Bubble Chamber

A novel technique for measuring thermonuclear rates at low energies
Challenges associated with the measurement of $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

Count rate estimate for:

$\sigma=1 \text{ pb}$, $I=100 \text{ p}\mu\text{A}$,
$T_{\text{target}}=12 \text{ \mu g/cm}^2$

$$\frac{dN}{dt} = \sigma \cdot I \cdot T \approx 1 \text{ count/day}$$
**Time Reversal Technique**

- $0(1,2)3$ vs $3(2,1)0$:

  \[
  \frac{\sigma_{23\rightarrow01}}{\sigma_{01\rightarrow23}} = \frac{(2j_o+1)(2j_1+1)}{(2j_2+1)(2j_3+1)} \frac{k_{01}^2}{k_{23}^2}
  \]

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

  \[
  \frac{\sigma_{\gamma,\alpha}}{\sigma_{\alpha,\gamma}} = \frac{2\mu_{\alpha,\gamma}c^2E_{\alpha,\gamma}}{2E_{\gamma}^2}
  \]

- The large range of incident $\gamma$-rays allows us to use targets with thickness of $\sim 1\text{-}10\ \text{g/cm}^2$

\[
L = I.T.\varepsilon \approx 8.4 \times 10^{32} \\
R = L.\sigma \approx 70 \text{ counts/day/pb}
\]
Bubble Chamber : For Nuclear Astrophysics
Proof of Principle Experiment at HIγS

**Case Study:**

$^{15}\text{N}(\alpha,\gamma)^{19}\text{F}$ via the time inverse $^{19}\text{F}(\gamma,\alpha)^{15}\text{N}$ process

**Astrophysical Motivation:**

This reaction is the last link in the thermonuclear reaction chain leading to formation of fluorine in AGB stars

**Resonance under study:**

$E_x = 5.337 \text{ MeV}$, $J^\pi = \frac{1}{2}^+$

**Target + Buffer Fluid:**

$C_4F_{10} + \text{H}_2\text{O}$

**Superheat conditions:**

$T = 30^\circ\text{C}$, $P = 3 \text{ atm}$

$100 \text{ Hz Digital Camera}$ \hspace{1cm} $\Delta t = 10 \text{ ms}$

$N_\gamma = 2 \times 10^3 - 3 \times 10^6 \gamma/\text{sec}$
Lower Limit of HIγS Measurement

Electron Beam Energy : 400 MeV
Electron Beam Current : 41 mA
Interaction Length: 35m

Strong Bremsstrahlung background when coupled with large cross-sections at high energies
Goal of the Experiment at JLab

- First test of the bubble chamber with a Bremsstrahlung beam
- Study the cosmic background level
- Study the background contributions from photodisintegration of nuclei in the superheated N$_2$O liquid

**Background from oxygen isotopes and nitrogen in N$_2$O**

a) $^{18}\text{O}(\gamma,\alpha)^{14}\text{C}$ (Q-value = -6.23 MeV)
b) $^{17}\text{O}(\gamma,\alpha)^{13}\text{C}$ (Q-value = -6.36 MeV)
c) $^{14}\text{N}(\gamma,p)^{13}\text{C}$ (Q-value = -7.55 MeV)
d) $^{17}\text{O}(\gamma,n)^{16}\text{O}$ (Q-value = -4.14 MeV)
Bubble Distribution

**HlγS Data**

**Jlab Data**

8 MeV, 0.035 μA

8 MeV, 0.4 μA
Results from the Experiment

Electron Kinetic Energy (MeV)

- $^{18}\text{O}(\gamma,\alpha)^{14}\text{C} + ^{17}\text{O}(\gamma,\alpha)^{13}\text{C}$
- $^{14}\text{N}(\gamma,p)^{13}\text{C}$

Rate (Hz) (1 μA)

- Cosmic Background

Electron Kinetic Energy (MeV)

- $^{18}\text{O}(\gamma,\alpha)^{14}\text{C} + ^{17}\text{O}(\gamma,\alpha)^{13}\text{C}$

Rate (Hz) (1 μA)
Conclusions

✓ New limit of γ-ray insensitivity of the bubble chamber: 1 in $10^{12}$ (earlier limit = 1 in $10^9$)

✓ Cosmic background rate: JLab = 1 in 17 minutes, HIγS = 1 in 2 minutes

✓ Rate limit of the bubble chamber is $10^{-3}$ counts/s at 4 MeV beam energy, we reach this limit at a cross-section of 10 pb for $C_4F_{10}$ target fluid!

Future Plans

✓ Study $^{19}F(\gamma,\alpha)^{15}N$ at cross-sections below 3 nb (beam time approved at JLab in August 2016)

✓ Study of $^{16}O$ enrichment: $^{17,18}O < 10^{-6}$
THANK YOU
Back - Up
$^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$ is an ideal case for a Bremsstrahlung beam:

- Very steep cross-section, only photons near the endpoint contribute to the yield
- No structure (resonances)
Penfold-Leiss Cross-section Unfolding

- Measure yields at electron beam kinetic energy $E = E_1, E_2 \ldots E_n$
- Yield can be expressed as the convolution of the cross-section with the Bremsstrahlung spectrum:

$$\gamma(E_i) = \int_{\text{threshold}}^{E_i} N_\gamma(E_i, k)\sigma(k)dk \approx \sum_{j=1}^{i} N_\gamma(E_i, \Delta, k_j)\sigma(k_j)$$

Where $N_\gamma(E_i, \Delta, k_j)$ is the number of gammas in the energy bin of width $\Delta = E_i - E_{i-1}$

- The solution to the above equation gives the cross-section and the corresponding error as follows:

$$\sigma_i = \frac{1}{N_{ii}} \left[ \gamma_i - \sum_{j=1}^{i-1} (N_{ij}\sigma_j) \right]$$

$$\left( \frac{d\sigma_i}{\sigma_i} \right)^2 = \frac{[dy_i]^2 + \sum_{j=1}^{i-1} (N_{ij}d\sigma_j)^2}{[\gamma_i - \sum_{j=1}^{i-1} (N_{ij}\sigma_j)]^2}$$
Role of $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reaction in Stellar Helium Burning

- It defines the ratio of carbon to oxygen in stellar cores and, as a result, in the universe
- It affects the synthesis of most of the elements of the periodic table
- Determines the minimum mass required by a star to become a supernova
Suppression of neutron events by a factor of 100 using acoustic signals
Traditional Techniques

Assuncao et al., PRC73, 055801 (2006)

9 EUROGAM detectors

Count rate estimate for:

\( \sigma = 1 \text{ pb}, \, I = 100 \, \mu\text{A}, \, T_{\text{target}} = 12 \, \mu\text{g/cm}^2 \)

\[
\frac{dN}{dt} = \sigma \cdot I \cdot T \approx 1 \text{ count/day}
\]