Nuclear Astrophysics

Jeff Blackmon (LSU)

1. Introduction, Formalism, Big Bang and H burning
2. He burning, Heavy elements & s process
3. Stellar Explosions
Mass log (abundance)

Big Bang
In the beginning... Space, time, matter, & energy began with the Big Bang

Observations in 3 very different epochs probe the Big Bang

Nucleosynthesis

CMB -The afterglow

Stellar observations
Optical Observations: Type Ia Supernova

Type Ia: very bright thermonuclear explosions resulting in the total destruction of a star

- Shape of light curve $\rightarrow$ true brightness
- Observed brightness $\rightarrow$ distance from earth
- Doppler shift $\rightarrow$ velocity relative to earth

Tycho’s supernova

Objects are moving away from earth with velocity faster than Hubble’s Law

The expansion of the universe is **accelerating**

2011 Nobel Prize

Riess  Perlmutter  Schmidt
DARK ENERGY (e.g. cosmological constant) exerts a “negative pressure” causing the acceleration

4.5 ± 0.3% of universe is baryonic → test with nucleosynthesis
The Homogeneous BBN Model

- Assume adiabatic expansion ($\nu$ flavors)
  - $T(t)$ and $\rho(t)$
- n/p ratio set by weak strength (n half-life)
- Only free parameter is baryon/photon ratio

~All free neutrons into $^4$He
Mass 5 & 8 gaps inhibit formation of heavy elements

$p \sim 75\%$
$^4$He $\sim 25\%$
$^2$H, $^3$He $\sim 10^{-5}$
$^7$Li $\sim 10^{-10}$
Nuclear reactions in the lab & in space

In the lab:

\[
\frac{\text{reactions}}{s} = \frac{\text{ions}}{s} \frac{\text{atoms}}{cm^2} \sigma
\]

In astrophysical events:

\[
\frac{\text{reactions}}{cm^3 s} = \int \frac{n_x}{cm^3} \frac{n_y}{cm^3} v \sigma(v) \phi(v) dv
\]

\[
\phi(v) = 4\pi v^2 \left( \frac{\mu}{2\pi kT} \right)^{3/2} \exp\left( -\frac{\mu v^2}{2kT} \right)
\]

\[
\frac{\text{reactions}}{cm^3 s} = \frac{n_x}{cm^3} \frac{n_y}{cm^3} \langle ov \rangle
\]

\[
\langle ov \rangle = \sqrt{\frac{8}{\pi \mu}} (kT)^{3/2} \int_0^\infty \sigma E e^{-E/(kT)} dE
\]
The Gamow window

\[ \langle \sigma v \rangle = \sqrt{\frac{8}{\pi \mu}} (kT)^{3/2} \int_0^\infty \sigma E e^{-E/(kT)} \, dE \]

\[ \sigma \equiv \frac{S}{E} e^{-\sqrt{E_G/E}} \]

\[ E_G \equiv \frac{2\mu}{\hbar^2} \left( \pi Z_1 Z_2 e^2 \right)^2 \]

\[ \langle \sigma v \rangle = \sqrt{\frac{8}{\pi \mu}} (kT)^{3/2} \int_0^\infty S e^{-\sqrt{E_G/E}} e^{-E/(kT)} \, dE \]

<table>
<thead>
<tr>
<th>Reaction</th>
<th>site</th>
<th>( T ) ((10^6 \text{ K}))</th>
<th>( kT ) ((\text{keV}))</th>
<th>( r_{\text{turn}} ) ((\text{fm}))</th>
<th>( r ) ((\text{fm}))</th>
<th>( E_0 ) ((\text{keV}))</th>
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</thead>
<tbody>
<tr>
<td>p+p</td>
<td>sun</td>
<td>15</td>
<td>1.3</td>
<td>1100</td>
<td>2.5</td>
<td>6</td>
</tr>
<tr>
<td>p+N</td>
<td>CNO</td>
<td>30</td>
<td>2.6</td>
<td>3900</td>
<td>4.3</td>
<td>42</td>
</tr>
<tr>
<td>( \alpha + C )</td>
<td>red giant</td>
<td>190</td>
<td>16</td>
<td>1060</td>
<td>4.8</td>
<td>300</td>
</tr>
<tr>
<td>p+F</td>
<td>nova</td>
<td>300</td>
<td>26</td>
<td>500</td>
<td>4.5</td>
<td>230</td>
</tr>
<tr>
<td>( \alpha + S )</td>
<td>x-ray burst</td>
<td>1000</td>
<td>86</td>
<td>500</td>
<td>5.9</td>
<td>1800</td>
</tr>
<tr>
<td>He+He</td>
<td>big bang</td>
<td>2000</td>
<td>170</td>
<td>33</td>
<td>3.8</td>
<td><strong>580</strong></td>
</tr>
</tbody>
</table>
Direct Laboratory Measurements

Directly measure cross sections in the lab at the lowest possible energies.

- Bombarding energy range ~ 10 keV to ~MeV
- High currents (~ mA)
- Long run times
- Efficient detectors to obtain high statistics
- Pure, stable targets
- Absolute cross section measurements
  - Good normalization & careful control of systematic uncertainties
- Background suppression crucial
Textbook example

\[ S \equiv \sigma E e^{\sqrt{\frac{E_G}{E}}} \]

\[ E_G \equiv \frac{2 \mu}{\hbar^2} \left( \pi Z_1 Z_2 e^2 \right)^2 \]

Previous experimental limit

Need \( \sigma \) here for sun

1400 m rock coverage
cosmic $\mu$ reduction = $10^{-6}$
muon rate $\sim 1$ (/m$^2$ h)
$^3\text{He}(\alpha,\gamma)^7\text{Be}$

Gyürky et al., PRC 75, 035805 (2007).
**Simple Big Bang Reaction Network**

1. \( n \leftrightarrow p \)
2. \( p(n,\gamma)d \)
3. \( d(p,\gamma)^3\text{He} \)
4. \( d(d,n)^3\text{He} \)
5. \( d(d,p)t \)
6. \( t(d,n)^4\text{He} \)
7. \( t(\alpha,\gamma)^7\text{Li} \)
8. \( ^3\text{He}(n,p)t \)
9. \( ^3\text{He}(d,p)^4\text{He} \)
10. \( ^3\text{He}(\alpha,\gamma)^7\text{Be} \)
11. \( ^7\text{Li}(p,\alpha)^4\text{He} \)
12. \( ^7\text{Be}(n,p)^7\text{Li} \)

\[
\frac{dN_d}{dt} = N_p N_n \langle \sigma v \rangle_2 - N_d N_p \langle \sigma v \rangle_3 \\
- N_d N_d \langle \sigma v \rangle_4 - N_d N_d \langle \sigma v \rangle_5
\]

\[
\frac{dN_t}{dt} = N_d N_d \langle \sigma v \rangle_5 + N_{^3\text{He}} N_n \langle \sigma v \rangle_8 \\
- N_t N_d \langle \sigma v \rangle_6 - N_t N_\alpha \langle \sigma v \rangle_7 - \lambda_t N_t
\]
Solve the reaction rate network.
**Theoretical Abundance Prediction**

- **Keck Telescopes**

- **Quasi-Stellar Object (QSO)**

- **“Primordial” Interstellar Gas Cloud**
  (absorbs light)

- **Deuterium**

- **Hydrogen**

- **10^{-10}**

- **"Primordial" Interstellar Gas Cloud**

- **Quasi-Stellar Object (QSO)**

- **Deuterium abundance observations range of densities consistent with observations & theory**

- **D / H = 2.8 ± 0.4 • 10^{-5}**

- **Uncertainties from nuclear physics**

- **η = ρ_{baryon} / ρ_{photon}**

- **Theoretical Abundance Prediction**

- **Abundance Observations can be used to constrain matter density - the only free parameter - independent of WMAP**
• $^7\text{Li}$ production is particularly sensitive to matter density.

• Certain low mass stars may preserve the $^7\text{Li}$ abundance they were formed with.

$^7\text{Li} / \text{H} = 1.3 \times 2.0 \times 10^{-10}$
• Most abundances agree with BBN calculations using WMAP $\eta$

• One problem: $^7$Li

**Cosmological Li problem**

• Direct $\sigma$ measurements have seemingly ruled out any nuclear solution

• Is Spite plateau really reflective of primordial abundances?

![Diagram showing cosmic abundances and destruction of $^7$Li](image)

$^7$Li/H vs. Iron content relative to the sun

Weiss, Einstein Online, adapted from Vangeioni
Hydrogen burning in stars

Hydrostatic equilibrium

\[ \frac{dP(r)}{dr} = -\frac{GM_{\text{in}}(r)\rho(r)}{r^2} \]

Energy conservation

\[ \frac{dL(r)}{dr} = \frac{\varepsilon(r)\rho(r)}{4\pi r^2} \]

Pressure

\[ P(r) = P_{\text{gas}}(r) + P_{\text{rad}}(r) \]

For sun (non-degenerate)

\[ P_{\text{gas}}(r) = \frac{k}{\langle m \rangle} \rho(r)T(r) \]

\[ P_{\text{rad}}(r) = \frac{1}{3} aT^4(r) \ll P_{\text{gas}}(r) \]

Inner 70% of sun’s radius is dominated by radiative heat transport

Large T,P gradient

Opacity: photons absorbed and emitted at shorter \( \lambda \)

Luminosity/opacity/T relationship \( \Rightarrow L \propto M^4 \)

The sun

\[ M = 2 \times 10^{30} \text{ kg} \]

\[ \rho(0) = 150 \text{ g/cm}^3 \]

\[ T(0) = 1.5 \times 10^7 \text{ K} \]

\[ T(\text{surf}) = 5800 \text{ K} \]

\[ L = 3.8 \times 10^{26} \text{ W} \]

5x10^4 yr for energy produced in sun’s core to be reach surface
The sun’s energy is produced by nuclear fusion in its core.

Result is $4p \rightarrow 4\text{He} + 2e^+ + 2\nu + 27 \text{ MeV}$

$27 \text{ MeV} = 4 \times 10^{-12} \text{ J}$

$* \ 10^{38} \text{ fusions/s} = 4 \times 10^{26} \text{ Watts}$
Solar fusion: The pp-chains

Thanks to substantial efforts in experiment, theory & evaluation

pp-1: 5% \(^1\text{H}(p,e^+\nu)^2\text{H}  \\
      5% \(^2\text{H}(p,\gamma)^3\text{He}  \\
      7% \(^3\text{He}(^3\text{He},2p)^4\text{He} \quad 84.7\%  \\

pp-2: 3% \(^3\text{He}(\alpha,\gamma)^7\text{Be} \quad 13.8\%  \\
      7\text{Be}(e^-,\nu)^7\text{Li} \quad 13.78\%  \\
      13% \(^7\text{Li}(p,\alpha)^4\text{He}  \\

pp-3: 5-10% \(^7\text{Be}(p,\gamma)^8\text{B} \quad 0.02\%  \\
      ^8\text{B}(\beta^+\nu)^2^4\text{He}  \\

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

Only \(\nu\) most experiments measure
\(^3\text{He}(^3\text{He},2p)^4\text{He}\)

- 1999 – First measurement of a pp reaction \(\sigma\) at the solar Gamow widow
- Somewhat unique situation ➔ 2 protons with \(E_p > 6\) MeV

**I \approx 1 mA**

- Windowless \(^3\text{He}\) gas target
- 2 events/month at lowest energy \((E_{cm} = 16\) keV\)
- Effect of electron screening has been largely resolved
- About 7% uncertainty at solar energies

Why *still* measure solar neutrinos?

- $^8\text{B}$ flux $\sim4\%$ precision
  $\rightarrow$ Super-K, SNO, Borexino, . . .
- $^7\text{Be}$ flux $\sim5\%$ precision
  $\rightarrow$ Borexino
- Others
  $\rightarrow$ Radiochemical (integral)
- Neutrino flavor oscillation
  $\rightarrow$ Neutrinos have mass
  $\rightarrow$ Mass $\neq$ Flavor eigenstates

- But weak constraints on photospheric luminosity ($\text{pp}$ neutrino flux)
- What is contribution of CNO cycle to solar energy generation?
- Is photospheric composition reflective of solar core?

Need precise measure of pp & CNO solar $\nu$ flux