Nuclear Astrophysics - I

Carl Brune
### Astrophysics and Cosmology

#### Observations
- Electromagnetic Spectrum: radio, microwave, IR, optical, UV, x-rays, γ-rays
- Neutrinos
- Cosmic Rays
- Meteorites
- Terrestrial Abundances
- Gravitational Waves

#### Underlying Physics
- Atomic Physics
- Nuclear Physics
- Particle Physics
- Statistical Mechanics
- Hydrodynamics
- Gravity (General Relativity)
- …..
Nuclear Astrophysics

Nuclear Physics plays a very important role in astrophysics because:

- **Nuclear reactions can provide a tremendous amount of energy** e.g. $^3\text{He} + ^3\text{He} \rightarrow 2p + ^4\text{He} + 13 \text{ MeV}$
- **Nuclei are created and destroyed via nuclear reactions** (aka nucleosynthesis)

**Scenarios include:**

- Stellar processes
- Big Bang
- Cosmic-ray induced processes
- ...
Expansion of the Universe

After the Big Bang, the universe expanded and cooled. At about $10^{-4}$ second, the universe consisted of a soup of quarks, gluons, electrons, and neutrinos. When the temperature of the Universe, $T_{\text{universe}}$, cooled to about $10^{10}$ K, this soup coalesced into protons, neutrons, and electrons. As time progressed, some of the protons and neutrons formed deuterium, helium, and lithium nuclei. Still later, electrons combined with protons and these low-mass nuclei to form neutral atoms. Due to gravity, clouds of atoms contracted into stars, where hydrogen and helium fused into more massive chemical elements. Exploding stars (supernovae) form the most massive elements and disperse them into space. Our earth was formed from supernova debris.

- Age of Universe: 13.7 Gyr
- Age of Solar System: 4.5 Gyr
Exploded 3,000 years ago
169,000 light-years away
Blue: O$^+$
Green: O$^{2+}$
Pink: S$^+$

Supernova Remnant N132D
### “Laundry List” of Processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Product/Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Big Bang Nucleosynthesis</td>
<td>Light Elements (A&lt;10)</td>
</tr>
<tr>
<td>Hydrogen Burning</td>
<td>Main sequence of stellar evolution (A&lt;60)</td>
</tr>
<tr>
<td>Helium Burning</td>
<td>Red giants (A&lt;60, especially $^{12}$C and $^{16}$O)</td>
</tr>
<tr>
<td>“Heavy Ion” Burning</td>
<td>Late stages of massive star evolution (terminates at Fe)</td>
</tr>
<tr>
<td>S Process</td>
<td>“Slow” neutron capture (A&gt;60)</td>
</tr>
<tr>
<td>R Process</td>
<td>“Rapid” neutron capture (A&gt;60)</td>
</tr>
<tr>
<td>RP Process</td>
<td>Rapid proton capture: novae and x-ray bursters</td>
</tr>
<tr>
<td>$\gamma$ Process</td>
<td>Photodisintegration</td>
</tr>
<tr>
<td>Cosmic-Ray Spallation</td>
<td>Li and Be</td>
</tr>
<tr>
<td>$\nu$–induced reactions</td>
<td>?</td>
</tr>
<tr>
<td>Neutron Stars</td>
<td>R-Process site?</td>
</tr>
</tbody>
</table>
Nuclear Binding Energies

Number of nucleons in nucleus

Average binding energy per nucleon (MeV)

Binding energy per nucleon
What is the needed Nuclear Physics?

- Nuclear masses, Q values
- Half lives, decay modes
- Resonance energies, partial widths
- Reaction cross sections

Breit-Wigner Formula

\[ \sigma(E) = \frac{2J + 1}{(2J_1 + 1)(2J_2 + 1)} \frac{\pi}{k^2} \frac{\Gamma_1 \Gamma_3}{(E - E_R)^2 + \Gamma^2/4} \]

Reaction Rate Formalism:

T = temperature
k = Boltzmann constant

Consider the process: 1 + 2 → 3 + 4

where \( n_i \) = number density of species \( i \)

\[ \frac{dn_3}{dt} = n_1 n_2 \langle \sigma v \rangle \]

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

Charged Particles

Coulomb barrier:
S = “astrophysical S factor”

\[ \sigma = \frac{S}{E} \exp \left( -\sqrt{\frac{E_G}{E}} \right) \]

Neutron-induced Reactions

No Coulomb barrier
\[ \sigma \sim E^{-1/2} \]

Statistical Reactions ( A>60 )

- Reaction rate determined by many resonances
- Rates can be computed using statistical methods
- Requires systematic information: level densities, optical potentials,…
Big Bang Nucleosynthesis

- Standard Model of Particle Physics
- General Relativity
- Homogeneity and Isotropy
- Nuclear Cross Sections

Light Elements

Single free parameter: Baryon Density
(or $\Omega = \text{baryon-to-photon ratio}$)

Goals:

- Determine $\Omega$
- Compare to astronomical observations
- Test physics input, e.g.
  - 3 neutrino generations
  - phase transitions?
• 11 cross sections
• neutron lifetime
• $E \sim 100$ keV

Measure in the lab!

Inverse reactions also included
$^3\text{H}(\alpha, \gamma)^7\text{Li}$

calculation: K.M. Nollett
$^3\text{He}(n,p)^3\text{H}$

Data: CRB et al. (1999)
Evolution of the Elements
Observing $^2$H with QSOs

Older data

Keck Data
D/H can be extracted:

<table>
<thead>
<tr>
<th>QSO</th>
<th>$\log_{10}D/H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PKS 1937-1009</td>
<td>-4.49(4)</td>
</tr>
<tr>
<td>Q1009+2956</td>
<td>-4.40(7)</td>
</tr>
<tr>
<td>Q0130-4021</td>
<td>&lt; -4.17</td>
</tr>
<tr>
<td>HS 0105+1619</td>
<td>-4.60(4)</td>
</tr>
</tbody>
</table>

It would appear that we know the primordial Deuterium abundance within ~5%!
Lithium Observations

![Graph showing lithium observations]
We have observations for D, $^3$He, $^4$He, and $^7$Li which are thought to represent primordial abundances.

Big Bang Nucleosynthesis:
$\Omega_B h^2 = 5.1(6) \times 10^{-10}$

The lithium data are not in good agreement.
Cosmic Microwave Background
# Cosmic Microwave Background: Inferences

**WMAP Year 1 (Bennett et al.)**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{\text{tot}}$ (total density)</td>
<td>1.02(2)</td>
</tr>
<tr>
<td>$S_7$ (dark energy density)</td>
<td>0.73(4)</td>
</tr>
<tr>
<td>$S_m$ (matter density)</td>
<td>0.27(4)</td>
</tr>
<tr>
<td>$S_b$ (baryon density)</td>
<td>0.044(4)</td>
</tr>
<tr>
<td>$t_0$ (age of universe)</td>
<td>13.7(2) Gyr</td>
</tr>
<tr>
<td>$\theta_0$ (baryon-to-photon ratio)</td>
<td>$6.1(3) \times 10^{-10}$</td>
</tr>
</tbody>
</table>

**Consistent (sort of...)**

Big Bang Nucleosynthesis: $\theta_0 = 5.1(6) \times 10^{-10}$
$S_m + S_7 = 1$
$S_7 \sim 0.75$
Present Status of BBN

- Exciting new developments in observations of the CMB, light elements, and distant supernovae. New CMB data, including polarization, are coming soon from WMAP.
- Agreement is reasonable but not perfect. Lithium?
- From a nuclear physics point of view the field is mature, but higher-accuracy data are needed.
- Recently completed or ongoing measurements:
  - $p(\text{n}, ()d$
  - $d(d,p)t$ and $d(d,n)^3\text{He}$ - D.S. Leonard et al. (UNC/TUNL)
  - $^3\text{He}(^4\text{He}, ()^7\text{Be}$
Classical Novae

- 2-3 / month in our Galaxy
- Binary star systems
- Mass transferred from less massive star (red giant) to white dwarf companion
- Hydrogen gas burns explosively with CNO nuclei → thermonuclear explosion

- Elements as heavy as calcium may be synthesized
- Primary target for gamma-ray telescopes ($^7$Be, $^{18}$F, $^{22}$Na, $^{26}$Al)
Additional Features of Novae

- CO WDs: $X(^{12}\text{C}) : X(^{16}\text{O}) : X(^{20}\text{Ne}) = 5 : 5 : 0.1$
- ONe WDs: $X(^{16}\text{O}) : X(^{20}\text{Ne}) : X(^{24}\text{Mg}) = 10 : 6 : 1$
- Peak temperatures $\sim 0.2\text{-}0.4 \text{ GK} \ (\sim 20 \text{ keV})$
- 30 novae / yr, $10^{10}$ yr, $2 \times 10^{-5} \text{ M}_{\odot}$ / outburst
- Barely contribute to overall Galactic abundances
- Important for individual nuclei (e.g. $^{17,18}\text{O}$)
Time Evolution of Peak Temperature

V1974 Cygni

S. Starrfield et al.
Time Evolution of Peak Luminosity

V1974 Cygni

S. Starrfield et al.
The Hot CNO Cycle

- Powers nova explosions
- Hydrogen → Helium
- Large uncertainties in some reactions

- $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$
  - $^{17}\text{O}$, $^{18}\text{F}$ production
- $^{18}\text{F}(p,\alpha)^{15}\text{O}$ and $^{18}\text{F}(p,\gamma)^{19}\text{Ne}$
  - $^{15}\text{N}$, $^{18}\text{F}$ production
  - $^{17}\text{O}/^{18}\text{O}$ ratios
Time Evolution of Abundances

Iliadis et al.
Charged Particle Reactions $A = 15 - 40$

Key Features:
- Resonant contributions (usually dominant)
- Non-resonant contributions
- Coulomb barrier

Resonance Properties:
- Energy
- Partial Widths
- Spin and Parity

All properties are important!

Typical Cross Section

Graph showing the cross section as a function of center-of-mass energy ($E_{c.m.}$ in MeV) with resonances and non-resonant contribution indicated.
More on Resonances

- Need high precision for $E_r$ (~few keV)
- Must rely on experiment
- Theoretical approaches are more helpful for the strength

For a narrow resonance:

$$<\sigma v> \% \text{ (strength)} (kT)^{-3/2} e^{-E_r/kT}$$

Example: $^{18}\text{F}(p,\alpha)^{15}\text{O}$
Mirror Symmetry

- Predict resonance energies
- Estimate partial widths
- Isobaric Mass Multiplet Eq.

stable nucleus
Summary of Today’s Lecture

- The Big Picture regarding Nuclear Astrophysics
- Big-Bang Nucleosynthesis
- Overview of Novae

Next: experiments relevant to Novae
The Holifield RIB Facility at Oak Ridge National Lab

p, d, or α
Hot, fibrous production target

25 MV tandem
Ion source
Mass analysis
RIB (300 keV)

To experiments

ORIC

Ion Source Assembly
PA Tube
RF Structure
Beam Line to RIB injector

Central Magnetic Channel
Lower Magnetic Channel
Electrostatic Deflector
Experimental Approach

\[ \sim 5 \times 10^5 \, ^{18}\text{F}/\text{sec} \]

CH\textsubscript{2} target

Si Strip Detectors
Results
## Results

<table>
<thead>
<tr>
<th>$E_r$ (keV)</th>
<th>$J^\pi$</th>
<th>$\Gamma_p$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>$3/2^+$</td>
<td>$4 \times 10^{-37}$</td>
</tr>
<tr>
<td>26</td>
<td>$1/2^-$</td>
<td>$3 \times 10^{-20}$</td>
</tr>
<tr>
<td>38</td>
<td>$3/2^+$</td>
<td>$2 \times 10^{-14}$</td>
</tr>
<tr>
<td>287</td>
<td>$5/2^+$</td>
<td>$4 \times 10^{-5}$</td>
</tr>
<tr>
<td>330</td>
<td>$3/2^-$</td>
<td>$2.2(0.7) \times 10^{-3}$</td>
</tr>
<tr>
<td>665</td>
<td>$3/2^+$</td>
<td>$15.2(1.0)$</td>
</tr>
</tbody>
</table>

![Graph](image_url)
Reaction Rate

The graph shows the variation of the reaction rate constant $N_A <\sigma v>$ (in cm$^3$ mole$^{-1}$ s$^{-1}$) as a function of temperature (in GK). Multiple curves are plotted, each labeled with a specific temperature value: 665, 330, 38, 287, and 8. The x-axis represents the temperature (GK), while the y-axis represents the reaction rate constant on a logarithmic scale.
For the Future

Mirror Nucleus:
$^{18}\text{F}(d,p)^{19}\text{F}$
proton spectrum

- Lower-energy resonances very uncertain
- Too weak to measure directly
- Study mirror nucleus more carefully
- Proton transfer reactions?

Note: SPI/INTEGRAL should be able to see 511-keV photons following a nova outburst provided it is with ~5kpc of earth!
The Origin of $^{26}$Al in our Galaxy

- source of 1809-keV gamma rays
- half-life = 0.73 million years

Novae are likely a significant source, via the sequence $^{24}\text{Mg}(p,\gamma)^{25}\text{Al}(\beta^+)^{25}\text{Mg}(p,\gamma)^{26}\text{Al}$:

- Evidence from pre-solar grains
- Predicted by models (ONe novae)

$^{26}\text{Al}$ is not produced if this sequence occurs:
$^{24}\text{Mg}(p,\gamma)^{25}\text{Al}(p,\gamma)^{26}\text{Si}(\beta^+)^{26}\text{mAl}(\beta^+)^{26}\text{Mg}$
1809-keV flux distribution (COMPTEL on CGRO)
Expanded Reaction Network

Many more nuclei must be taken into consideration!
Changes in temperature can change the path!
Edwards Accelerator Laboratory

- 4.5-MV tandem accelerator
- p, d, $^3$,$^4$He, heavy ion beams
- 30 m time-of-flight tunnel
Neutron Time-of-Flight Technique

\[ ^{24}\text{Mg} + ^{3}\text{He} \rightarrow ^{26}\text{Si}(\ast) + n \]

- Beam \(^{3}\text{He}\)
- Target \(^{24}\text{Mg}\)
- Neutron flight path (#30m)
- Neutron detector

- time of flight \(\Delta t\) neutron energy
- kinematics \(Y_E_x\) in \(^{26}\text{Si}\)
- \(\Delta t\) \(1\text{ns}\)
- long flight path, low \(E_n\) desirable

Excellent energy resolution achievable!
Neutron Energy Spectra
(Y. Parpottas)

full spectra

$^{24}\text{Mg}(^{3}\text{He},n)^{26}\text{Si}(*$)

Key Result

Mirror nucleus leads us to expect $3^+$ and $0^+$ in this region.
Implications for $^{25}\text{Al}(p,\gamma)^{26}\text{Si}$

<table>
<thead>
<tr>
<th>$E_r$ (keV)</th>
<th>$J^\pi$</th>
<th>$\Gamma_p$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>152</td>
<td>$1^+$</td>
<td>$1 \times 10^{-12}$</td>
</tr>
<tr>
<td>394</td>
<td>$3^+$</td>
<td>$3 \times 10^{-3}$</td>
</tr>
<tr>
<td>428</td>
<td>$0^+$</td>
<td>$2 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

- Our reaction rate is a factor $\sim 20$ smaller at nova temperatures than previously thought.
- The $J^\pi$ assignments should be verified.
Implications for $^{26}$Al production in Novae

- Calculations using the previous reaction rate found that novae could produce up to 20% of the observed galactic $^{26}$Al (Jose’ et al.).

- Recent numerical studies (Iliadis et al. 2002) find less sensitivity to this reaction rate than expected.

- Other nuclear physics inputs have significant uncertainties.

- Recent data from SPI/INTEGRAL indicates other source may be more important.
Unveiling massive star nucleosynthesis in Cygnus X
1809 keV gamma-ray line emission from radioactive $^{26}$Al decay

SPI/INTEGRAL 1809 keV line spectrum of Cygnus X

Flux: $(7.2 \pm 1.8) \times 10^{-5}$ ph cm$^{-2}$ s$^{-1}$
Position: $1808.4 \pm 0.3$ keV $\Rightarrow v_{rad} = -41 \pm 50$ km s$^{-1}$
Width: $3.3 \pm 1.3$ keV $\Rightarrow \Delta v = 550 \pm 210$ km s$^{-1}$

DRAO radio image of ionising massive star clusters in Cygnus X that are at the origin of the $^{26}$Al production detected by SPI

Jürgen Knödlseder (on behalf of the INTEGRAL team), Centre d’Etude Spatiale des Rayonnements, Toulouse, France
In Summary:

- Two reactions important for energy generation and nucleosynthesis in novae have been investigated.
- At Ohio University we are presently working on $^{17}\text{O}(^{3}\text{He,n})^{19}\text{Ne}$ (M. Hornish, H. Hadizadeh, T. Massey, CRB,…).
- Many labs are working on these questions with both stable beams (OU, UNC/Duke, Yale, Texas A&M,…) and radioactive beams (ORNL, NSCL, ANL, TRIUMF,…).
- We look forward to new data from ground- and space-based observatories and other probes of our universe.
Rare Isotope Accelerator
Nuclear Astrophysics at RIA

<10 MeV beams
- p-, α-, n-induced reaction rates
  (ANC, nucleon transfer, …)
- nuclear structure experiments

Stopped beams
- Masses
- β, βn, βp, p decays

>100 MeV beams
- p-, α-, n-induced reaction rates
  (transfer/knockout, Coulomb breakup)
- β, βn, βp, p decays
- charge exchange reactions
- TOF mass measurements
- Nuclear structure experiments

<1 MeV beams
- p-, α-induced reaction rates
  (direct measurements)
- resonant scattering

Neutron Facility
- n-capture on radioactive targets

Neutron Facility
- n-capture on radioactive targets
RIA Floor Plan

MSU, February 2004

47 m • 24 m
RIA Intensities

From a Multibeam Driver, Mass Separated Intensities (ions/s)

400 MeV/u
100 kW

- Stable isotopes
- $> 10^{2}$
- $10^{2}$ - $10^{4}$
- $10^{4}$ - $10^{6}$
- $10^{6}$ - $10^{8}$
- $10^{8}$ - $10^{10}$
- $10^{10}$ - $10^{12}$

Proton Number

Neutron Number