Bubble Chamber: A novel technique for measuring thermonuclear rates at low energies
OUTLINE

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• The Bubble Chamber
• Work at H1γS with a monochromatic γ-beam
• Work at JLAB with a bremsstrahlung beam
• Conclusions and Future Plans
Astrophysical Motivation
Stellar Helium Burning

- Radiative capture of hydrogen or helium on light nuclei are some of the most important processes in stellar nucleosynthesis.
- Helium burning proceeds via the triple-alpha process:
  
  i. $\alpha + \alpha \leftrightarrow ^8\text{Be}$  
     \[T_{1/2} \approx 10^{-16} \text{ s}\]
  
  ii. $\alpha + ^8\text{Be} \rightarrow ^{12}\text{C} + \gamma$  
      (proceeds via Hoyle state at 7.654 MeV)
  
  iii. $\alpha + ^{12}\text{C} \rightarrow ^{16}\text{O} + \gamma$
Why is the $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reaction important?

- 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
Challenges associated with the measurement of $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

- Very low cross sections ($\sigma \approx 10^{-17}$ b) make a direct measurement into the Gamow window ($E_0 \approx 300$ keV) impossible.
- Subthreshold resonances cannot be measured at resonance energies.
- Interference between E1 and E2 components.
Some Experimental Direct Measurement Results

\[ \sigma(E) = E^{-1} \exp(-2\pi \eta) S(E) \]

\[ \eta = \frac{1}{137} Z_\alpha Z_{12c} \sqrt{\frac{m_{12c\alpha}}{2ECM}} \]

Lowest cross-section measured \( \approx 1.9 \times 10^{-11} \) b.
Only R-matric extrapolations are available into the astrophysically relevant energy region (\( \sim 300 \) keV)
Reaction Rate Measuring Techniques

Traditional

- Bombarding $^{12}$C with $\alpha$-particle beams or bombarding a helium gas target with a carbon beam

Count rate estimate for:

\[ \sigma = 1 \text{ pb} \, (= 10^{-9} \text{ mb}) \]
\[ I = 100 \text{ p}\mu\text{A} \]
\[ T_{\text{target}} = 12 \text{ \mu g/cm}^2 \]

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

▪ Reciprocity Theorem for nuclear reactions:

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

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

\[\begin{align*}
12C_{(\alpha,\gamma)}^{16}O & \text{ vs } 16O_{(\gamma,\alpha)}^{12}C : \\
\frac{\sigma_{\gamma,\alpha}}{\sigma_{\alpha,\gamma}} = \frac{2\mu_{\alpha,\gamma}c^2E_{\alpha,\gamma}}{2E_{\gamma}^2} & = \frac{2 \cdot 4 \cdot 12 \cdot 1000 \cdot 1}{2 \cdot 16 \cdot 8 \cdot 8} \approx 50
\end{align*}\]

▪ The large range of incident $\gamma$-rays allows us to use targets with thickness of $\sim 1-10 \text{ g/cm}^2$, leading to a factor of $10^{5-6}$ improvement in luminosity:

\[
R = \sigma \cdot L \\
L = I \cdot T \cdot \varepsilon
\]
The Bubble Chamber
Time Reversal + Bubble Chamber

- Time reversal provides a gain factor of approximately 50
- Bubble chamber measures total cross section, E1+E2
- In a 3cm cell, number of $^{16}$O target nuclei = $3.5 \times 10^{22}$ /cm$^2$ 
  ===» target density up to $10^5$ times higher than conventional targets
- Detection efficiency of 100%
- Insensitive to γ-rays at least up to 1 part in $10^9$

\[ L \approx 8.4 \times 10^{32} \]
\[ R \approx 70 \text{ counts/day/pb} \]
Mechanical Design of the Bubble Chamber
Fluids in the Glass Vessel

**Active Fluid:**
- Molecular content of target ions should be maximized
- Transparent liquid is a convenient choice for using optical imaging techniques to detect the bubble events

**Buffer Fluid:**
- It must be immiscible with active fluid to form a meniscus
- Solubility between active fluid and buffer fluid must be very low
- It should not become superheated in the pressure/temperature range chosen for the experiment

The active fluid should be kept clean and must only come in contact with smooth surfaces. Therefore it is only allowed to come in contact with the glass pressure vessel or the buffer fluid which provides a smooth interface for the transmission of pressure changes from the hydraulic system.
Active Target to study the $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$ System

☑ Liquid Oxygen :
  a) Requires cryogenic bubble chamber
  b) In the past such a device has been operated only in pulsed mode
  c) Need continuously operating bubble chamber

☑ H$_2$O :
  a) Requires relatively high pressures and temperatures ($T = 200 – 250 \degree C$)
  b) After few hours of operation, the buffer fluid caused etching of the interior glass vessel

☑ CO$_2$ :
  a) Presence of $^{12}\text{C}$ requires separation of the $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$ events from $^{12}\text{C}(\gamma,3\alpha)$ events
  b) Low $^{13}\text{C}(\gamma,n)$ threshold ($= -4.9 \text{ MeV}$) leads to neutron production, hence ruling out the possibility to use $^{13}\text{CO}_2$
  c) At low temperatures, formation of hydrates changes transparency of the superheated liquid

☑ N$_2$O :
  a) Cross-sections above $^{14}\text{N}(\gamma,p)^{13}\text{C}$ (threshold = 7.5 MeV) are quite large

☑ Methanol:
  a) Flammability issues makes it less ideal and presence of carbon leads to same issues as seen with CO$_2$
Working Principle of the Bubble Chamber

*Bringing a fluid (N\textsubscript{2}O) into its superheated state:*

- Starting at a point where N\textsubscript{2}O is gaseous under ambient pressure and temperature (1)
- Temperature is decreased liquefying the gas (1 to 2)
- Pressure is released while keeping the temperature constant (2 to 3)

At stage 3, N\textsubscript{2}O is still a liquid but in a superheated state!

If left undisturbed, the fluid remains liquid in this superheated state.
Formation of a bubble (nucleation):

- When a particle moves in a liquid, it deposits energy along its track until it is stopped.
- If enough energy is deposited within a short distance, the liquid vaporizes and a “proto-bubble” forms.
- Only bubbles with $r > R_c$ grow to be macroscopic:

$$ R_c = \frac{2s}{(PV - PL)} $$

where $s$ is the surface tension of the liquid.

- The total energy and stopping power threshold conditions are:

$$ \frac{dE}{dx} \geq \left( \frac{dE}{dx} \right)_c = \frac{E_c}{aR_c} $$

$$ E \geq E_c = -\frac{4}{3} \pi R_c^3 \Delta P + \frac{4}{3} \pi R_c^3 \rho_v H_{lv} + 4\pi R_c^2 (s - T \frac{ds}{dT}) $$

The contribution of four terms to the critical energy ($E_c$) necessary to induce nucleation in $N_2O$ at an operating pressure of 580 psi.
Stopping Power Curves

Particles above the horizontal (dE/dx)c threshold and to the right of the vertical Ec threshold induce nucleation.

By varying the pressure and temperature conditions of the liquid some ion species can be discriminated while others detected.

The energy loss of electrons, neutrons and $\gamma$-rays is too small to appear in the plot. However, they may transfer momentum to other ions by scattering interactions.
Work At HlyS
Monochromatic $\gamma$-beam at HI$\gamma$S

$\gamma$-rays generated by Compton backscattering of free electron laser (FEL) light from high-energy electron beam bunches.
**Proof of Principle Experiment at HlγS**

**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:**

$\text{C}_4\text{F}_{10} + \text{H}_2\text{O}$

**Superheat conditions:**

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

100 Hz Digital Camera

$\Delta t = 10 \text{ ms}$
First determination of an astrophysical cross section with a bubble chamber: The $^{15}$N(α, γ)$^{19}$F reaction

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\[ N_\gamma = 2 \times 10^3 - 3 \times 10^6 \gamma/\text{sec} \]
Lower Limit of H\(\gamma\)S 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
Work At JLab
Bremsstrahlung Beam

$^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$ is an ideal case for a Bremsstrahlung beam:

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

Bremsstrahlung spectra calculated using GEANT4 and FLUKA
Goal of the Experiment

- Test the performance 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) $^{18}$O($\gamma,\alpha$$^{14}$C ( Q-value = -6.23 MeV)

b) $^{17}$O($\gamma,\alpha$$^{13}$C ( Q-value = -6.36 MeV)

c) $^{14}$N($\gamma,p$$^{13}$C ( Q-value = -7.55 MeV)

d) $^{17}$O($\gamma,n$$^{16}$O ( Q-value = -4.14 MeV)
Experimental Set-Up for the N$_2$O Bubble Chamber
Filling of the glass vessel with \( \text{N}_2 \): Glass Vessel with Hg Containment Vessel + Insulation Hydraulic System Chiller
Bubble Formation and Data Acquisition
First Half of the Experiment

<table>
<thead>
<tr>
<th>Energy Measured (MeV)</th>
<th>Superheat Pressure (psi)</th>
<th>Superheat Temperature (°C)</th>
<th>Beam Current (μA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.7</td>
<td>325</td>
<td>-8</td>
<td>0.4</td>
</tr>
<tr>
<td>8</td>
<td>325</td>
<td>-8</td>
<td>0.4</td>
</tr>
<tr>
<td>8</td>
<td>325</td>
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<td>0.04</td>
</tr>
<tr>
<td>8</td>
<td>310</td>
<td>-8</td>
<td>0.035</td>
</tr>
</tbody>
</table>

Graph showing rates (Hz) versus electron kinetic energy (MeV) with different reactions. The reactions are:

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

Graph also shows cosmic background.
Bubble Distribution

H\(\gamma\)S Data

JLab Data

8 MeV, 0.4 \(\mu\)A

8 MeV, 0.035 \(\mu\)A
Bubble Size

H$_2$O bubble

N$_2$O bubble

C$_4$F$_{10}$ bubble
Beam Position Test

Original Position

Left by 4 mm

Right by 5 mm

Down by 6 mm

Up by 4 mm
Second Half of The Experiment

<table>
<thead>
<tr>
<th>Energy Measured (MeV)</th>
<th>Superheat Pressure (psi)</th>
<th>Superheat Temperature (°C)</th>
<th>Beam Current (μA)</th>
</tr>
</thead>
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</tr>
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</tr>
<tr>
<td>4</td>
<td>325</td>
<td>-8</td>
<td>10</td>
</tr>
</tbody>
</table>

![Graph showing Electron Kinetic Energy (MeV) vs. Rate (Hz)](image)

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

![Graph showing Cosmic Background](image)
Problems Encountered during the Experiment

- Beam position was not very well defined
- Mercury droplets on the glass vessel
- Could not reduce beam current below 35 nA

- At high beam currents (10 μA), we observed lot of camera scintillation events

- During the last few days, beam induced background became very high throughout the volume of the bubble chamber.

![Image: 6.5 MeV, 10 μA](image1)

![Image: 7.6 MeV, 1 μA](image2)
Conclusions And Future Plans
Conclusions

- New limit of γ-ray insensitivity of the bubble chamber: 1 in $10^{12}$
- Cosmic background rate: JLab = 1 in 17 minutes, H1γS = 1 in 2 minutes
- Rate limit of the bubble chamber is $10^{-3}$ counts/s at 4 MeV beam energy

If we consider a 3 cm long glass vessel filled with $C_4F_{10}$ (1.5 g/cm$^3$) bombarded by $10^{11}$ γ/s, out of which 1% are “good” γs, we get:

$$\frac{N_R}{t} = \sigma I N_T = 10^{-1} \text{ counts/s/nb}$$

Since our rate limit is $10^{-3}$, we reach this limit at a cross-section of 10 pb!
Future Plans

- Design a single fluid bubble chamber
- Place scanners in the beam line to get a more accurate estimate of the beam position
- Move the camera further back which will allow to put more shielding around the camera as well as lower the number of scintillations at higher beam currents
- Since the number of gammas interacting with the bubble chamber at Jlab is higher than that at HiγS, run with lower beam currents
✓ Study $^{19}\text{F}(\gamma,\alpha)^{15}\text{N}$ at cross-sections below 3 nb (beam time approved at JLab from May 31 – June 15, 2016)

✓ Acoustic signal discrimination to suppress neutron background

✓ Study of $^{16}\text{O}$ enrichment: $^{17,18}\text{O} < 10^{-6}$ (how to measure exactly)
Collaboration

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THANK YOU

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Back - Up
Penfold-Leiss Cross-section Unfolding

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

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

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:

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

$$
\left( \frac{d\sigma_i}{\sigma_i} \right)^2 = \frac{[(dy_i)^2 + \sum_{j=1}^{i-1} (N_{ij}d\sigma_j)^2]}{[\gamma_i - \sum_{j=1}^{i-1} (N_{ij}\sigma_j)]^2}
$$