Direct ($\alpha,p$) Reaction Measurements with HELIOS and the study of $^{20}\text{Ne}(\alpha,p)^{23}\text{Na}$

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\((\alpha, p)\) Reactions in Explosive Nucleosynthesis - XRBs

- **Type I X-ray bursts (XRBs):**
  - thermonuclear explosions on neutron star surface in binary system
  - \(T_{\text{peak}} = 1 - 2\) GK
  - time scale 10 – 100 s
  - recurrent events (hours to days)

- **Nucleosynthesis:**
  - triple-\(\alpha\) process
  - CNO breakout – \(^{18}\text{Ne}(\alpha, p)^{21}\text{Na}\)
  - \((\alpha, p)\) process
  - rapid proton capture (\(rp\)) process
  - synthesis up to \(A\sim100\)

(α,p) Reactions in Explosive Nucleosynthesis - XRBs

• Sensitivity studies of XRB nucleosynthesis:
  – vary reactions individually
  – show only a handful of reactions significantly effect bursts

• Effects of (α,p) reactions in XRBs:
  – shape of light curve
  – energy output
  – elemental abundances
  – double-peaked bursts(?)

Cyburt et al., 2016 (submitted)

(α,p) Reactions in Explosive Nucleosynthesis - SNeIa

• Type Ia Supernovae:
  – thermonuclear explosion of white dwarf star in binary system
  – progenitor uncertain
  – disruptive explosion; no remnant
  – $T_{\text{peak}} \sim 8$ GK

• Nucleosynthesis in SNeIa:
  – C+C, C+O, O+O fusion
  – $\alpha$-chain reactions
  – production of >50% Fe content of Galaxy

Bravo et al., PRC 85, 055805 (2012)
Type Ia Supernovae Sensitivity Studies

• Variation of reaction rates by factor of 10 up and down

• Two independent studies show high sensitivity to:
  - $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$
  - $^{12}\text{C} + ^{12}\text{C}$
  - $^{20}\text{Ne}(\alpha,p)^{23}\text{Na}$
  - $^{20}\text{Ne}(\alpha,\gamma)^{24}\text{Mg}$
  - $^{30}\text{Si}(p,\gamma)^{31}\text{P}$

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Direct ($\alpha, p$) measurements with HELIOS at Argonne National Laboratory

ATLAS
Direct \((\alpha, p)\) measurements with HELIOS

- HELIcal Orbit Spectrometer (HELIOS)
  - repurposed MRI magnet
  - magnetic field aligned with beam axis
  - commissioned 2008

- Ideal for studying reactions with radioactive ion beams
  - unique particle identification from time-of-flight
  - high geometrical efficiency
  - improve resolution (avoid kinematic compression)

\[ ^4\text{He}(^{34}\text{Ar}, p)^{37}\text{K} \text{ gs} \]
\[ ^4\text{He}(^{34}\text{Ar}, p)^{37}\text{K} 3 \text{ MeV} \]

<table>
<thead>
<tr>
<th>Particle</th>
<th>p</th>
<th>(^3\text{He})</th>
<th>d, (^4\text{He})</th>
<th>t</th>
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<tr>
<td>TOF(ns)</td>
<td>21.9</td>
<td>32.8</td>
<td>43.7</td>
<td>65.6</td>
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</tbody>
</table>
Direct \((\alpha, p)\) measurements with HELIOS

- Direct \((\alpha, p)\) measurement needs:
  - \(^4\text{He}\) gas target
    - cryogenically cooled
    - commissioned with \(^{14}\text{C}(d,p)^{15}\text{C}\), \(^{14}\text{C}(^{3}\text{He},d)^{15}\text{N}\) Spring 2013
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    - beam monitoring/normalization
    - position information
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high rate: 500 kHz
energy resolution: <5%
position sensitivity
mass separation at low A
First Direct \((\alpha, p)\) Study with HELIOS: \(^{20}\text{Ne}(\alpha, p)^{23}\text{Na}\)

- Direct study of \(^{20}\text{Ne}(\alpha, p)^{23}\text{Na}\)
  - protons detected in HELIOS Si array
  - \(^{23}\text{Na}\) detected in ionization chamber
  - normalized via known \((d, p)\) reaction

- Part I completed December 2014
  - \(E_{\text{beam}} = 107, 100, 88\) MeV
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First Direct \((\alpha,\rho)\) Study with HELIOS: 
\(^{20}\text{Ne}(\alpha,\rho)^{23}\text{Na}\)

- Part II completed July 2015
- Normalization via \((\alpha,\alpha)\) scattering and \((d,\rho)\) on solid target
- Dissertation of Jianping Lai (LSU) – August 2016
\( ^{20}\text{Ne}(\alpha,p)^{23}\text{Na} \) Cross Sections

- Normalized cross section for \( ^{20}\text{Ne}(\alpha,p)^{23}\text{Na} \):
  - in agreement with Hauser-Feshbach calculations
  - in agreement with inverse reaction cross section

- Future plans:
  - determining contribution from excited states (present data)
  - measurements at more (and lower) energies
  - study affects on SNeIa models
Current Developments: ANASEN

- Array for Nuclear Astrophysics and Structure with Exotic Nuclei (ANASEN)
  - designed for direct (α, p) reaction studies
    - extended, active gas target
    - proportional counter
    - Si detector array

Current Developments:

- ANASEN
- RIB
- p recoil (via window)

Kevin Macon, PhD Thesis (LSU)
- 37\(^{\text{K}}\)(p, p\(^{\text{37}}\)\(^{\text{K}}\)) (first RIB measurement @ ReA3)
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Nuclear Astrophysics measurements:

- \(^{14}\text{N}(\alpha,p)^{17}\text{O}\) (stable beam FSU)
- \(^{18}\text{Ne}(\alpha,p)^{21}\text{Na}\) (RIB from RESOLUT @ FSU)
  - Kevin Macon, PhD Thesis (LSU)
- \(^{37}\text{K}(p,p)^{37}\text{K}\) (first RIB measurement @ ReA3)
Summary

• \((\alpha,p)\) reactions play a significant role in stellar explosive nucleosynthesis

• Direct measurements are challenging:
  – radioactive ion beams
  – gas targets
  – low cross sections

• Multiple methods underdevelopment for direct \((\alpha,p)\) measurements:
  – HELIcal Orbit Spectrometer (HELIOS) at ATLAS facility
  – ANASEN
  – JENSA gas-jet target with Si detector array

• First direct measurement of \(^{20}\text{Ne}(\alpha,p)^{23}\text{Na}\):
  – proof-of-principle of HELIOS method
  – important for Type Ia Supernova nucleosynthesis
THANKS!

**ATLAS staff and operators**

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