Nuclear Astrophysics

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1. Introduction, BBN & charged-particle reactions
2. Stellar evolution, heavy elements & neutrons
3. Stellar explosions & neutron stars
GW170817 = AT2017gfo

- Multiwavelength (optical, infrared, x-ray, . . .) observations of kilonova → GW170817

Kasen et al., Nature, Nov. 2017

Analysis of Chandra observations

- “Smoking gun” evidence for robust r process in n star mergers
Beta decay properties and the r process

- Decay properties (half-lives) and neutron emission probabilities affect the abundances in the r process
- Few measurements possible thus far
- Efficient techniques are needed to push far away from stability

- Almost all nuclei along the r process path are important
- It is crucial to produce and study these nuclei

Surman et al. (2013)
Beta Decay Example: RIBF @ RIKEN

- Isotopes produced by fragmentation
- EM separated and implanted into Si detector stack
- Identified by TOF and $\Delta E-E$
- Decay $\beta$ and $\gamma$ measured
- Dozens of isotopes studied

Some \((n,\gamma)\) capture rates are important

Abundances are very sensitive to most atomic masses and decay properties

Most mass models do not reliably extrapolate away from stability

Need measurements of nuclear properties in neutron-rich nuclei
Atomic masses

- About 2400 isotopes have measured masses
- Average precision better than 0.1 ppm

Results from 6 Penning trap programs

G. Audi, NPA729,1  
B. Singh, nuclearmasses.org  

Courtesy Dave Lunney
Penning Traps: In a Nutshell

- Trap electrodes in a hyperboloid geometry ($r_0/z_0 \approx 1.16$)
- Placed inside uniform magnetic field
- Three types of motion:
  - Axial ($\omega_z$)
  - Reduced cyclotron ($\omega_c$)
  - Magnetron motion ($\omega$)
- Drive trapped ions into an excitation using RF signal
- Ions are ejected from the trap and measure their time-of-flight to a detector
- Resonant enhancement at the ion cyclotron frequency: $\omega_c$

The mass of the trapped ions are measured indirectly by determining the cyclotron frequency: $\omega_c = qB/m$
The r process

mass uncertainty [keV]

G. Audi, Nucl. Phys. A 729, 1
B. Singh, nuclearmaSSes.org
- Under construction on existing NSCL Site (MSU)
- New gas stopping technology + post accelerator
- New Powerful driver LINAC
  → 200 MeV/u for U
  → 400 kW
- TPC $720M
- Civil construction completed March 2017
- CD-4 ~FY2021
Detailed study of neutron-rich nuclei important for astrophysics
  • Including A~190 mass peak
Core-Collapse Supernovae

Stars > 10 solar masses
Higher gravity
Faster burning stages
Less mass loss
C burning
O burning
Si burning

Weak interaction plays an important role

➢ Electron capture affects formation of shock wave.
➢ Neutrino interactions help drive the explosion.
➢ Neutrino induced reactions alter nucleosynthesis.
➢ Weak rates are not well understood:
  • GT strength distributions
  • First-forbidden contribution
Calculations favor *proton-rich* ejecta

- Nuclear statistical equilibrium favors production of $^{56}$Ni
- Weak interactions can produce neutrons boosting masses produced

**vp process**

Abundances relative to solar
- with $\nu$ reactions
- without $\nu$ reactions


- Possible additional source for intermediate mass elements?
- Contributes to anomalous abundance of light “p” isotopes?
Weak interaction rates

• Great improvements in weak rates from theory (nuclear shell model calculations)
  See Langanke & Martinez-Pinedo, RMP (2003)

• Gamow-Teller strengths can be determined from charge exchange reactions
• (p,n) or (n,p) measurements test shell model predictions and effective interactions
• Some studies so far with stable nuclei

• First measurements now with radioactive nuclei
• (p,n) measurements using Low-Energy Neutron Detector (LENGA) developed with the S800 and radioactive beams.
Stellar Explosions in Binary Systems

- Most stars are in binary systems
  - Some close enough to interact (transfer mass)
- Most common thermonuclear explosions are in such systems
- Driven by nuclear reactions on stable and proton-rich nuclei
- Higher $T \rightarrow$ higher $\sigma$

- **Novae**
  - White dwarf
  - $\sim$40/yr in our Galaxy
  - Recurrence times?

- **X-ray bursts**
  - On surface of neutron star
  - Frequently recur (hours $\rightarrow$ days)
  - Influences evolution of system

- **Type Ia Supernovae**
  - White dwarf + ?
  - SD? DD? Both?!?
  - Star completely destroyed
  - Fe-group production in Galaxy (late times)
Discovering Novae

 ➢ The most common stellar explosion
  • About 3 dozen per year in Milky Way

 ➢ Characterized by increase in brightness of 8-15 magnitudes ($10^3$-$10^6$ times)
  • Peak reached in < 24 h
  • Much slower decay (weeks)
  • Recur after $t > 1000$ yr ?
  • Discovered by amateurs
  • 100’s observers networking around the world
  • Usually discovered photographically

 ➢ Nova Ophiuchi 2006 No. 2
  • Discovered April 6, 2006
  • Peter Williams, Sydney Australia
  • Visual discovery (Magnitude 10)
  • Peak brightness 9.2
  • Confirmation:
    – William Liller (Chile)
    – Tom Krajci (US)
    – Jaciej Reszelski (Poland)

 ➢ RS Oph is a recurrent novae.
  • Few observed but many more possible.
  • Distribution of recurrence times unknown
Many nova reactions have been recently determined

**Notable direct measurements***

- $^{13}\text{N}(p,\gamma)^{14}\text{O}$ (Decrock et al., PRL (1991))
- $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ (Chipps et al., PRL (2009))
- $^{18}\text{F}(p,\alpha)^{15}\text{O}$ (TRIUMF/ORNL/LLN/ANL)
- $^{17}\text{O}(p,\gamma)^{18}\text{F}$ (Newton et al., PRC (2010))
- $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$ (D'Auria et al., PRC (2004))
- $^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$ (Sallaska et al., PRL (2010))
- $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$ (Erikson et al., PRC (2010))
- $^{26}\text{Al}(p,\gamma)^{27}\text{Si}$ (Ruiz et al., PRL (2006)).

Others: $^{18}\text{F}(p,\gamma)^{19}\text{Ne}$, $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$, ...
ISOL facility with highest primary beam intensity (100 µA, 500 MeV protons)

Now adding high intensity electron driver (ARIEL)

ISAC II:
> 6 AMeV for A<150

ISAC I:
60 keV & 1.7 AMeV

~3500 RIB hours /yr
$(p,\gamma)$ at ISAC

$\text{H}_2$ gas target

recoil+$\gamma$ coincidences provide sensitive selection of events

http://dragon.triumf.ca
S. Engel et al., NIM A553 (2005) 491.
$^{21}\text{Na}(p,\gamma)^{22}\text{Na}$ with DRAGON

2.6 yr half-life and 1.27 MeV gamma ray make $^{22}\text{Na}$ a prime observational target

In 1999: $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$ rate uncertain by $>10^5 \times$ (Jose, Coc, Hernanz, ApJ520).)

$\omega_\gamma = 1.03 \pm 0.21$ meV

$\omega_\gamma = 556 \pm 77$ meV

$\Gamma = 16$ keV

$E_r = 205.7 \pm 0.5$ keV

Higher rate for 206 keV resonance $\rightarrow$ ~25% less $^{22}\text{Na}$

Uncertainty~25%

SEparator for CApture Reactions (SECAR)

*Being developed for NSCL/FRIB by MSU, Notre Dame, ORNL, LSU, Mines, . . .*

- Next-generation EM separator for direct measurements of capture reactions at FRIB
- Two Wien filter design provides high mass resolution and suppression of scattered beam
- Current under construction (DOE/NSF)
- SECAR to be commissioned in 2020
  - Will be ready for first experiments at FRIB
Indirect approaches – $^{25}\text{Al}(p,\gamma)^{26}\text{Si}$

- One of the most important rates for understanding $^{26}\text{Al}$ in novae
  - Rates depend on properties of low-lying s-wave resonances ($2^+$ and $3^+$ states in $^{26}\text{Si}$)

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{25}\text{Al}(p,p)^{25}\text{Al}$</td>
<td>Chen et al., PRC (2012)</td>
</tr>
<tr>
<td>$^{27}\text{Si}(p,d)^{26}\text{Si}$</td>
<td>Chen et al., PRC (2012)</td>
</tr>
<tr>
<td>$^{28}\text{Si}(p,t)^{26}\text{Si}$</td>
<td>Matic et al., PRC (2011)</td>
</tr>
<tr>
<td>$^{28}\text{Si}(p,t)^{26}\text{Si}$</td>
<td>Chipps et al., PRC (2010)</td>
</tr>
<tr>
<td>$^{28}\text{Si}(p,t)^{26}\text{Si}$</td>
<td>Matic et al., PRC (2010)</td>
</tr>
<tr>
<td>$^{25}\text{Al}(d,n)^{26}\text{Si}$</td>
<td>Peplowski et al., PRC (2009)</td>
</tr>
<tr>
<td>$^{28}\text{Si}(\alpha,^6\text{He})^{26}\text{Si}$</td>
<td>Kwon et al., JKPS (2008)</td>
</tr>
<tr>
<td>$^{12}\text{C}(^{16}\text{O},2n)^{26}\text{Si}$</td>
<td>Seweryniak et al., PRC (2007)</td>
</tr>
<tr>
<td>$^{28}\text{Si}(p,t)^{26}\text{Si}$</td>
<td>Bardayan et al., PRC (2006)</td>
</tr>
<tr>
<td>$^{28}\text{Si}(p,t)^{26}\text{Si}$</td>
<td>Parikh et al., PRC (2005)</td>
</tr>
<tr>
<td>$^{24}\text{Mg}(^{3}\text{He},n)^{26}\text{Si}$</td>
<td>Parpottas et al., PRC (2004)</td>
</tr>
<tr>
<td>$^{28}\text{Si}(p,t)^{26}\text{Si}$</td>
<td>Bardayan et al., PRC (2002)</td>
</tr>
<tr>
<td>$^{29}\text{Si}(^{3}\text{He},^{6}\text{He})^{26}\text{Si}$</td>
<td>Caggiano et al., PRC (2002)</td>
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Type Ia Supernovae

Single Degenerate (SD)  Double Degenerate (DD)
Nuclear physics of Type Ia

- Most important nuclear physics is fusion of C, O, Ne nuclei
  - $^{12}\text{C} + ^{12}\text{C} \rightarrow \rightarrow$
  - $^{12}\text{C} + ^{16}\text{O} \rightarrow \rightarrow$

- Measurements needed to lower energies
- Resonances could contribute in a few cases
X-ray vision

The RXTE All-Sky Monitor Movie

➢ Over 100 sources in the Milky Way
  • Do not confuse with Gamma ray-bursts
➢ Recur on a semi-regular time scale
➢ Thermonuclear explosion on surface of a neutron star
➢ Observations provide crucial insights into neutron star properties

http://heasarc.gsfc.nasa.gov/xte_weather/
Neutron star reactions

Neutron Star Surface

- H, He fuel
- atmosphere
- ashes
- ocean
- outer crust
- inner crust

Why do burst durations vary? (10s – min)
What nuclei are made in the explosion?
  - Galactic nucleosynthesis contribution?
  - Start composition for deeper processes?

Deep H, C, … burning

- Origin of Flares?
- Origin of Superbursts?

Electron captures
Pycnonuclear reactions

- Gravitational wave emission?
- Crust heating?
- Dissipation of magnetic fields?
Nuclear reactions drive explosion

- Reaction rates are crucial
  - Thermonuclear events
  - Energy generation (light curve)
  - Abundances (spectra)
  - Evolution of system
  - \((p, \gamma)\) and \((\alpha, p)\) reactions w/ large uncertainties

- Not all reactions are equally important
  - Sensitivity studies help to identify reactions that are likely most important
  - Caveat: Depends on assumptions of astrophysical model

Calculated X-ray light curve

Cyburt et al., AJSS (2010)

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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>(^{15}\text{O}(\alpha, \gamma)^{19}\text{Ne})</td>
<td>K04, K04-B1, K04-B6</td>
</tr>
<tr>
<td>(^{18}\text{Ne}(\alpha, p)^{21}\text{Na})</td>
<td>K04-B1, K04-B6</td>
</tr>
<tr>
<td>(^{22}\text{Mg}(\alpha, p)^{26}\text{Al})</td>
<td>F08</td>
</tr>
<tr>
<td>(^{26}\text{Al}(p, \gamma)^{24}\text{Si})</td>
<td>K04-B1</td>
</tr>
<tr>
<td>(^{24}\text{Mg}(\alpha, p)^{27}\text{Al})</td>
<td>K04-B2</td>
</tr>
<tr>
<td>(^{26}\text{Si}(\alpha, p)^{31}\text{P})</td>
<td>F08</td>
</tr>
<tr>
<td>(^{30}\text{S}(\alpha, p)^{33}\text{Cl})</td>
<td>K04-B4, K04-B5</td>
</tr>
<tr>
<td>(^{34}\text{Cl}(p, \gamma)^{32}\text{Ar})</td>
<td>K04-B3</td>
</tr>
<tr>
<td>(^{32}\text{S}(\alpha, p)^{35}\text{Cl})</td>
<td>K04-B2</td>
</tr>
<tr>
<td>(^{36}\text{Cl}(p, \gamma)^{34}\text{Ar})</td>
<td>K04-B2</td>
</tr>
<tr>
<td>(^{56}\text{Ni}(\alpha, p)^{59}\text{Cu})</td>
<td>S01</td>
</tr>
<tr>
<td>(^{60}\text{Cu}(p, \gamma)^{63}\text{Zn})</td>
<td>S01</td>
</tr>
</tbody>
</table>

Array for Nuclear Astrophysics and Structure with Exotic Nuclei

(α,p) with active gas target

2x12 Super-X3 (4x4 Resistive)

New QQQ (16x16)

CsI

End View w/o PC

Side View

PC wires

Beam

window
$^{18}\text{Ne}(\alpha,p)^{21}\text{Na}$ vs. $^{18}\text{Ne}(\alpha,2p)^{20}\text{Ne}$
Conclusion

Nuclear physics is central to answering some challenging questions related to astrophysics:

- What are the origins of the heavy elements?
- What are the progenitors of Type Ia supernovae?
- What is the mechanism involved in core collapse supernovae?
- What is the evolution of interacting binary systems?
- What are the properties of neutron stars?

New nuclear data and astrophysical observations are the keys to solving these cosmic questions