The Origin of Oxygen in the Universe –
A New Approach to an Old Quest(ion)

K. E. Rehm
Physics Division
Argonne National Laboratory
Influence of the $^{12}\text{C}(\alpha,\gamma)$ rate in stars - I

Relative abundance of elements by weight

Universe

- Hydrogen 73%
- Helium 25%
- Oxygen 1%
- Other 1%

Human Body

- Oxygen 61%
- Carbon 23%
- Hydrogen 10%
- Nitrogen 2.6%
- Calcium 1.4%
- Phosphorus 1.1%
- Other 0.9%
Influence of the $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ rate in stars - II

Heger, Woosley, & Boyse (2002)
$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

- ..a problem of paramount importance to nuclear astrophysics.
- ..the “holy grail” of nuclear astrophysics

W. Fowler

Outline

• Brief status report of previous experiments
  $^{12}\text{C}(\alpha,\gamma)^{16}\text{O},\ 4\text{He}(^{12}\text{C},^{16}\text{O})\gamma,\ldots$

• The time inverse reaction $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$
  advantages, disadvantages

• Outlook
Level structure of $^{16}$O

No resonance but interferences

S-factor
$S_{\text{cap}}(^{12}\text{C}(\alpha,\gamma)^{16}\text{O})=120 \pm 40 \text{ keVb}$
\[ ^{12}\text{C}(\alpha, \gamma)^{16}\text{O} \]

R. Kunz, thesis, 2002

\[ \alpha(^{12}\text{C}, ^{16}\text{O})\gamma \]

D. Schuermann et al. EPJA 26, 301 (2001)
**Luminosity**

\[ R = L \cdot \sigma \]

- **\( R \)**: Rate (counts/time)
- **\( L \)**: Luminosity
- **\( \sigma \)**: cross section

\[ L = I \cdot T \cdot \varepsilon \]

- **\( I \)**: incident beam (particles/sec)
- **\( T \)**: target thickness (atoms/cm\(^2\))
- **\( \varepsilon \)**: detection efficiency
luminosity of recent experiments

\[ \text{\(10^{31}\)} \]

\[ \text{\(10^{30}\)} \]

\[ \text{\(10^{29}\)} \]

\[ \text{\(10^{28}\)} \]

\[ \text{\(10^{27}\)} \]

\[ \text{\(10^{26}\)} \]

\[ \text{\(10^{25}\)} \]

\[ \text{\(10^{24}\)} \]

\[ \text{\(10^{23}\)} \]

\[ \text{\(10^{22}\)} \]

\[ \text{\(10^{21}\)} \]

\[ \text{\(10^{20}\)} \]

\[ \text{\(10^{19}\)} \]

\[ \text{\(10^{18}\)} \]

\[ \text{\(10^{17}\)} \]

\[ \text{\(10^{16}\)} \]

\[ \text{\(10^{15}\)} \]

\[ \text{\(10^{14}\)} \]

\[ \text{\(10^{13}\)} \]

\[ \text{\(10^{12}\)} \]

\[ \text{\(10^{11}\)} \]

\[ \text{\(10^{10}\)} \]

\[ \text{\(10^{9}\)} \]

\[ \text{\(10^{8}\)} \]

\[ \text{\(10^{7}\)} \]

\[ \text{\(10^{6}\)} \]

\[ \text{\(10^{5}\)} \]

\[ \text{\(10^{4}\)} \]

\[ \text{\(10^{3}\)} \]

\[ \text{\(10^{2}\)} \]

\[ \text{\(10^{1}\)} \]

\[ \text{\(10^{0}\)} \]

\[ \text{\(10^{-1}\)} \]

\[ \text{\(10^{-2}\)} \]

\[ \text{\(10^{-3}\)} \]

\[ \text{\(10^{-4}\)} \]

\[ \text{\(10^{-5}\)} \]

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\[ \text{\(10^{-15}\)} \]

\[ \text{\(10^{-16}\)} \]

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\[ \text{\(10^{-30}\)} \]

\[ \text{\(10^{-31}\)} \]

\[ \text{\(10^{-32}\)} \]

\[ \text{\(10^{-33}\)} \]

\[ \text{\(10^{-34}\)} \]

\[ \text{\(\gamma\)-ray detection} \]

\[ \text{\(\text{particle detection}\)} \]

\[ \text{1987} \]

\[ \text{1991} \]

\[ \text{1995} \]

\[ \text{1999} \]

\[ \text{2003} \]

\[ \text{2007} \]

\[ \text{2011} \]

\[ \text{2015} \]

Eilat, April 2011
Expected count rates per day for 1 pb

- γ-ray detection
- particle detection
$^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$

$\alpha(^{12}\text{C}, ^{16}\text{O})\gamma$
Indirect techniques (since 2000)

$^{12}\text{C}(^{6}\text{Li},d)^{16}\text{O}$:
- A. Belhout et al. NPA 793, 178 (2007)

$^{12}\text{C}(\alpha,\alpha)^{12}\text{C}$:
- P. Tischhauser et al. PRC 79, 055803(2009)

$^{16}\text{N} \ \beta$-decay:
- X. D. Tang et al. PRC81, 045809 (2010)

$^{16}\text{O}$ Coulomb dissociation:
- F. Fleurot et al. PLB616, 167 (2005)
Measure the time-inverse reaction:

$^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$

Advantages:

- Phase space factor for inverse reactions
- Large range of 8-10 MeV $\gamma$’s: use thicker target (tens of g/cm$^2$ (e.g. water) vs. tens of $\mu$g/cm$^2$)

Disadvantages:

- Lower intensities for beams of $\gamma$-rays
Advantages of inverse reactions Coulomb dissociation vs. (p,γ) reactions

\[
\frac{\sigma_{23\to01}}{\sigma_{01\to23}} = \frac{(2j_o + 1)(2j_1 + 1) k_{01}^2}{(2j_2 + 1)(2j_3 + 1) k_{23}^2}
\]

For \(^{12}\text{C}(\alpha,\gamma)^{16}\text{O}\) vs \(^{16}\text{O}(\gamma,\alpha)^{12}\text{C}\)

\[
\frac{\sigma_{\gamma,\alpha}}{\sigma_{\alpha,\gamma}} = \frac{2\mu_{\alpha,\gamma}c^2E_{\alpha,\gamma}}{2E_{\gamma}^2} = \frac{2 \cdot 4 \cdot 12 \cdot 1000 \cdot 1}{2 \cdot 16 \cdot 8 \cdot 8} \approx 50
\]
\[ ^{16}\text{O}(\gamma,\alpha)^{12}\text{C} \]

- Need a source of 7-10 MeV \(\gamma\)’s
- Need a detector that works with an oxygen-containing target material
- Detects \(\alpha\) and \(^{12}\text{C}\)
- Is insensitive to \(\gamma\)’s at the level of better than \(10^{-11}\)

\[ \rightarrow \] Use Free Electron Laser Facility (\(\text{H}l\gamma\text{S}\)) + Detector with superheated liquids
The HI\gamma S Free Electron Laser Facility at DUKE

I_{\gamma} \sim 5 \times 10^7 \text{ photons/sec}
Test setup (diameter 2.5 cm)
Preparation of a superheated liquid:

Charged particle production \((^{16}\text{O}(\gamma,\alpha)^{12}\text{C})\) leads to bubble formation.

Difficulties (for water):
- High T (~250°C)
- High P (~75 atm)
Expected count rates/day at HIγS for 1 pb (in blue) (with a 30 cm long cylinder)
Plan to improve with a 200 Ci $^{137}\text{Cs}$ source in a shielded vault
Test version of a superheated droplet detector
Using refrigerants: H$_2$C$_2$F$_4$, C$_4$F$_{10}$

P~ 1-6 atm
T~20-50 C

2 fast cameras
A ‘successful’ bubble

$\Delta t = 10$ ms
‘Proof of principle’ experiment:

- Check the expected increase in luminosity
- Check detection efficiency in a system with known cross section
- Check possible backgrounds (wall effects, beam contaminants)

use $^{19}\text{F}(\gamma,\alpha)^{15}\text{N}$ experiment
use 10x smaller vessel filled with $\text{C}_4\text{F}_{10}$
for a resonance at $E_\gamma=5.3$ MeV with $<\sigma_{\text{max}}(\alpha,\gamma)> = 1$ µb.
with $L=10^{33}$ /sec/cm$^2$ we expect $10^3$ events/sec.
reduce $\gamma$-rate by $\sim 3$ orders of magnitude.
First tests with $\text{C}_2\text{H}_2\text{F}_4$

- $\gamma$ beam
- Bubbles from $^{19}\text{F}(\gamma,\alpha)^{15}\text{N}$
- Bubbles from cosmic rays (2%)
- 1 cm
Position sensitivity in 3D

Cu collimator

Camera-1

Camera-2
Position sensitivity in 3D

Δx < 1 mm
Proof of principle worked ✓

In order to measure a 5 µb cross section we had to turn down the γ-intensity by 4 orders of magnitude

Open questions:

• what material for $^{16}$O:
  - liquid oxygen (safety?)
  - water (high p,T)
  - $N_2O$ (asphyxiation)

• background reactions
  - Bremsstrahlung
  - $^{17,18}$O, d contaminants
Missed bubble with water

High T (~250 C)
High P (~50 atm)

Need pressure vessel!
P~75 atm
T=250 C
Influence of isotopic impurities

- Want to measure $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$, but water has $^2\text{H}$, $^{17,18}\text{O}$ impurities up to the $2\times10^{-3}$ level.
- Possible background reactions:
  - $^{18}\text{O}(\gamma,n)^{17}\text{O}$ followed by n-recoils
  - $^{17}\text{O}(\gamma,n)^{16}\text{O}$ followed by n-recoils
  - $^{18}\text{O}(\gamma,\alpha)^{14}\text{C}$
  - $^{17}\text{O}(\gamma,\alpha)^{13}\text{C}$
  - $d(\gamma,n)p$ followed by n-recoils
- Reactions on $^{17,18}\text{O}$ and $^{29}\text{Si}$ in the glass vessel.

Need isotopically depleted water.
Summary

Developing a new technique for measuring $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

+ Improved yields through use of inverse reaction
+ Uses a $10^6$ thicker target
- Needs a tunable $\gamma$-beam (hope for improvement)

Proof of principle done with the $^{15}\text{N}(\alpha,\gamma)^{19}\text{F}$ reaction

Future:

- Test the high-$p,T$ water bubble chamber
- Improve Bremsstrahlung-background
- Improve acoustical analysis
- Improve enrichment of water
Collaborators:

**Argonne:**
- B. DiGiovine
- K. Gullikson
- D. Henderson
- R. J. Holt
- K. E. Rehm
- C. Ugalde

**FNAL**
- A. Robinson
- A. Sonnenschein

**Duke University**
- R. Raut
- G. Rusev
- A. Tonchev

**U. of North Carolina**
- A. Champagne

**U. of Illinois**
- N. Sturchio