{2} Y_{\text{He}} \cdot Y_{\text{He}} \cdot \rho \cdot N_A \langle \sigma \nu \rangle_{\text{He}(^3\text{He},2\text{p})} + Y_{\text{He}} \cdot Y_{\text{He}} \cdot \rho \cdot N_A \langle \sigma \nu \rangle_{\text{He}(p,\gamma)}
\]

\[
\frac{d^4\text{He}}{dt} = \frac{1}{2} Y_{\text{He}} \cdot Y_{\text{He}} \cdot \rho \cdot N_A \langle \sigma \nu \rangle_{\text{He}(^4\text{He},2\text{p})}
\]
Nuclear Reactions and Energy Generation

Reactions in the CNO cycles

CNO-1: $^{12}\text{C}(p,\gamma)^{13}\text{N}$
$^{13}\text{N}(\beta^+\nu)^{13}\text{C}$
$^{13}\text{C}(p,\gamma)^{14}\text{N}$
$^{14}\text{N}(p,\gamma)^{15}\text{O}$
$^{15}\text{O}(\beta^+\nu)^{15}\text{N}$
$^{15}\text{N}(p,\alpha)^{12}\text{C}$

$S_{^{12}\text{C}(p,\gamma)} = 3 \times 10^{-3}$ MeV-barn
$S_{^{14}\text{N}(p,\gamma)} = 2 \times 10^{-3}$ MeV-barn
$S_{^{15}\text{N}(p,\alpha)} = 1 \times 10^{+2}$ MeV-barn

CNO-2: $^{15}\text{N}(p,\gamma)^{16}\text{O}$
$^{16}\text{O}(p,\gamma)^{17}\text{F}$
$^{17}\text{F}(\beta^+\nu)^{17}\text{O}$
$^{17}\text{O}(p,\alpha)^{14}\text{N}$

$S_{^{15}\text{N}(p,\gamma)} = 5 \times 10^{-2}$ MeV-barn

CNO-3: $^{17}\text{O}(p,\gamma)^{18}\text{F}$
$^{18}\text{F}(\beta^+\nu)^{18}\text{O}$
$^{18}\text{O}(p,\alpha)^{15}\text{N} \Rightarrow \text{CNO-4}$

Solar Neutrino Fluxes

[Diagram of solar neutrino fluxes with Gallium, Chlorine, SuperK, SNO data points and energy spectrum.]