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

Rashi Talwar

OUTLINE

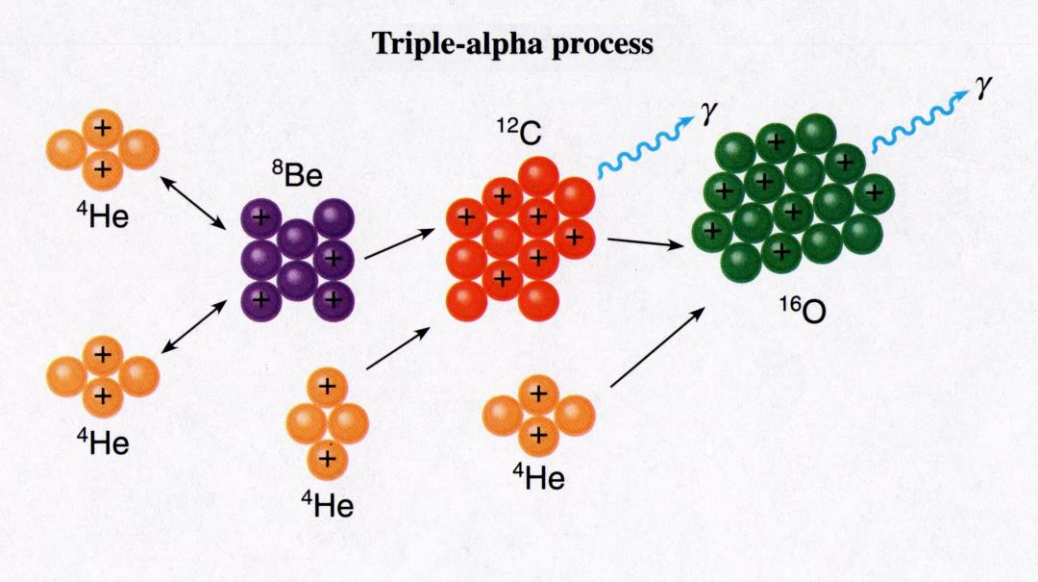
- Astrophysical Motivation
- The Bubble Chamber
- Work at HIγS with a monochromatic γ-beam
- Work at JLAB with a bremsstrahlung beam
- Conclusions and Future Plans

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 :

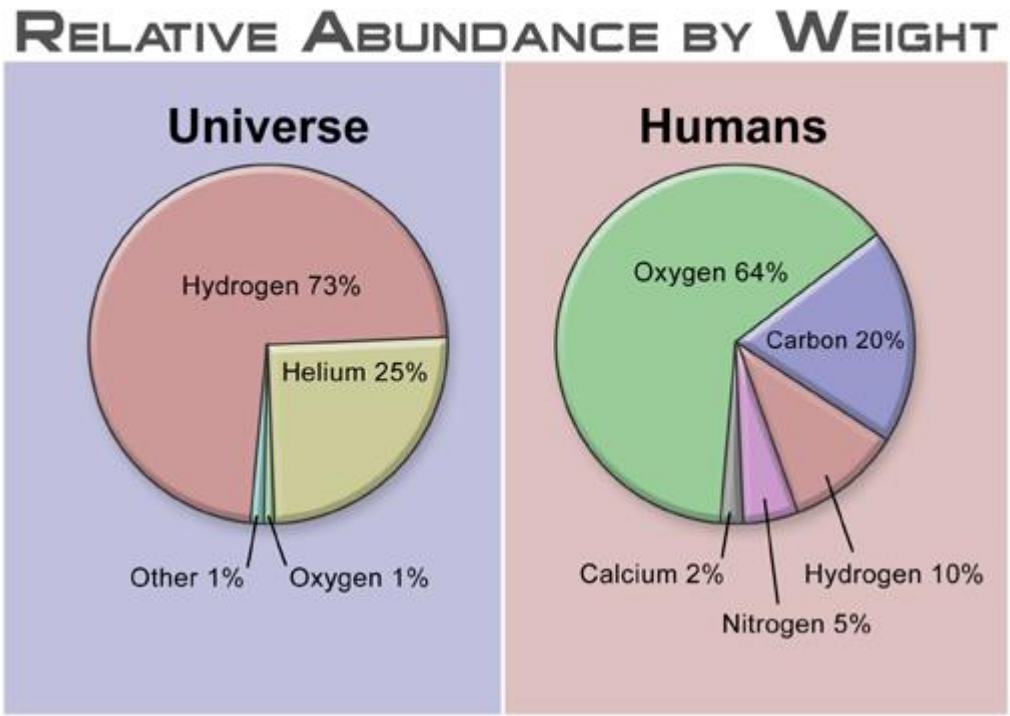


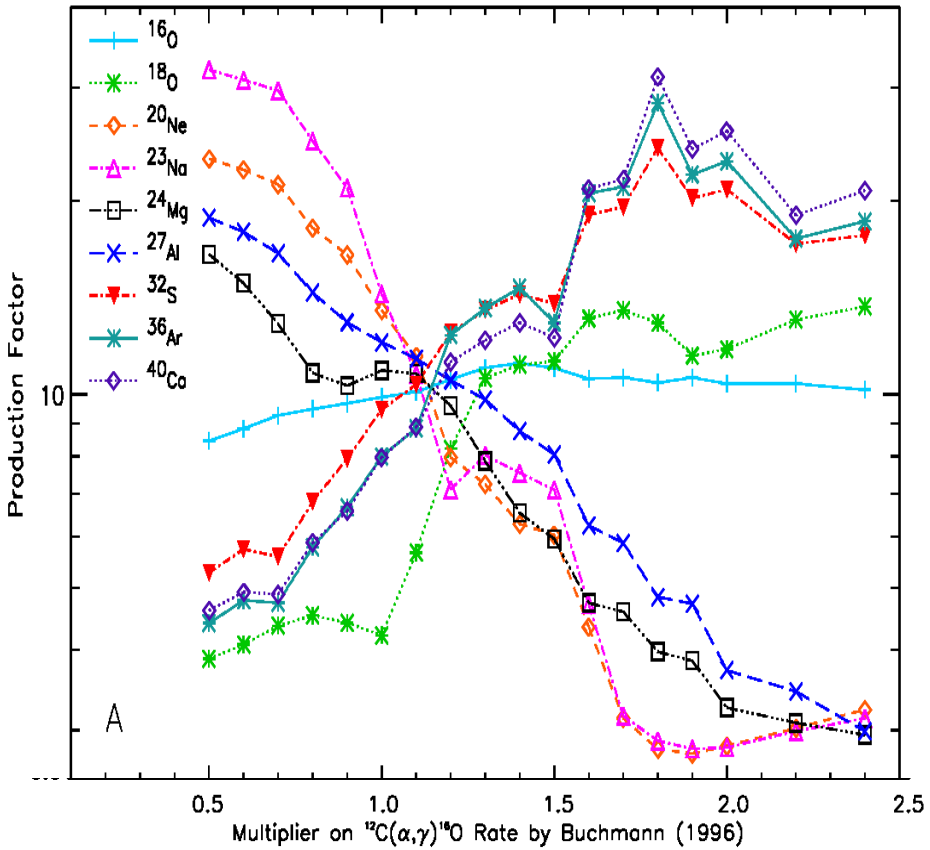
i. $\alpha + \alpha \leftrightarrow {}^{8}\mathrm{Be}$
($T_{1/2} \approx 10^{-16}$ s)

ii. $\alpha + {}^{8}\mathrm{Be} \rightarrow {}^{12}\mathrm{C} + \gamma$
(proceeds via Hoyle state at 7.654 MeV)

iii. $\alpha + {}^{12}\mathrm{C} \rightarrow {}^{16}\mathrm{O} + \gamma$

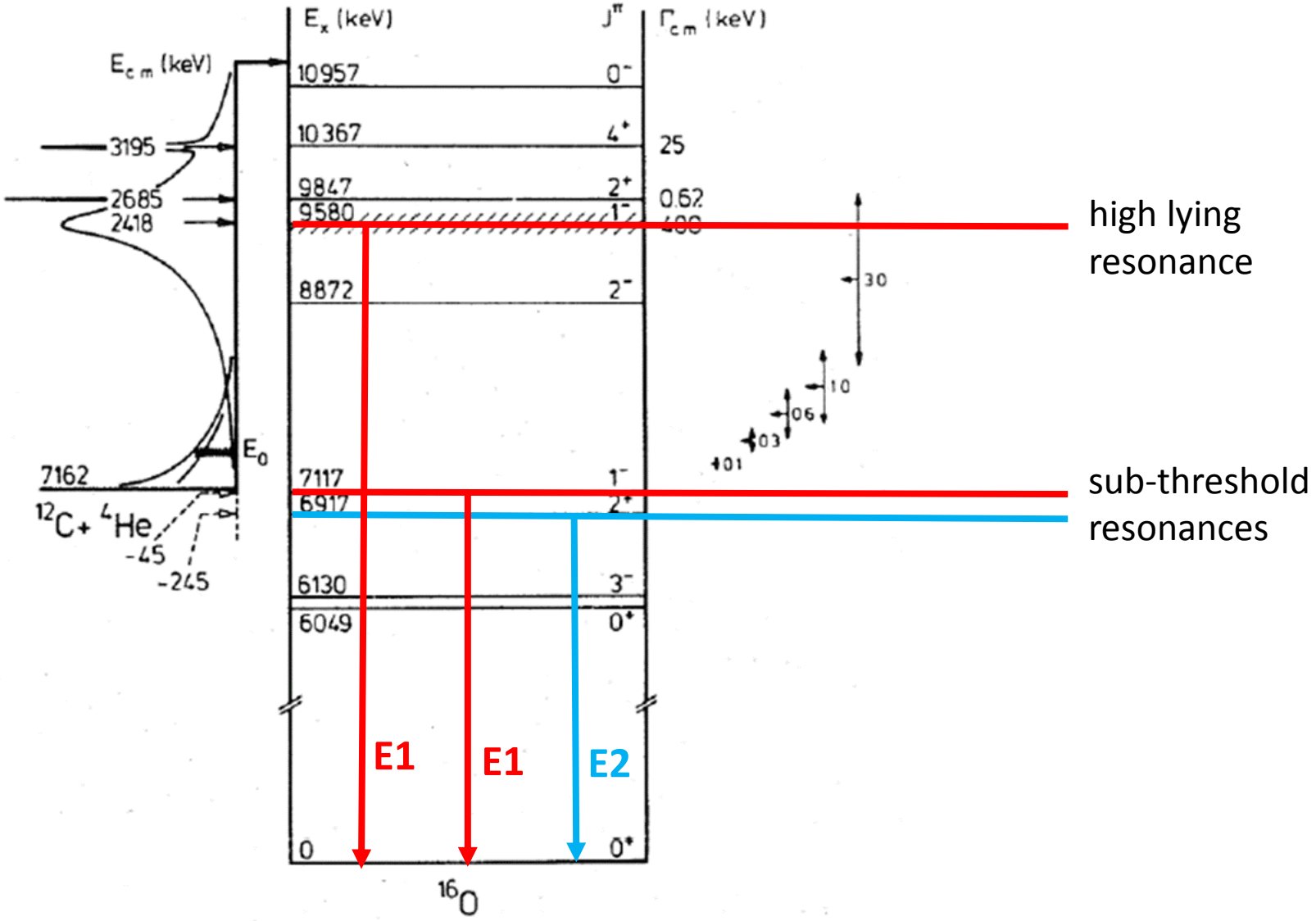
Why is the $^{12}C(\alpha,\gamma)^{16}O$ reaction important?





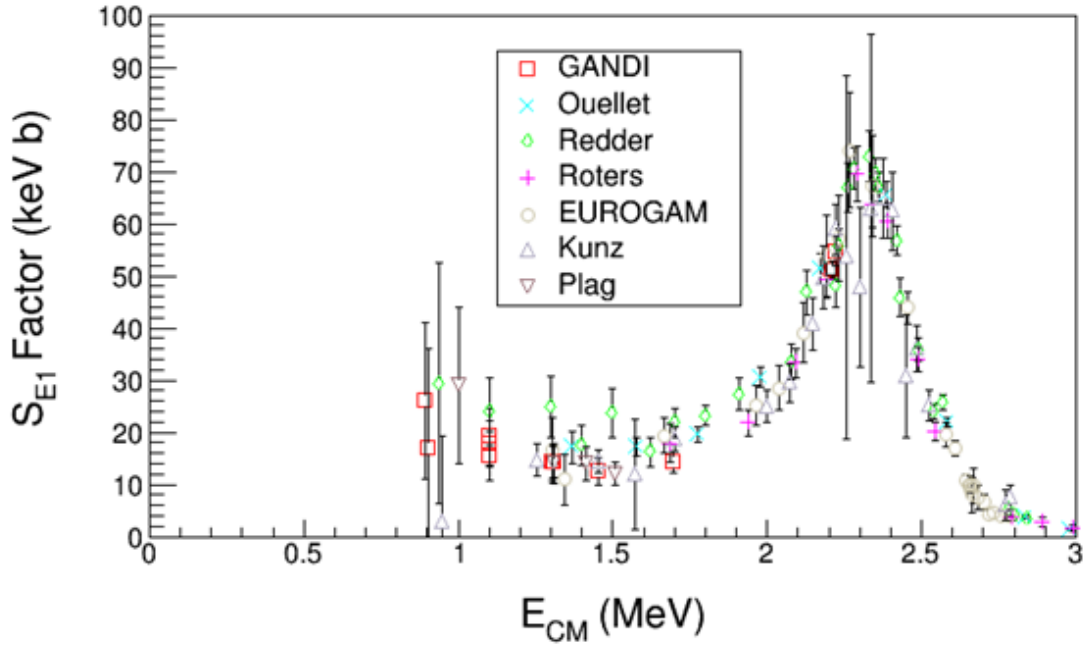
- It defines the ratio of carbon to oxygen in stellar cores and, as a result, in the universe
- It affects the synthesis of most of the elements of the periodic table
- Determines the minimum mass required by a star to become a supernova

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



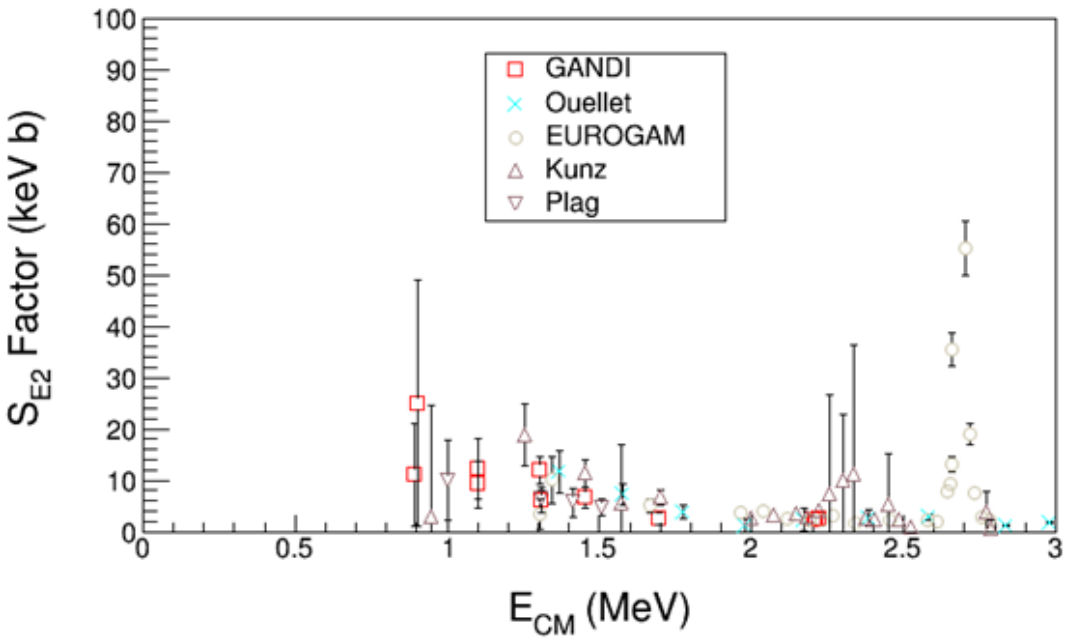
- very low cross sections ($\sigma \approx 10^{-17}$ b) make a direct measurement into the Gamow window ($E_0 \approx 300$ keV) impossible
- subthreshold resonances cannot be measured at resonance energies
- Interference between E1 and E2 components

Some Experimental Direct Measurement Results



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

$$\eta = \frac{1}{137} Z_{\alpha} Z_{^{12}C}\sqrt{\frac{m_{^{12}C\alpha}}{2ECM}}$$



Lowest cross-section measured ≈ 1.9 X 10^{-11} b. Only R-matric extrapolations are available into the astrophysically relevant energy region (~ 300 keV)

Reaction Rate Measuring Techniques

Traditional

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

Count rate estimate for:

σ=1 pb (=10^{-9} mb)

I=100 pμA

T_{target}=12 μg/cm^2

$$\frac{dN}{dt} = \sigma . I . T \cong 1\ count/day$$

Time Reversal

- Reciprocity Theorem for nuclear reactions :

0(1,2)3 vs 3(2,1)0 : $$\frac{\sigma_{23\to 01}}{\sigma_{01\to 23}} = \frac{(2j_o+1)(2j_1+1)}{(2j_2+1)(2j_3+1)}\frac{k_{01}^2}{k_{23}^2}$$

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

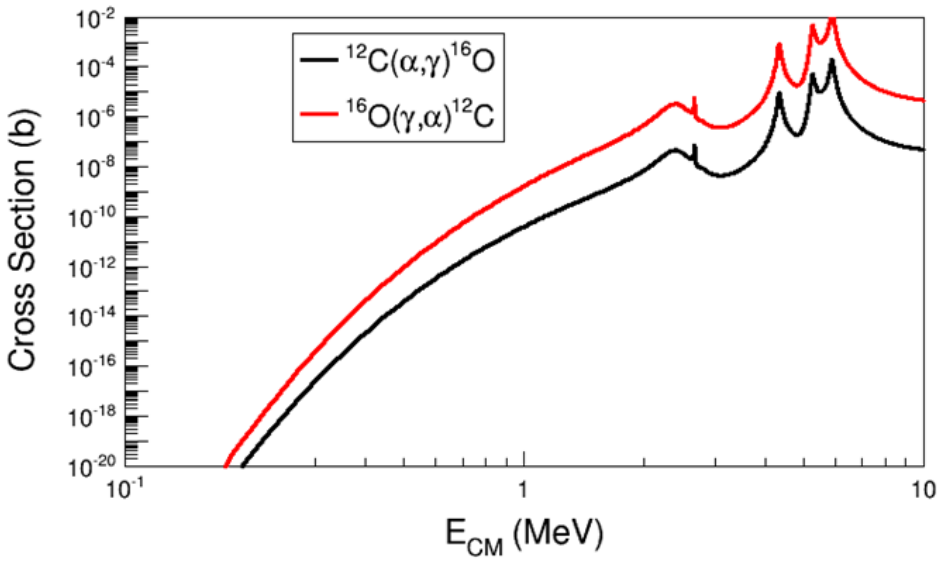
- The large range of incident γ-rays allows us to use targets with thickness of ~ 1-10 g/cm^2, leading to a factor of $10^{5\text{-}6}$ improvement in luminosity :

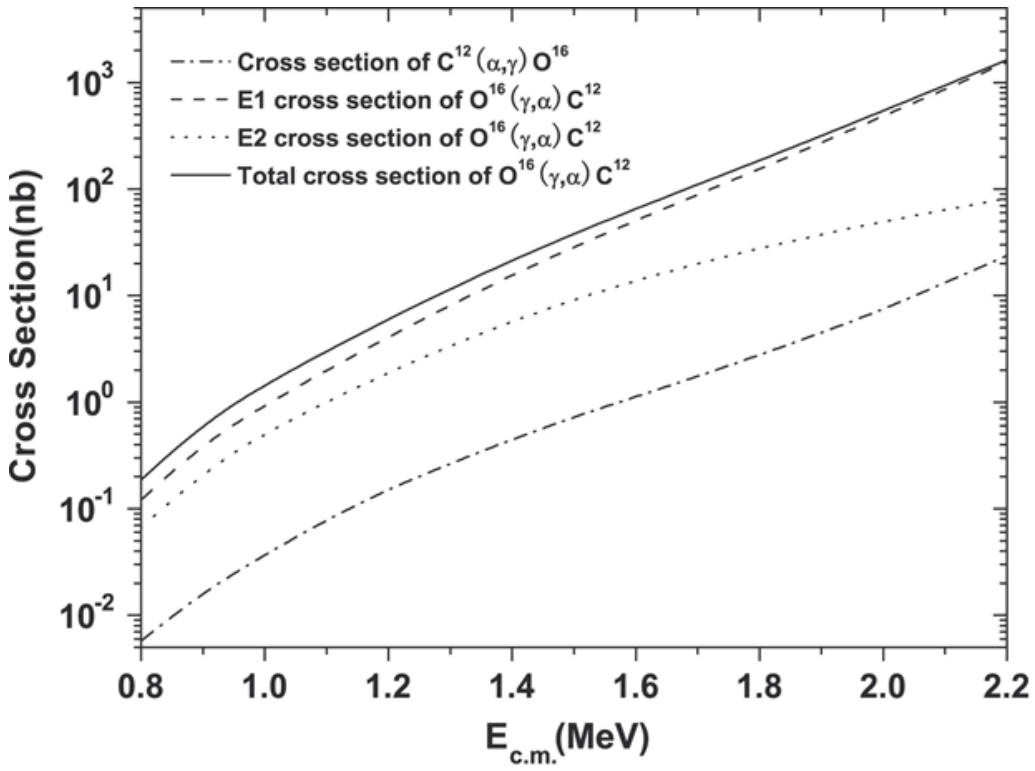
$$R = \sigma . L$$
$$L = I . T . \varepsilon$$

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 = $3.5X10^{22}$ /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

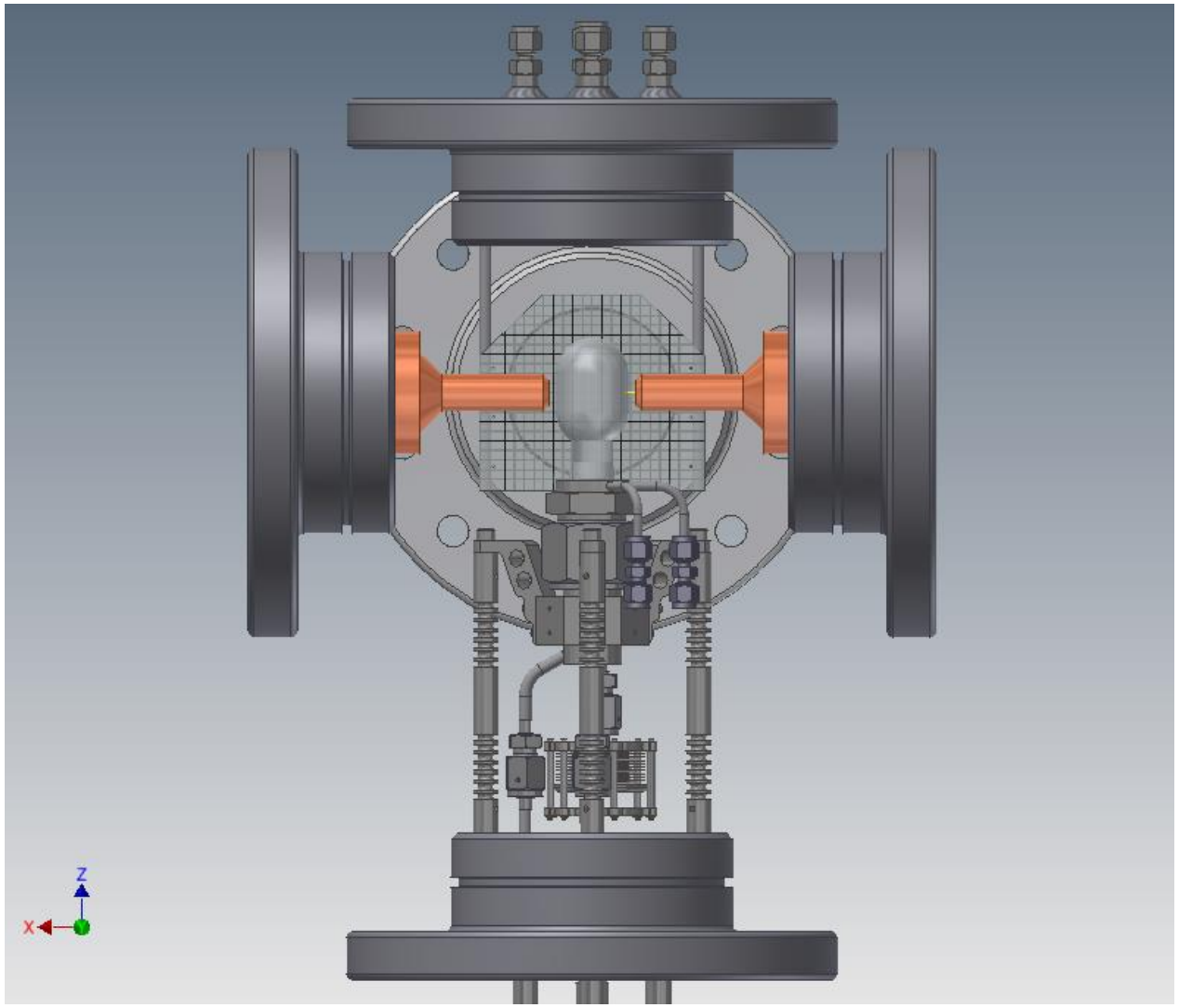


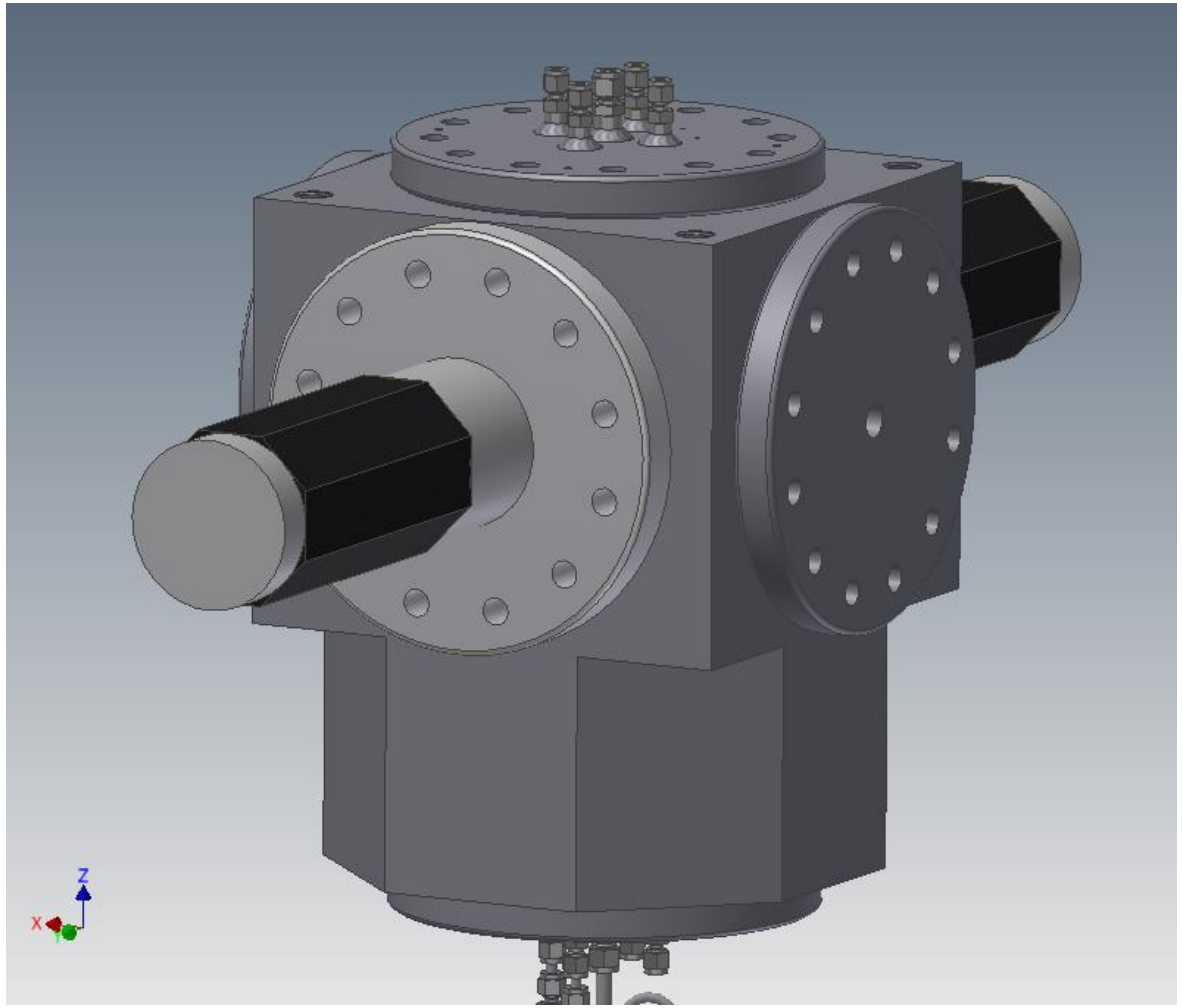


$$L \cong 8.4\ X\ 10^{32}$$

$$R \cong 70\ counts/day/pb$$

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 $^{16}O(\gamma,\alpha)^{12}C$ 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_2O :

a) Requires relatively high pressures and temperatures (T = 200 – 250 °C)
b) After few hours of operation, the buffer fluid caused etching of the interior glass vessel

- ✓ CO_2 :

a) Presence of ^{12}C requires separation of the $^{16}O(\gamma,\alpha)^{12}C$ events from $^{12}C(\gamma,3\alpha)$ events
b) Low $^{13}C(\gamma,n)$ threshold (= -4.9 MeV) leads to neutron production, hence ruling out the possibility to use $^{13}CO_2$
c) At low temperatures, formation of hydrates changes transparency of the superheated liquid

- ✓ N_2O :

a) Cross-sections above $^{14}N(\gamma,p)^{13}C$ (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

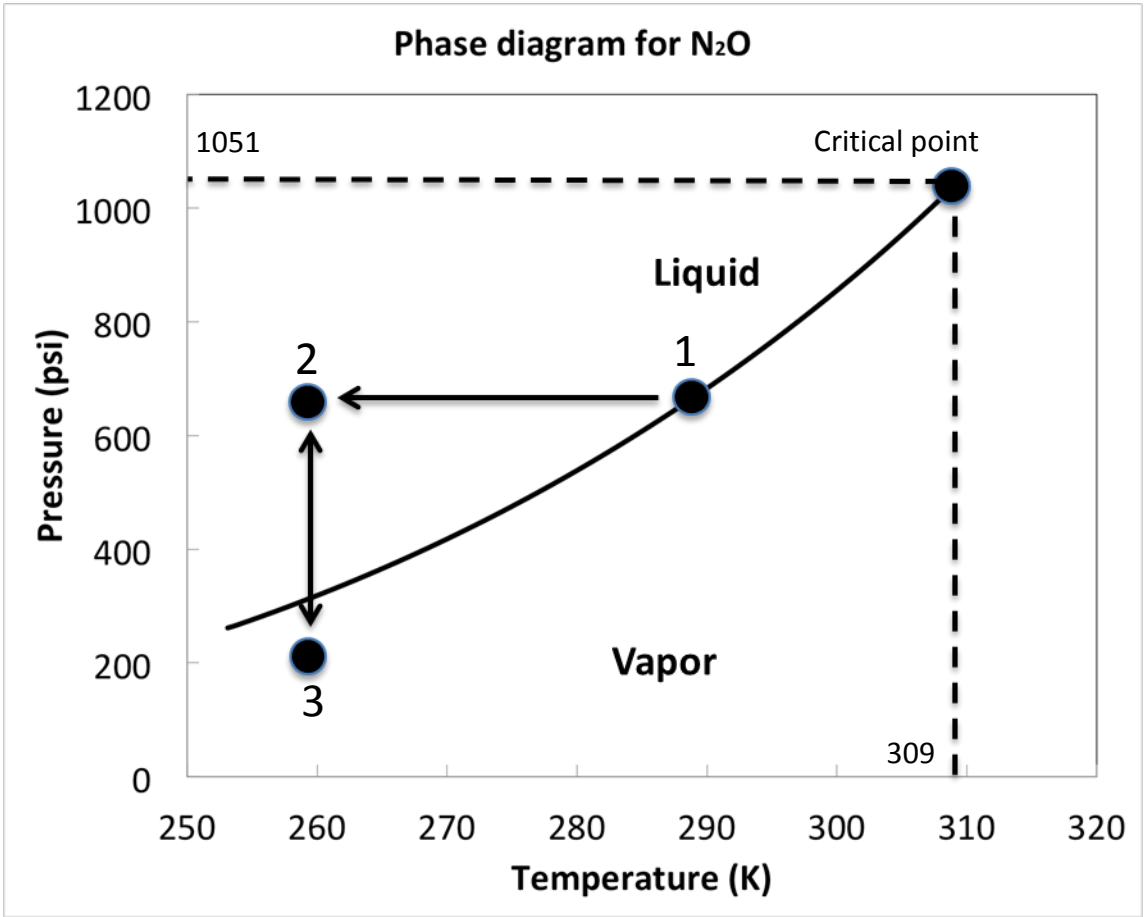
Working Principle of the Bubble Chamber

Bringing a fluid (N_2O) into its superheated state :

- Starting at a point where N_2O 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_2O 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 :

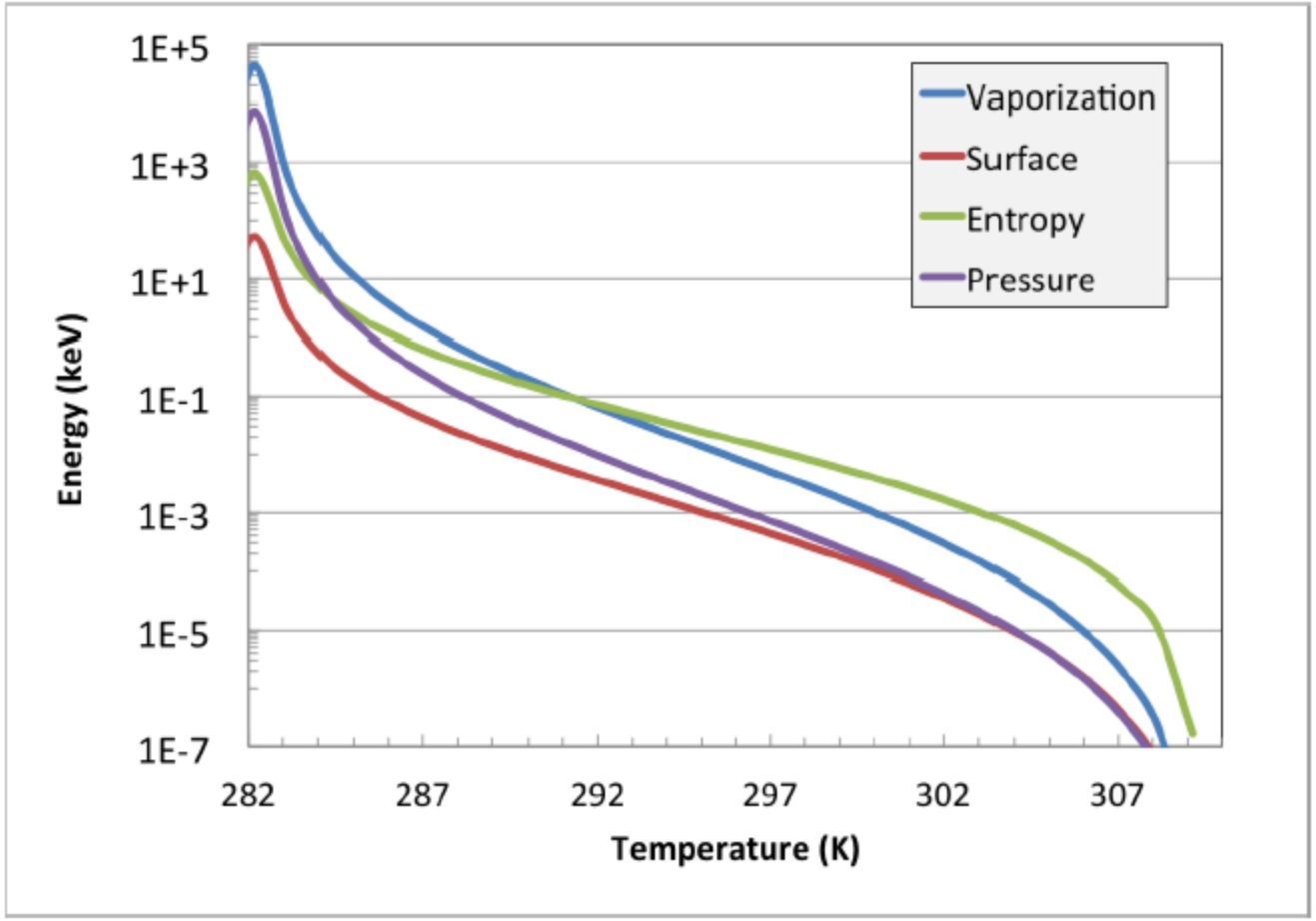
$$R_c = 2s/(Pv - Pl)$$

where s is the surface tension of the liquid

- The total energy and stopping power threshold conditions are :

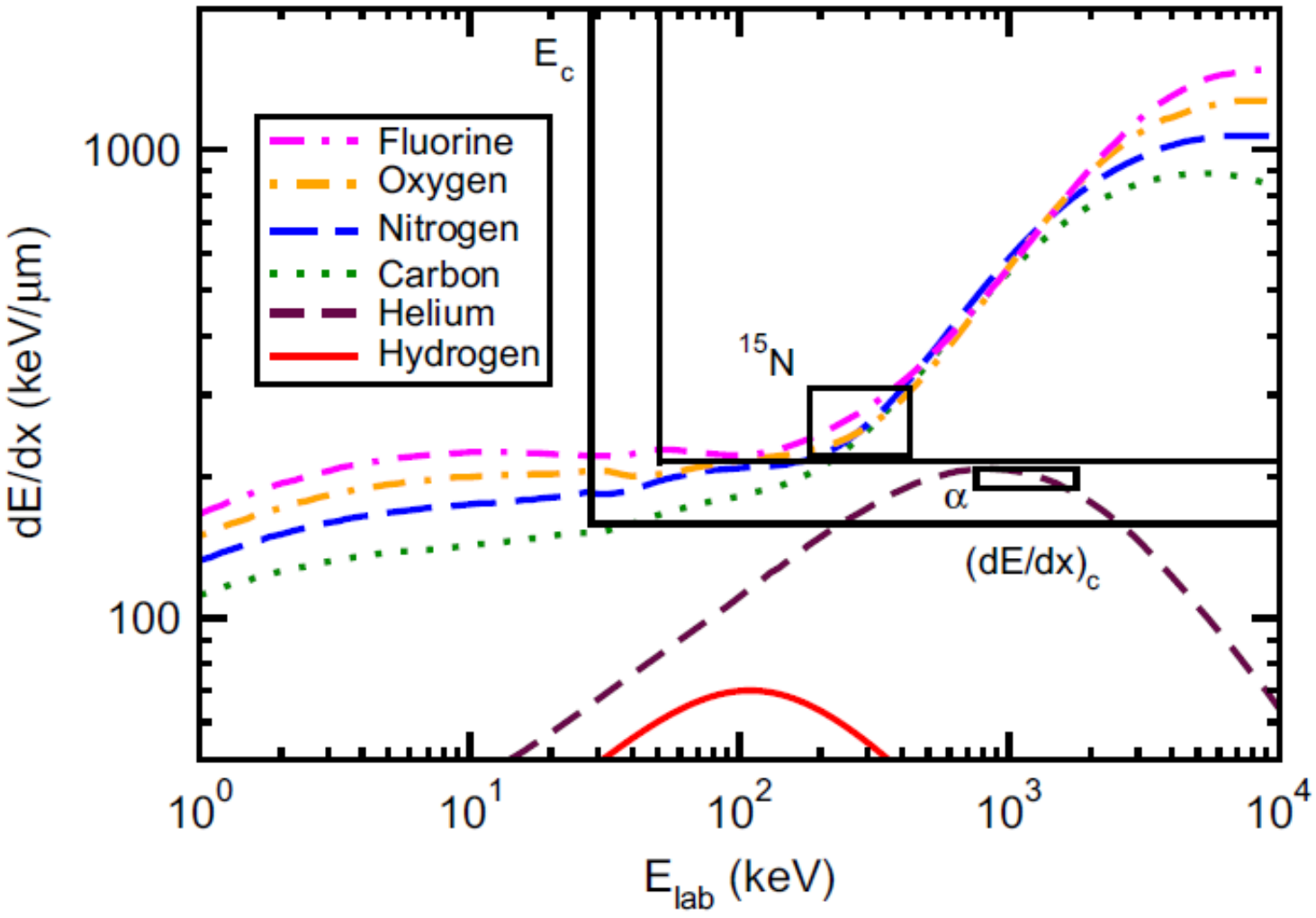
$$\frac{dE}{dx} \geq \left(\frac{dE}{dx}\right)_c = \frac{E_c}{aR_c}$$

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



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.

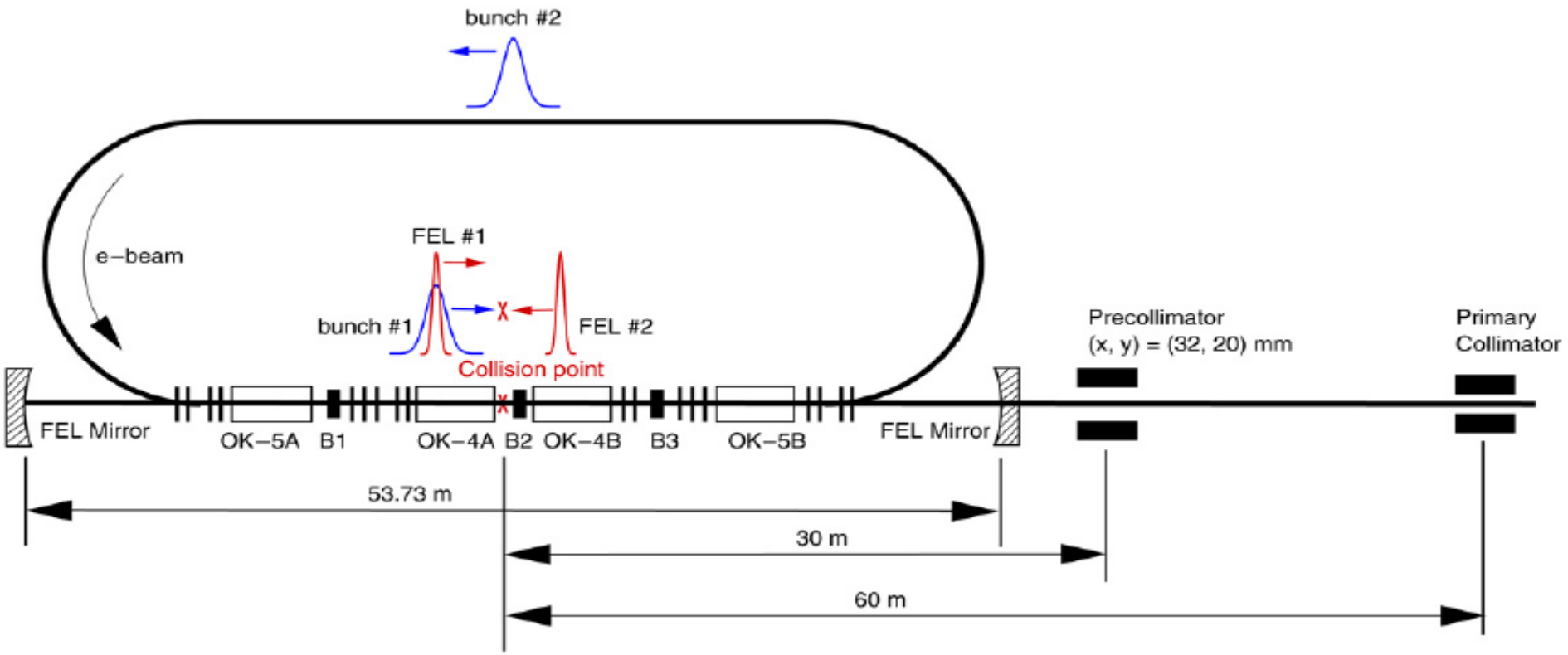
By varying the pressure and temperature conditions of the liquid some ion species can be discriminated while others detected.

The energy loss of electrons, neutrons and γ-rays is too small to appear in the plot. However, they may transfer momentum to other ions by scattering interactions.

Work At HIγS

Monochromatic γ-beam at HIγS

γ- rays generated by Compton backscattering of free electron laser (FEL) light from high-energy electron beam bunches



Bubble Chamber

Proof of Principle Experiment at HIγS

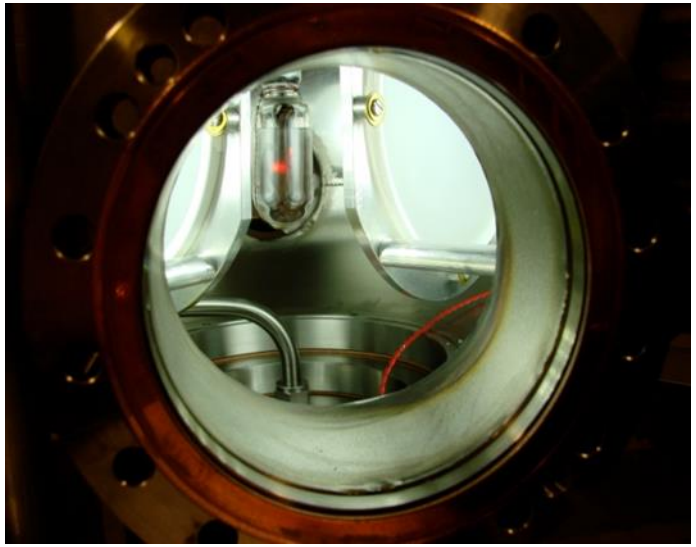
Case Study : $^{15}N(\alpha,\gamma)^{19}F$ via the time inverse $^{19}F(\gamma,\alpha)^{15}N$ process

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

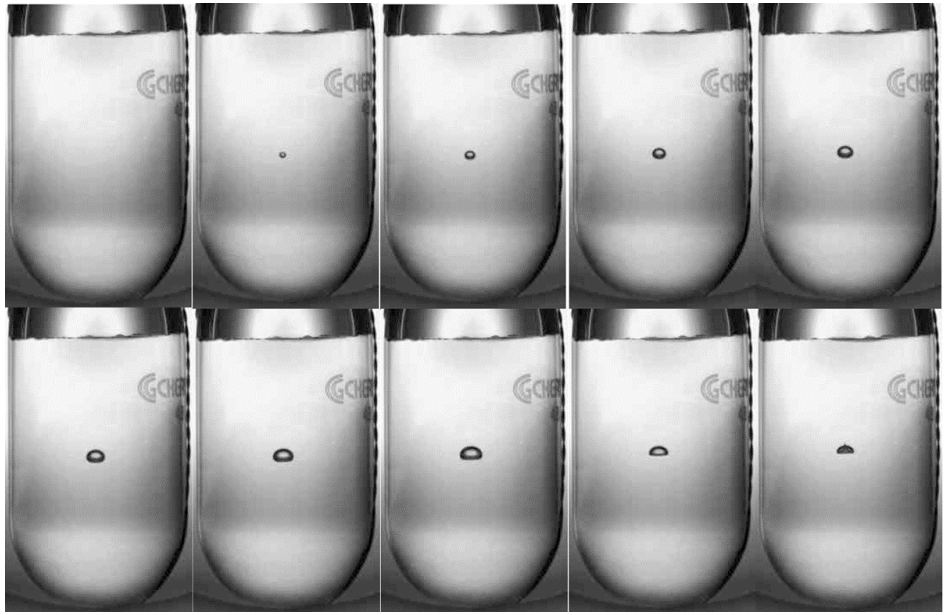
Resonance under study : E_x = 5.337 MeV, $J^\pi = ½^+$

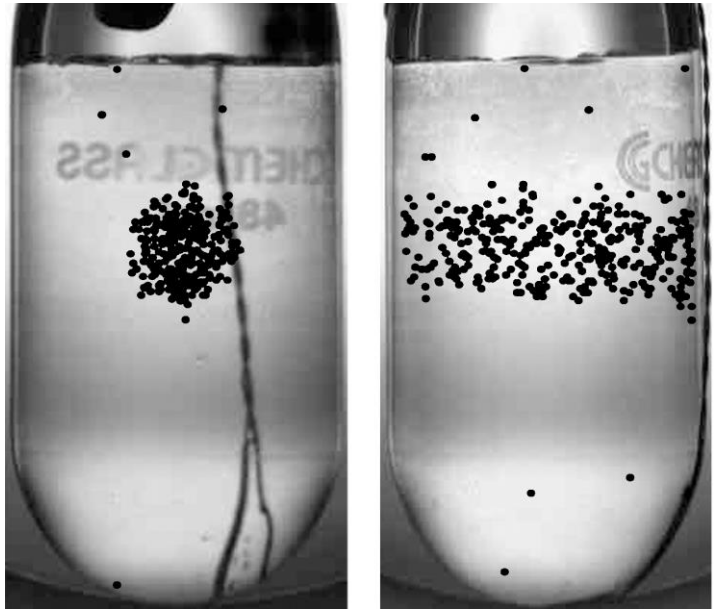
Target + Buffer Fluid : $C_4F_{10} + H_2O$

Superheat conditions : T = 30°C, P = 3 atm



100 Hz Digital Camera Δt = 10 ms





Contents lists available at SciVerse ScienceDirect

Physics Letters B

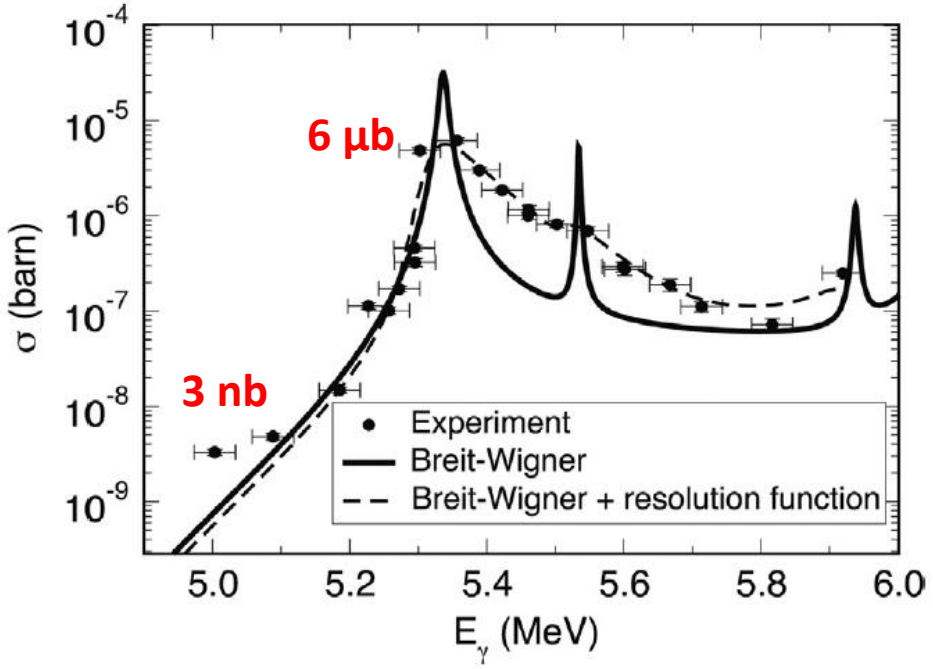
www.elsevier.com/locate/physletb

First determination of an astrophysical cross section with a bubble chamber: The $^{15}N(\alpha,\gamma)^{19}F$ reaction

C. Ugalde [a,*], B. DiGiovine [b], D. Henderson [b], R.J. Holt [b], K.E. Rehm [b], A. Sonnenschein [c], A. Robinson [d], R. Raut [e,f,1], G. Rusev [e,f,2], A.P. Tonchev [e,f,3]

[a] Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA
[b] Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA
[c] Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[d] Department of Physics, University of Chicago, Chicago, IL 60637, USA
[e] Department of Physics, Duke University, Durham, NC 27708, USA
[f] Triangle Universities Nuclear Laboratory, Durham, NC 27708, USA

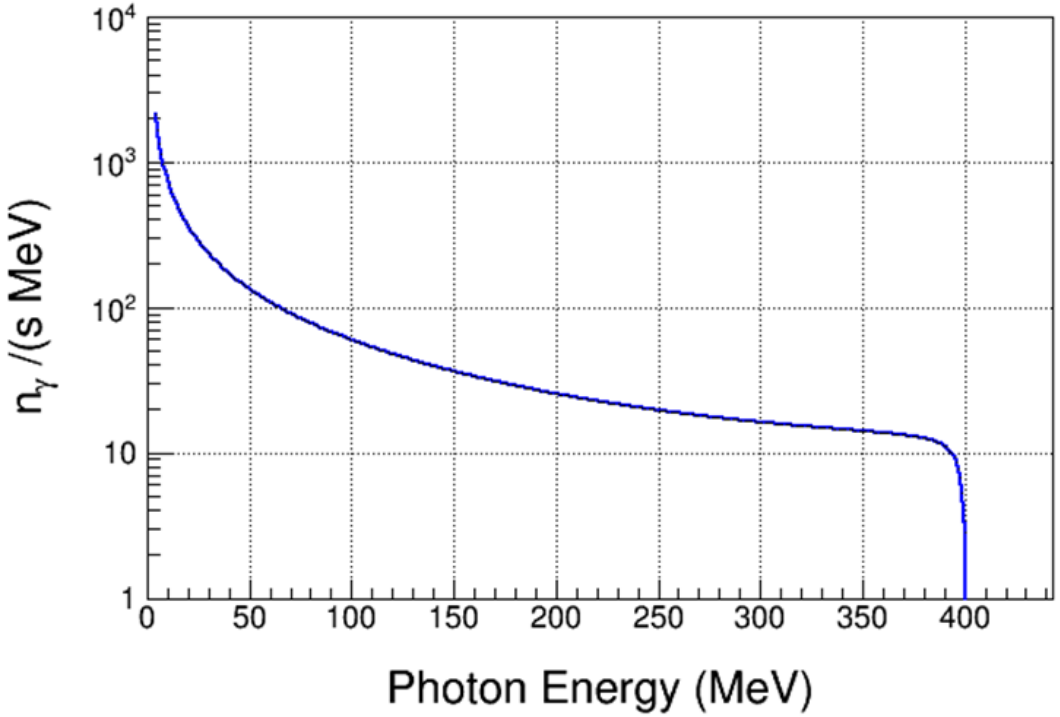
$N_\gamma = 2 \times 10^3 - 3 \times 10^6\ \gamma/\text{sec}$

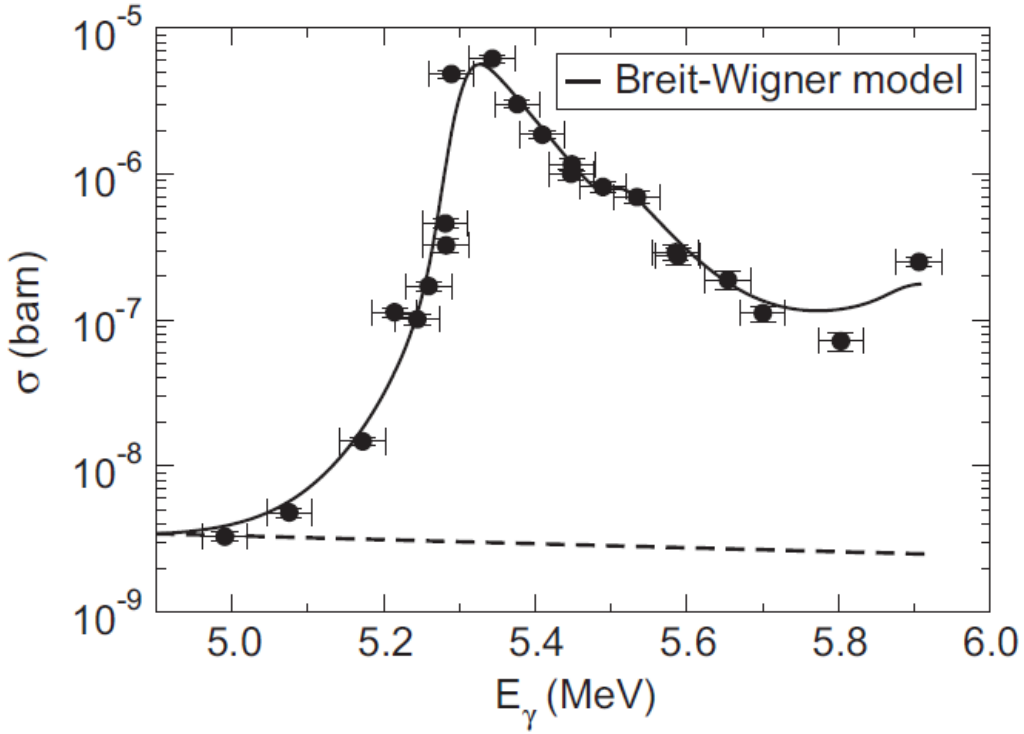


Lower Limit of HIγS Measurement

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



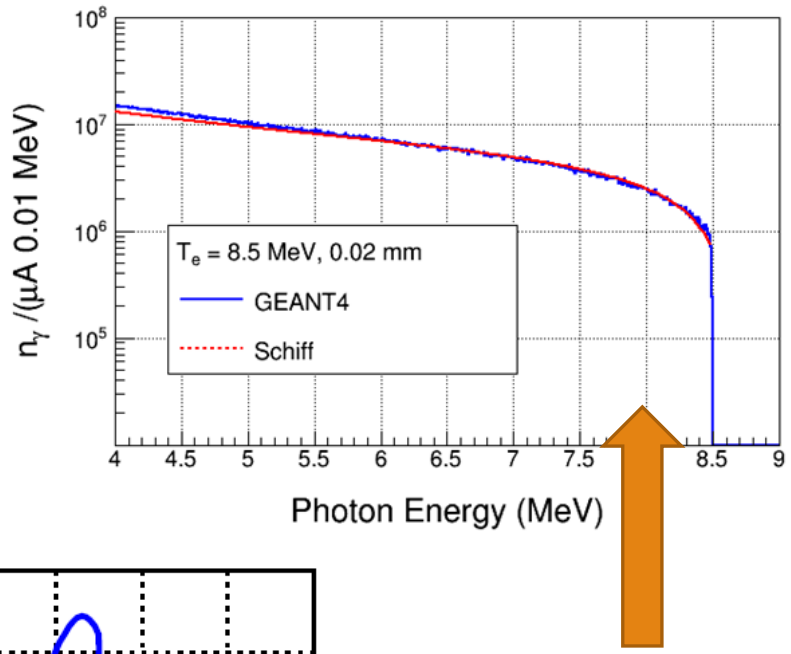


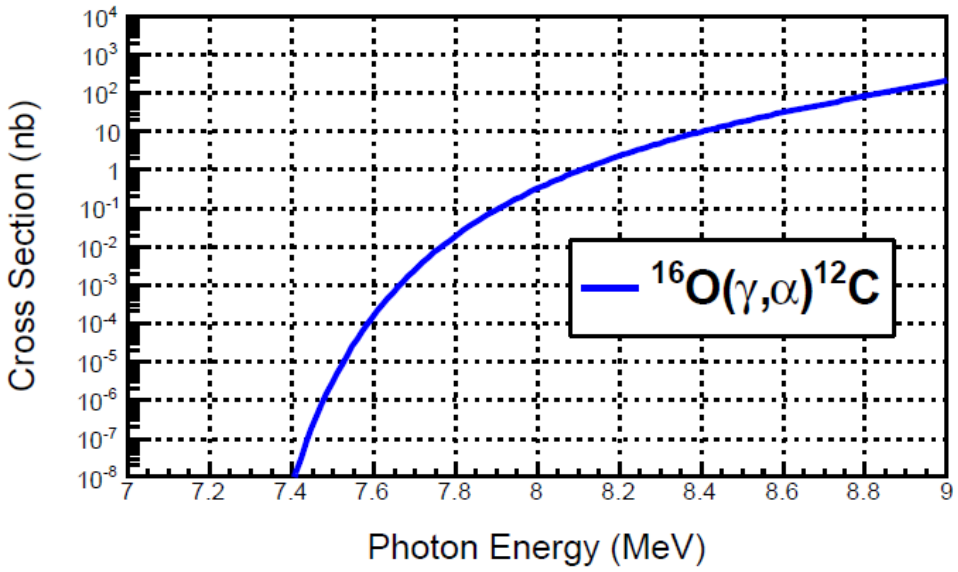
Work At JLab

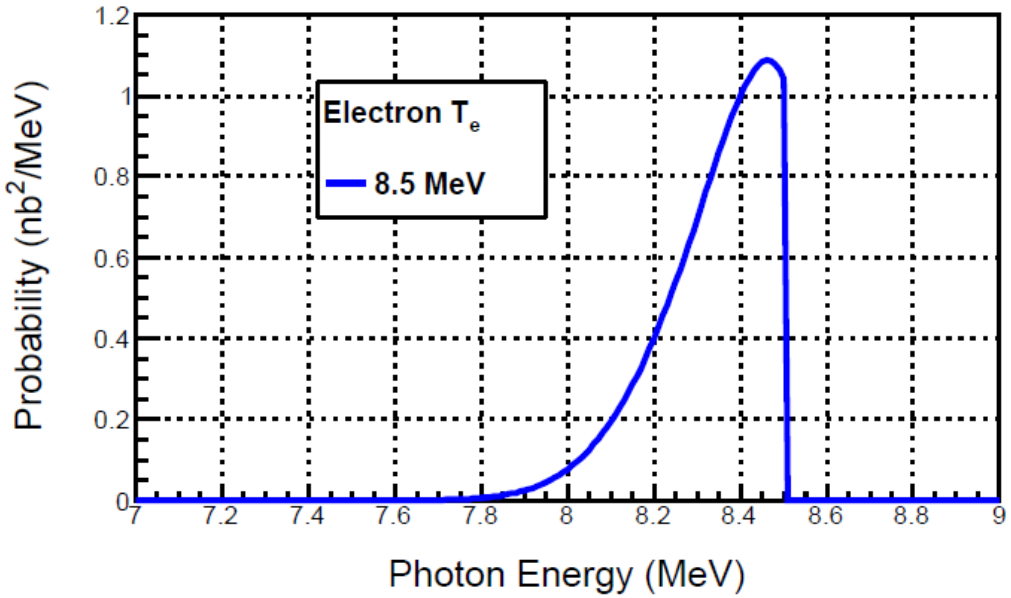
Bremsstrahlung Beam

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

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







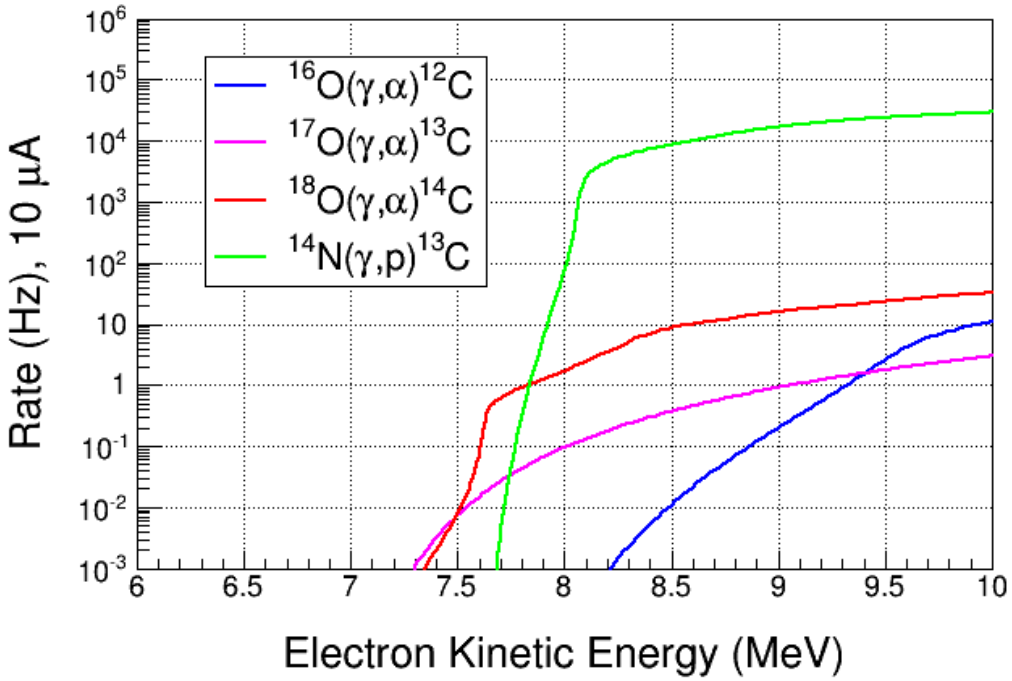
Bremsstrahlung spectra calculated using GEANT4 and FLUKA

Goal of the Experiment

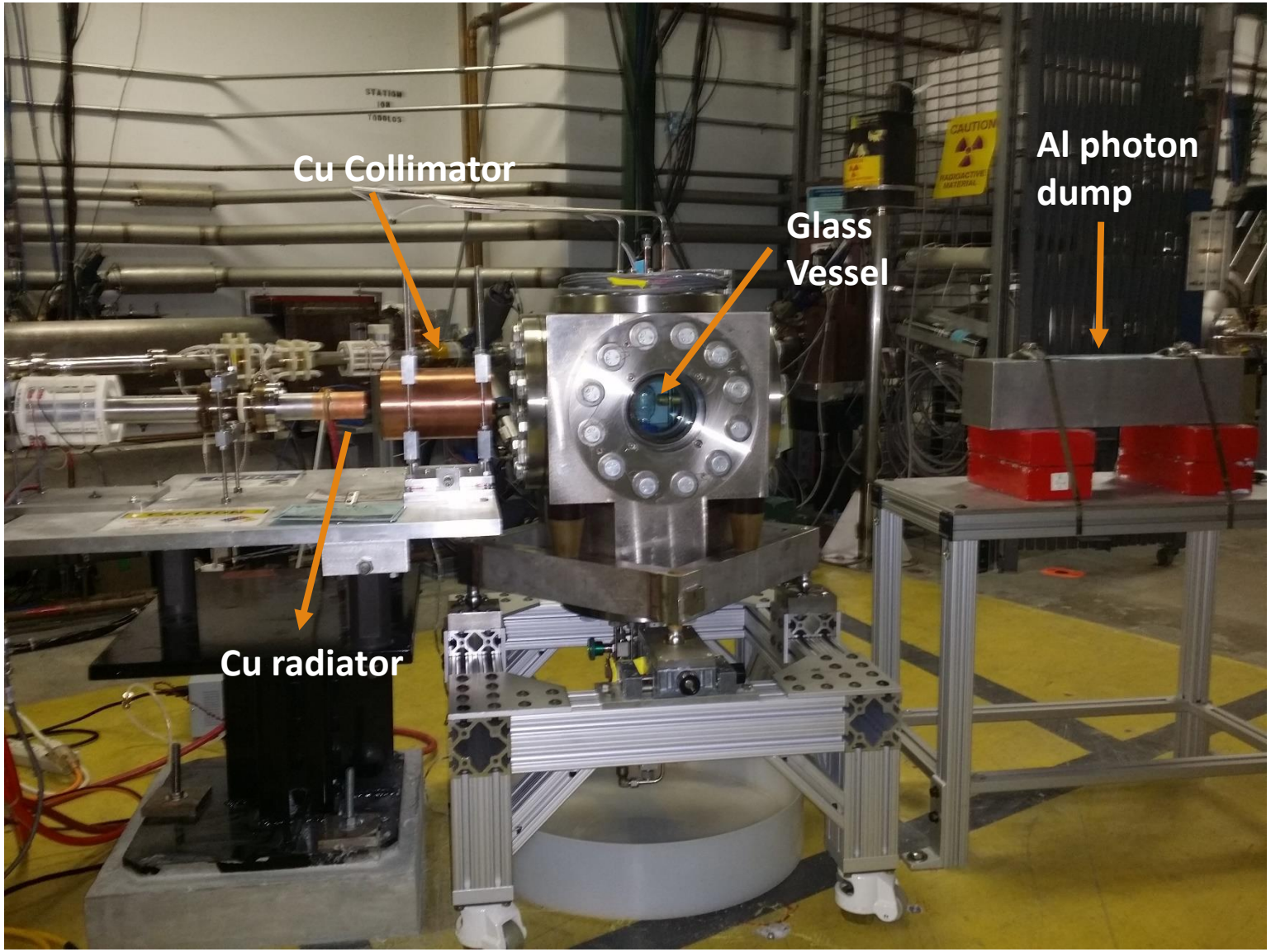
- Test the performance of the bubble chamber with a Bremsstrahlung beam
- Study the cosmic background level
- Study the background contributions from photodisintegration of nuclei in the superheated N_2O liquid

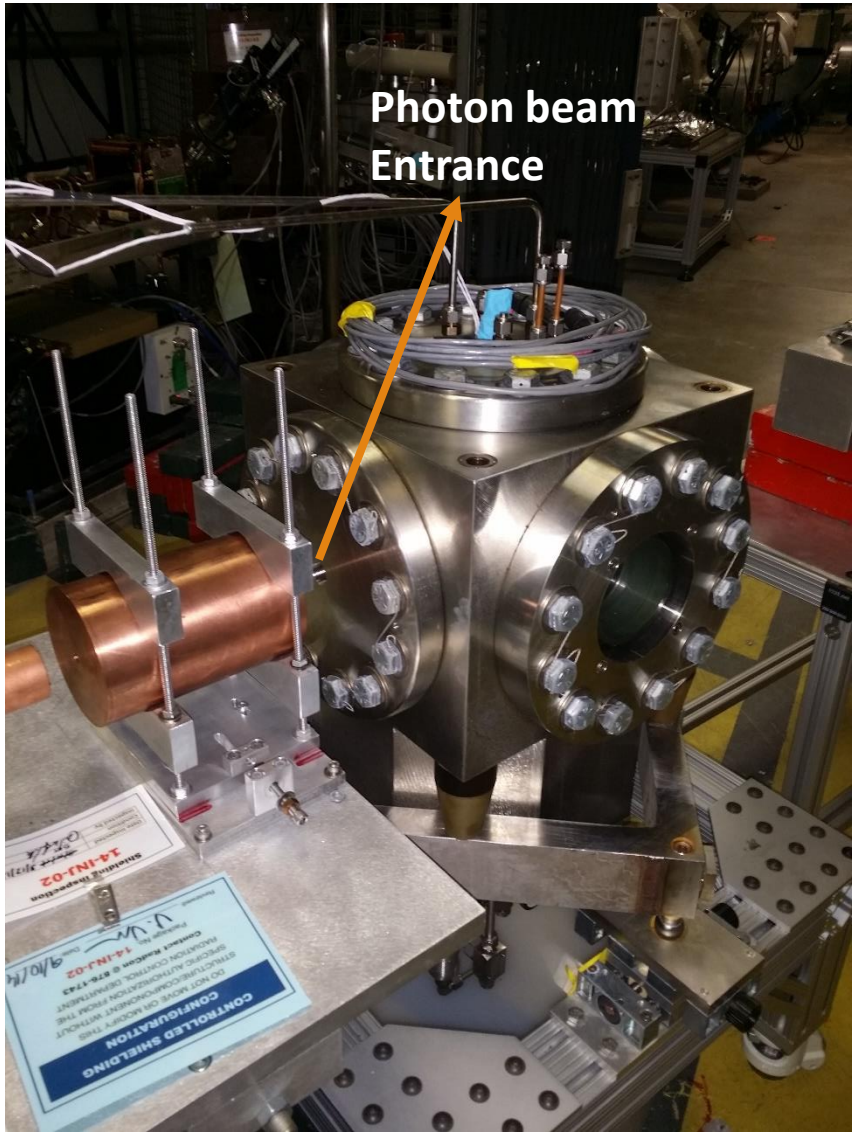
Background from oxygen isotopes and nitrogen in N_2O

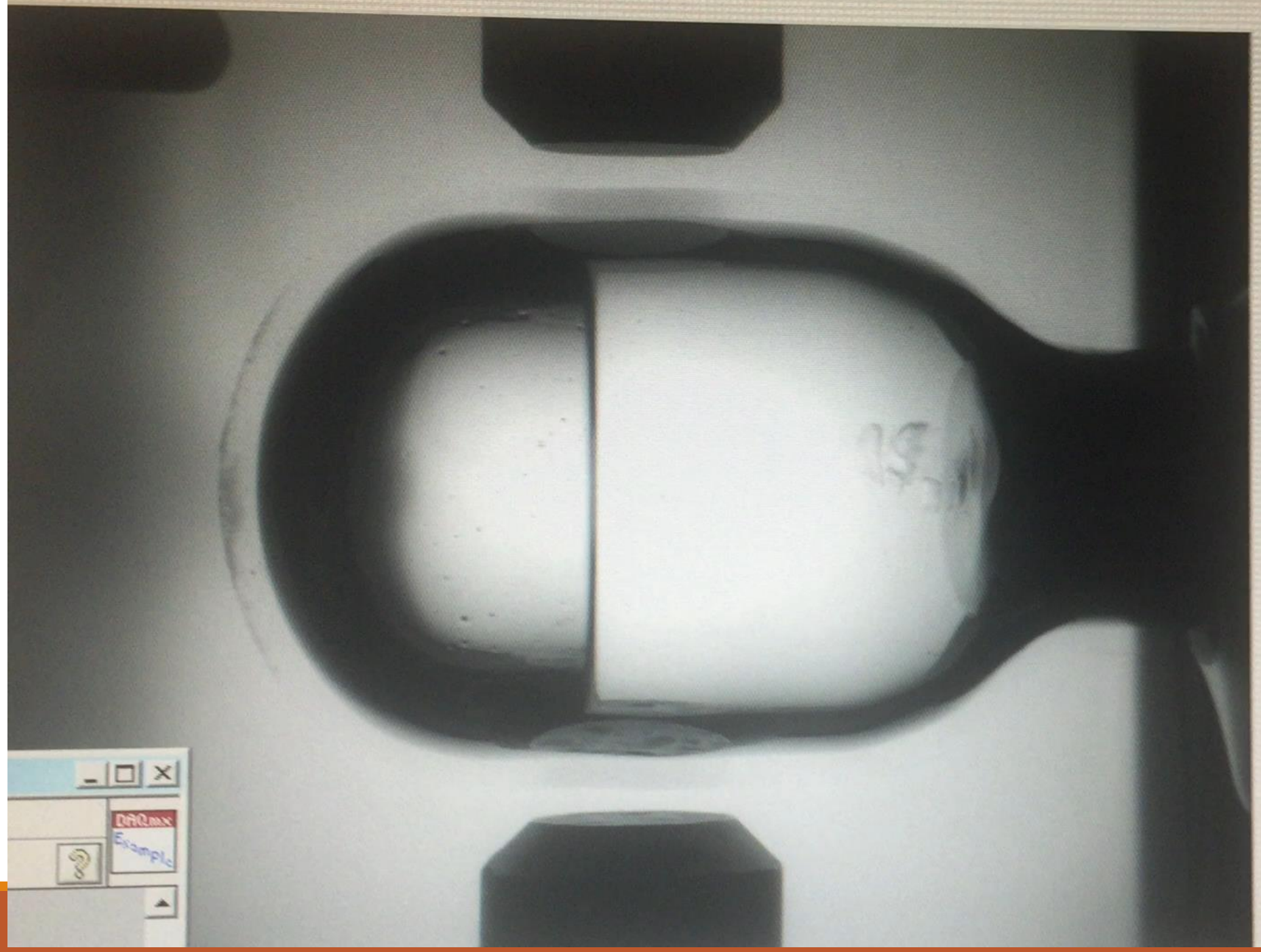
a) $^{18}O(\gamma,\alpha)^{14}C$ (Q-value = -6.23 MeV)
b) $^{17}O(\gamma,\alpha)^{13}C$ (Q-value = -6.36 MeV)
c) $^{14}N(\gamma,p)^{13}C$ (Q-value = -7.55 MeV)
d) $^{17}O(\gamma,n)^{16}O$ (Q-value = -4.14 MeV)



Experimental Set-Up for the N_2O Bubble Chamber







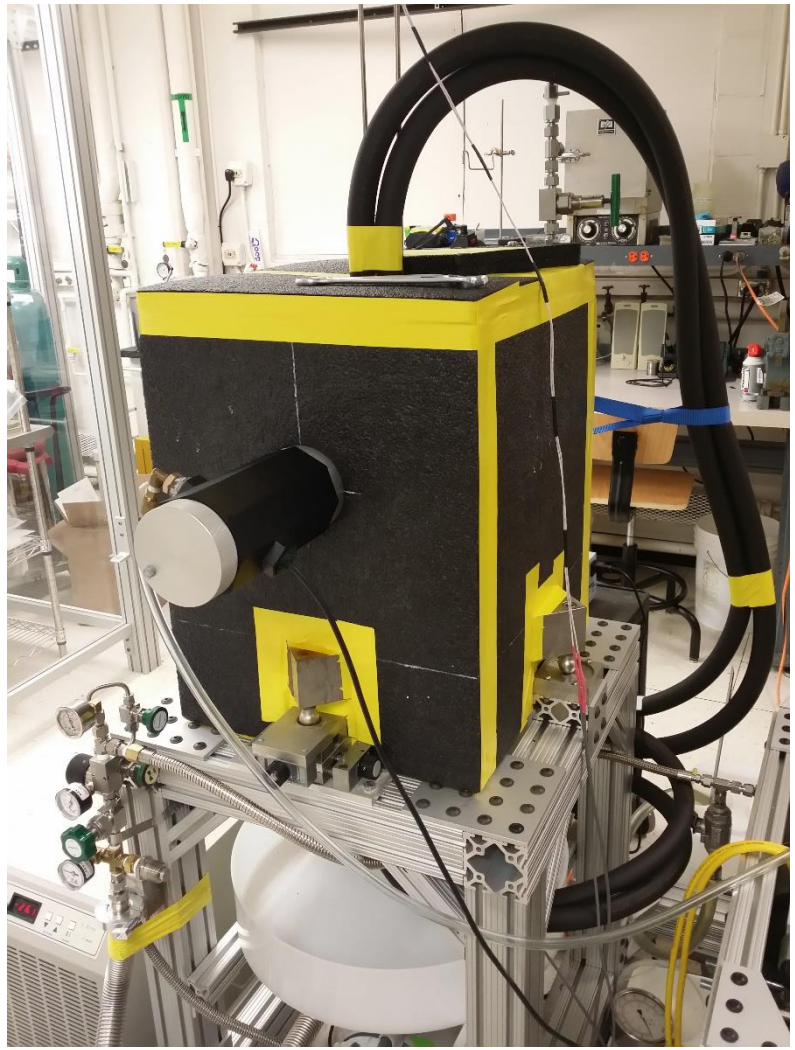
Back

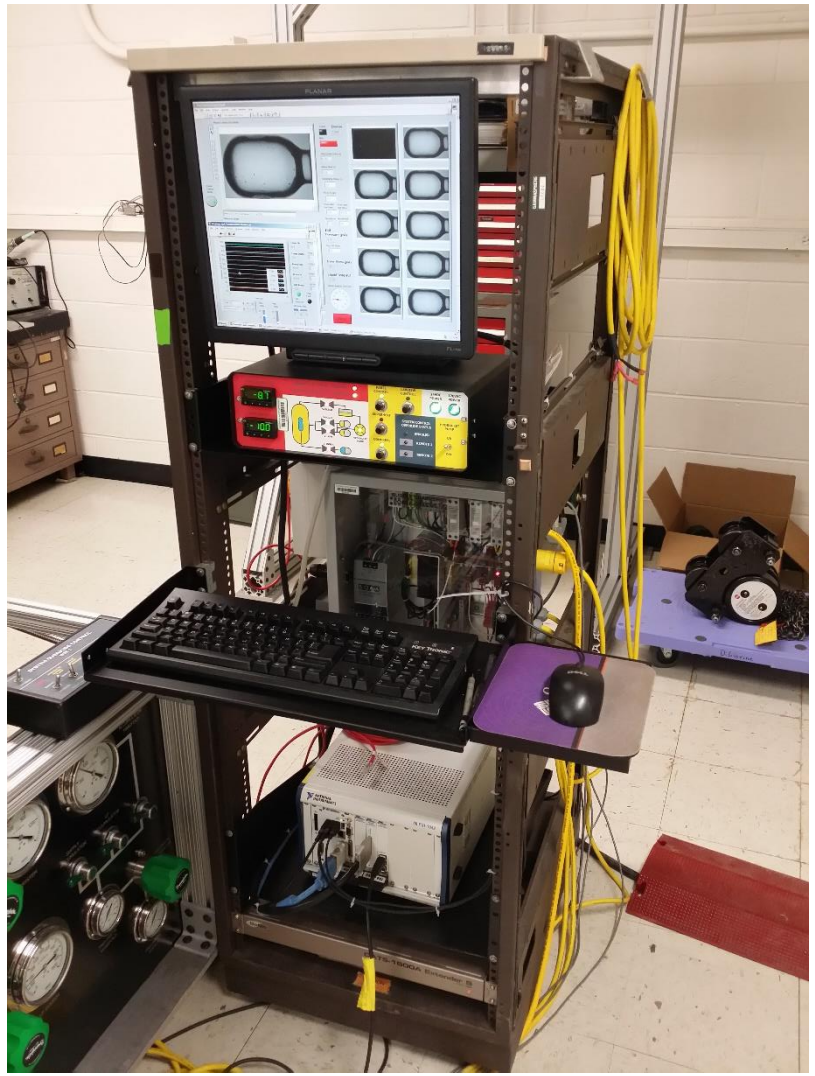
NI-IMAQdx Basics

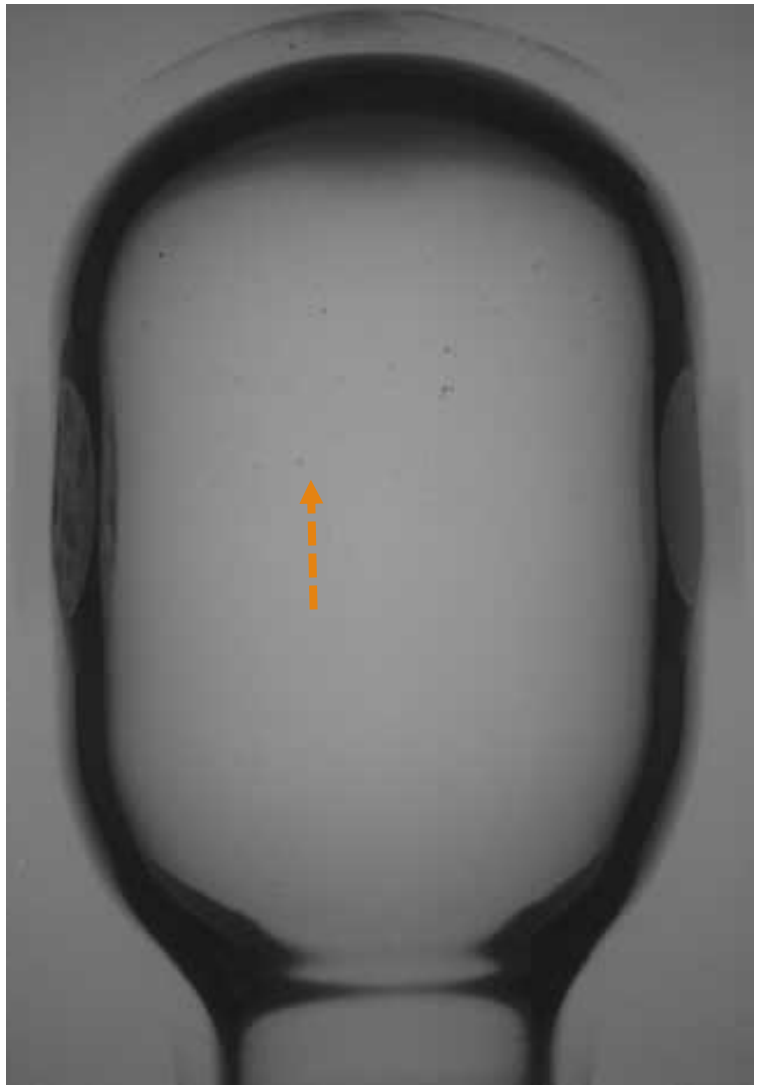
What do you want to do?

- Connect my camera
- Configure my device
- Set my remote image options

Bubble Formation and Data Acquisition

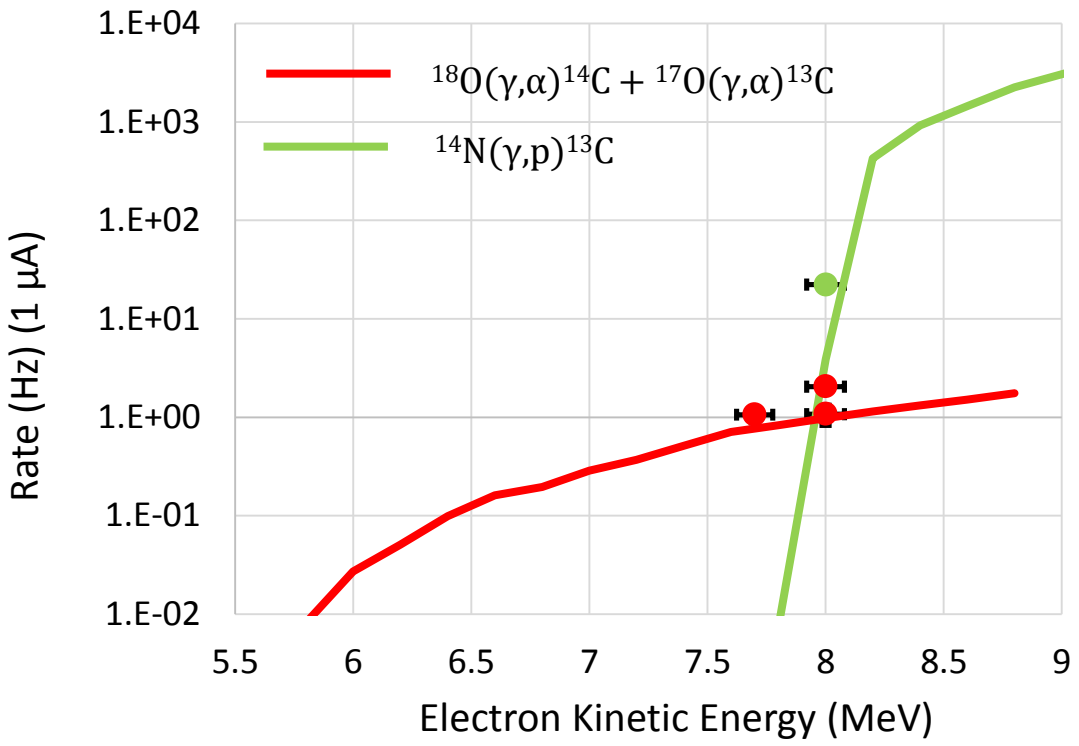


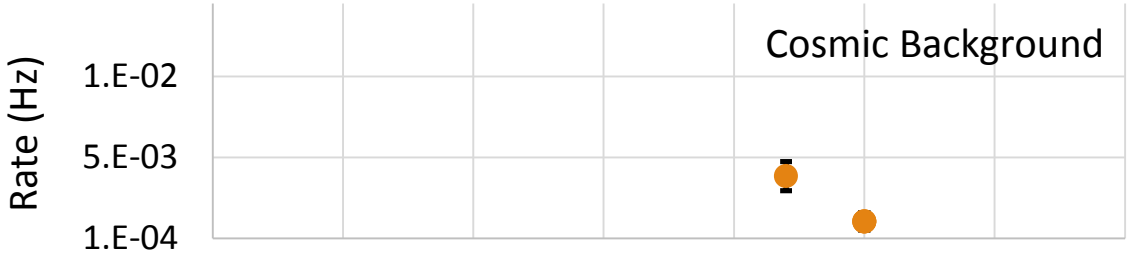




First Half of the Experiment

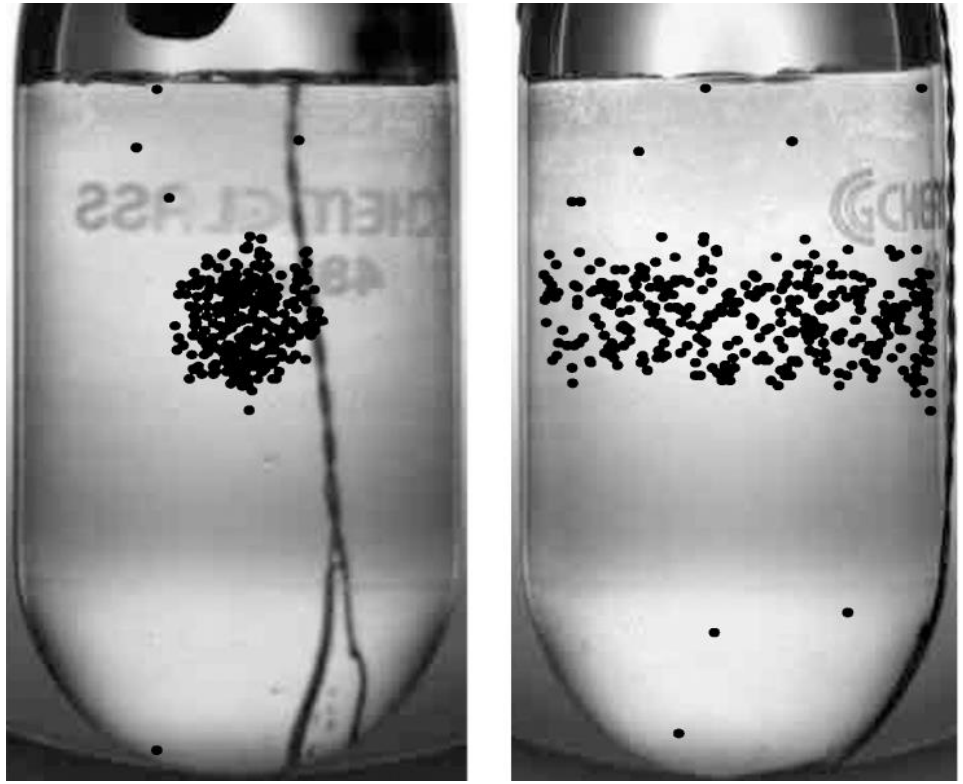
Energy Measured (MeV)	Superheat Pressure (psi)	Superheat Temperature (°C)	Beam Current (μA)
7.7	325	-8	0.4
8	325	-8	0.4
8	325	-8	0.04
8	310	-8	0.035



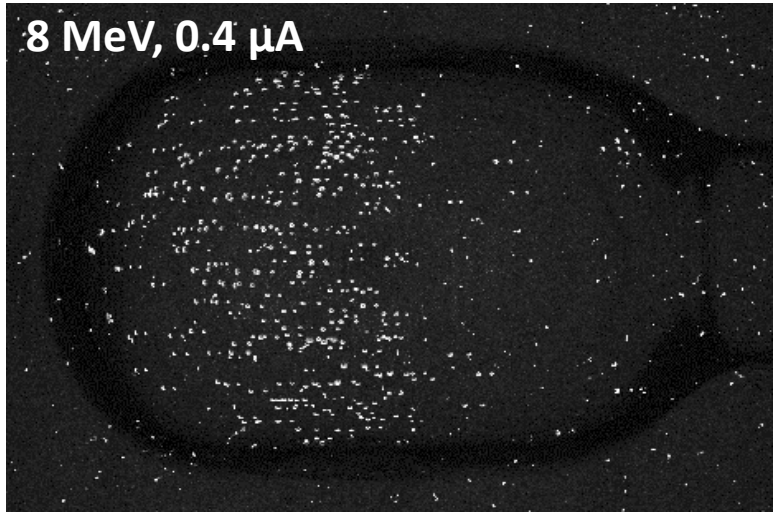


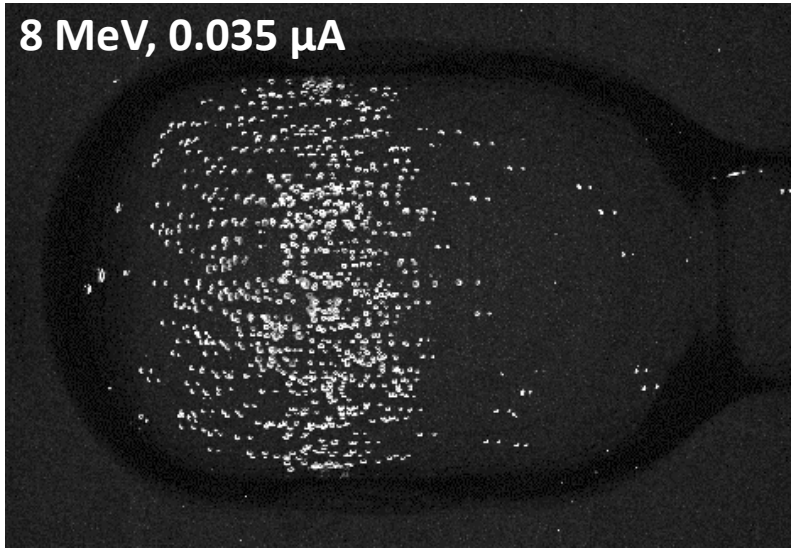
Bubble Distribution

HIγS Data

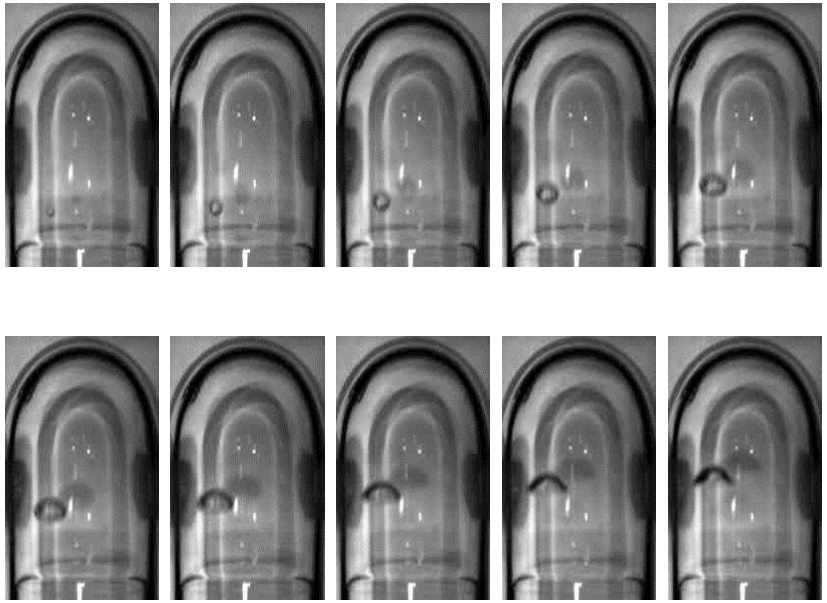


JLab Data



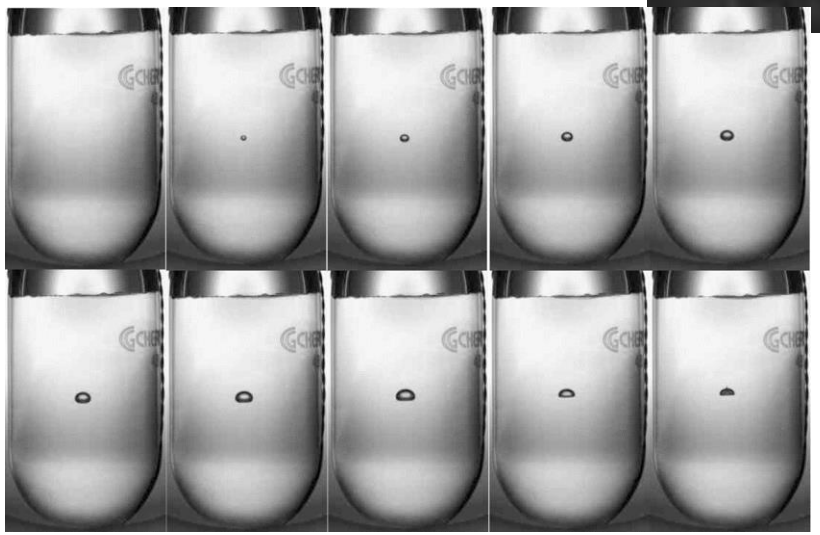


Bubble Size



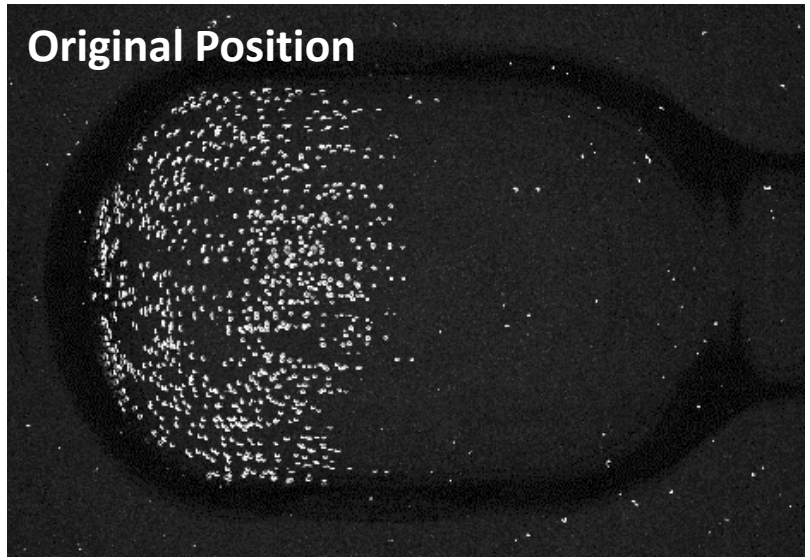
N_2O bubble

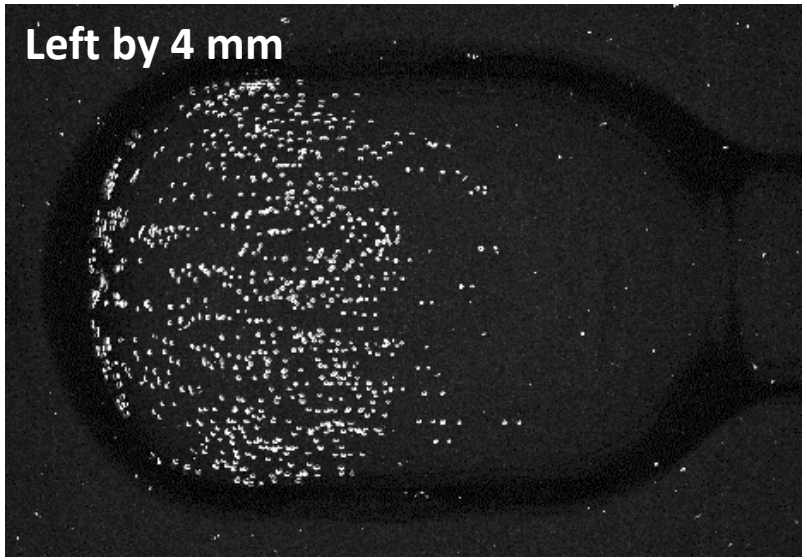
H_2O bubble

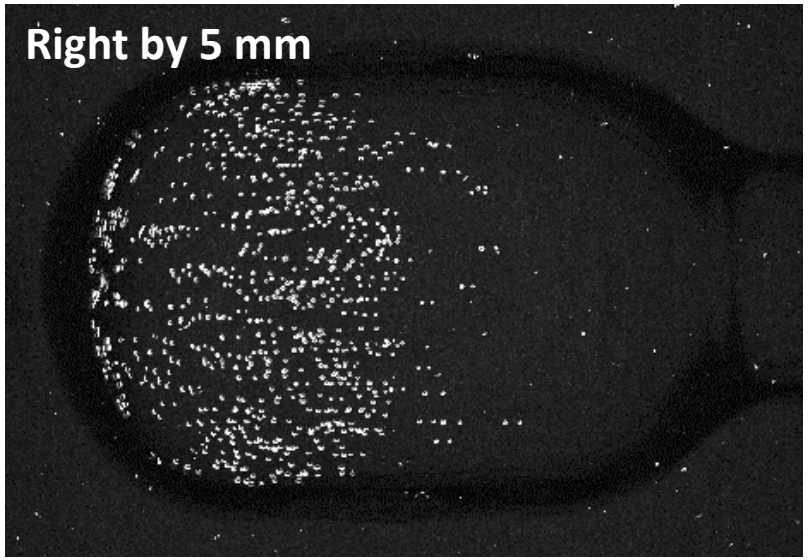


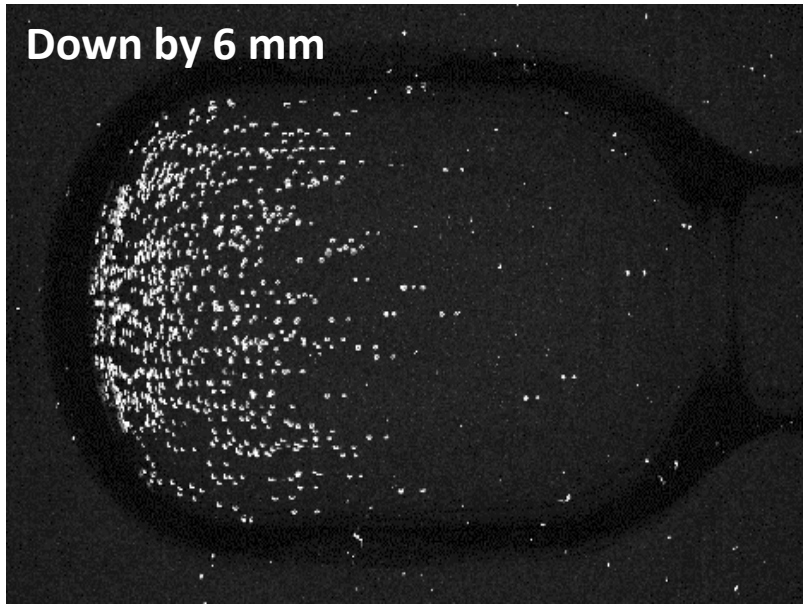
C_4F_{10} bubble

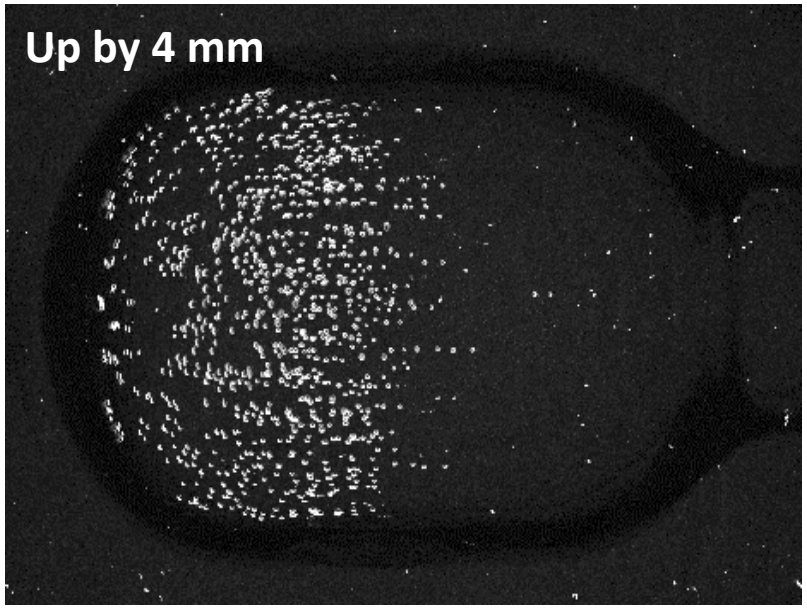
Beam Position Test





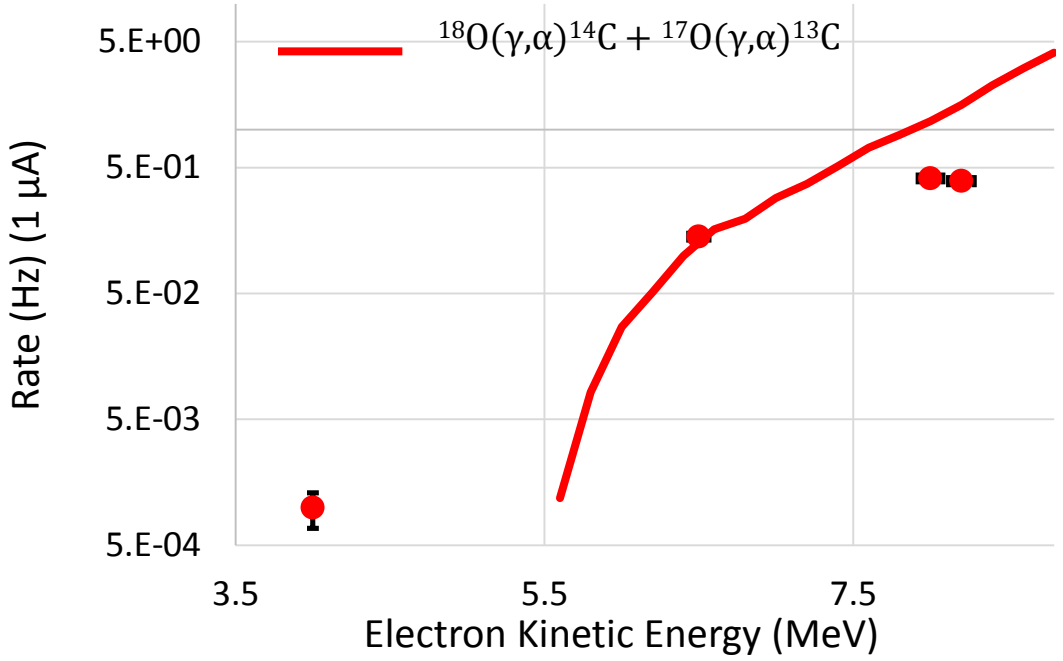


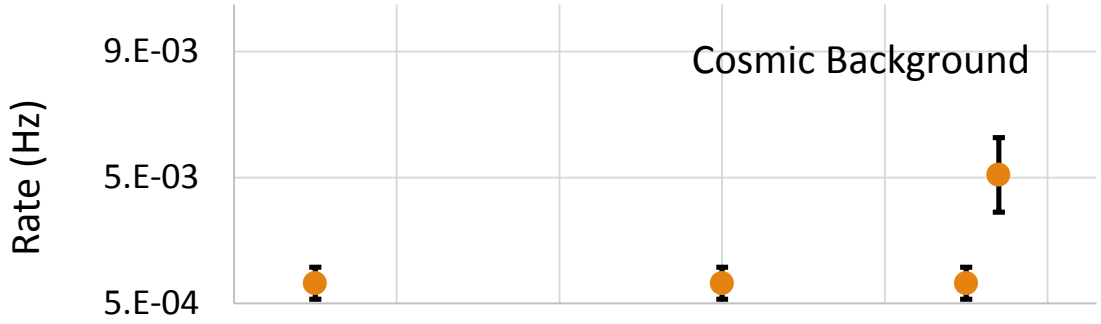




Second Half of The Experiment

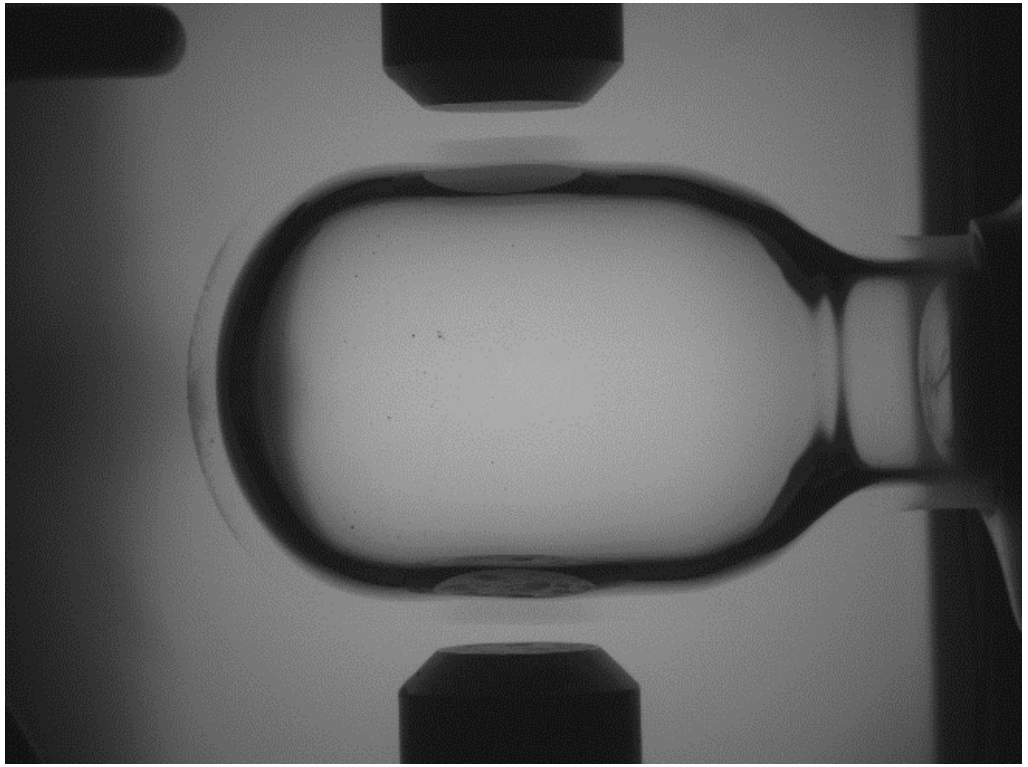
Energy Measured (MeV)	Superheat Pressure (psi)	Superheat Temperature (°C)	Beam Current (μA)
8	325	-8	0.4
8.2	325	-8	0.4
6.5	325	-8	1
4	325	-8	10

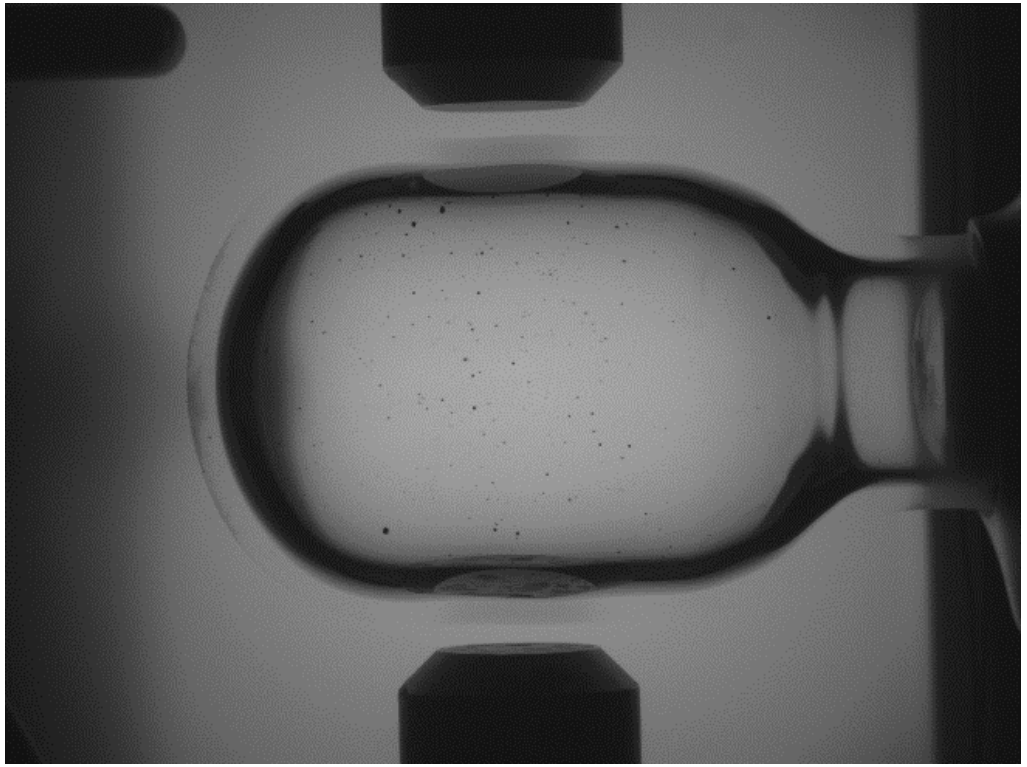




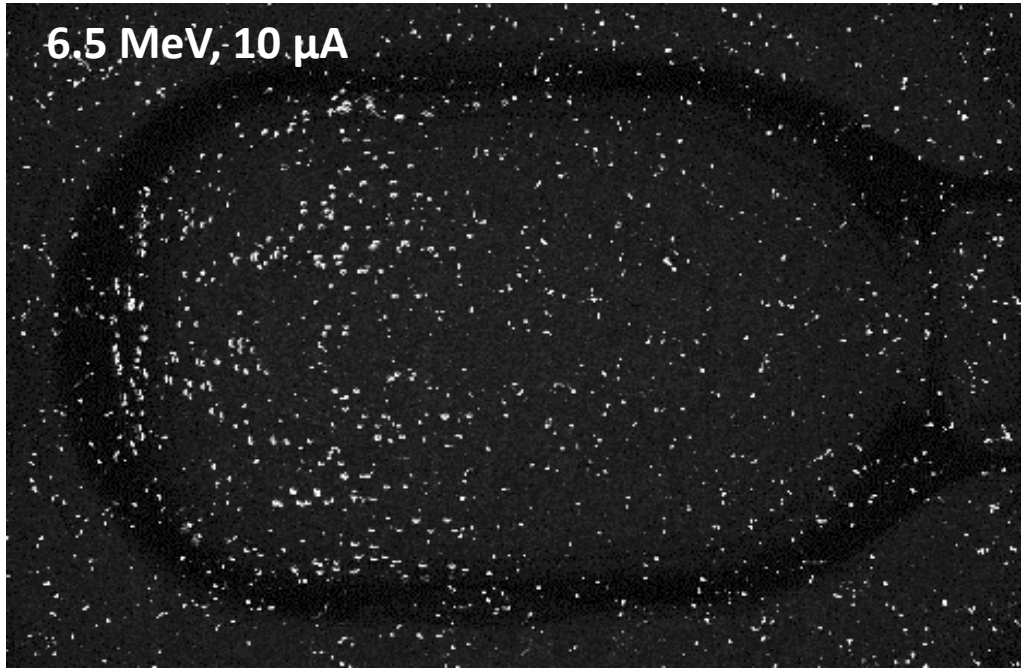
Problems Encountered during the Experiment

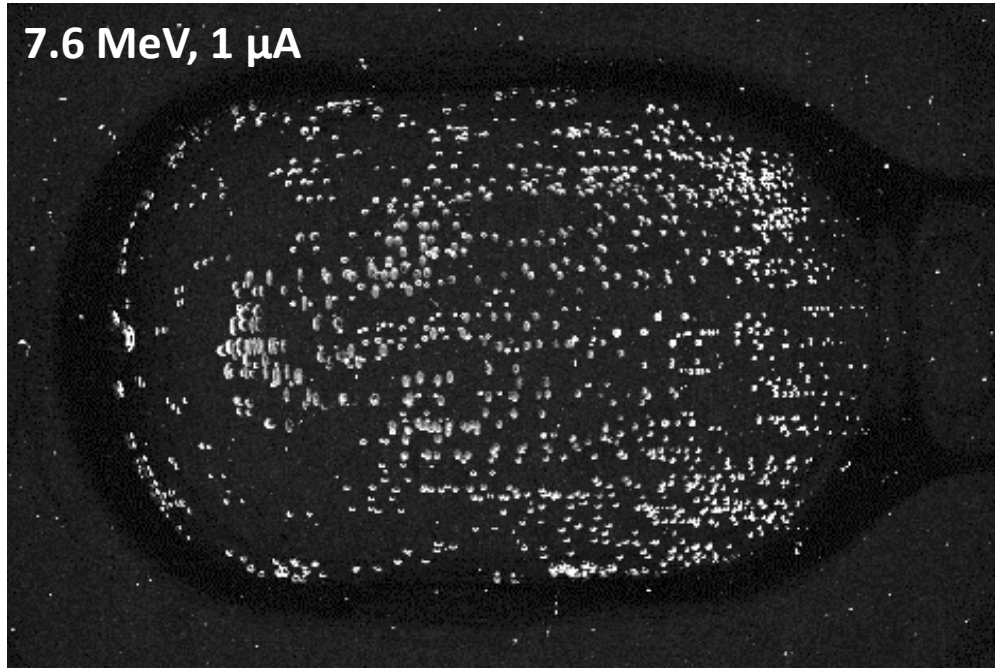
- Beam positon was not very well defined
- Mercury droplets on the glass vessel





- Could not reduce beam current below 35 nA
- At high beam currents (10 uA), 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.





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, HIγS = 1 in 2 minutes
- ✓ Rate limit of the bubble chamber is 10^{-3} counts/s at 4 MeV beam energy

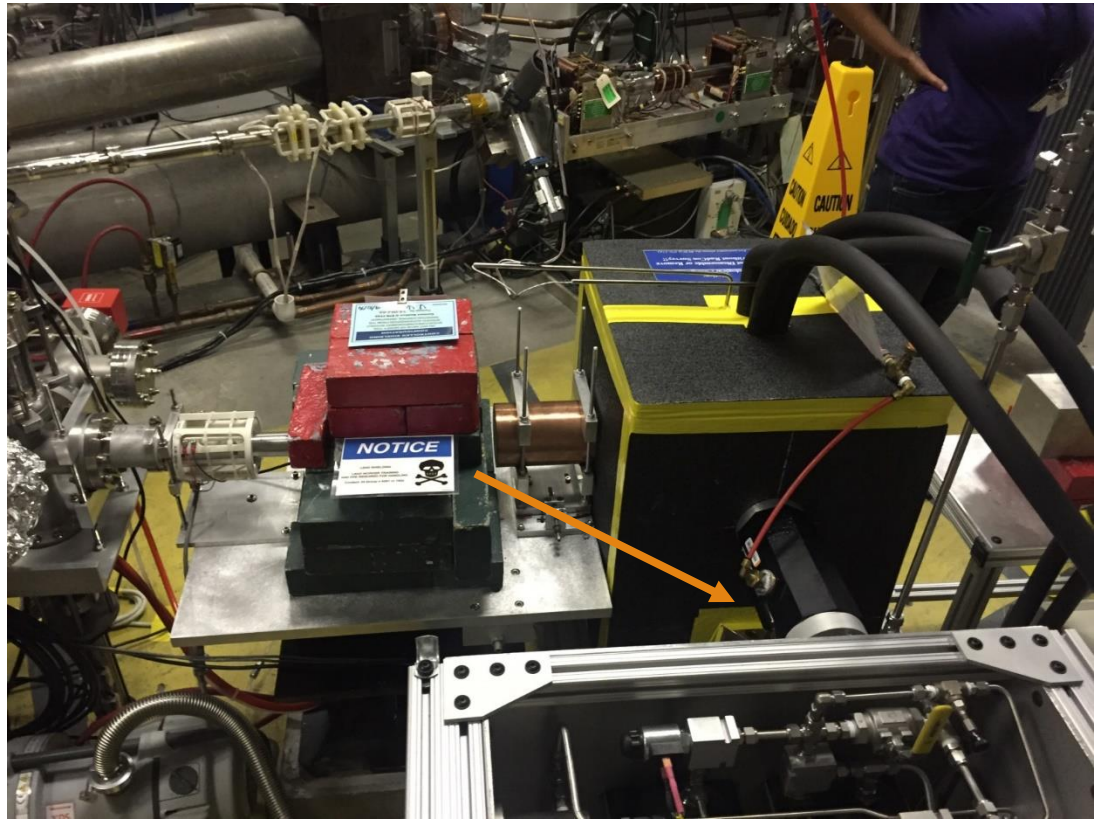
If we consider a 3 cm long glass vessel filled with C_4F_{10} (1.5 g/cm^3) bombarded by 10^{11} γ/s, out of which 1% are "good" γs, we get :

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

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

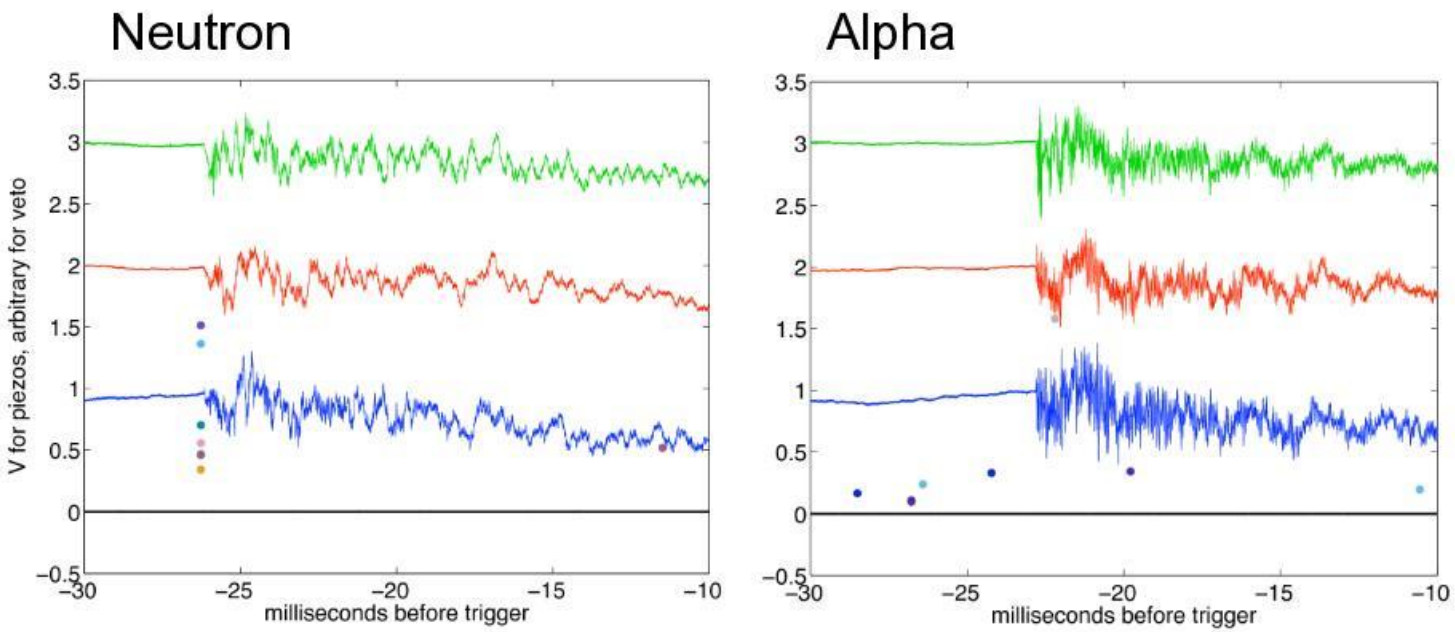


- ✓ Study $^{19}F(\gamma,\alpha)^{15}N$ at cross-sections below 3 nb (beam time approved at JLab from May 31 – June15, 2016)

- ✓ Acoustic signal discrimination to suppress neutron background

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

Suppression of neutron events by a factor of 100 using acoustic signals



Collaboration

Argonne NATIONAL LABORATORY

B. DiGiovine
R. J. Holt
K. E. Rehm
R. Talwar

UIC UNIVERSITY OF ILLINOIS AT CHICAGO

C. Ugalde

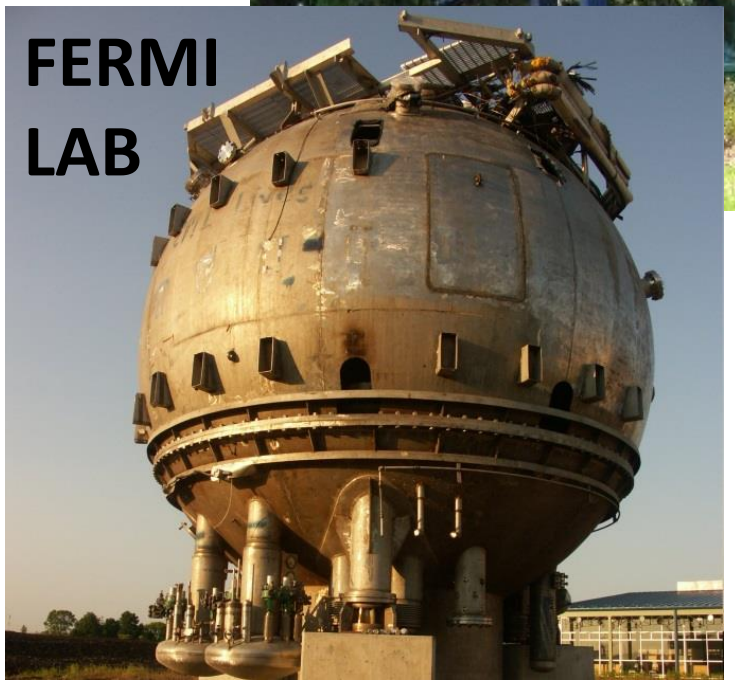
Jefferson Lab

J. Benesch
J. Grames
G. Kharashvili
D. Meekins
D. Moser
M. Poelker
M. Stutzman
R. Suleiman
C. Tennant

Fermilab

A. Robinson
A. Sonnenschein

THANK YOU



Back - Up

Penfold-Leiss Cross-section Unfolding

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

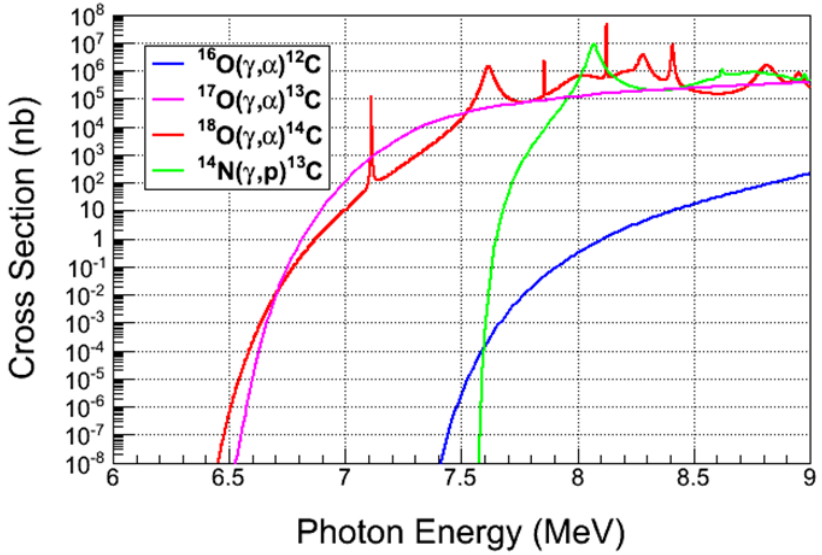
$$y(E_i) = \int_{threshold}^{Ei} N_\gamma(E_i, k)\sigma(k)dk \approx \sum_{j=1}^{i} N_\gamma(E_i, \Delta, k_j)\sigma(k_j)$$

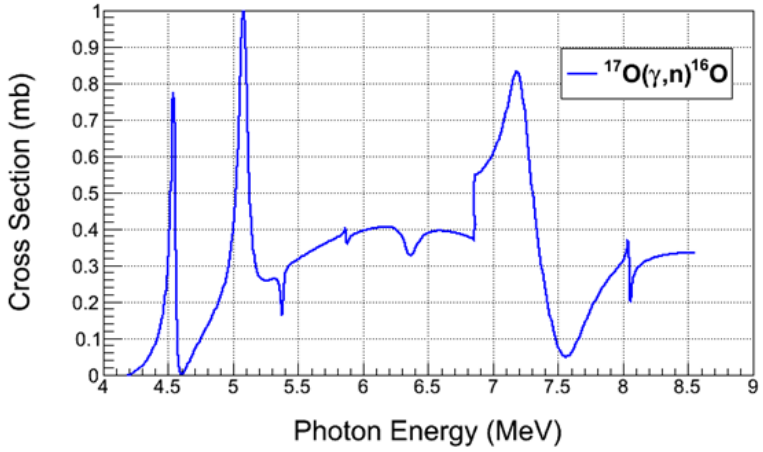
Where $N_\gamma(E_i, \Delta, k_j)$ is the number of gammas in the energy bin of width $\Delta = E_i - E_{i-1}$

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

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

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


Cross Section (nb)
Photon Energy (MeV)
$^{16}O(\gamma,\alpha)^{12}C$
$^{17}O(\gamma,\alpha)^{13}C$
$^{18}O(\gamma,\alpha)^{14}C$
$^{14}N(\gamma,p)^{13}C$


Cross Section (mb)
Photon Energy (MeV)
$^{17}O(\gamma,n)^{16}O$