Nuclear Astrophysics with $\gamma$-ray beams

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

Key reaction for nucleosynthesis in massive stars, progenitors of Type Ia Supernovae, White Dwarf ages.

- Affects the synthesis of most of the elements of the periodic table
- Sets the C to O ratio in the universe
- Determines whether for a given initial mass, a star will become a black hole or a neutron star
- Determines the minimum mass a star requires to become a core collapse supernova
- The variation of the C/O ratio in the progenitor might be a cause of the variation of SNIa brightness
- Affects the constraints on the age of stellar populations from White Dwarfs
Helium Burning: Defines the size of the stellar core.

Rolfs and Rodney, 1988
Experiment record
Kunz et al. 2001
(100% error bar)

He burning \( \sigma \approx 1 \times 10^{-17} \text{ barn} \)

Yield \( \sim N_1 N_2 \sigma g \)
Time reversal symmetry: x100 gain in cross section

\[ \omega_A \frac{\sigma_A(X, \gamma)}{\lambda_\alpha^2} = \omega_B \frac{\sigma_B(\gamma, X)}{\lambda_\beta^2} \]
Our approach:
Inverse reaction + Bubble chamber + $\gamma$ ray beam

$\gamma + ^{16}\text{O} \rightarrow ^{12}\text{C} + \alpha$

- Extra gain (x100) by measuring time inverse reaction
- The target density up to x10$^6$ higher than conventional targets.
- Superheated water will nucleate from $\alpha$ and $^{12}\text{C}$ recoils
- The detector is insensitive to $\gamma$-rays (at least 1 part in 10$^{11}$)

Bremsstrahlung from JLab $\sim 10^9$ $\gamma$/s (top 250 keV)

Oxygen bubble chamber
Liquid target (internal detection)

The bubble chamber


Some Effects of Ionizing Radiation on the Formation of Bubbles in Liquids*

DONALD A. GLASER
University of Michigan, Ann Arbor, Michigan
(Received June 12, 1952)

Ingredients:
• Superheated liquid
• Ionizing radiation

Donald A. Glaser
Nobel Prize in Physics, 1960
Superheating of liquids

![Diagram of phase change between solid, liquid, and vapor states for water, illustrating superheating.](image)
\( \text{N}_2\text{O thresholds, Superheat} = 3.3 \, ^{\circ}\text{C}, \, E_\gamma=8.5 \, \text{MeV} \)
Ranges in water

- **Carbon (150-750 keV)**
- **Helium (450-2250 keV)**
Bubble growth and quenching. $^{19}\text{F}(\gamma,\alpha)^{15}\text{N}$ in R134a

$\Delta t = 10 \text{ ms}$
Bremsstrahlung beams

Jefferson Lab

Injector

20 cryomodules

add five cryomodules

CEBAF 12 GeV
Fluorine nucleosynthesis

Possible scenarios:
- a) Neutrino spallation in core collapse SN
- b) He intershell in AGB stars
- c) Core He burning in Wolf-Rayet stars

For AGB and WR scenarios,

\[ {}^{14}\text{N}(\alpha,\gamma){}^{18}\text{F}(\beta\nu){}^{18}\text{O}(p,\alpha){}^{15}\text{N}(\alpha,\gamma){}^{19}\text{F} \]

\[ {}^{15}\text{N}(\alpha,\gamma){}^{19}\text{F} \] still uncertain at stellar temperatures

Asymptotic Giant Branch star

Commissioning: \(^{19}\text{F}(\gamma,\alpha){}^{15}\text{N} \)
May 2018 Run
Jefferson Lab

\[ \text{C}_3\text{F}_8 \]

\[ p \sim 5.5 \text{ MeV/c} \]
Conclusions

Provided a proof of principle of operation of the bubble chamber as a low rate counter for use with $\gamma$-ray beams.

Ideal for nuclear astrophysics applications.

Bremsstrahlung radiation from the injector

Main challenges:
• Maximize beam intensity
• Minimize electron beam energy spread
• Minimize photo neutrons reaching bubble chamber

• Need excellent characterization of $\gamma$-ray beam properties