Pair Spectroscopy of the Hoyle State

T. Kibédi
Department of Nuclear Physics
Australian National University
Canberra, Australia
Tibor.Kibedi@anu.edu.au

Bungle Bungle Star Trails | Mike Salway
The triple-$\alpha$ rate in stellar He burning

1939: No stable A=5 to 8 elements

Triple-$\alpha$ process to bypass the gap; PR 55 (1939) 434

Hans A. Bethe (1906-2005)
The triple-$\alpha$ rate in stellar He burning

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1952: Carbon production rate calculated; APJ 115 (1952) 326
   $^4\text{He} + ^4\text{He} + 95 \text{ keV} \rightarrow ^8\text{Be} + \gamma$ ($^8\text{Be}$ g.s. resonance)
   $^4\text{He} + ^8\text{Be} \rightarrow ^{12}\text{C} + \gamma$
The triple-\(\alpha\) rate in stellar He burning

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   PR 92 (1953) 1095

Hans A. Bethe (1906-2005)
Edwin E. Salpeter (1924-2008)
Sir Fred Hoyle (1915-2001)
The triple-α rate in stellar He burning

The Crafoord Prize 1997 in Astronomy: “for their pioneering contributions to the study of nuclear processes in stars and stellar evolution”
The triple-\(\alpha\) rate in stellar He burning

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\[ ^4\text{He} + ^4\text{He} + 95 \text{ keV} \rightarrow ^8\text{Be} + \gamma \ (^{8}\text{Be \ g.s. resonance}) \]
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PR 92 (1953) 1095

1953: The 7.68 MeV state identified from \[ ^{14}\text{N}(d,\alpha)^{12}\text{C} \]
PR 92 (1953) 649

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New experimental results for the triple-$\alpha$ rate

- **Observation of a 16% alpha-decay branch bypassing the ground state of $^8$Be ($T_{1/2}=10^{-16}$ s; Raduta et al. PRL B705 (2011) 65)**
- **New upper limit: 0.1% (Kiresebom et al. PRL 108 (2012) 202501; Manfredi et al. PRC (2012) 037603)**
New experimental results for the triple-$\alpha$ rate

- $2^+$ excitation of the Hoyle state: $E=9.75(10)$ MeV, $\Gamma=750(150)$ keV (Freer et al. PRC86 (2012) 034320)

New theoretical results for the triple-α rate

Controversy over calculated reaction rates at low \((10^7 \text{ K})\) temperatures


HHR - Hyperspherical Harmonic R-matrix method
NACRE - Nuclear Astrophysics Compilation of REaction rates
CDCC - Continuum Discretized Coupled Channel
BW(3B) - three-body Breit Wigner
New theoretical results for the triple-α rate

- New ab initio calculations using lattice simulations effective field theory reproduce excitation energy (Epelbaum et al. PRL 106 (2011) 192501; PRL 109 (2012) 252501)
- 3-alpha microscopic cluster model (Vasilevsky et al., PRC 85 (2012) 034318)

<table>
<thead>
<tr>
<th></th>
<th>E, MeV</th>
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<tbody>
<tr>
<td></td>
<td>Exp</td>
<td>Theor</td>
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</tr>
<tr>
<td>0⁺</td>
<td>-7.2746</td>
<td>-11.372</td>
<td></td>
<td></td>
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<tr>
<td>Bound</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>0.3796</td>
<td>0.684</td>
<td>0.0085(10)</td>
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<tr>
<td>2⁺</td>
<td>-2.8357</td>
<td>-8.931</td>
<td>430(80)</td>
<td>9.95</td>
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Calculation of the triple-\(\alpha\) reaction (Rolfs and Rodney, 1988):

The rate per unit volume for the triple-\(\alpha\) reaction (Rolfs and Rodney, 1988):

\[
 r_{3\alpha} = \frac{N_\alpha^3}{2} \frac{3^{3/2}}{2} \left(\frac{2\pi\hbar^2}{M_\alpha kT}\right)^3 \frac{\Gamma_\alpha \Gamma_{rad}}{\hbar \Gamma} \exp\left(-\frac{Q_{3\alpha}}{kT}\right)
\]

\[\text{where} \quad Q_{3\alpha} = (M_{12\text{C}} - 3 \times M_\alpha) c^2 + E_r\]

Since \(\Gamma_{\text{rad}} << \Gamma_\alpha \approx \Gamma\), where \(\Gamma = \Gamma_\alpha + \Gamma_{\text{rad}}\) and \(T \approx 10^8 \text{ K}\):

\[
r_{3\alpha} \propto \Gamma_{\text{rad}} \exp\left(-\frac{Q_{3\alpha}}{kT}\right)
\]
Triple-α rate - how well it is known now

\[ r_{3\alpha} \propto \left[ \Gamma_{\text{rad}} \right] \exp(-[Q_{3\alpha}]/kT) \]

\[ \Gamma_{\text{rad}} = \left[ \frac{\Gamma_{\text{rad}}}{\Gamma} \right] \times \left[ \frac{\Gamma}{\Gamma_\pi(E0)} \right] \times [\Gamma_\pi(E0)] \]

“traditional approach”
Triple-\(\alpha\) rate – how well it is known now

\[
\begin{align*}
r_{3\alpha} & \propto \left[ \frac{\Gamma_{rad}}{\Gamma} \right] \exp\left( -\frac{Q_{3\alpha}}{kT} \right) \\
\Gamma_{rad} & = \left[ \frac{\Gamma_{rad}}{\Gamma} \right] \times \left[ \frac{\Gamma}{\Gamma_{\pi}(E0)} \right] \times \left[ \Gamma_{\pi}(E0) \right]
\end{align*}
\]

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<td>(\Gamma_{rad}/\Gamma)</td>
<td>4.13(11)(\times 10^{-4})</td>
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“traditional approach”

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Triple-\(\alpha\) rate - how well it is known now

\[ r_{3\alpha} \propto \left[ \frac{\Gamma_{\text{rad}}}{\Gamma} \right] \exp\left(-\frac{Q_{3\alpha}}{kT}\right) \]

\[ \Gamma_{\text{rad}} = \left[ \frac{\Gamma_{\text{rad}}}{\Gamma} \right] \times \left[ \frac{\Gamma}{\Gamma_{\pi}(E0)} \right] \times \left[ \Gamma_{\pi}(E0) \right] \]

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2005 Crannell et al: \(\Gamma_{\pi}(E0)=52.0(14)\) \(\mu\)eV; \(q=0.27-3.04\) fm\(^{-1}\); Extensive data from Darmstadt, Bates-CUA, NIKHEF-K & HEPL

2010 Chernykh et al: \(\Gamma_{\pi}(E0)=62.3(20)\) \(\mu\)eV; \(q=0.21-0.67\) fm\(^{-1}\); Darmstadt S-DALINAC

\(7+1\) measurements
Data discrepant

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Triple-\(\alpha\) rate – how well it is known now

\[
r_{3\alpha} \propto \left[ \frac{\Gamma_{\text{rad}}}{\Gamma} \right] \exp\left(-\frac{Q_{3\alpha}}{kT}\right)
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\Gamma_{\text{rad}} = \left[ \frac{\Gamma_{\text{rad}}}{\Gamma} \right] \times \left[ \frac{\Gamma}{\Gamma_\pi(E0)} \right] \times \left[ \Gamma_\pi(E0) \right]
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Largest known \(E0\) strength!

in “Wilkinson units”

\[S_{\text{wi,u.}} = |M_{\text{exp}}|^2 / |M_{\text{s.p.}}|^2 = 2.3(2) \text{ s.p.u.}\]

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Triple-α rate – how well it is known now

\[ r_{3\alpha} \propto \left[ \frac{\Gamma_{rad}}{\Gamma} \right] \exp\left( -\frac{Q_{3\alpha}}{kT} \right) \]

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“traditional approach”

Need 5% accuracy
New approach to determine $\Gamma_{rad}$

$\alpha$ decay 99.96%

$\gamma$ decay 0.04%

Observe both EM transitions in the same experiment to determine relative intensities

$$\Gamma_{rad} = \Gamma_{\gamma}(E2) + \Gamma_{\pi}(E0) + \Gamma_{\pi}(E2) + \Gamma_{CE}(E0) + \Gamma_{CE}(E2)$$

$\sim 98.5\%$  
$\sim 1.5\%$  
$\sim 0.088\%$  
$\sim 9 \times 10^{-6}\%$  
$\sim 3 \times 10^{-5}\%$

$$\Gamma_{rad} = \left[ \frac{\Gamma_{\pi}(E2)}{\Gamma_{\pi}(E0)} \right] \times \left[ 1 + \frac{1}{\left[ \alpha_{\pi}(E2) \right]} + 1 \right] \times \left[ \Gamma_{\pi}(E0) \right]$$

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Measuring electron-positron pairs

- $e^- - e^+$ particles share the available kinetic energy:
  \[ E_{\text{kin}} = E_+ + E_- = E_\gamma - 2 m_0 c^2 \]
  
  Need to observe both particles

- Pair emission rate: function of $Z$, $E_\gamma$, $E_+$, $\Theta$ and multipolarity; Born approx.
  \[ \Gamma_\pi(E0) \sim \rho^2(E0) \times \Omega_\pi(E0) \]
  \[ E_+ \approx E_- \]
  \[ \theta_{\text{sep}} \approx 60^\circ \]

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- Pair emission rate: function of $Z$, $E_\gamma$, $E_+$, $\Theta$ and multipolarity; Born approx.

\[ \alpha_\pi(E2) = \Gamma_\pi(E2)/\Gamma_\gamma(E2) \]

\[ E_+ \approx E_- \]

\[ \theta_{\text{sep}} \approx 30^\circ \]

\[ W_\pi(E0) \sim \rho^2(E0) \times \Omega_\pi(E0) \]

\[ W_\pi(E2) = \Gamma_\gamma(E2) \times \alpha_\pi(E2) \]

ICC

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\( \Omega(E_0) \) experiment vs. theory

- \( \Omega_{\pi}(E_0) \) - not accessible from experiment

\[ W_{\pi}(E_0) \sim \rho^2(E_0) \times \Omega_{\pi}(E_0) \]

- \( \Omega_K(E_0) / \Omega_{\pi}(E_0) \) is known for 5 cases only
Angular correlation data for $\Omega(E0)$ is rare

S. Devons and G.R. Lindsey
Nature (London) 164 (1949) 539

A.H. Wuosmaa et al. (APEX ANL)
PRC 57 (1998) R2794

SOLID LINE: Ch. Hoffmann et al.
PRC 53 (1996) 2313
DASHED LINE: Born Approximation

Born approximation for low Z and $\Theta_s<80^\circ$ is sufficient
New pair spectrometer
Absorber system & detector

Acceptance angles: 15.9° - 46.9°
Absolute singles efficiency: 0.5%/4π

Spectrometer response from simulations

(a) 7.654 MeV E0 in $^{12}$C

Si(Li) array @350 mm
Six detectors of 236 mm$^2$
FWHM ≈ 2.5 keV
Semikon GmbH

Absorbers made from HeavyMet
(density 18 gr/cm$^3$)
1 mm thick low Z skin (Torr Seal®)
Old/New Absorber system
Singles data

First in-beam tests
Original lens (Apr-2009)
New lens (Jun-2012)

$^{12}\text{C}(p,p')$ @ 10.5 MeV
2 mg/cm² target

~100
Old/New Absorber system
Singles data

First in-beam tests
Original lens (Apr-2009)
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$^{12}$C(p,p') @ 10.5 MeV
2 mg/cm² target

Pairs hitting the same segment
New Absorber system
Electrons & Positrons in coincidence

4.439 MeV E2

Experiment: $^{12}\text{C}(p,p')$ at 10.5 MeV

$$E \approx \frac{E_\gamma - 1.022 \text{ MeV}}{2}$$
New Absorber system
Electrons & Positrons in coincidence

Experiment: $^{12}\text{C}(p,p')$ at 10.5 MeV
Simulation: electrons
New Absorber system
Electrons & Positrons in coincidence

Experiment: $^{12}\text{C}(p,p')$ at 10.5 MeV
Simulation: electrons, positrons
New Absorber system

Electrons & Positrons in coincidence

4.439 MeV E2

Experiment: $^{12}$C(p,p$'$) at 10.5 MeV
Simulation: electrons
            positrons

Partial energy deposit from annihilation quanta
New Absorber system

Electrons & Positrons in coincidence

Experiment: $^{12}\text{C}(p,p')$ at 10.5 MeV
Simulation: electrons, positrons, summed

4.439 MeV E2
New Absorber system
Electrons & Positrons in coincidence

Experiment: $^{12}\text{C}(p,p')$ at 10.5 MeV
Simulation: electrons, positrons, summed

Compton electrons ($\hbar\omega=0.511$ MeV)
$^{54}\text{Fe}(p,p'g) @ 6.9 \text{ MeV}$

CSS hpGe

Singles electrons

Sum-coincidence pairs

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$^{54}\text{Fe}(p,p'g) \: @ \: 6.9 \text{ MeV}$

E.K. Warburton and D.E. Alburger,
Phys. Rev. C 6 (1972) 1224
\[ ^{54}\text{Fe}(p,p'g) @ 6.9 \text{ MeV} \]


CSS hpGe

Singles electrons

Sum-coincidence pairs
12C(p,p')12C* pair measurements
(Jun-2012)

- 55 h beam time with 100 nA on a 2 mg/cm² target
- “old” Honey detector (1997), 4.2 mm thick, reduced efficiency, continuous gain shifts
- TDC gate of +/- 6 ns wide!

graph showing peaks at 3215, 4439, 6050, and 7654 keV.
$^{12}\text{C}(p,p')^{12}\text{C}^*$ pair measurements
(Jun-2012)

800 nA on 3.5 mg/cm$^2$
2 NaI detectors

1977Al31 D. Alburger (1977)
Courtesy of Mitchel de Vries

100 nA on 2.0 mg/cm$^2$
6 Si(Li) detectors

ANU Super-e (2012)
Conclusion and outlook

**Current status**
- New pair spectrometer based on six Si(Li) detectors combined with a magnetic lens transporter
- High energy photon background drastically reduced
- High coincidence efficiency, optimized for E0 and E2: 1:1 vs. 500:1 (Alburger 1977)
- Less sensitive for correlation and attenuation effects ($E_+ \sim E_-$)
Conclusion and outlook

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Improvements
- 9 mm thick Si(Li) array: factor 2 higher efficiency for 7.7 MeV pairs
- 500 nA proton beam intensity: factor 5 higher yield

Challenges
- Evaluation of pair conversion efficiency accurately for up to 8 MeV transition energy
Acknowledgement

Collaborators
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