

Measurement of  $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$  with a Bubble Chamber  
and a Bremsstrahlung Beam at Jefferson Lab Injector

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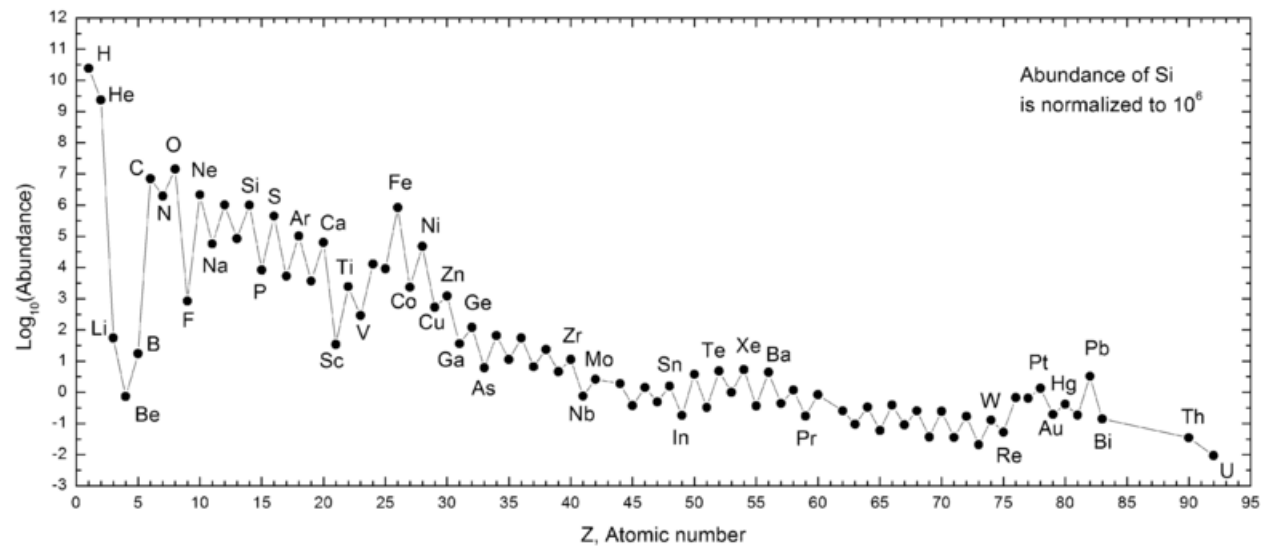
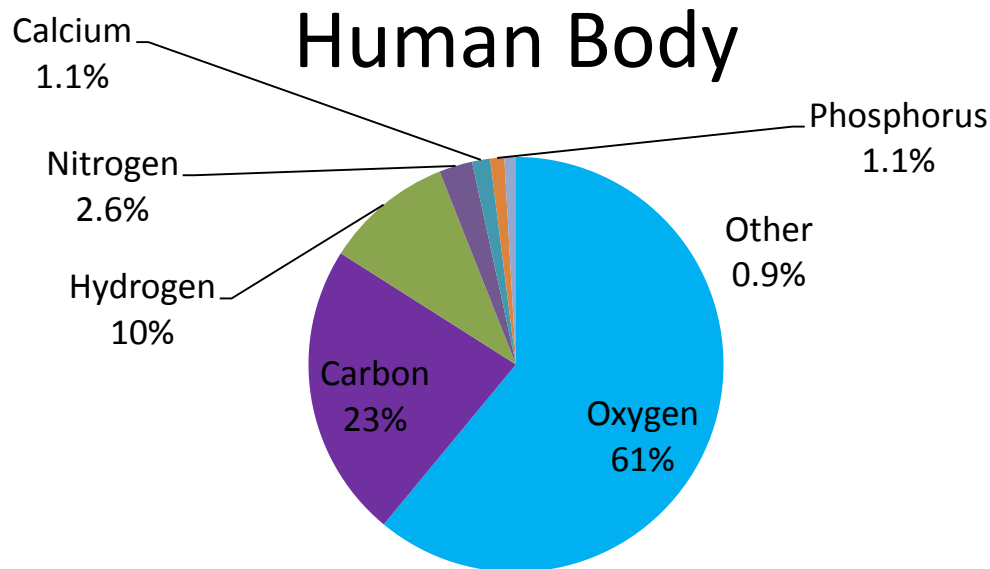
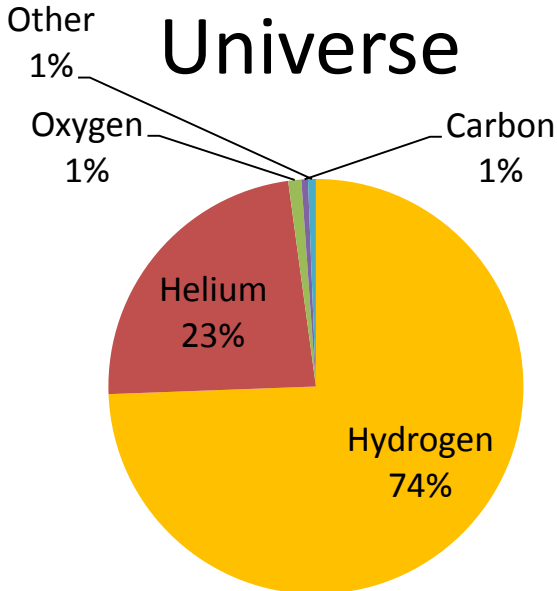


J. Benesch  
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# OUTLINE

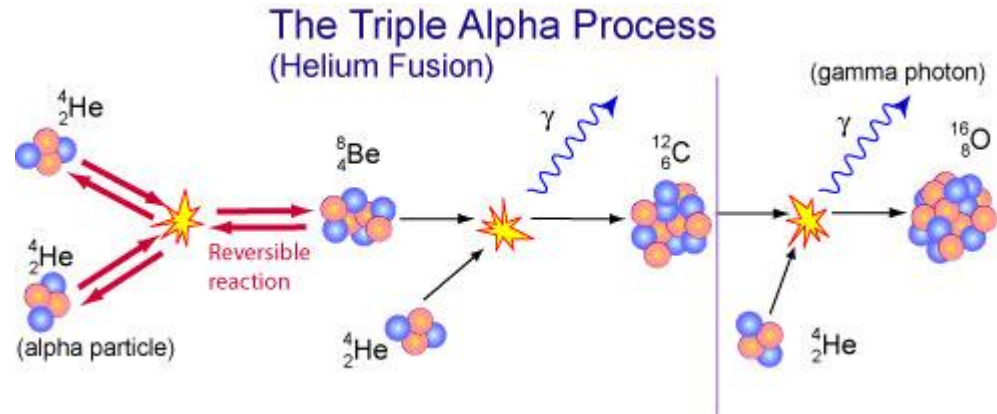
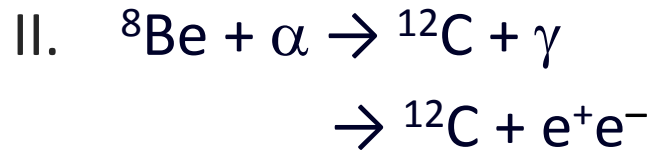
- Nucleosynthesis and the  $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$  Reaction
- Time-reversal Reaction:  $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$
- Bubble Chamber Theory and Design
- Work at HIGS
- Experimental Setup at Jefferson Lab Injector
- Bremsstrahlung Beam and Penfold-Leiss Unfolding
- Statistical and Systematic Errors
- Backgrounds and Ion Energy Distributions
- Safety
- Summary and Outlook

# RELATIVE ABUNDANCE OF ELEMENTS BY WEIGHT



# STELLAR HELIUM BURNING

- Helium Reactions:



- $\alpha + {}^{12}\text{C}$  burning at very small cross section  $\sigma \sim 10^{-17}$  barn

- Thermonuclear reaction rate involving two nuclei is:

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi m (k_B T)^3}} \int_0^\infty E \sigma(E) e^{-\frac{E}{k_B T}} dE$$

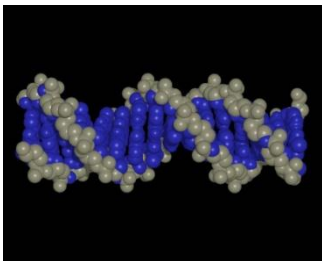
- Only narrow energy range is important

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

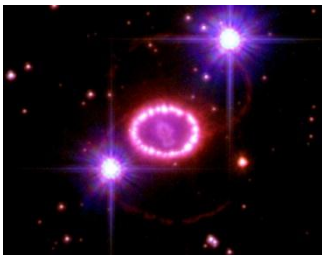
- The “holy grail” of nuclear astrophysics

Periodic Table of the Elements

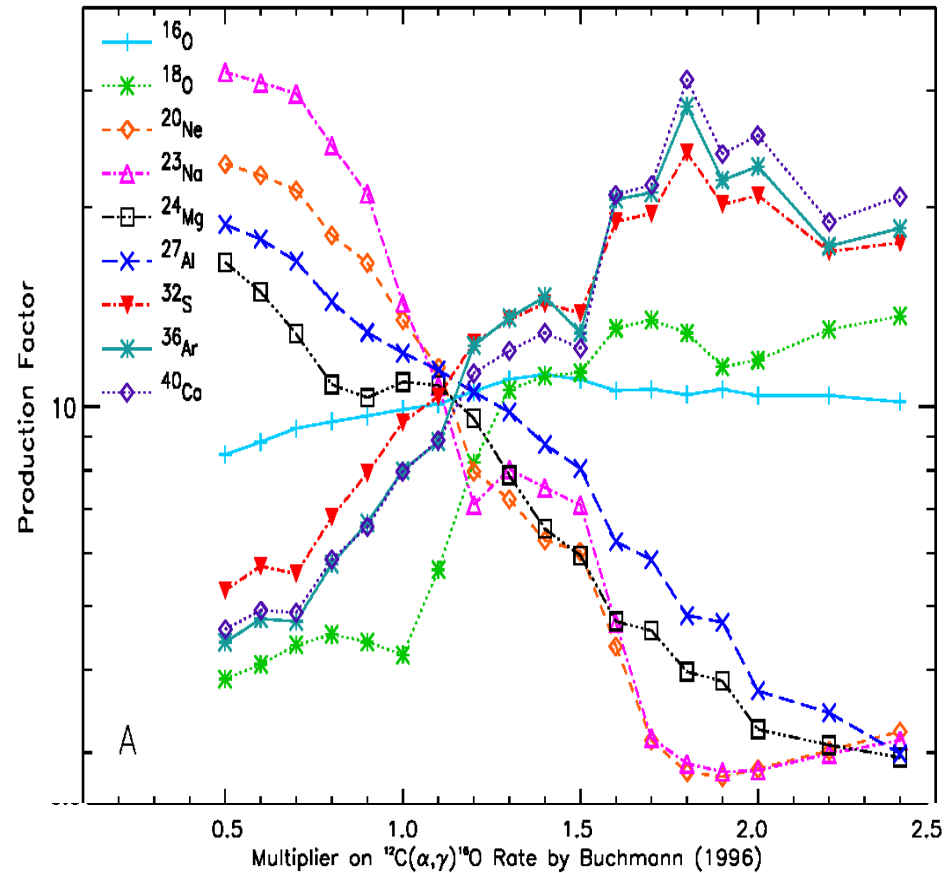
Affects the synthesis of most of the elements of the periodic table



Sets the C/O (=0.55) ratio in the universe



Determines the minimum mass a star requires to become a supernova



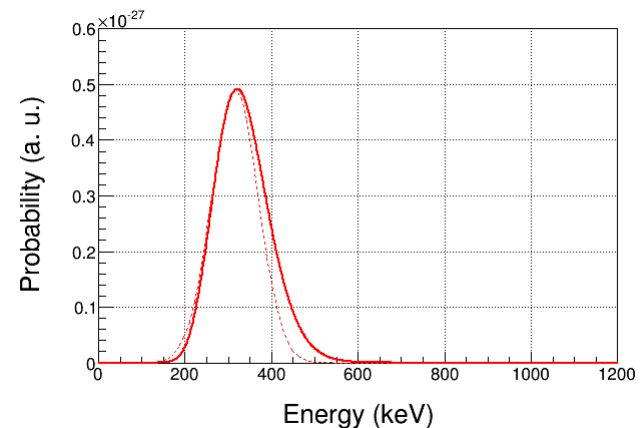
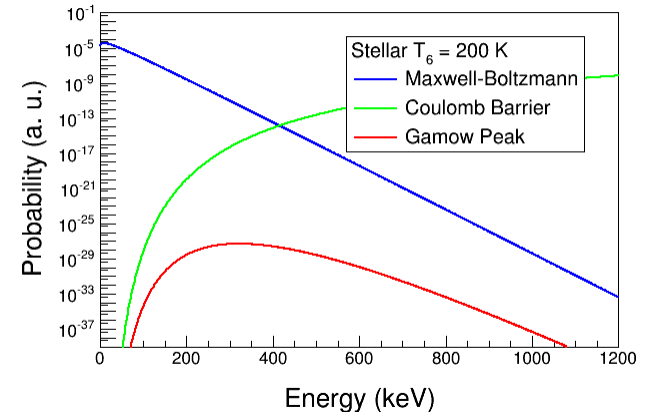
# THE GAMOW PEAK

- Narrow energy range where thermonuclear reactions is most likely to occur in stellar plasma is a product of two distributions:
  - Maxwell-Boltzmann energy distribution with  $e^{-E/k_B T}$
  - Penetration through Coulomb barrier with  $e^{-b/E^{1/2}}$

$$E_0 = 1.220 \left( Z_1^2 Z_2^2 A T_6^2 \right)^{1/3} \text{ keV}$$

$$W = 0.2368 \left( Z_1^2 Z_2^2 A T_6^5 \right)^{1/6} \text{ keV}$$

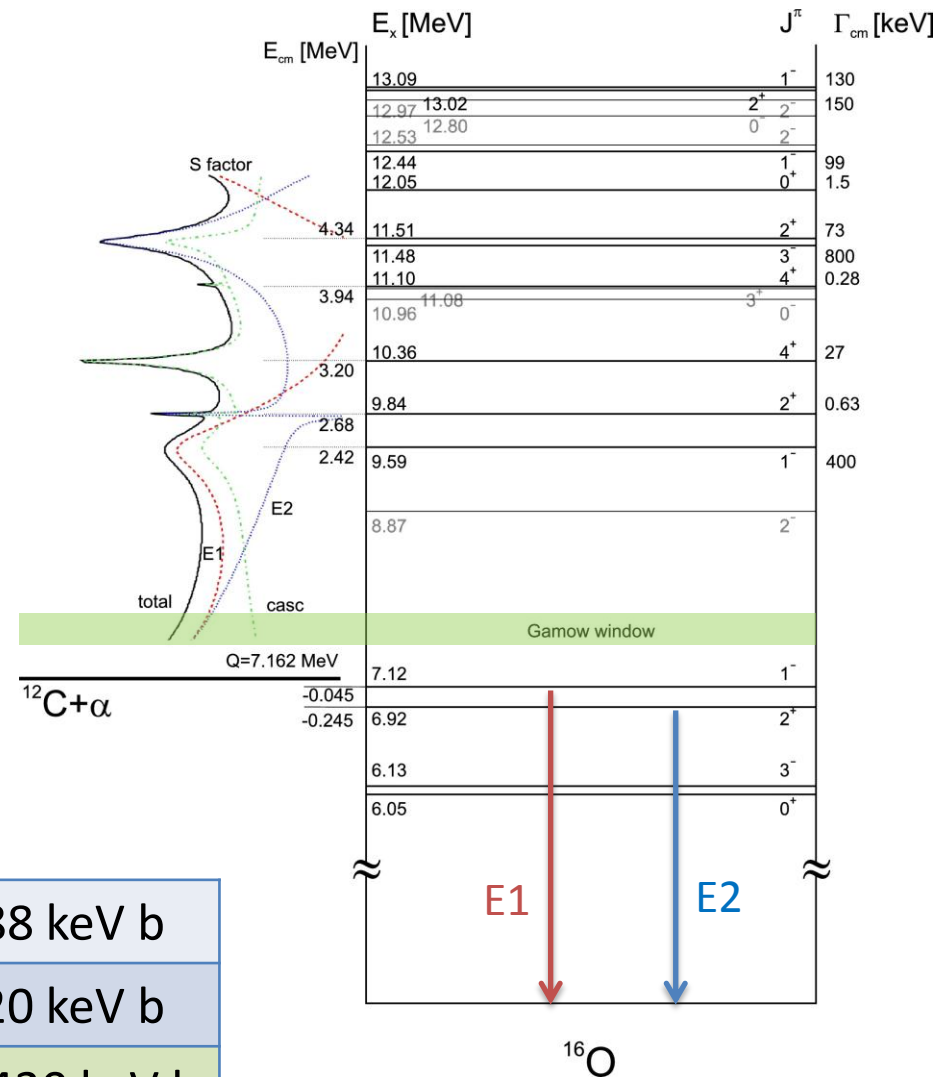
- For  $\alpha + {}^{12}\text{C}$  ( $Z_1=2, Z_2=6, A=3$ ), and stellar  $T=200 \cdot 10^6$  K:
  - Gamow Peak,  $E_0 = 315$  keV,  $W = 54$  keV
  - Maximum of Maxwell-Boltzmann energy distribution,  $k_B T = 17$  keV





# $\alpha + {}^{12}\text{C}$ RADIATIVE CAPTURE

- $\sigma(E_0)$  is dominated by  $p$ -wave (E1) and  $d$ -wave (E2) radiative capture to ( $J^\pi=0^+$ )  ${}^{16}\text{O}$  ground state
- Two bound states, at 6.92 MeV ( $J^\pi=2^+$ ) and 7.12 MeV ( $J^\pi=1^-$ ), with sub-threshold resonances at  $E_R=-0.245$  and  $-0.045$  MeV, provide most of  $\sigma(E_0)$  through their finite widths
- Distinguish E1 and E2 by measuring  $\gamma$  angular distributions



Transition $\rightarrow 0$ (E1)	$S_{E1}(300) = 1\text{--}288$ keV b
Transition $\rightarrow 0$ (E2)	$S_{E2}(300) = 7\text{--}120$ keV b
Total	$S_{\text{tot}}(300) = 40\text{--}430$ keV b



# Heroic efforts in search of $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

## ➤ Previous Experiments:

### A. Direct Techniques:

- I. Helium ions on carbon target:  $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$
- II. Carbon ions on helium gas:  $^4\text{He}(^{12}\text{C},^{16}\text{O})\gamma$

Experiment	Beam Current (mA)	Target (nuclei/cm <sup>2</sup> )	Time (h)
Redder	0.7	$^{12}\text{C}$ , $3 \cdot 10^{18}$	900
Ouellet	0.03	$^{12}\text{C}$ , $5 \cdot 10^{18}$	1950
Roters	0.02	$^4\text{He}$ , $1 \cdot 10^{19}$	5000
Kunz	0.5	$^{12}\text{C}$ , $3 \cdot 10^{18}$	700
EUROGAM	0.34	$^{12}\text{C}$ , $1 \cdot 10^{19}$	2100
GANDI	0.6 (?)	$^{12}\text{C}$ , $2 \cdot 10^{18}$	?
Schürmann	0.01	$^4\text{He}$ , $4 \cdot 10^{17}$	?
Plag	0.005	$^{12}\text{C}$ , $6 \cdot 10^{18}$	278

### B. Indirect Methods:

- I.  $\beta$ -delayed  $\alpha$  decay of  $^{16}\text{N}$  ( $J^\pi=2^-$ ,  $T_{1/2}=7.13$  sec, BR=0.12%).  
 $^{16}\text{N} \rightarrow \beta^- + ^{16}\text{O}^*(J^\pi=1^-) \rightarrow \alpha + ^{12}\text{C}$
- II. Elastic  $\alpha - ^{12}\text{C}$  Scattering

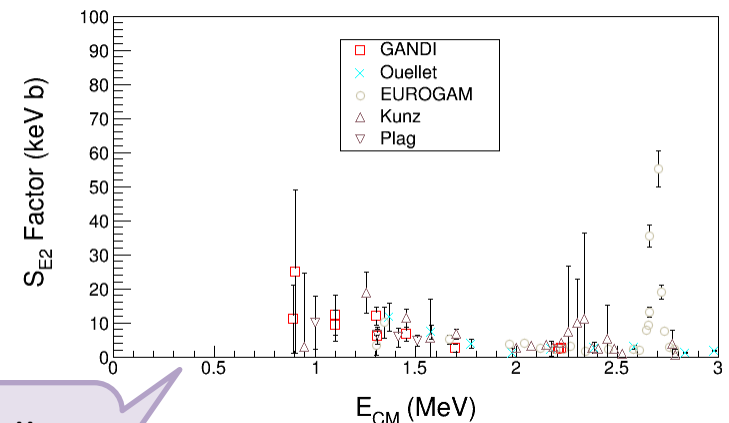
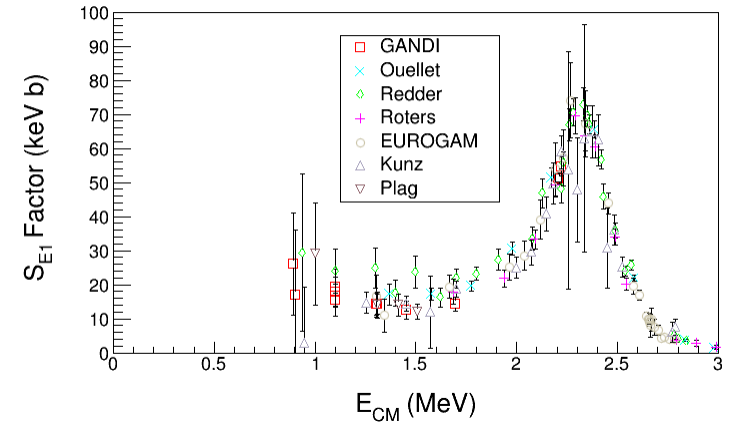
# ASTROPHYSICAL S-FACTOR $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

- Define S-Factor to remove both  $1/E$  dependence of nuclear cross sections and Coulomb barrier transmission probability:

$$S \equiv E_{CM} \sigma(\alpha, \gamma) e^{2\pi\eta}$$

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

Author	S(300) (keV b)
Schürmann (2012)	$161 \pm 19^{+8}_{-2}$
Hammer (2005)	$162 \pm 39$
Kunz (2001)	$165 \pm 50$



R-Matrix Extrapolation to stellar helium burning at  $E = 300$  keV

# RECIPROCITY RELATION: $(\gamma, \alpha)$ and $(\alpha, \gamma)$

➤  $A(\alpha, \gamma)B$ :

$$\sigma_{B\gamma}^{j \rightarrow i}(E_\gamma) = \frac{(2J_i + 1)(2J_\alpha + 1)}{2J_j + 1} \frac{m_{A\alpha} c^2 E_{A\alpha}}{E_\gamma^2} \sigma_{A\alpha}^{i \rightarrow j}(E_{A\alpha})$$

$$m_{A\alpha} c^2 = \frac{M(^{12}\text{C}) \cdot M(\alpha)}{M(^{12}\text{C}) + M(\alpha)} = 2796 \text{ MeV} \quad J_i = 0, J_j = 0, J_\alpha = 0$$

$$E_{A\alpha} = E_{CM}$$

$$Q = m_A + m_\alpha - m_B = 7.162 \text{ MeV}$$

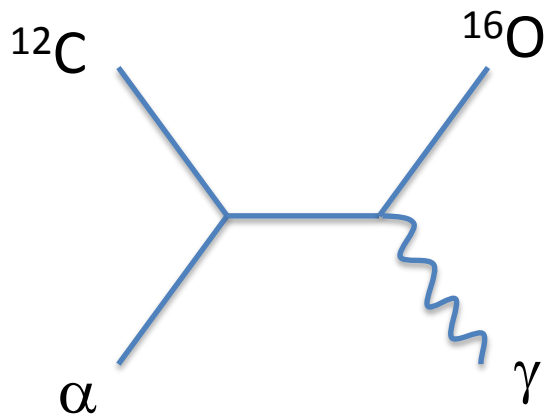
$$E_{CM} = \sqrt{m_B^2 + 2E_\gamma m_B} - m_B - Q$$

$$\cong E_\gamma - Q$$

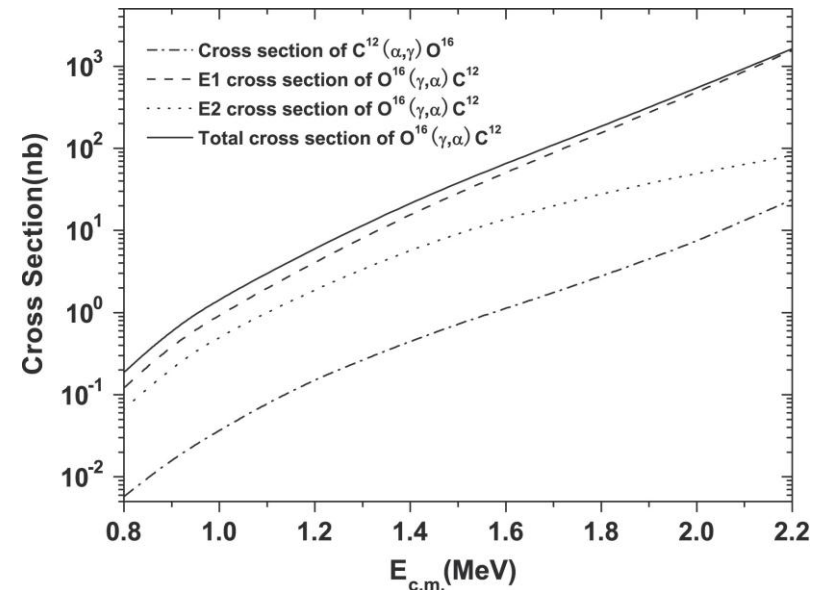
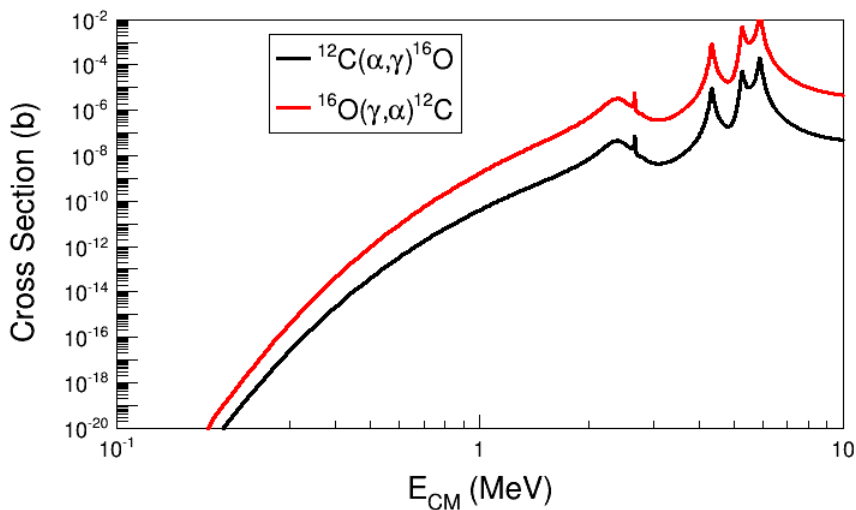
$$\sigma_{(\gamma, \alpha)}(E_\gamma) = \frac{m_{A\alpha} c^2 E_{CM}}{E_\gamma^2} \sigma_{(\alpha, \gamma)}(E_{CM})$$

➤  $\sigma(\gamma, \alpha)$  is over two orders of magnitude larger than  $\sigma(\alpha, \gamma)$

# TIME REVERSAL REACTION

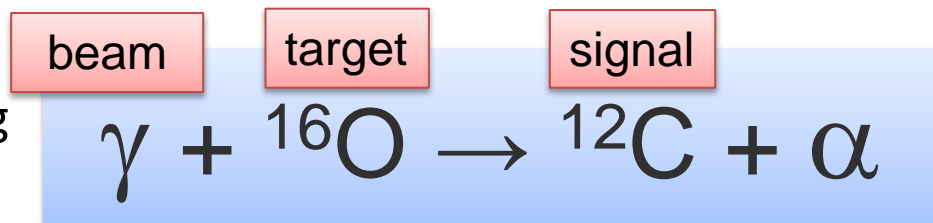


Bubble Chamber  
experiment measures total  
cross section, E1 + E2



# NEW APPROACH: REVERSAL REACTION + BUBBLE CHAMBER

- Extra gain (factor of 100) by measuring time reversal reaction
- Target density up to  $10^4$  higher than conventional targets. Number of  $^{16}\text{O}$  nuclei =  $3.5 \cdot 10^{22} / \text{cm}^2$
- Solid Angle and Detector Efficiency = 100%
- Superheated liquid will nucleate from  $\alpha$  and  $^{12}\text{C}$  recoils
- Electromagnetic debris (electrons and gammas, or positrons) do NOT trigger nucleation (detector is insensitive to  $\gamma$ -rays by at least 1 part in  $10^{11}$ ).

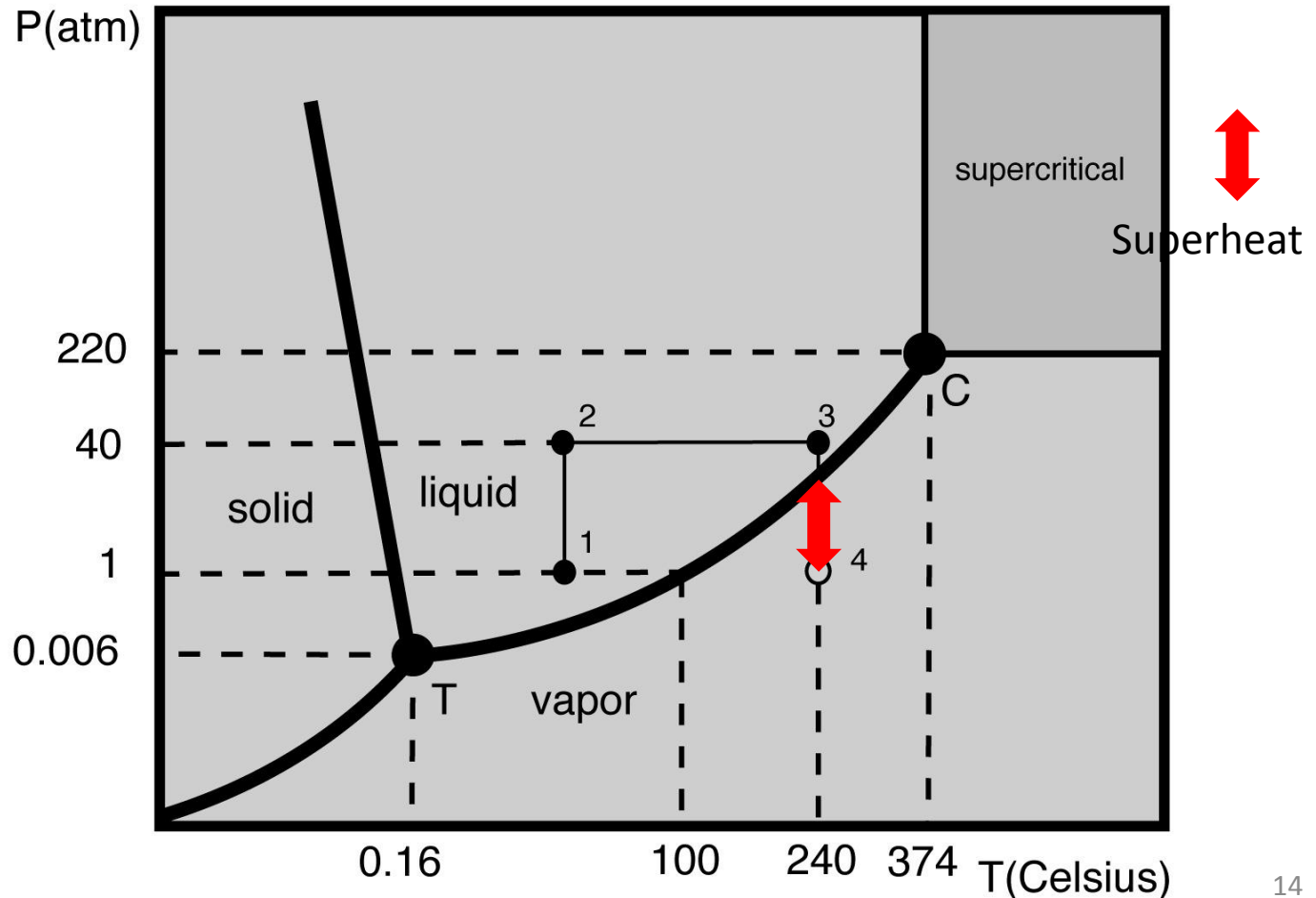


- Monochromatic  $\gamma$  beam at HIGS  $\sim 10^{7-8} \gamma/\text{s}$
- Bremsstrahlung at JLab  $\sim 10^9 \gamma/\text{s}$  (top 250 keV)

# BUBBLE CHAMBER THEORY AND DESIGN

- Donald Glaser, 86, won Nobel for inventing chamber to detect subatomic particles (1960)

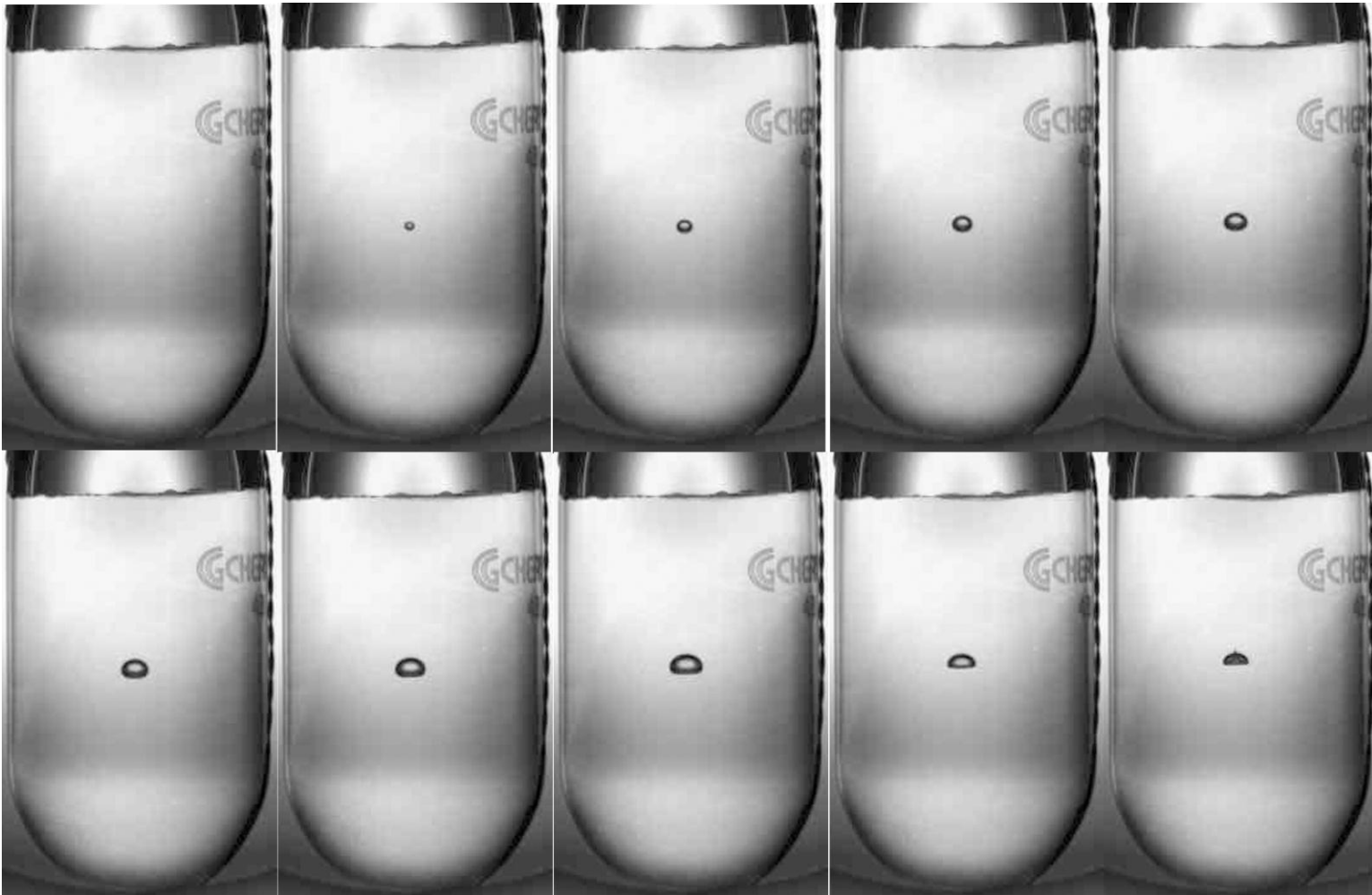
- Dark Matter
- COUPP F
- PICASSO
- SIMPLE P



# BUBBLE GROWTH AND QUENCHING

$^{19}\text{F}(\gamma, \alpha)^{15}\text{N}$  event in  $\text{C}_4\text{F}_{10}$

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



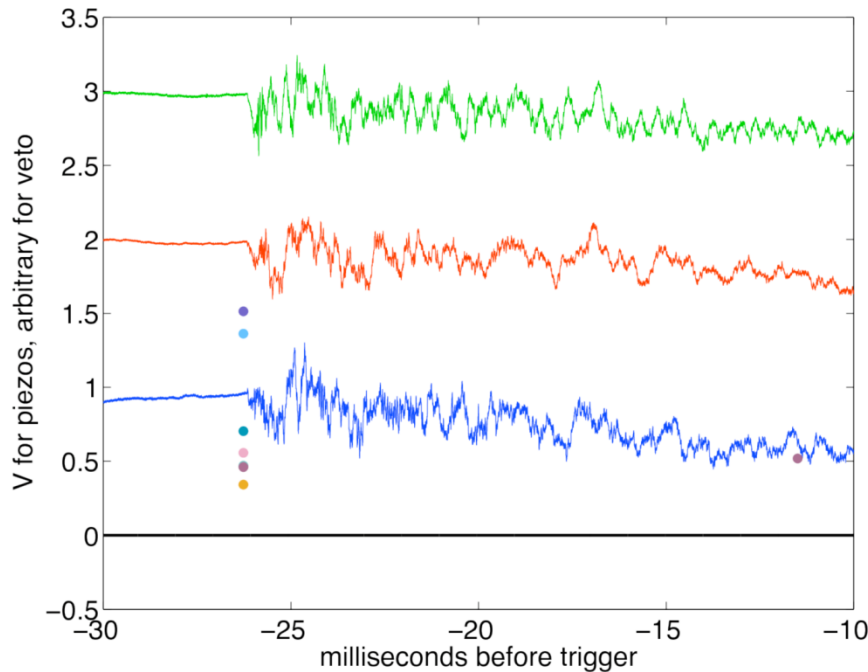


# ACOUSTIC SIGNAL: PARTICLE ID

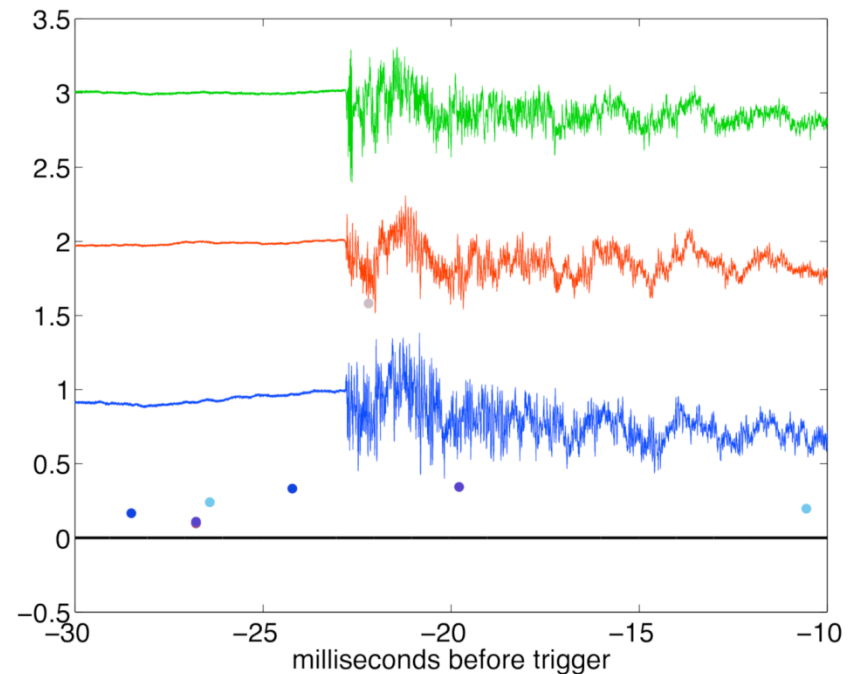
## Acoustic Signatures, time domain

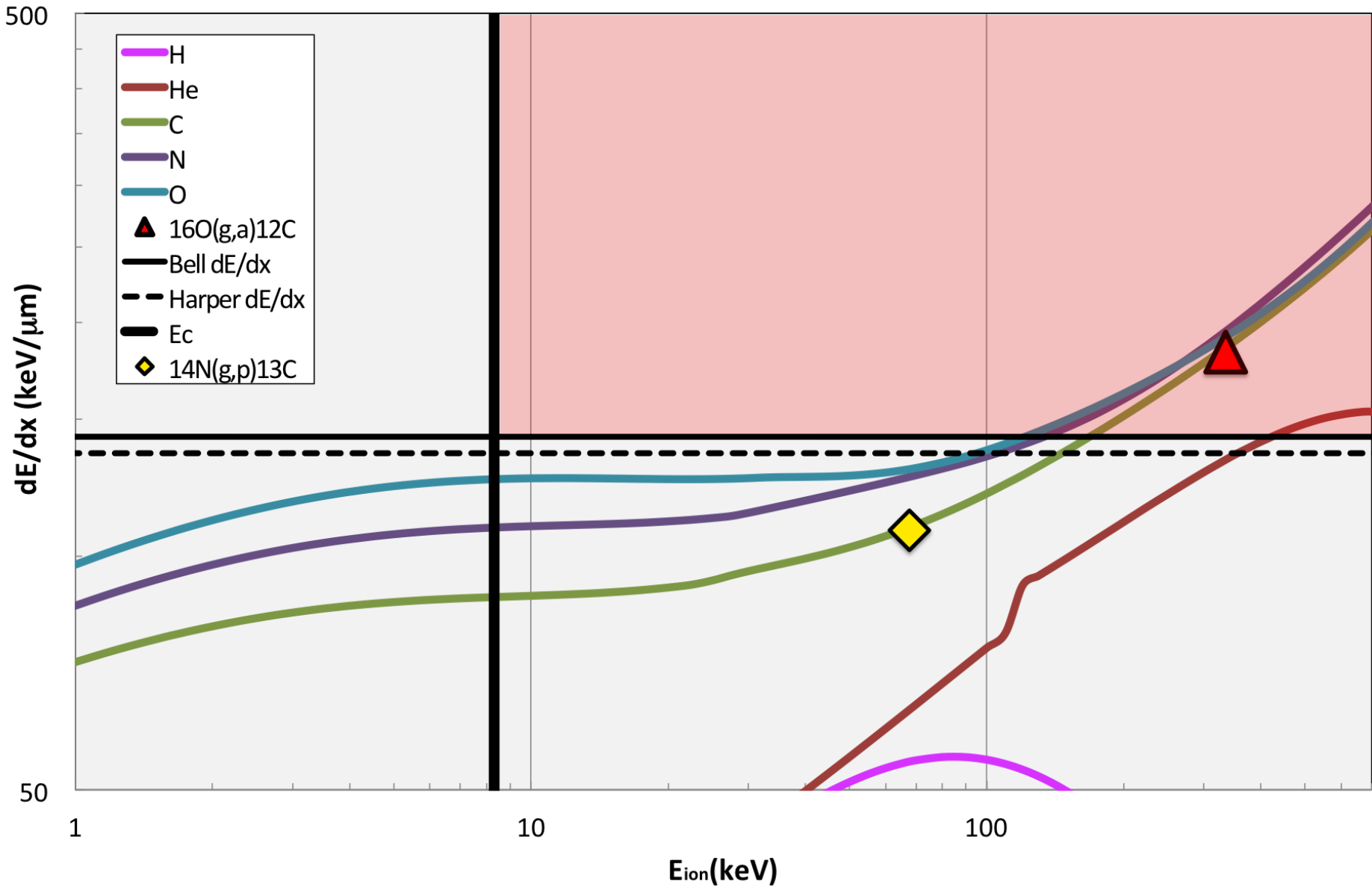
Suppress neutron events by x500 from acoustic signal – FNAL dark matter bubble chambers

### Neutron

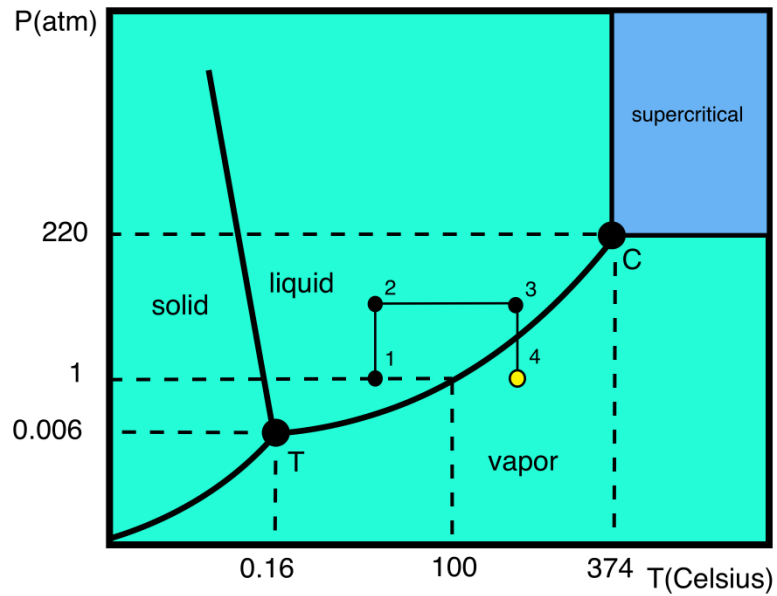


### Alpha

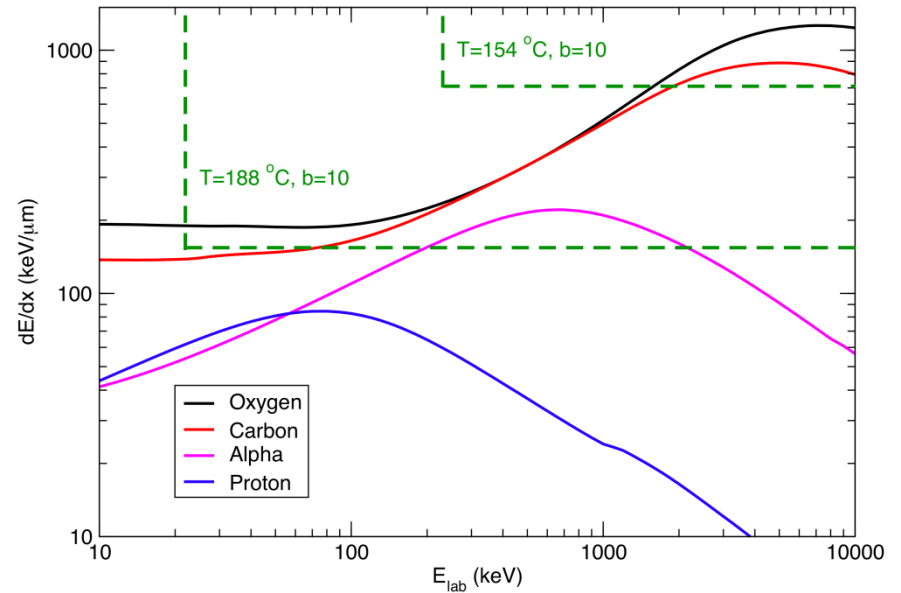




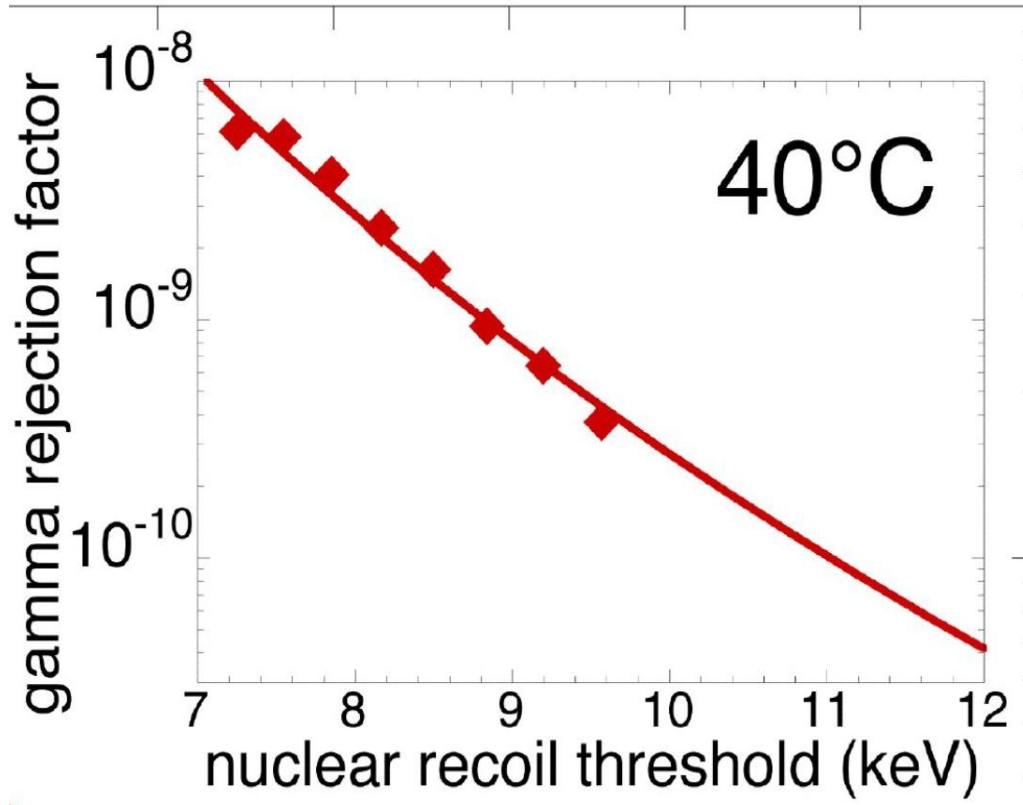
# Bubble chamber basics



Nucleation thresholds (Water)

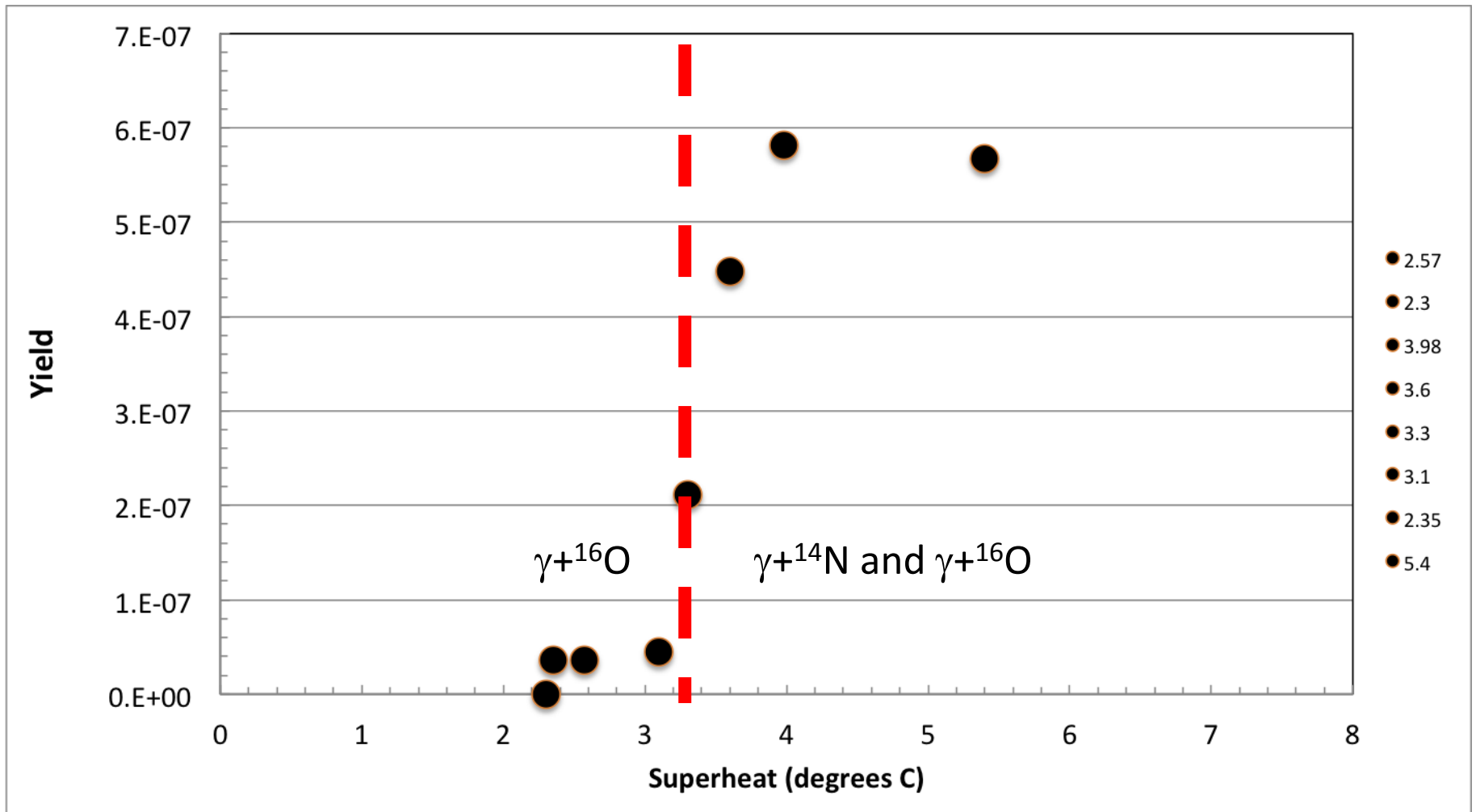


# Gamma suppression



**COUPP exp. FNAL**

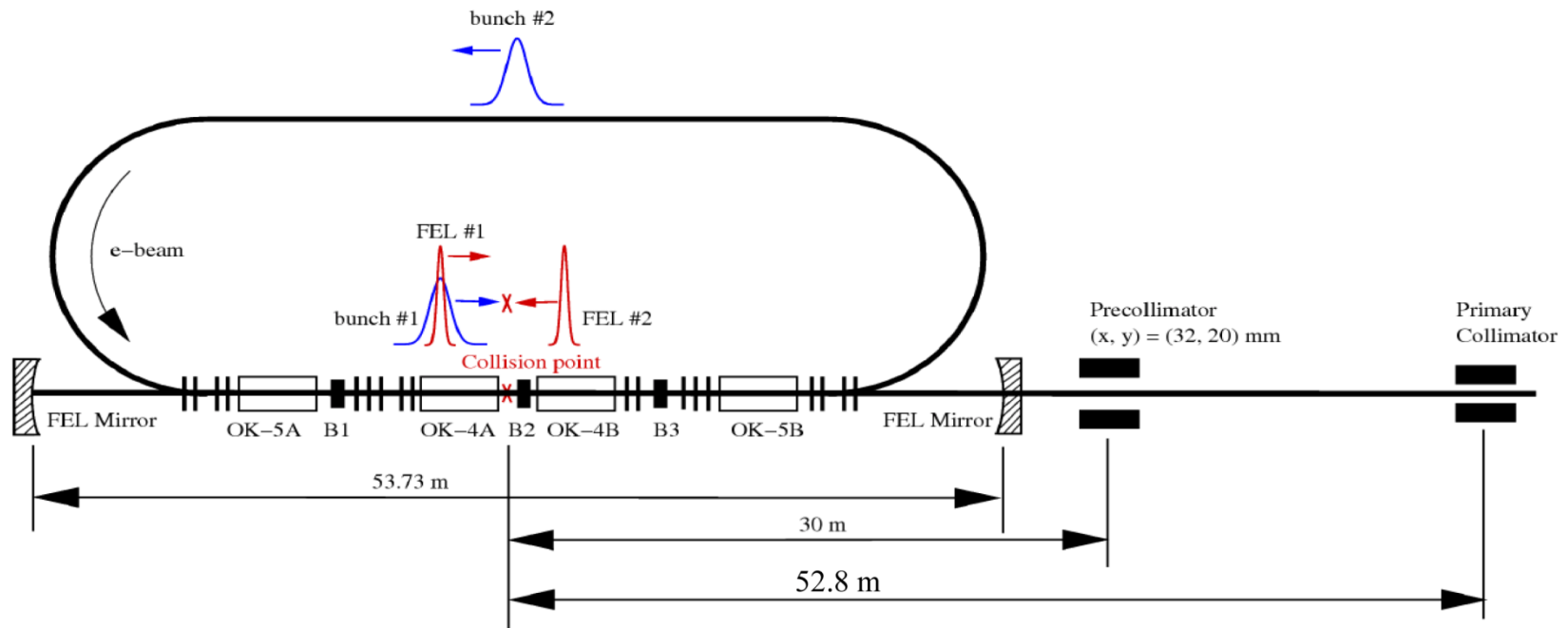
# EFFICIENCY CURVE



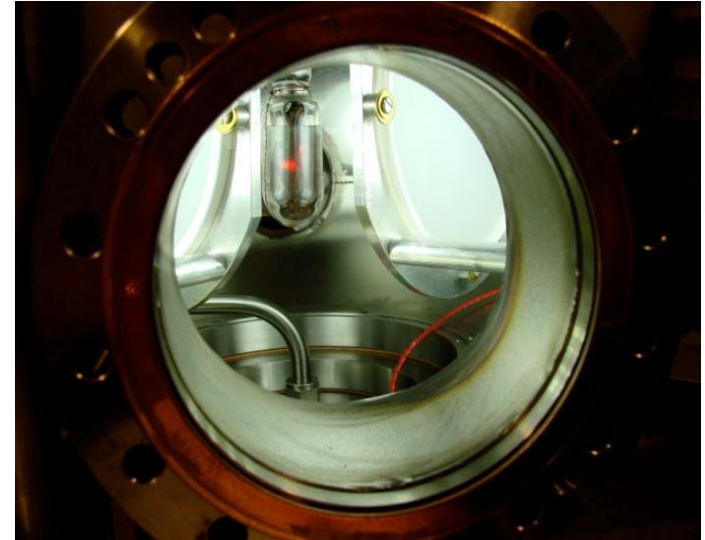
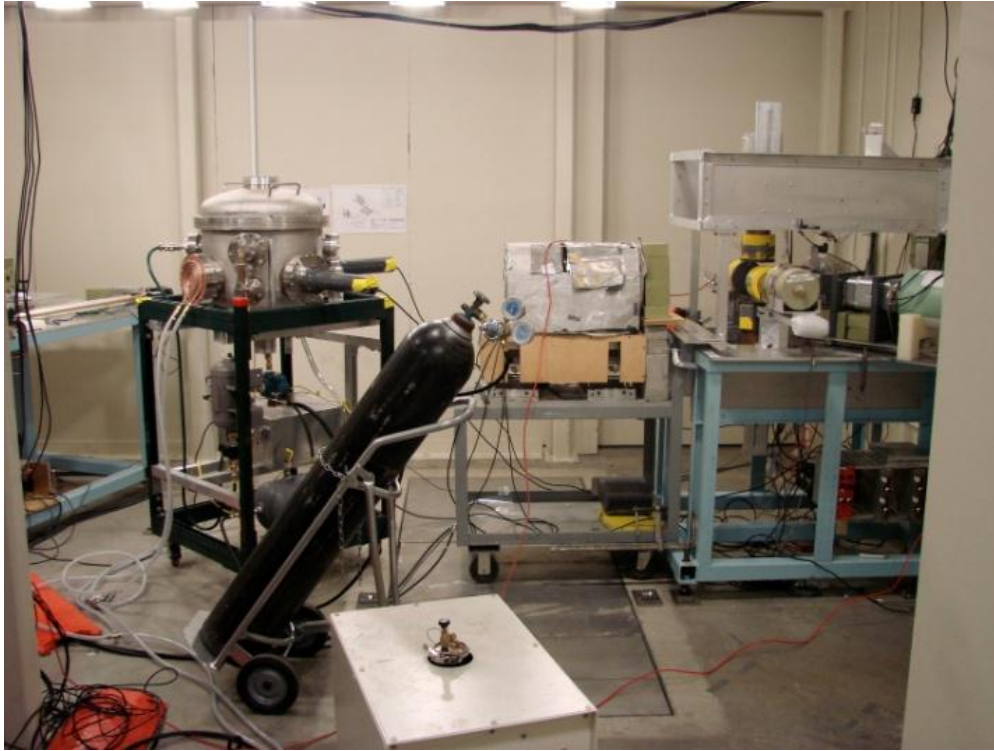
$\text{N}_2\text{O}$  efficiency curve, HIGS April 2013.  $E_\gamma = 9.7$  MeV

# BUBBLE CHAMBER AT HIGS

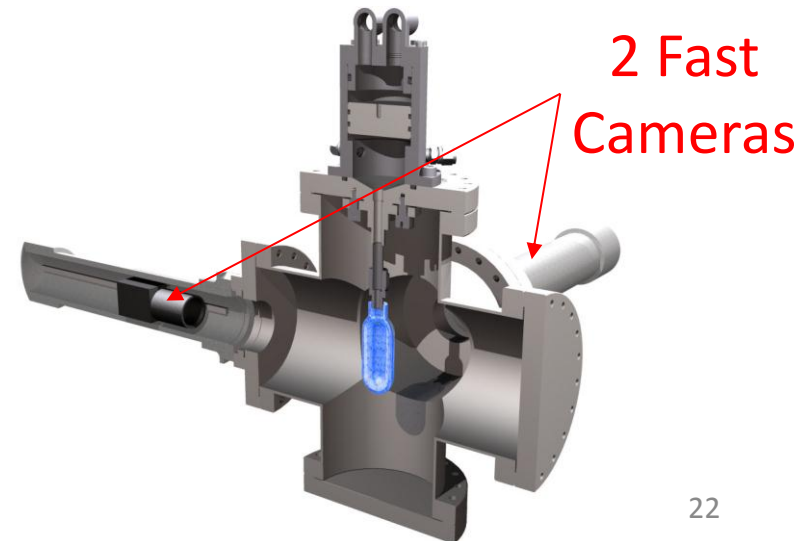
- I. High Intensity Gamma Source (HIGS) at Duke University
- II.  $\gamma$ -rays generated by Compton backscattering of free-electron-laser (FEL) light from high-energy electron beam bunches



# MEASURING $^{19}\text{F}(\gamma, \alpha)^{15}\text{N}$ AT HIGS



$\text{C}_4\text{F}_{10}$  Bubble Chamber  
 $T = 30^\circ\text{C}$   
 $P = 3 \text{ atm}$







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Physics Letters B

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

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

<sup>a</sup> Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA

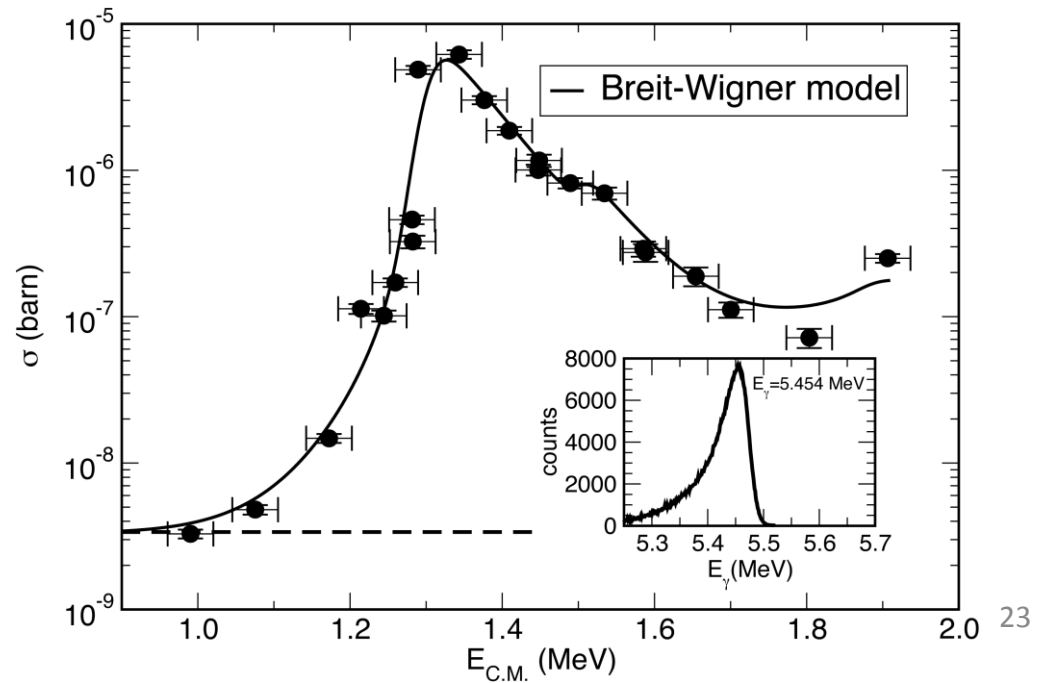
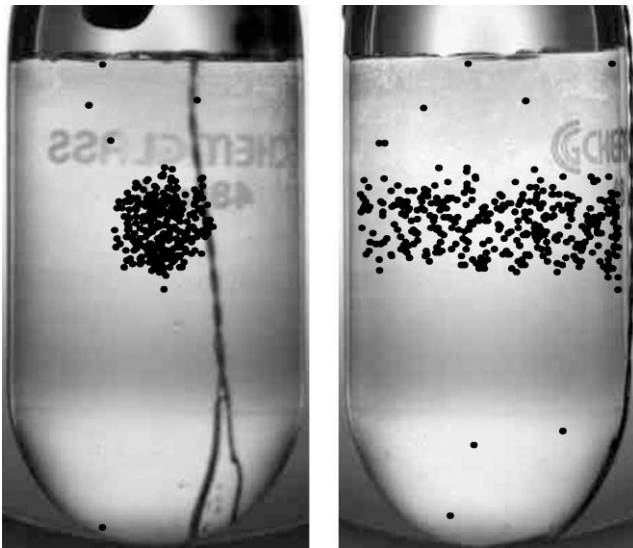
<sup>b</sup> Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA

<sup>c</sup> Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

<sup>d</sup> Department of Physics, University of Chicago, Chicago, IL 60637, USA

<sup>e</sup> Department of Physics, Duke University, Durham, NC 27708, USA

<sup>f</sup> Triangle Universities Nuclear Laboratory, Durham, NC 27708, USA



# BREMSSTRAHLUNG BACKGROUND AT HIGS

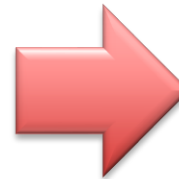
Vacuum:  $2 \times 10^{-10}$  Torr

Residual Gas:  $Z = 10$

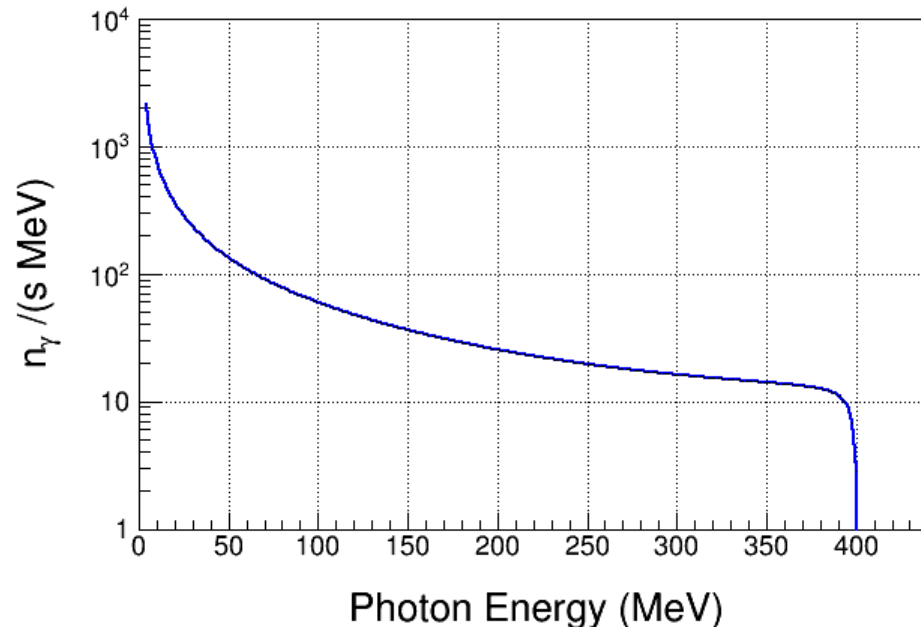
Electron Beam Energy: 400 MeV

Electron Beam Current: 41 mA

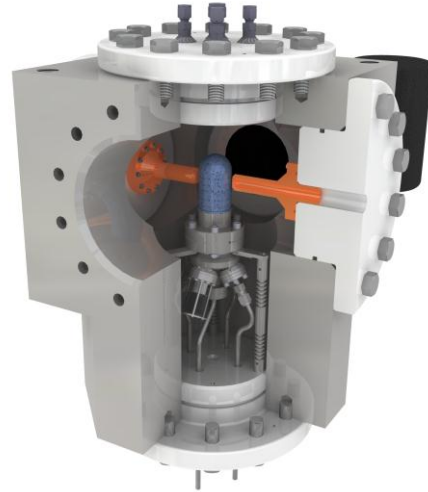
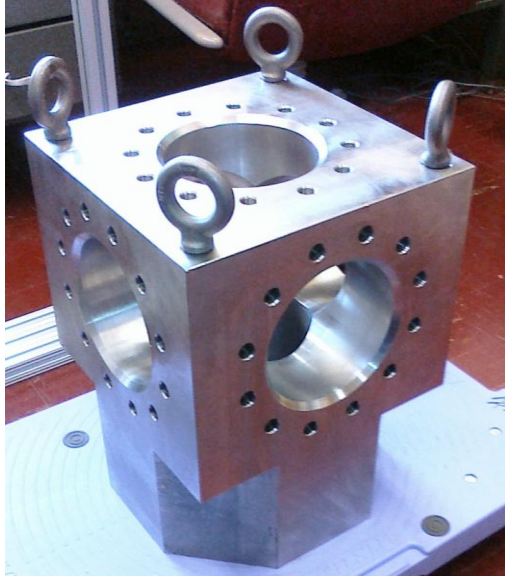
Interaction Length: 35 m



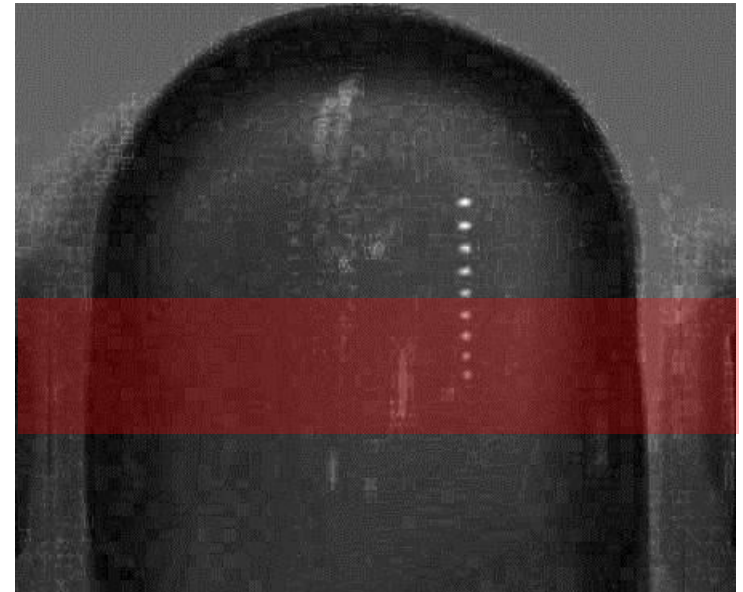
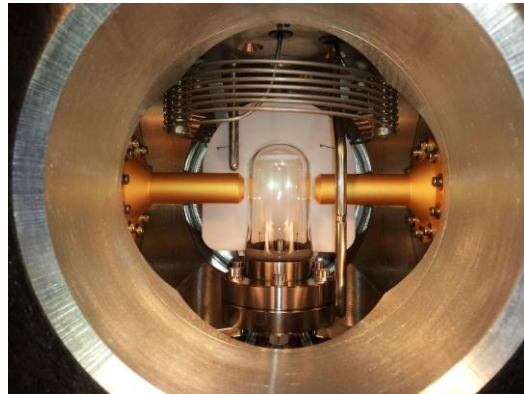
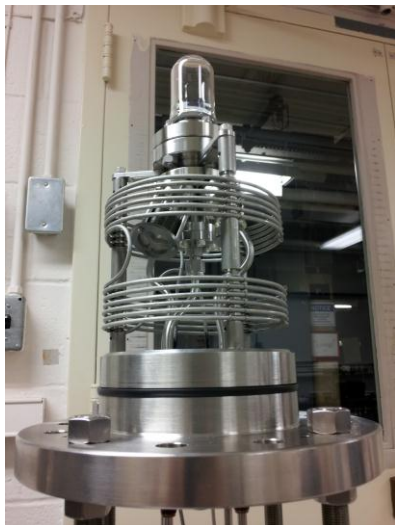
Strong Bremsstrahlung  
Background



# RECENT WORK



N<sub>2</sub>O Bubble Chamber:  
first  $\gamma+O \rightarrow \alpha+C$  bubble  
April 2013



# SUPERHEATED TARGETS

I. List of superheated liquids to be used in the experiment:

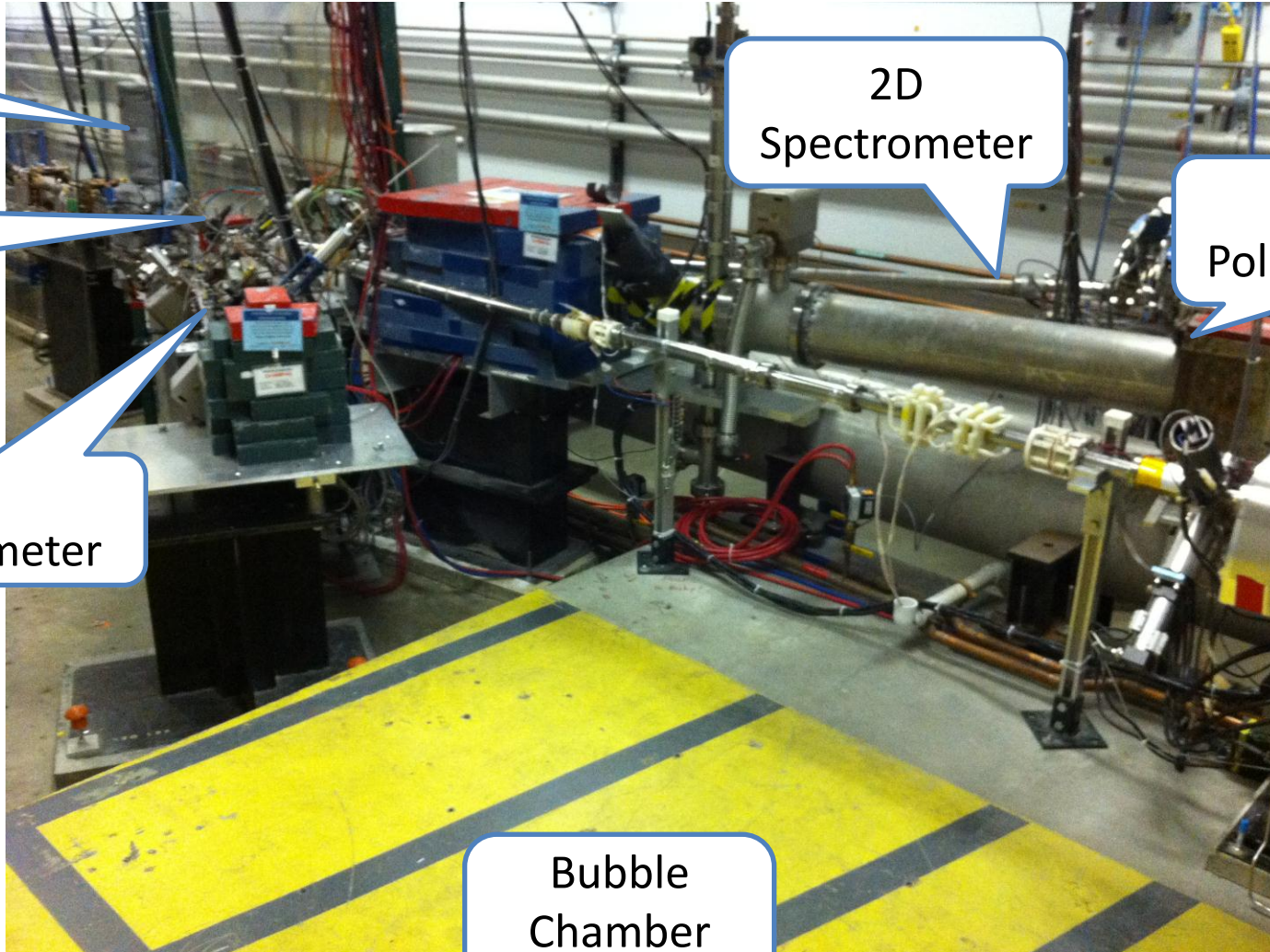
<b>N<sub>2</sub>O Targets</b>	<b><sup>16</sup>O</b>	<b><sup>17</sup>O</b>	<b><sup>18</sup>O</b>
Natural Target	99.757%	0.038%	0.205%
<sup>16</sup> O Target		Depleted > 5,000	Depleted > 5,000
<sup>17</sup> O Target		Enriched > 80%	<1.0%
<sup>18</sup> O Target		<1.0%	Enriched > 80%

II. Readout:

- I. Optical Camera
- II. Acoustic Signal to discriminate between ( $\gamma, \alpha$ ) and ( $\gamma, n$ ) events



# EXPERIMENTAL SETUP



BCM

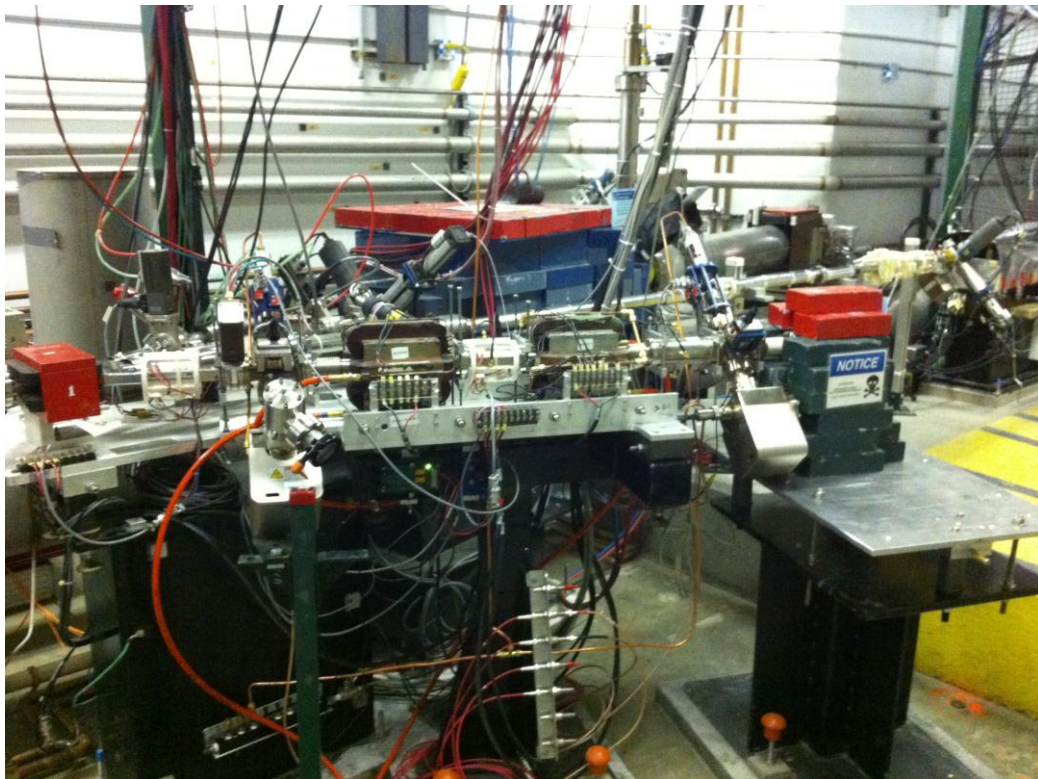
5 MeV  
Dipole

5D  
Spectrometer

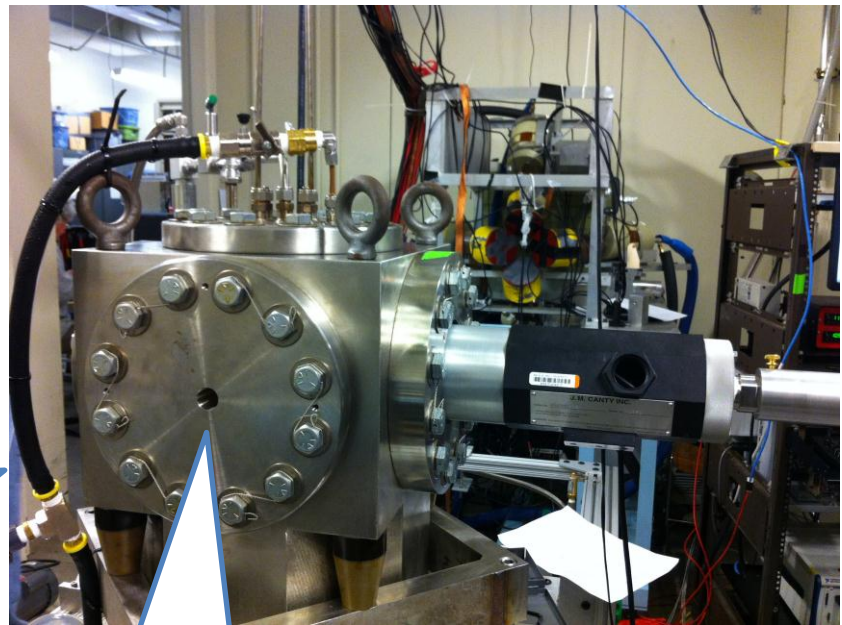
2D  
Spectrometer

Mott  
Polarimeter

Bubble  
Chamber  
location



5D  
Spectrometer



Bubble  
Chamber at  
HIGS

Photon Beam  
Entrance



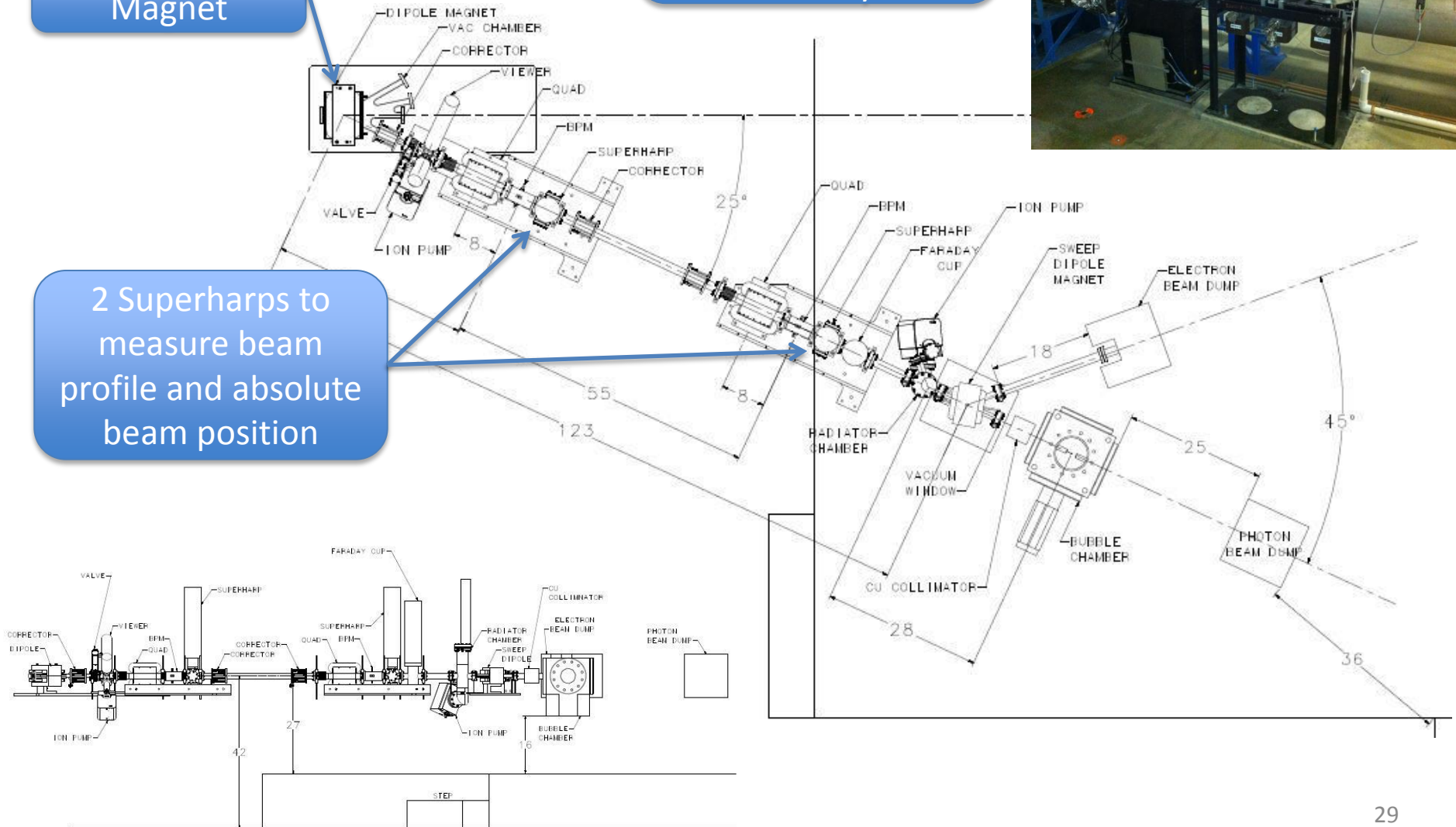
# BEAMLINE

Replace Dipole Magnet

New Fast Valve to protect from vacuum failure in front of ¼ Cryo-unit



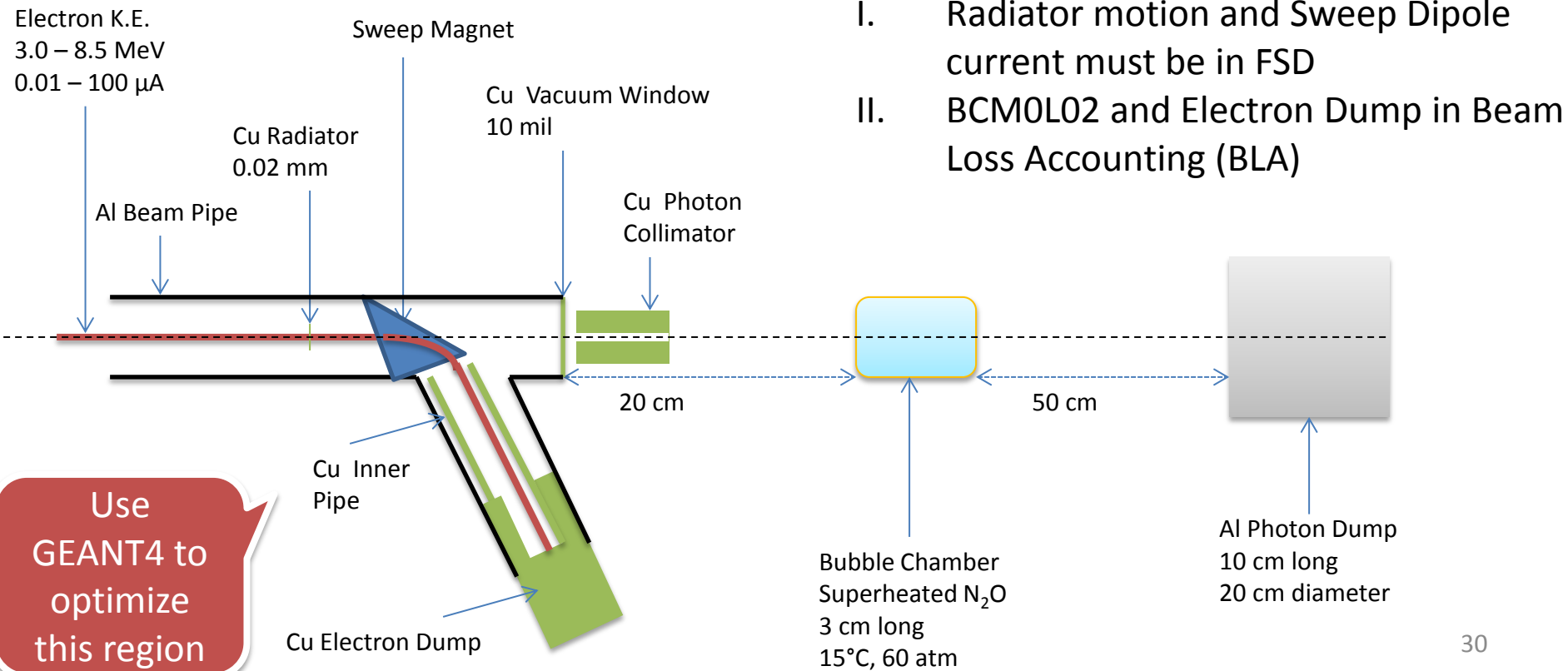
2 Superharps to measure beam profile and absolute beam position





# SCHEMATICS

- Power deposited in radiator (100  $\mu$ A and 8.5 MeV) :
  - I. 0.02 mm: Energy loss = 21 keV, P = 2.1 W
  - II. 0.10 mm: Energy loss = 112 keV, P = 11 W
- Pure Copper and Aluminum (high neutron threshold):
  - I.  $^{63}\text{C}(\gamma, n)$  threshold = 10.86 MeV
  - II.  $^{27}\text{Al}(\gamma, n)$  threshold = 13.06 MeV



# BEAM REQUIREMENTS

## I. Beam Properties at Radiator:

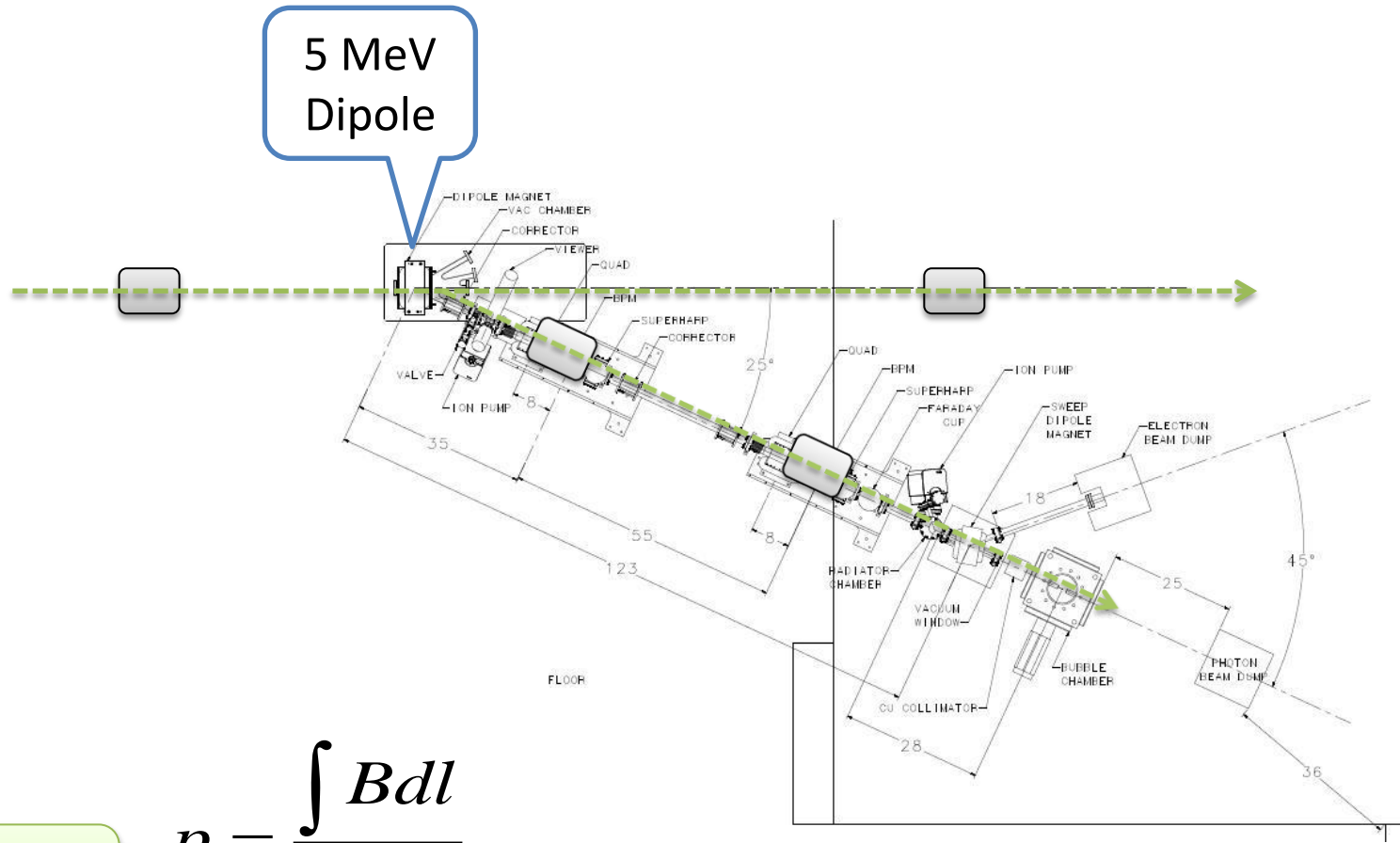
Beam Kinetic Energy, (MeV)	7.9 – 8.5
Beam Current ( $\mu\text{A}$ )	0.01 – 100
Absolute Beam Energy	<0.1%
Relative Beam Energy	<0.02%
Energy Resolution (Spread), $\sigma_T/T$	0.06%
Beam Size, $\sigma_{x,y}$ (mm)	1 – 2

II. PEPPo achieved  $p=8.25$  MeV/c or K.E.=7.75 MeV. Maximum stable  $\frac{1}{4}$ - cryounit cavity gradients achieved: 8.4 MV/m and 6.1 MV/m (7.25 MV/m average). Vacuum in the beam line indicates that field emission and desorbed gas are the most problematic, but improve with processing.

III. Helium process the  $\frac{1}{4}$ -cryounit

# ABSOLUTE BEAM ENERGY

□ BPM



Electron Beam Momentum

$$p = \frac{\int Bdl}{\theta}$$

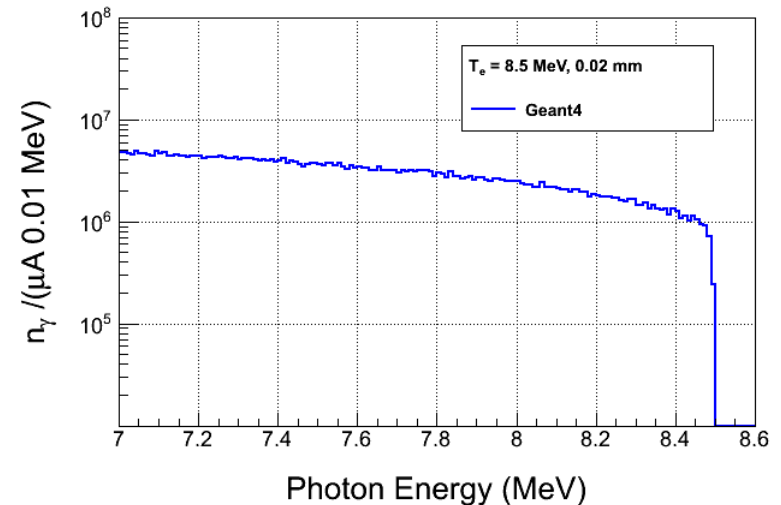
Parameter	Term	Now	Goal
Dipole – linearity	$\delta B/B$	0.25%	0.02%
Dipole – spatial	$\delta BL/BL$	0.10%	0.02%
Dipole – reproduce	$\delta B/B$	0.10%	0.02%
Dipole – power supply	$\delta I/I$	0.20%	0.02%
Position – surveys	$\delta \theta/\theta$	0.01%	0.01%
Position – BPM calibration	$\delta \theta/\theta$	0.05%	0.05%
Stray magnetic field	$\delta \theta/\theta$	0.05%	0.05%
<b>TOTAL</b>	<b><math>\delta P/P</math></b>	<b>0.36%</b>	<b>&lt;0.10%</b>

## Goal:

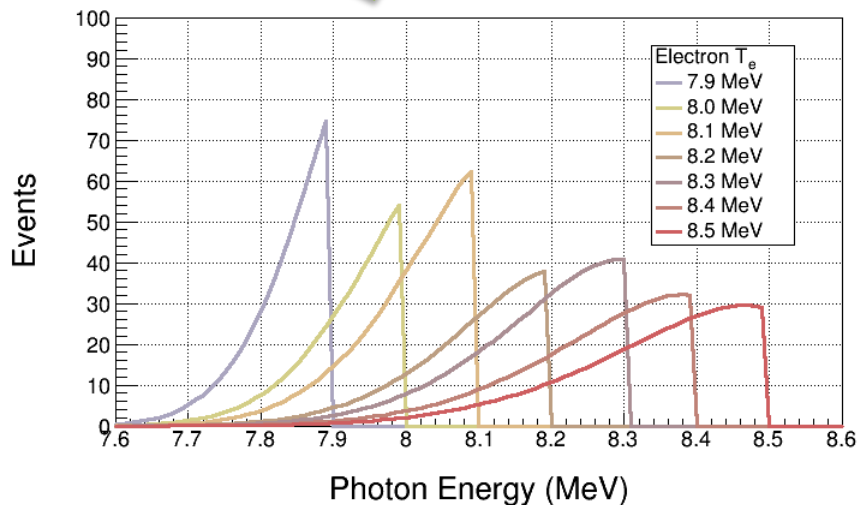
- I. Jay Benesch designed and now fabricating higher quality dipole (more uniformity, higher field)
- II. New Hall Probe: 0.01% accuracy, resolution to 2 ppm, and a temperature stability of 10 ppm/°C
- III. Relative beam energy error: <0.02%

# BREMSSTRAHLUNG BEAM

- Use both GEANT4 and FLUKA to calculate Bremsstrahlung spectra
- Monte Carlo simulation of bremsstrahlung at radiotherapy energies is well studied, accuracy: 5%



Bremsstrahlung  
Peaks



- $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$  is ideal case for Bremsstrahlung beam and Penfold – Leiss Unfolding :
- Very steep; only photons near endpoint contribute to yield
  - No-structure (resonances)

# GEANT4 SIMULATION

- Both GEANT4 and FLUKA use models that calculate wrong photo–nuclear cross sections. Both do not allow for user’s cross sections.
  - I. Use GEANT4 and FLUKA to produce the photon spectrum impinging on the super heated liquid.
  - II. Fold the above photon spectrum with our cross sections in stand-alone codes.
- Use GEANT4 to design Radiator/Collimator/Dump
- Geometry in GEANT4:

# PENFOLD-LEISS CROSS SECTION UNFOLDING

- Measure Yields at:  $E = E_1, E_2, \dots, E_n$  where,

$$E_i - E_{i-1} = \Delta, i = 2, n$$

$$Y(E_i) = \int_{th}^{E_i} n_\gamma(E_i, k) \sigma(k) dk \approx \sum_{j=1}^i N_\gamma(E_i, \Delta, E_j) \sigma(E_j)$$

- The solution can be written in two forms:

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

- Or, Matrix form:

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} = \begin{bmatrix} N_{\gamma,11} & 0 & \cdots & 0 \\ N_{\gamma,21} & N_{\gamma,22} & \cdots & 0 \\ \vdots & \ddots & \ddots & 0 \\ N_{\gamma,n1} & N_{\gamma,n2} & \cdots & N_{\gamma,nn} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \vdots \\ \sigma_n \end{bmatrix}$$

$$[Y] = [N] \bullet [\sigma]$$

$$[\sigma] = [N]^{-1} \bullet [Y]$$



# STATISTICAL ERROR PROPAGATION

- Note:  $\frac{dy_i}{y_i} = \frac{1}{\sqrt{y_i}}$        $\frac{dN_{ij}}{N_{ij}} = \frac{1}{\sqrt{N_{ij}}} \approx 0$

$$dy_i = \sqrt{y_i} \qquad dy_i = \sqrt{y_i + 2y_i^{bg}}$$

In case of  
background  
Subtraction

- With:

$$[B] = [N]^{-1}$$

$$[\sigma] = [B] \bullet [Y]$$

- Then:

$$[d\sigma^2] = [B] \bullet [dY^2] \bullet [B]^T$$

- Where:

$$[dY^2] = \begin{bmatrix} y_1 & 0 & \cdots & 0 \\ 0 & y_2 & \cdots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & y_n \end{bmatrix}$$

$$\begin{aligned} \text{var}(y_i, y_i) &= y_i \\ \text{cov}(y_i, y_j) &= 0 \end{aligned}$$

$$[d\sigma^2] = \begin{bmatrix} d\sigma_1^2 & \text{cov}(\sigma_1, \sigma_2) & \cdots & \text{cov}(\sigma_1, \sigma_n) \\ \text{cov}(\sigma_2, \sigma_1) & d\sigma_2^2 & \cdots & \text{cov}(\sigma_2, \sigma_n) \\ \vdots & \ddots & \ddots & \vdots \\ \text{cov}(\sigma_n, \sigma_1) & \text{cov}(\sigma_n, \sigma_2) & \cdots & d\sigma_n^2 \end{bmatrix}$$

Although,

$$\begin{aligned} \text{cov}(y_i, y_j) &= 0, \\ \text{cov}(\sigma_i, \sigma_j) &\neq 0 \end{aligned}$$

$$(d\sigma_i)^2 = \frac{1}{N_{ii}^2} \left[ dy_i^2 + \sum_{j=1}^{i-1} (N_{ij} d\sigma_j)^2 + \sum_{k=1}^{i-1} \sum_{l=1}^{i-1} N_{ik} \text{cov}(\sigma_k, \sigma_l) N_{il} \right]$$

For mono-  
chromatic  
beam

$$\left( \frac{d\sigma_i}{\sigma_i} \right)^2 = \left( \frac{dy_i}{y_i} \right)^2 = \frac{1}{y_i}$$

# RESULTS

- I. Radiator Thickness = 0.02 mm
- II. Bubble Chamber Thickness = 3.0 cm. Number of  $^{16}\text{O}$  nuclei =  $3.474e22 / \text{cm}^2$
- III. Background subtraction of  $^{18}\text{O}(\gamma, \alpha)^{14}\text{C}$  .  $^{17}\text{O}(\gamma, n)^{16}\text{O}$ : Still to do

$$[N] = \begin{bmatrix} 3.267e14 & 0 & 0 & 0 & 0 & 0 & 0 \\ 9.782e13 & 6.439e13 & 0 & 0 & 0 & 0 & 0 \\ 5.013e13 & 3.858e13 & 2.539e13 & 0 & 0 & 0 & 0 \\ 1.494e13 & 1.236e13 & 9.514e12 & 6.258e12 & 0 & 0 & 0 \\ 8.540e12 & 7.369e12 & 6.097e12 & 4.692e12 & 3.086e12 & 0 & 0 \\ 3.801e12 & 3.370e12 & 2.908e12 & 2.406e12 & 1.852e12 & 1.217e12 & 0 \\ 2.075e12 & 1.875e12 & 1.663e12 & 1.435e12 & 1.187e12 & 9.137e11 & 6.004e11 \end{bmatrix}$$

Electron Beam K. E.	Beam Current ( $\mu\text{A}$ )	Time (hour)	$y_i$	$dy_i$ (no bg)	$dy_i/y_i$ (no bg, %)	$dy_i$ (with bg)	$dy_i/y_i$ (with bg, %)
7.9	100	100	545	23	4.2	134	24.6
8.0	100	20	581	24	4.1	77	13.3
8.1	80	10	852	29	3.4	60	7.0
8.2	20	10	634	25	3.9	40	6.3
8.3	10	10	812	28	3.4	39	4.8
8.4	4	10	746	27	3.6	36	4.8
8.5	2	10	763	28	3.7	32	4.2

# SYSTEMATIC ERROR PROPAGATION

- For absolute beam energy uncertainty of  $\delta E$  ( $= 0.1\%$ ) and zero relative beam energy uncertainty:

$$\frac{dy_i}{y_i} = \frac{y_i(E_i + \delta E) - y_i(E_i)}{y_i(E_i)}$$

$$\frac{dN_{ij}}{N_{ij}} = \frac{N_{ij}(E_i + \delta E) - N_{ij}(E_i)}{N_{ij}(E_i)}$$

$$E_0 = 7.8 + \delta E$$

$$E_i = E_0 + i\Delta$$

$E_i$ (MeV)	$dy_i/y_i$ (%)	$d\sigma_i/\sigma_i$ (%)
7.9	12.5	12.6
8.0	10.8	10.5
8.1	9.3	9.1
8.2	8.0	7.1
8.3	7.0	6.3
8.4	6.3	5.8
8.5	5.6	5.2

This is the cross section dependence on energy

- Accounted for  $dN_{ij}$  due to energy error when calculating  $dy_i$

$$\approx \frac{\delta E}{i\Delta}$$

$$\left[ \frac{dN_{ij}}{N_{ij}} \right] = \begin{bmatrix} 0.100 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.058 & 0.050 & 0 & 0 & 0 & 0 & 0 \\ 0.041 & 0.039 & 0.033 & 0 & 0 & 0 & 0 \\ 0.031 & 0.031 & 0.029 & 0.025 & 0 & 0 & 0 \\ 0.025 & 0.025 & 0.025 & 0.023 & 0.020 & 0 & 0 \\ 0.021 & 0.021 & 0.021 & 0.021 & 0.020 & 0.017 & 0 \\ 0.018 & 0.018 & 0.018 & 0.018 & 0.018 & 0.017 & 0.022 \end{bmatrix}$$

- With:

$$[B] = [N]^{-1}$$

$$[\sigma] = [B] \bullet [Y]$$

- Then:

$$[d\sigma^2] = [B] \bullet \left( [dY^2] + [dN^2] \bullet [\sigma^2] \right) \bullet [B]^T$$

- Where:

Note: Correlation Coefficient = 1

$$[dY^2] = \begin{bmatrix} (dy_1)^2 & dy_1 dy_2 & \cdots & dy_1 dy_n \\ dy_2 dy_1 & (dy_2)^2 & \cdots & dy_n dy_n \\ \vdots & \ddots & \ddots & \vdots \\ dy_n dy_1 & dy_n dy_2 & \cdots & (dy_n)^2 \end{bmatrix}$$

$$\begin{aligned} \text{var}(y_i, y_i) &= (dy_i)^2 \\ \text{cov}(y_i, y_j) &= \rho_{ij} dy_i dy_j \end{aligned}$$

No point-to-point systematic

$$[d\sigma^2] = \begin{bmatrix} d\sigma_1^2 & \text{cov}(\sigma_1, \sigma_2) & \cdots & \text{cov}(\sigma_1, \sigma_n) \\ \text{cov}(\sigma_2, \sigma_1) & d\sigma_2^2 & \cdots & \text{cov}(\sigma_2, \sigma_n) \\ \vdots & \ddots & \ddots & \vdots \\ \text{cov}(\sigma_n, \sigma_1) & \text{cov}(\sigma_n, \sigma_2) & \cdots & d\sigma_n^2 \end{bmatrix}$$

$$[dN^2] = \begin{bmatrix} (dN_{11})^2 & 0 & \cdots & 0 \\ (dN_{21})^2 & (dN_{22})^2 & \cdots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ (dN_{n1})^2 & (dN_{n2})^2 & \cdots & (dN_{nn})^2 \end{bmatrix}$$

$$[\sigma^2] = \begin{bmatrix} \sigma_1^2 & 0 & \cdots & 0 \\ 0 & \sigma_2^2 & \cdots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & \sigma_n^2 \end{bmatrix}$$



# SYSTEMATIC ERROR PROPAGATION

$$\begin{aligned} (d\sigma_i)^2 \cong & \frac{1}{N_{ii}^2} \left[ dy_i^2 - 2dy_i \sum_{j=1}^{i-1} N_{ij} d\sigma_j \right. \\ & + \sum_{j=1}^{i-1} (N_{ij} d\sigma_j)^2 + \sum_{k=1}^{i-1} \sum_{l=1}^{i-1} N_{ik} \text{cov}(\sigma_k, \sigma_l) N_{il} \\ & \left. + \sum_{j=1}^{i-1} (dN_{ij} \sigma_j)^2 + (dN_{ii} \sigma_i)^2 \right] \end{aligned}$$

No point-to-point systematic

$\text{cov}(y_i, y_j) \neq 0,$   
 $\text{cov}(\sigma_i, \sigma_j) \neq 0$

# OTHER SYSTEMATIC ERRORS

Beam Current, $\delta I/I$	3%
Photon Flux, $\delta\phi/\phi$	5%
Radiator Thickness, $\delta R/R$	3%
Bubble Chamber Thickness, $\delta T/T$	3%
Bubble Chamber Efficiency, $\varepsilon$	5%

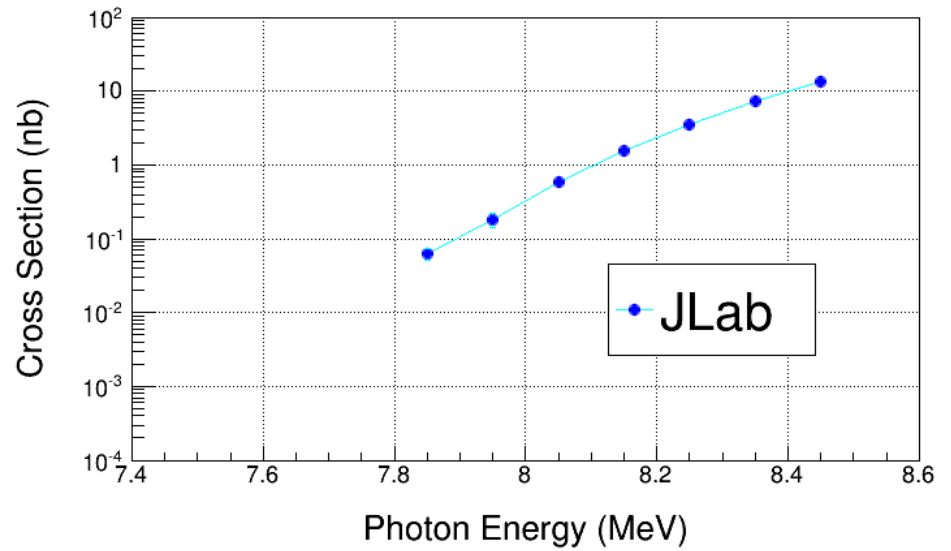
Simulation

- Then:

$$(dy_i)^2 = (dy_i(\delta E))^2 + \left[ \left( \frac{\delta I}{I} \right)^2 + \left( \frac{\delta R}{R} \right)^2 + \left( \frac{\delta T}{T} \right)^2 + \varepsilon^2 \right] y_i^2$$

$$(dN_{ij})^2 = \left( \frac{\delta\phi}{\phi} \right)^2 N_{ij}^2$$

Electron Beam K. E.	Cross Section (nb)	Stat Error (no bg, %)	Stat Error (with bg, %)
7.9	0.046	4.4	24.5
8.0	0.185	6.0	20.7
8.1	0.58	6.3	14.7
8.2	1.53	8.2	13.8
8.3	3.49	9.1	13.3
8.4	7.2	10.6	13.8
8.5	13.6	12.2	14.8



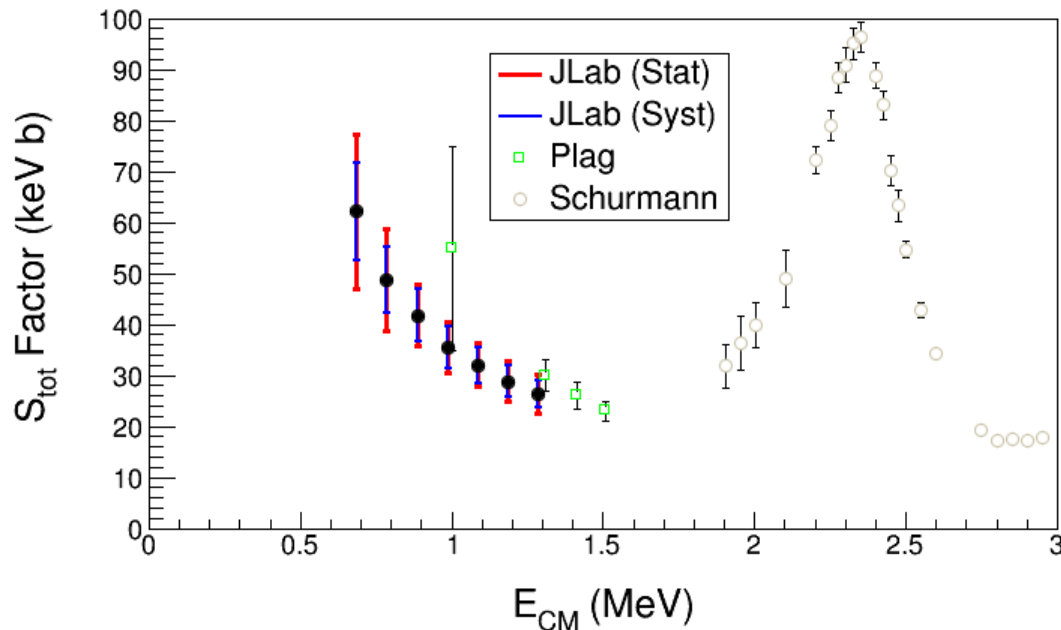
Electron Beam K. E.	Cross Section (nb)	Sys Error (Energy, %)	Sys Error (Total, %)
7.9	0.046	12.5	15.3
8.0	0.185	10.2	13.5
8.1	0.58	8.3	12.2
8.2	1.53	7.0	11.4
8.3	3.49	6.0	10.7
8.4	7.2	5.3	10.5
8.5	13.6	4.7	10.1

**Note:** Relative systematic errors do not get amplified in PL Unfolding

# THE $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ S-Factor

- Statistical Error: dominated by background subtraction from  $^{18}\text{O}(\gamma,\alpha)^{14}\text{C}$  (depletion = 5,000)

Electron Beam K. E.	Gamma Energy (MeV)	$E_{CM}$ (MeV)	Cross Section (nb)	$S_{tot}$ Factor (keV b)	Stat Error (%)	Sys Error (Total, %)
7.9	7.85	0.69	0.046	62.2	24.5	15.3
8.0	7.95	0.79	0.185	48.7	20.7	13.5
8.1	8.05	0.89	0.58	41.8	14.7	12.2
8.2	8.15	0.99	1.53	35.5	13.8	11.4
8.3	8.25	1.09	3.49	32.0	13.3	10.7
8.4	8.35	1.19	7.2	28.8	13.8	10.5
8.5	8.45	1.29	13.6	26.3	14.8	10.1



Bubble Chamber experiment measures total S-Factor,  $S_{E1} + S_{E2}$

# BACKGROUNDS

## I. Background from oxygen isotopes and nitrogen in N<sub>2</sub>O:

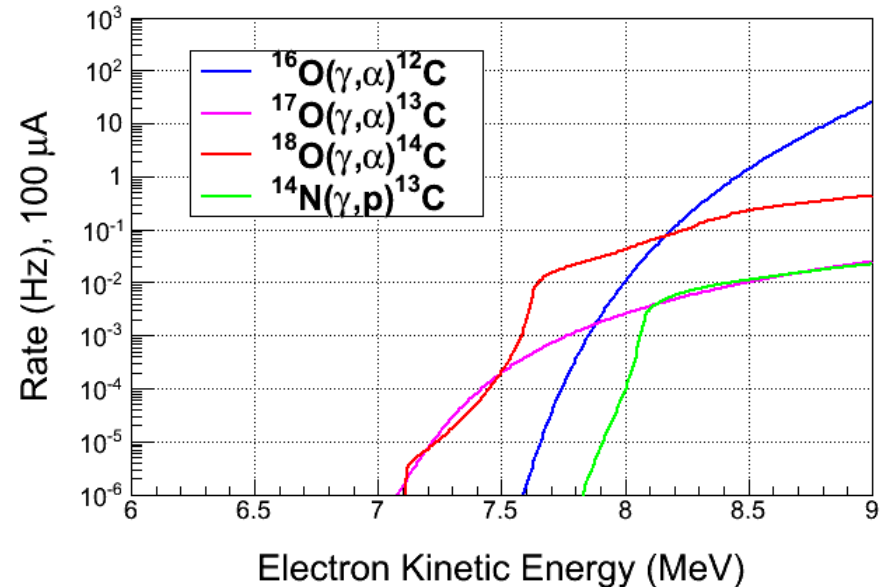
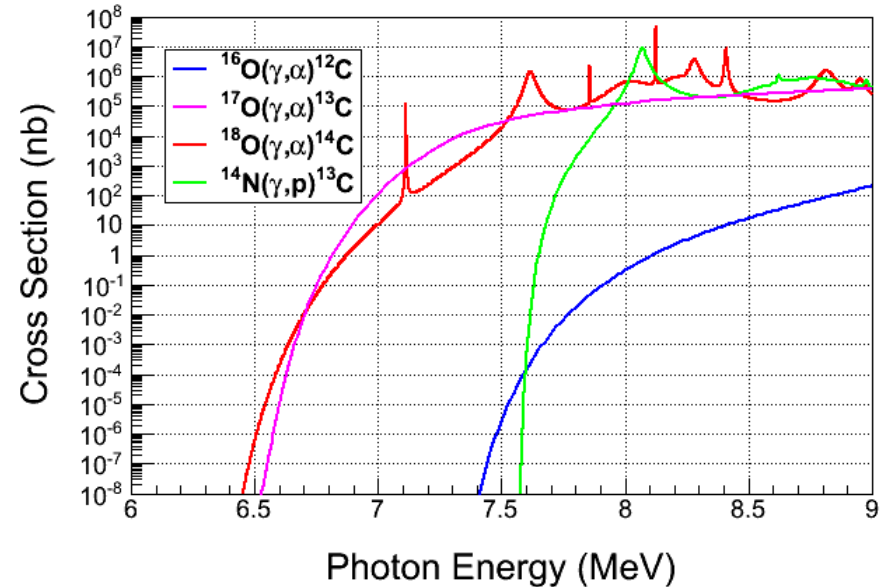
- $^{18}\text{O}(\gamma, \alpha)^{14}\text{C}$
- $^{17}\text{O}(\gamma, \alpha)^{13}\text{C}$
- $^{14}\text{N}(\gamma, p)^{13}\text{C}$

### ➤ Natural Abundance:

- I.  $^{17}\text{O}$ : 0.038%
- II.  $^{18}\text{O}$ : 0.205%

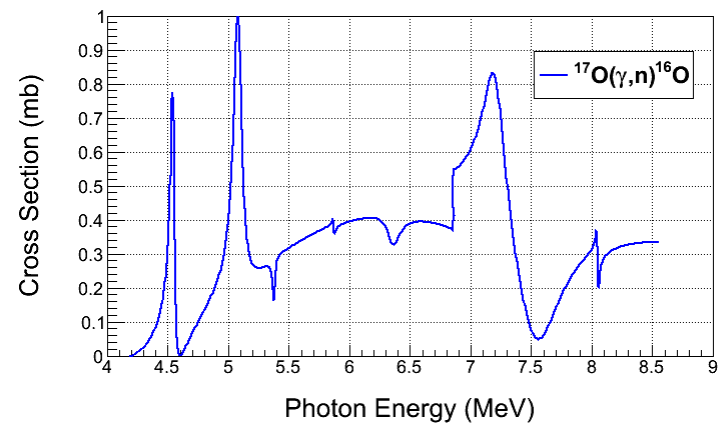
### ➤ Expected Rates:

- I.  $^{17}\text{O}(\gamma, \alpha)^{13}\text{C}$ , depletion=5,000
- II.  $^{18}\text{O}(\gamma, \alpha)^{14}\text{C}$ , depletion=5,000
- III.  $^{14}\text{N}(\gamma, p)^{13}\text{C}$ , detection eff.=  $10^{-8}$



## II. Background from:

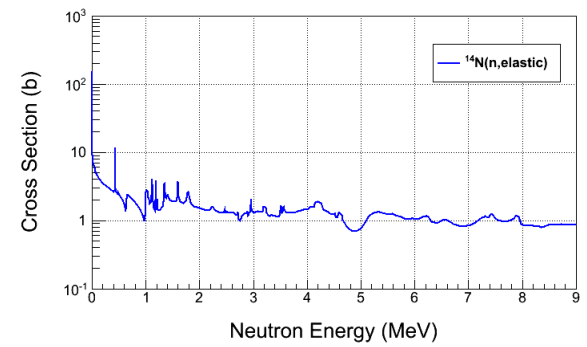
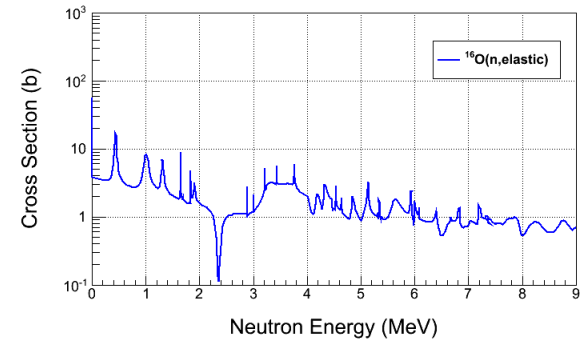
- $^{17}\text{O}(\gamma,n)^{16}\text{O}$  and secondary (n,n) neutron-nucleus elastic scattering



## III. Cosmic-ray background:

- $\mu^\pm$ -nuclear
- neutron-nuclear elastic scattering

➤ Reject neutron background using the acoustic signal (500 factor)





# ION ENERGY DISTRIBUTIONS

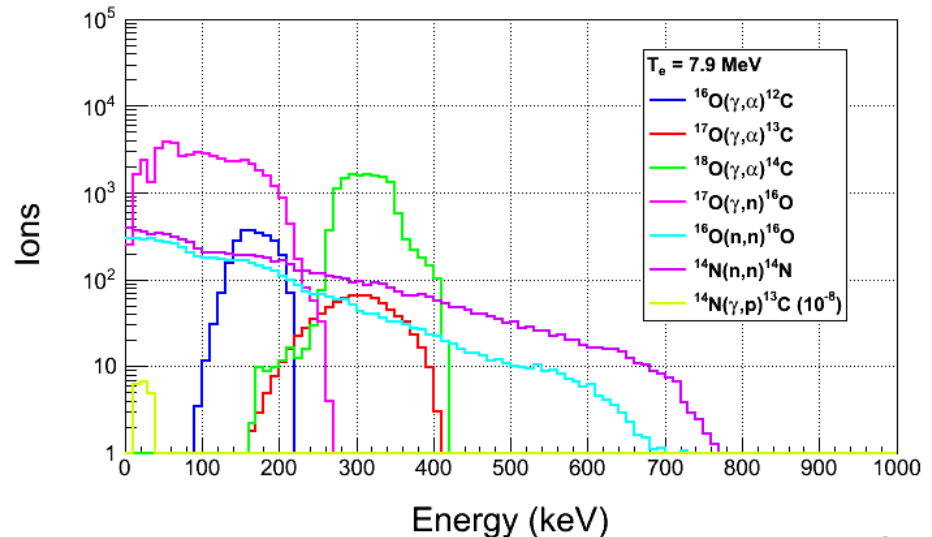
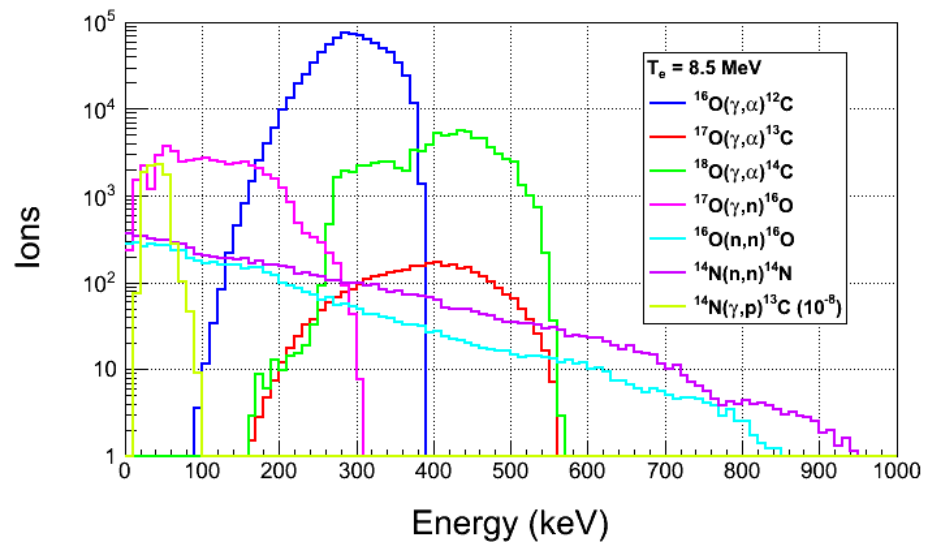
➤ Suppress background  
with Bubble Chamber threshold

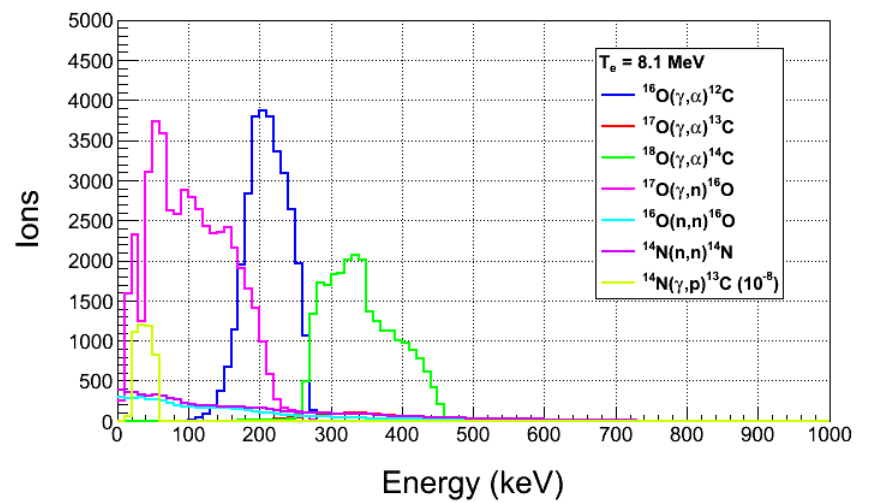
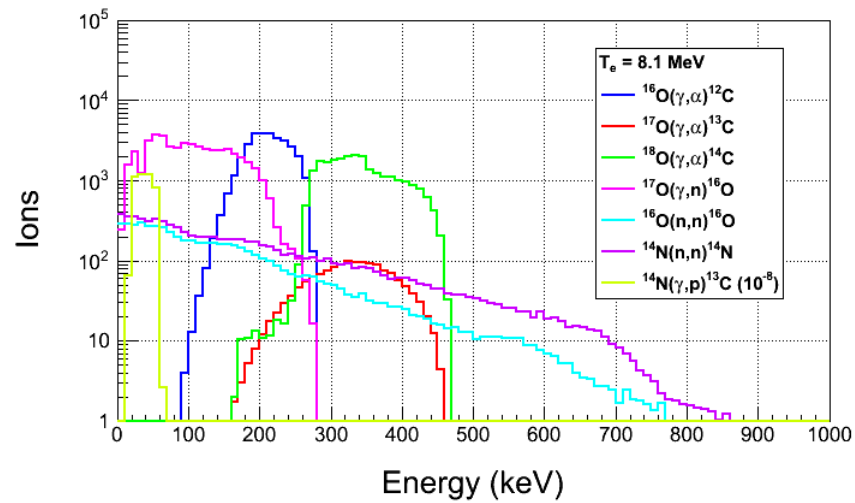
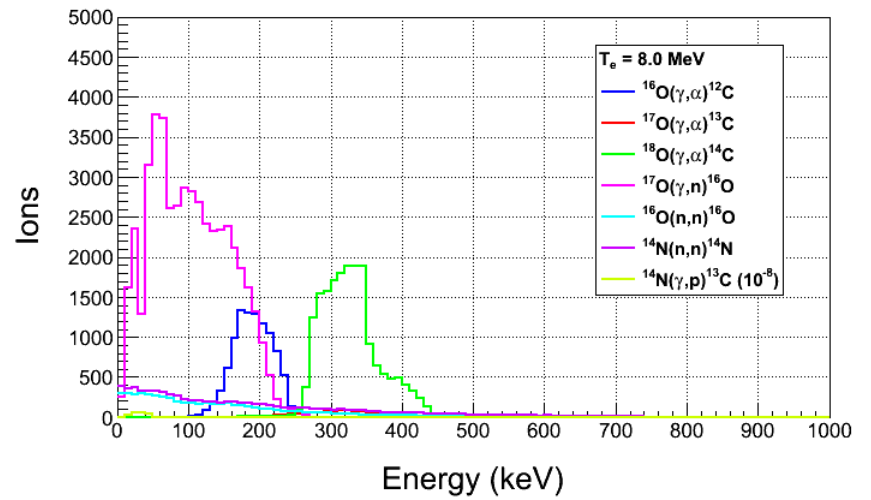
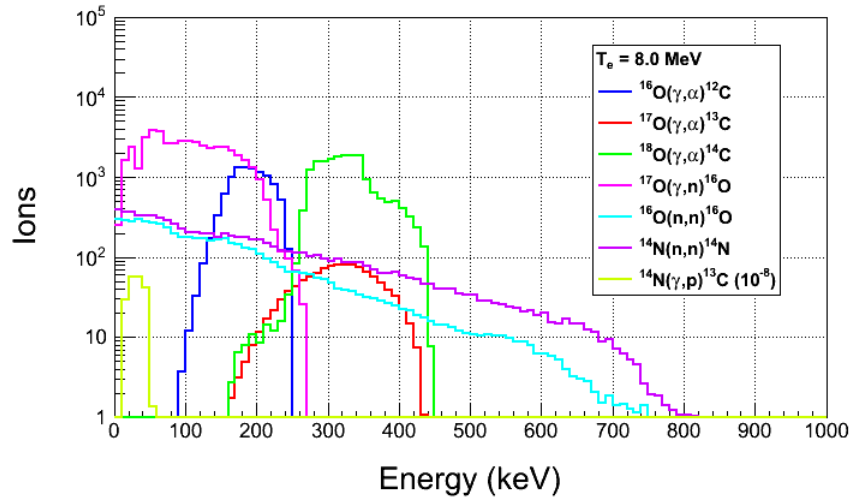
➤ Calculated with Depletion:

- I.  $^{17}\text{O}$  depletion = 5,000
- II.  $^{18}\text{O}$  depletion = 5,000

➤ Threshold Efficiency (function of superheat):

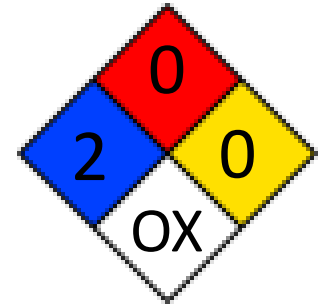
Particle	Efficiency
$e^\pm$	$<10^{-11}$
$\gamma$	$<10^{-11}$
$(\gamma, n)$	$2 \times 10^{-3}$





# SAFETY

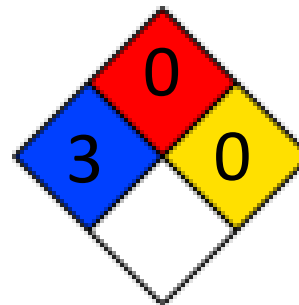
- Super heated liquid  $N_2O$ , Nitrous oxide (laughing gas)
  - I. At room temperature, it is a colorless, non-flammable gas, with a slightly sweet odor and taste



- High pressure system:
  - I. Design Authority: Dave Meekins
  - II. T =
  - III. P =

- Buffer liquid: Mercury

- I. Closed system
- II. Volume: 135 mL



# SUMMARY AND OUTLOOK

- Test N<sub>2</sub>O Bubble Chamber at HIGS (February 2014)
- Perform  $^{18}\text{O}(\gamma,\alpha)^{14}\text{C}$  and  $^{17}\text{O}(\gamma,\alpha)^{13}\text{C}$  experiments at HIGS (Summer 2014)
- Test Bubble Chamber at JLab with Bremsstrahlung beam (October 2014)
- If successful, run depleted N<sub>2</sub>O bubble chamber at JLab  $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$
  
- Bubble Chamber issues:
  - Piezo–electric acoustical signal
  - Deadtime study (now  $\tau \pm d\tau = 10.0 \pm 0.9$  sec)
  - Measure O-isotopes depletion
  
- Background tests:
  - Measure cosmic–ray background
  - Study chamber efficiency vs. superheat

# BACKUP SLIDES

# COST ESTIMATE

- I. New beamline components:
  - I. New Dipole Magnet and Hall Probe
  - II. 2 Super Harps
  - III. Fast Valve
- II. Summary of labor cost by group:

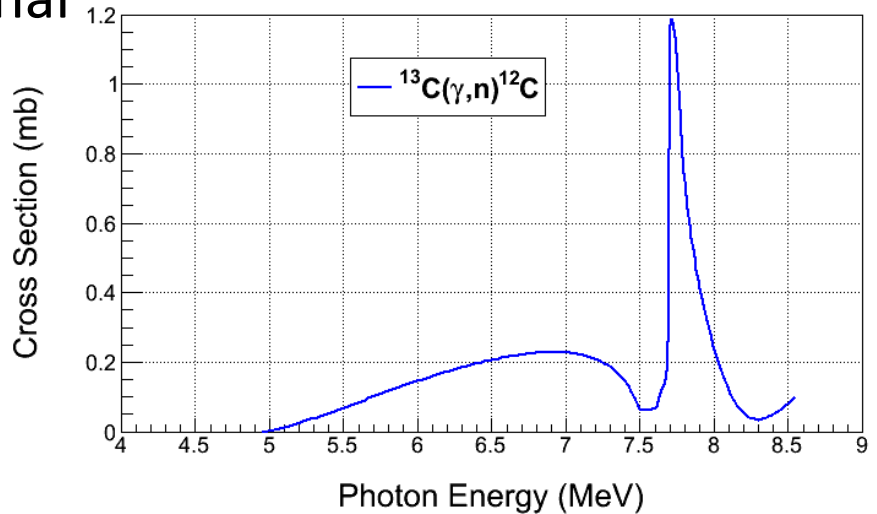
Group	Labor
Survey & Alignment	3 wks x 2
Magnet Test	1 wk x 2
Engineering Design	16 wks
Software	3 wks x 2
EES	6 wk x 2
EH&Q	4 wks

Item	Material Procurement	Shop	Labor
New Dipole Magnet	Dipole Magnet (\$8,000) Hall Probe System (\$10,000)		Design (2 week) Mapping (1 week) EESDC (1 week) Alignment (2 days)
New Beamline	2 Super Harps (20,000) Fast Valve (\$23,000)	Pipes + Pedestals (\$20,000)	Design (6 weeks) Alignment (1 week) Software (6 weeks) EES (6 weeks)
Radiator (cooled ladder, FSD)	0.02 and 0.10 mm Cu foils (\$2,000)	\$4,000	Design (2 week) Alignment (2 days)
Sweep Dipole			
Electron Dump	Pure Cu (\$5,000)	Dump + Pipes (\$15,000)	Design (4 weeks) Alignment (1 day)
Cu Collimator	Pure Cu (\$5,000)	Collimator + Stand (\$5,000)	Design (1 week) Alignment (1 day)
Photon Dump & Stand	Pure Al (\$3,000)	\$4,000	Design (1 week) Alignment (1 day)
Safety Review			4 weeks
Install			6 weeks
Bubble Chamber			Alignment (1 week)
<b>Total</b>	<b>\$76,000</b>	<b>\$48,000</b>	<b>\$80,000</b>
Indirect G&A (55.65%)	\$42,300	\$26,400	\$42,500
Indirect Stat & Fringe (57.15%)			\$45,700
<b>Total</b>	<b>\$118,300</b>	<b>\$74,400</b>	<b>\$168,200</b>

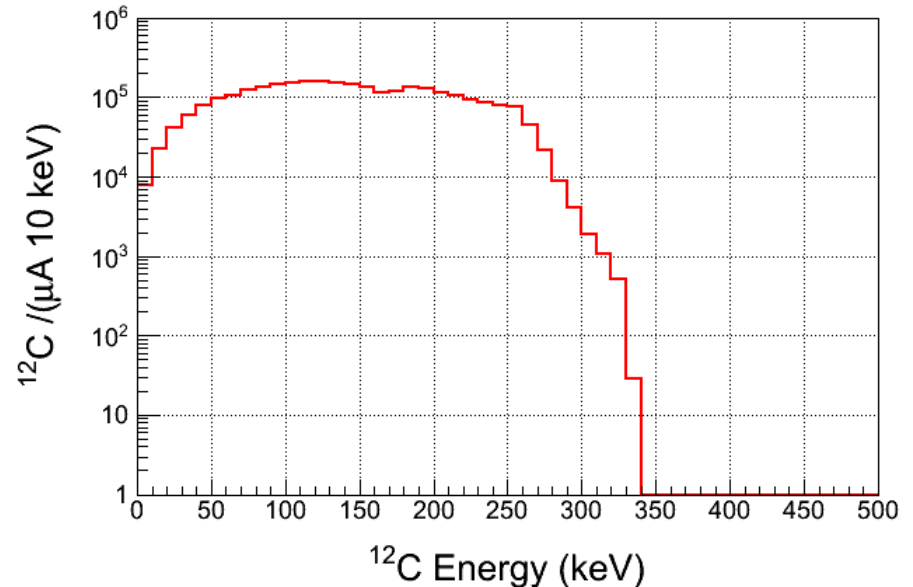
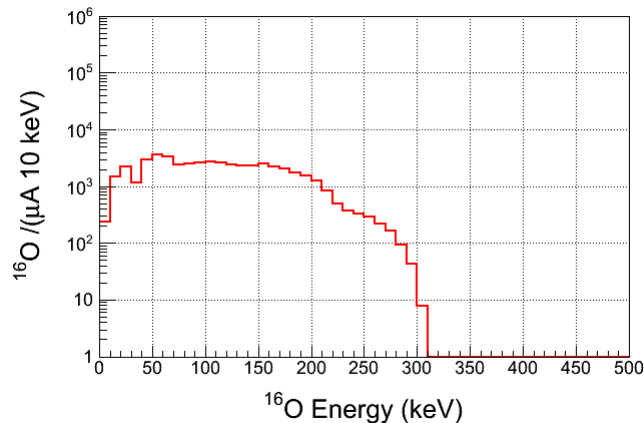


# CO<sub>2</sub> SUPERHEATED LIQUID?

- Similar Bubble Chamber operational parameters as N<sub>2</sub>O
- Natural Abundance: <sup>13</sup>C: 1.07%
- Depletion: <sup>13</sup>C depletion=1,000
- <sup>13</sup>C(γ,n)<sup>12</sup>C Background



For comparison, <sup>17</sup>O(γ,n)<sup>16</sup>O



- <sup>12</sup>C(γ,2α)α Background

# WATER SUPERHEATED LIQUID?

- Etching of glass vessel by superheated H<sub>2</sub>O
- T = 250°C
- P = 75 atm
- Background from secondary neutron–nucleus elastic scattering by neutrons from  $d(\gamma,n)p$

