

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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January 9, 2014





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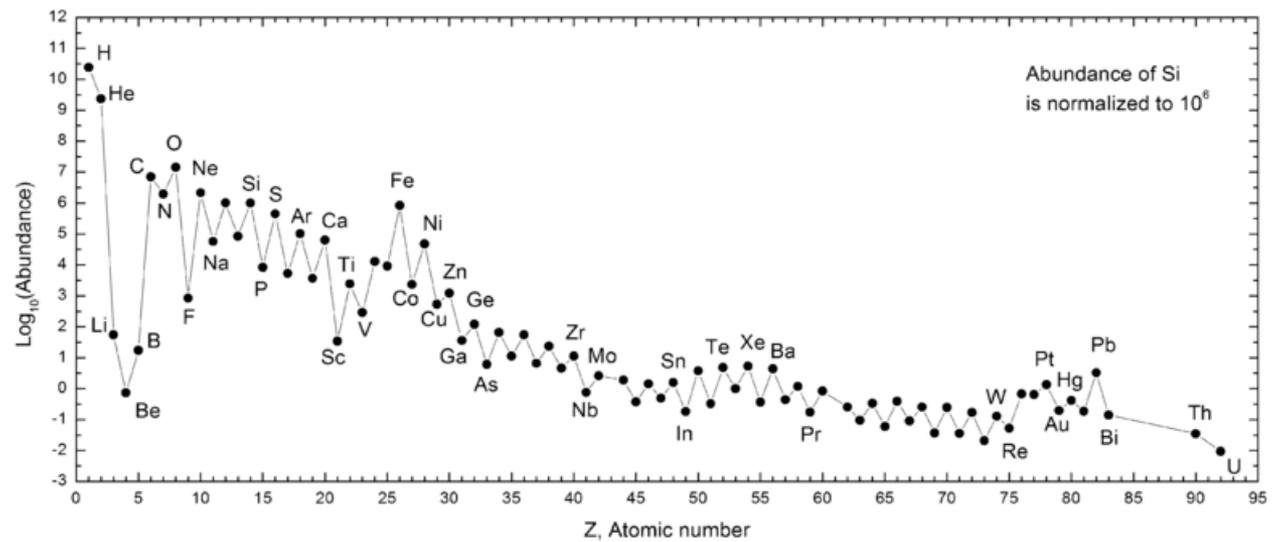
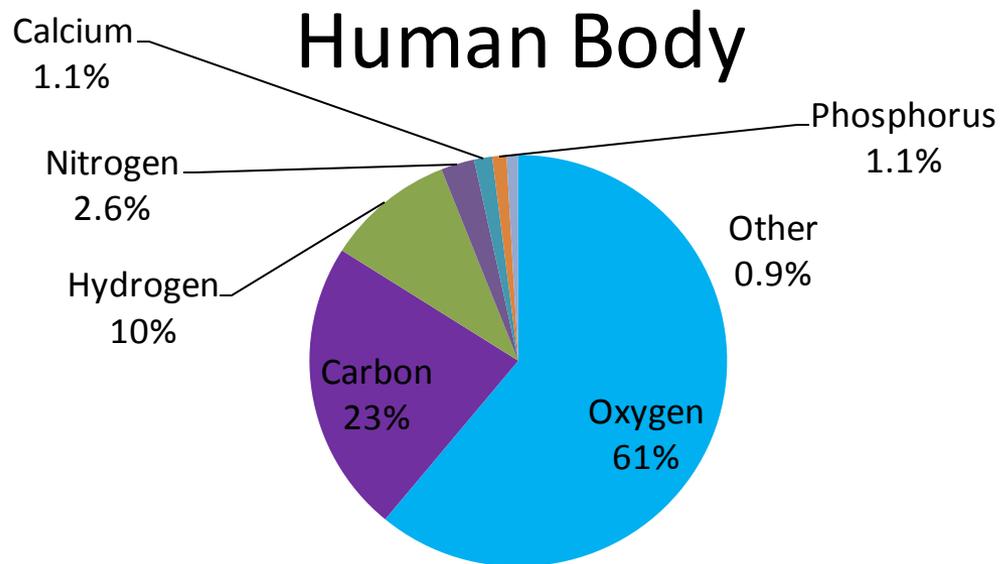
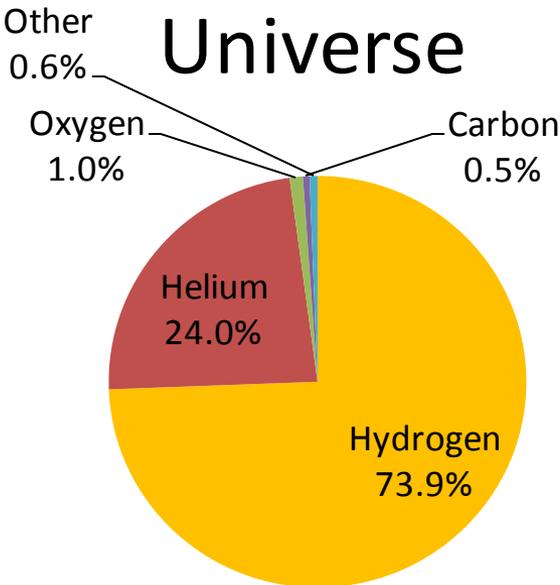
J. Benesch
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[https://wiki.jlab.org/ciswiki/index.php/Bubble Chamber](https://wiki.jlab.org/ciswiki/index.php/Bubble_Chamber)

OUTLINE

- Nucleosynthesis and the $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ Reaction
- Time Reversal Reaction: $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$
- The Bubble Chamber
- 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

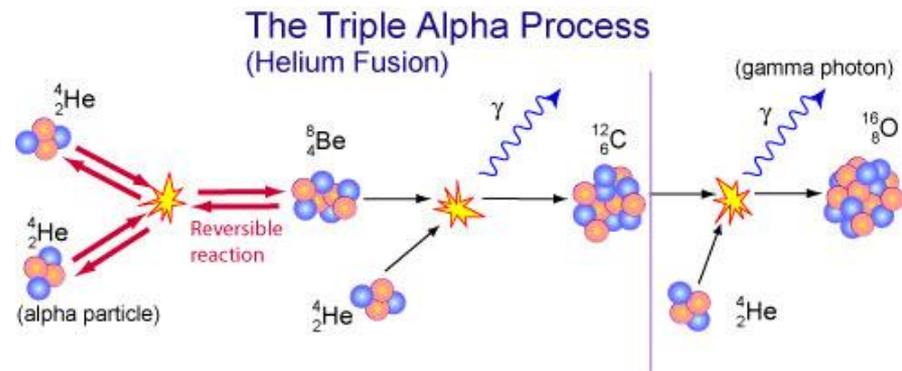


STELLAR HELIUM BURNING

- Helium Reactions:



(slow, otherwise no ${}^{12}\text{C}$ remains)



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

➔ Currently, reaction rate error is large ($\pm 35\%$)

Goal $< \pm 10\%$

- Thermonuclear reaction rate involving two nuclei is:

Only narrow energy range is important (Gamow Peak)

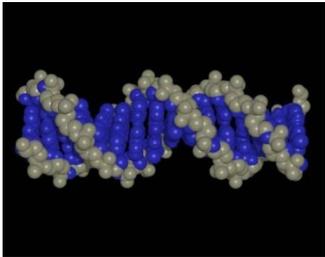
$$R = \sqrt{\frac{8}{\pi m (k_B T)^3}} \int_0^\infty E \sigma_{tot}(E) e^{-\frac{E}{k_B T}} dE$$

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

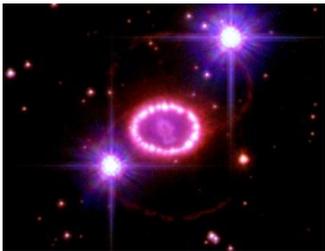
- The *holy grail* of nuclear astrophysics

Periodic Table of the Elements

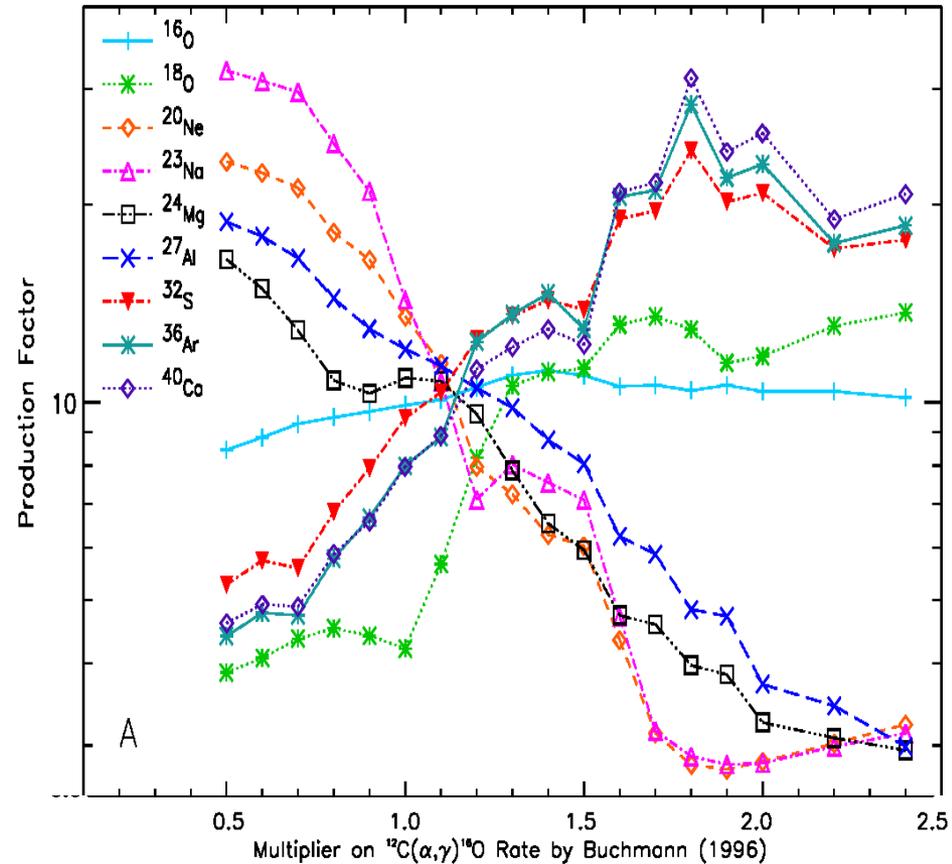
Affects the synthesis of most of the elements of the periodic table



Sets the $N(^{12}\text{C})/N(^{16}\text{O})$ (≈ 0.4) ratio in the universe



Determines the minimum mass a star requires to become a supernova



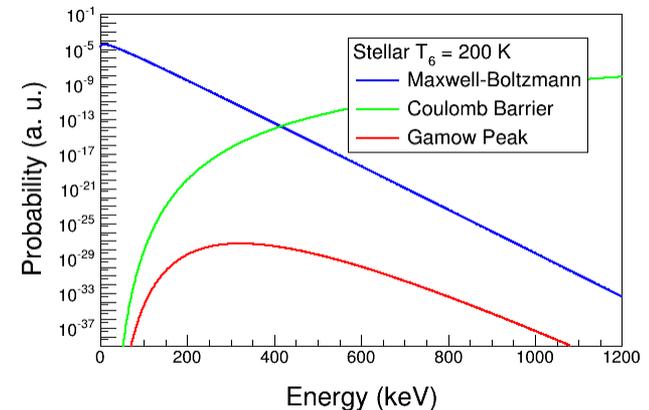
THE GAMOW PEAK

- Narrow energy range where thermonuclear reactions is most likely to occur in stellar plasma is a product of two distributions:

- I. Maxwell-Boltzmann energy distribution with $e^{-E/k_B T}$
- II. Penetration through Coulomb barrier with $e^{-b/E^{1/2}}$

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

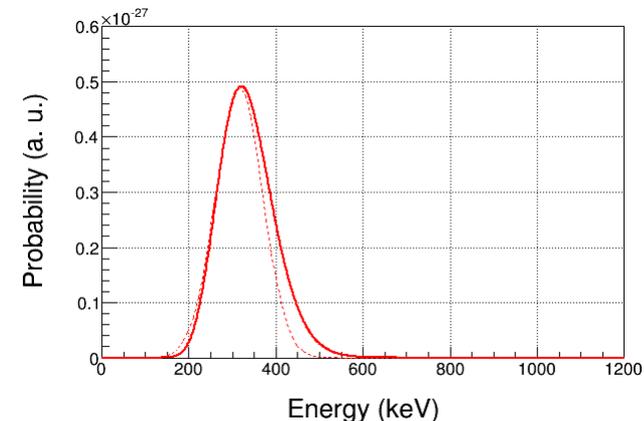
$$W = 0.2368 \left(Z_1^2 Z_2^2 A T_6^5 \right)^{1/6} \text{ keV}$$



- For $\alpha + {}^{12}\text{C}$ ($Z_1=2, Z_2=6, A=3$),

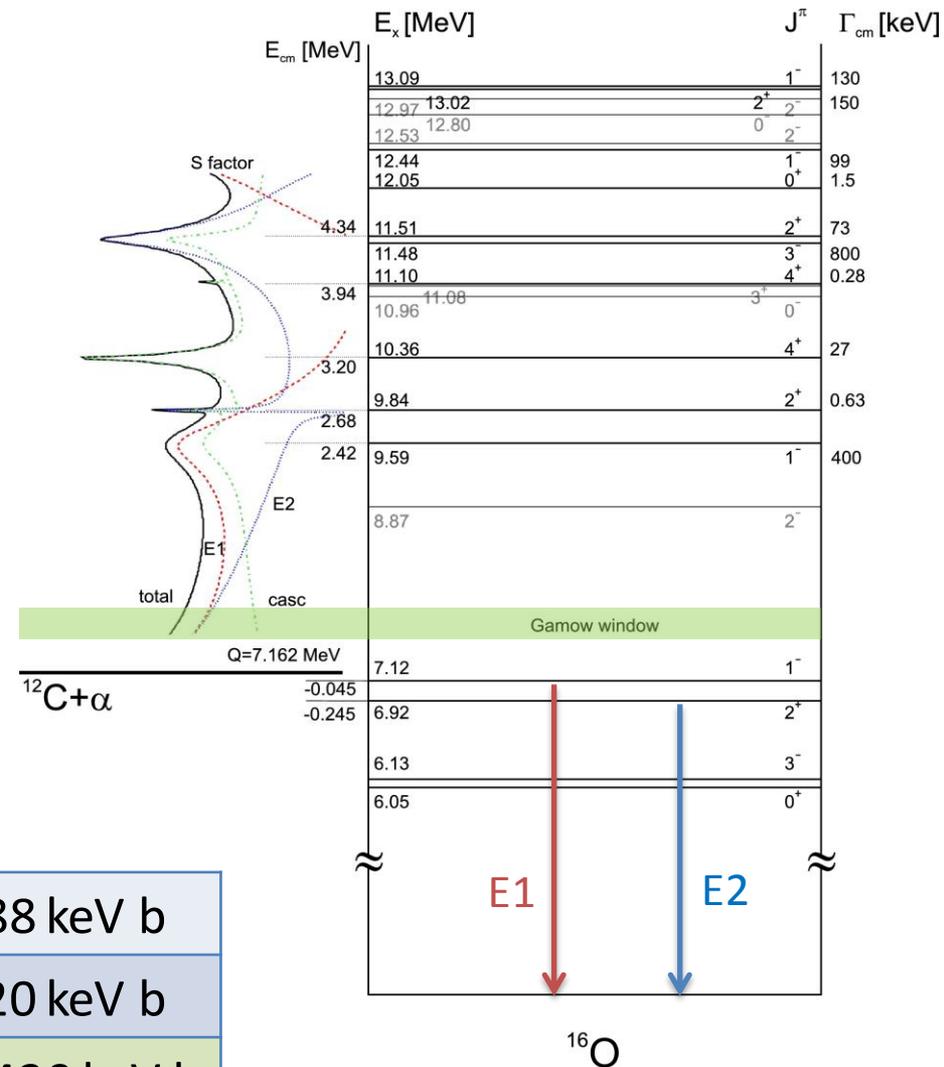
and stellar $T=200 \cdot 10^6$ K:

- **Gamow Peak, $E_0 \approx 300$ keV, $W \approx 50$ keV**
(in Center-of-Mass (CM) of $\alpha + {}^{12}\text{C}$ system)
- Maximum of Maxwell-Boltzmann energy distribution, $k_B T = 17$ keV



$\alpha + {}^{12}\text{C}$ REACTION

- $\sigma(E_0)$ 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 γ 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 | $S_{tot}(300) = 40\text{--}430$ keV b |

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

➤ Previous Experiments:

A. Direct Measurements:

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

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

B. Indirect Measurements:

- I. β -delayed α decay of ^{16}N ($J^\pi=2^-$, $T_{1/2}=7.13$ s, 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

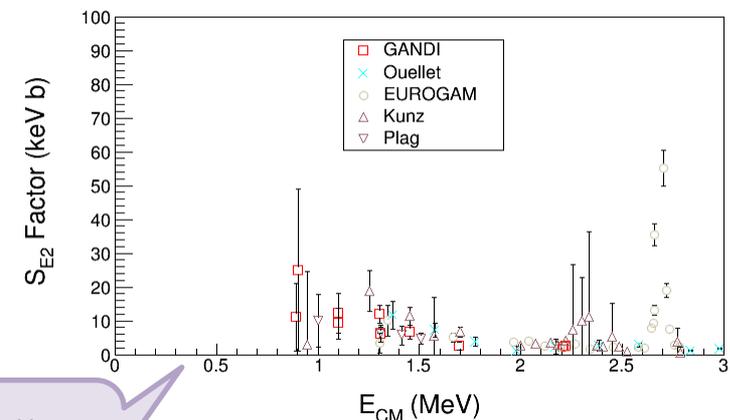
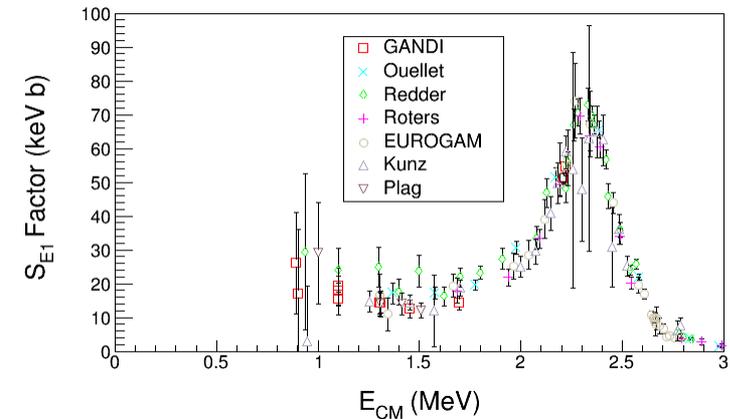
ASTROPHYSICAL S-FACTOR $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

- 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 ± 39 |
| Kunz (2001) | 165 ± 50 |



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

RECIPROCITY RELATION: (γ, α) and (α, γ)

➤ $A(\alpha, \gamma)B$:

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

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

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

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

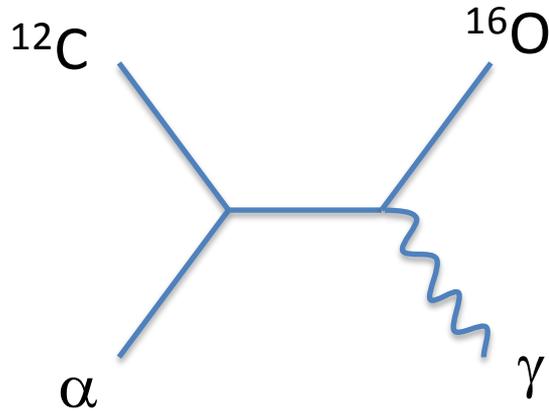
$$E_{CM} = \sqrt{m_B^2 + 2E_\gamma m_B} - m_B - Q$$

$$E_\gamma \cong E_{CM} + Q$$

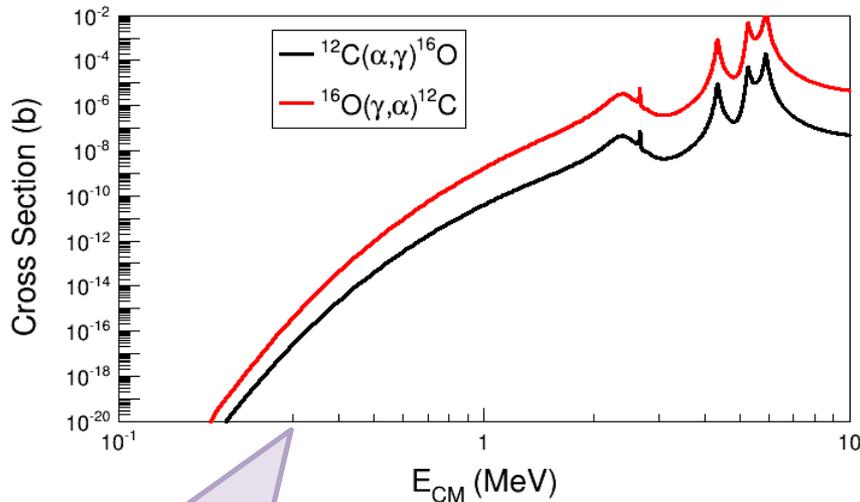
$$\sigma_{(\gamma, \alpha)}(E_\gamma) = \frac{m_{A\alpha} c^2 E_{CM}}{E_\gamma^2} \sigma_{(\alpha, \gamma)}(E_{CM})$$

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

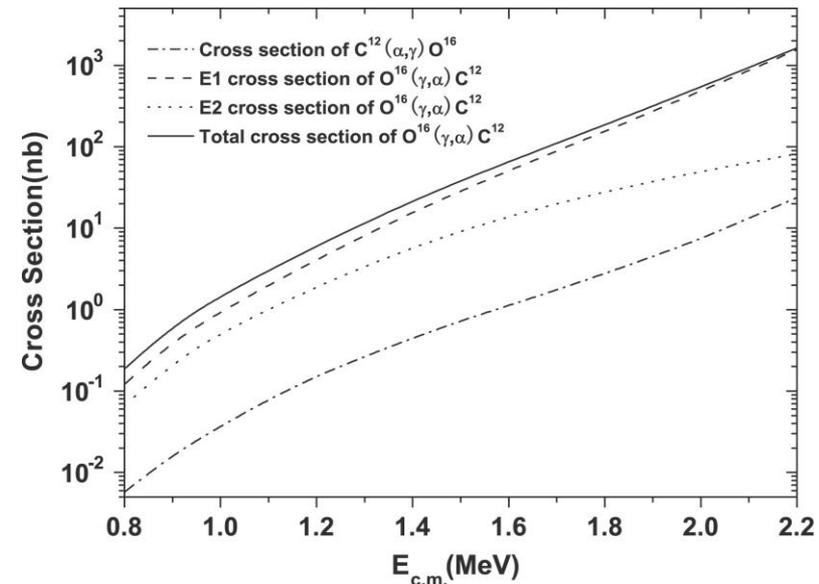
TIME REVERSAL REACTION



- Bubble Chamber experiment measures total cross section, E1 + E2.
- We can separate E1 and E2 if we use linearly polarized γ but cannot measure α and ^{12}C angular distribution

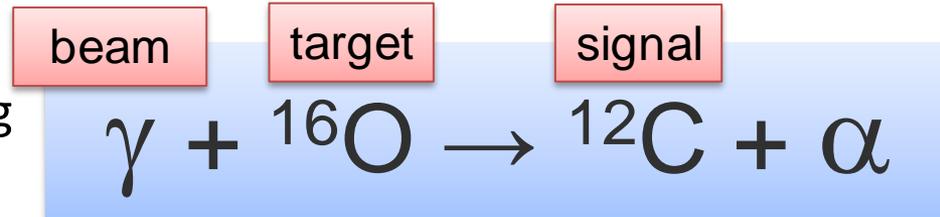


Stellar helium burning
at $E = 300$ keV



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}O nuclei = $3.5 \cdot 10^{22} / \text{cm}^2$ (3.0 cm cell)
- Solid Angle and Detector Efficiency = 100%
- Superheated liquid will nucleate from α and ^{12}C recoils
- Electromagnetic debris (electrons and gammas, or positrons) do NOT trigger nucleation (detector is insensitive to γ -rays by at least 1 part in 10^{11}).



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

THE BUBBLE CHAMBER

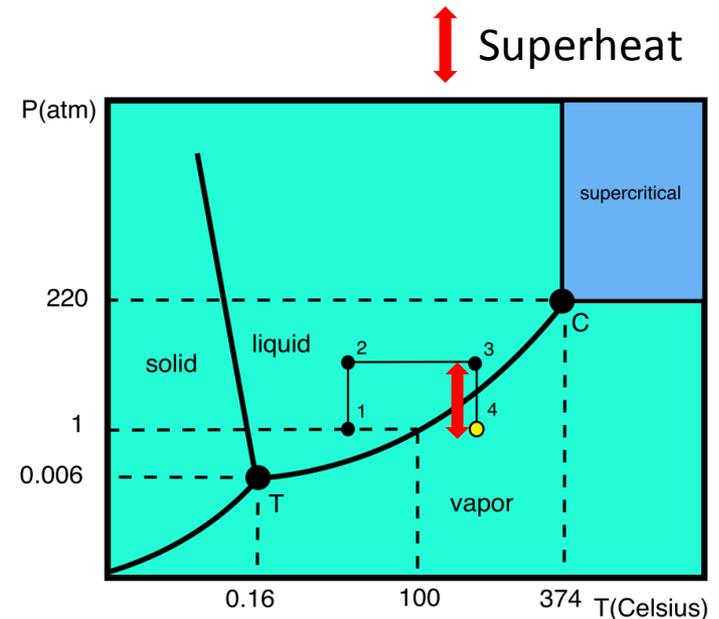
- Donald Glaser won Nobel Prize for inventing chamber to detect particles (1960)
- Now being used in Dark Matter Search Experiments: COUPP, PICASSO, SIMPLE

Superheat Preparation:

- Liquid is pressurized at ambient temperature (1 to 2)
- Then pressure is kept constant while temperature is increased to above boiling point (2 to 3)
- Finally pressure is slowly released while keeping temperature constant (3 to 4)
- At this point (4), water is still liquid but now superheated

Bubble Formation:

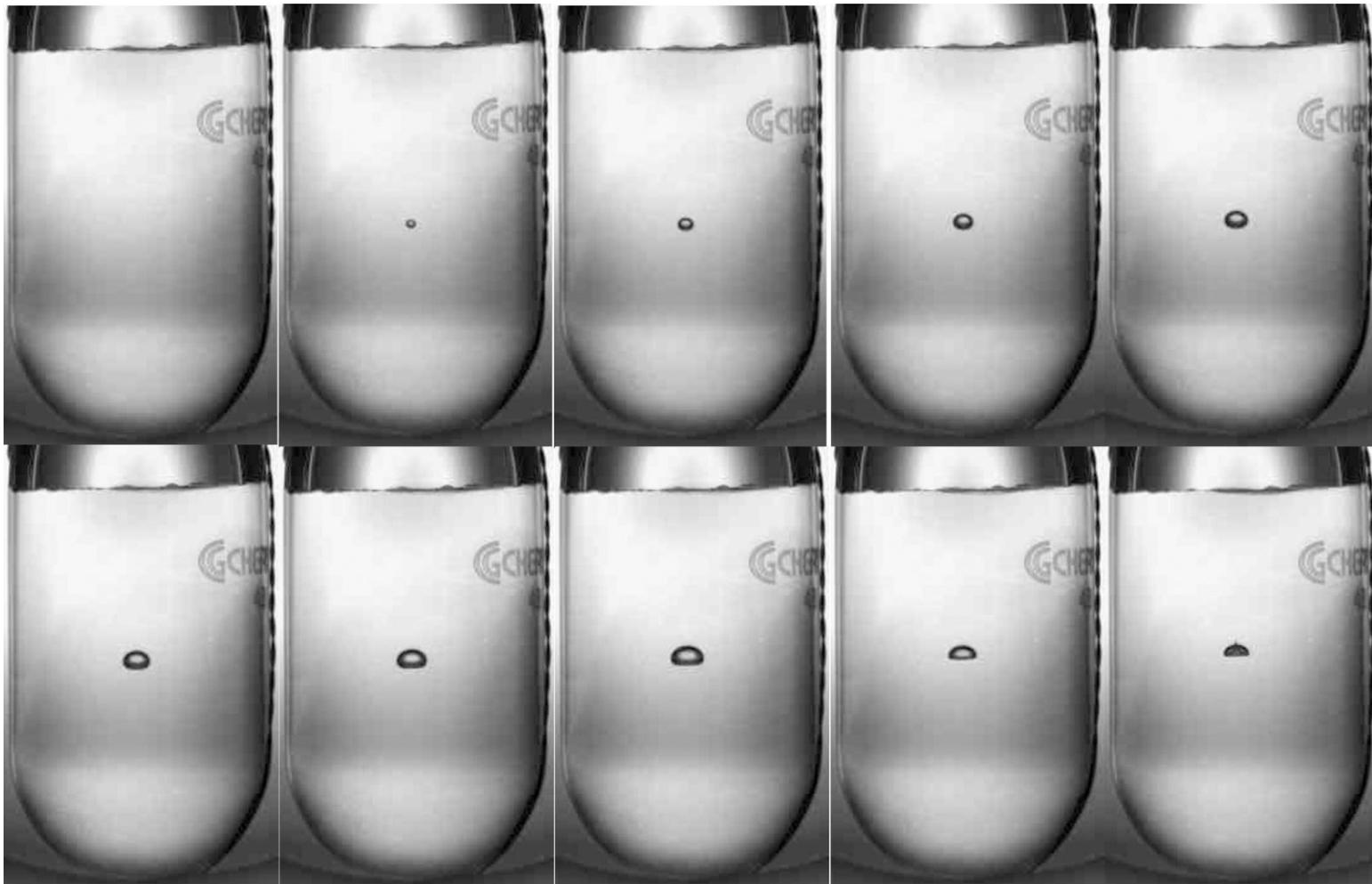
- Particle energy loss will induce vaporization
- Resultant vapor bubble is observable either **visibly** or **audibly**
- Bubble growth is captured by a camera
- Pressure is increased (4 to 3) to quench bubble. It takes about few seconds for liquid to return to a stable state
- Superheat is restored by releasing pressure again (3 to 4), and cycle is repeated for each bubble event



BUBBLE GROWTH AND QUENCHING

$^{19}\text{F}(\gamma, \alpha)^{15}\text{N}$ event in C_4F_{10}

Fast Digital Camera: $\Delta t = 10$ ms



3.0 cm

BUBBLE CHAMBER PRINCIPLE

- I. Only bubbles with $r > R_c$ grow to be macroscopic

$$R_c = 2s / (P_v - P_l)$$

s : Surface tension

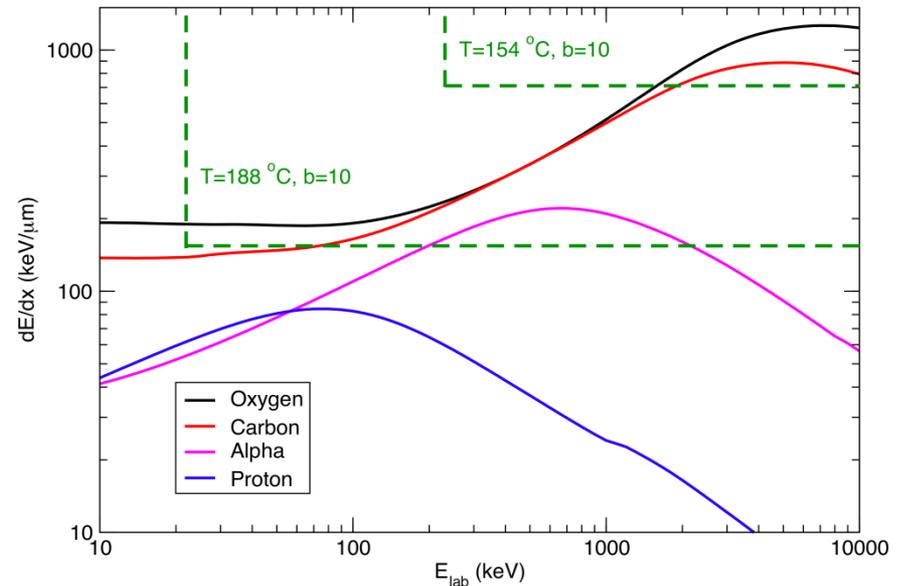
- II. Bubble requires minimum deposited energy (E_c) within minimum distance L_c ($=\alpha R_c$, 10s of nm to a few μm)

$$\frac{dE}{dx} > \left(\frac{dE}{dx} \right)_c = \frac{E_c}{\alpha R_c}$$

α : free parameter (to determined experimentally)

- III. Particle must be over thresholds in both dE/dx and E

Nucleation thresholds (Water)



$$E \geq E_c = \frac{4}{3} \pi R_c^3 (\rho h + P_l) + 4\pi R_c^2 \left(s - T \frac{\partial s}{\partial T} \right)$$

ACOUSTIC SIGNAL DISCRIMINATION

I. Bubble growth produces an audible click which is recorded by piezo-electric transducers

II. Neutron Events:

I. $^{17}\text{O}(\gamma, n)^{16}\text{O}$

II. Neutron–nucleus elastic scattering:
 $^{16}\text{O}(n, n)$, $^{14}\text{N}(n, n)$

Ions ^{16}O or ^{14}N will generate a single bubble

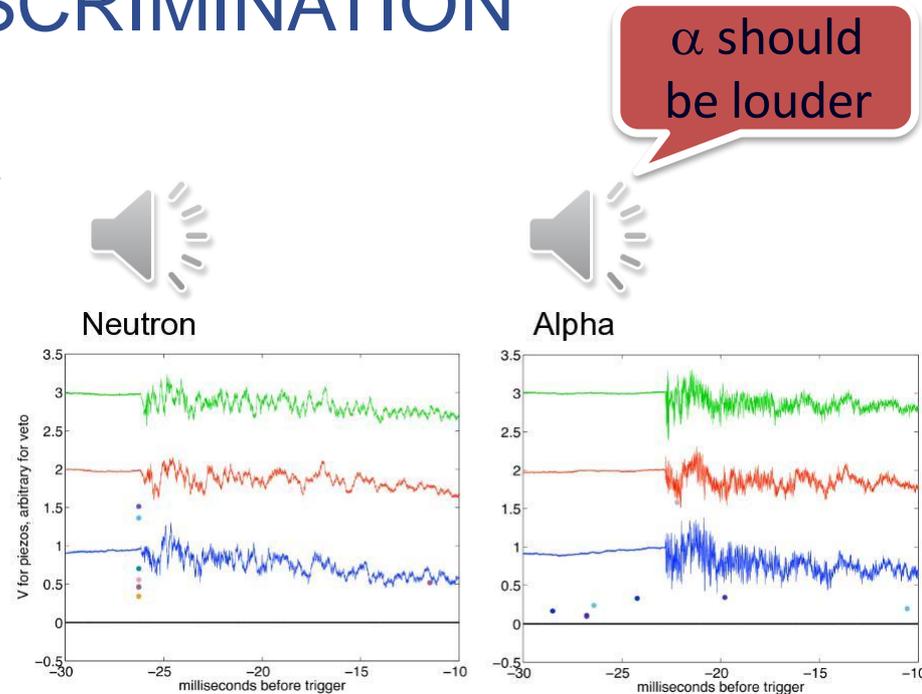
III. Alpha Events:

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

II. $^{17}\text{O}(\gamma, \alpha)^{13}\text{C}$

III. $^{18}\text{O}(\gamma, \alpha)^{14}\text{C}$

Ions $^{12}\text{C}+\alpha$ or $^{13}\text{C}+\alpha$ or $^{14}\text{C}+\alpha$ will generate a combined multi-bubble

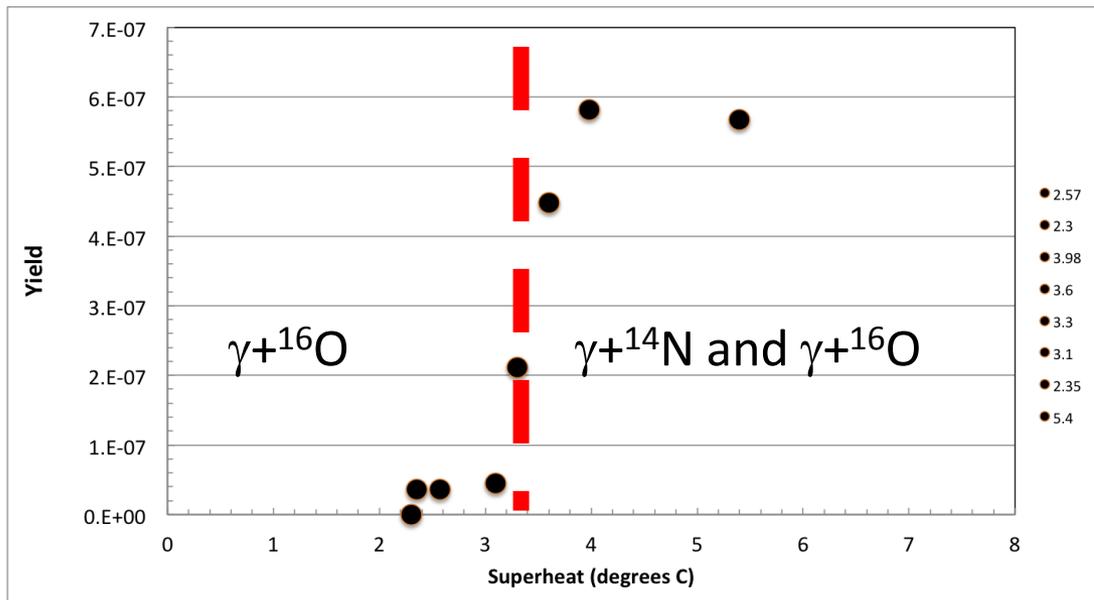
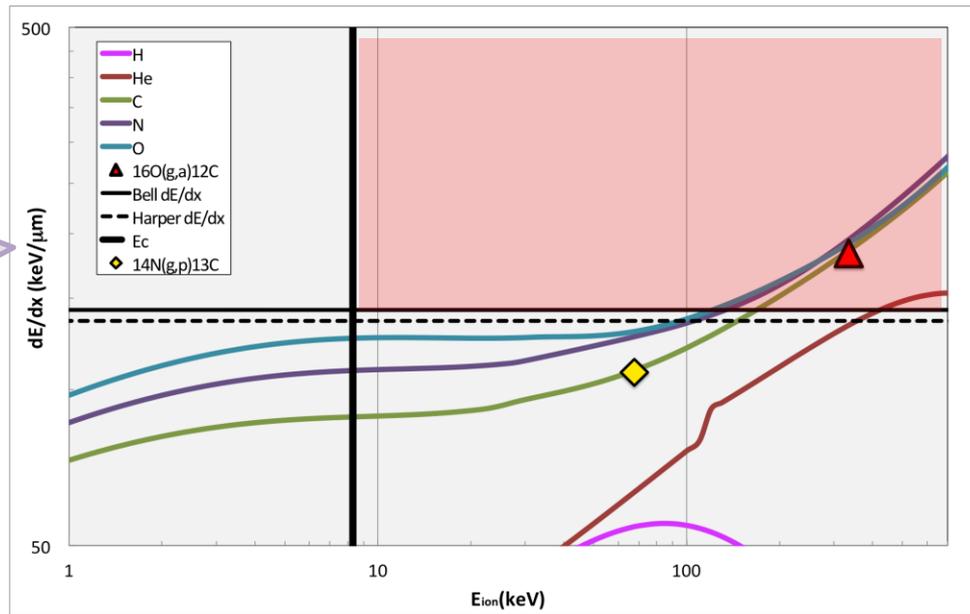


COUPP, FNAL, courtesy of A. Sonnenschein

Suppress neutron events
by 100 from acoustic
signal

EFFICIENCY CURVE

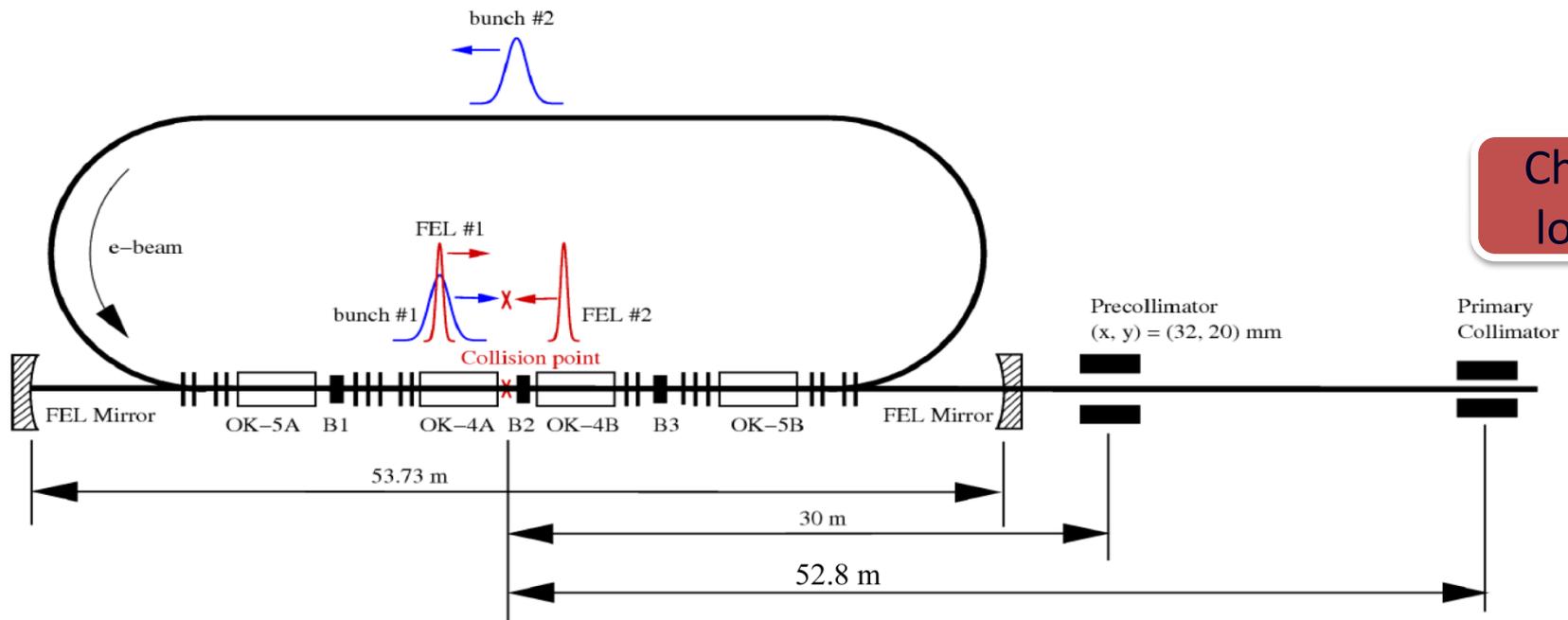
N₂O thresholds,
 Superheat = 3.3 °C,
 E_γ = 8.5 MeV



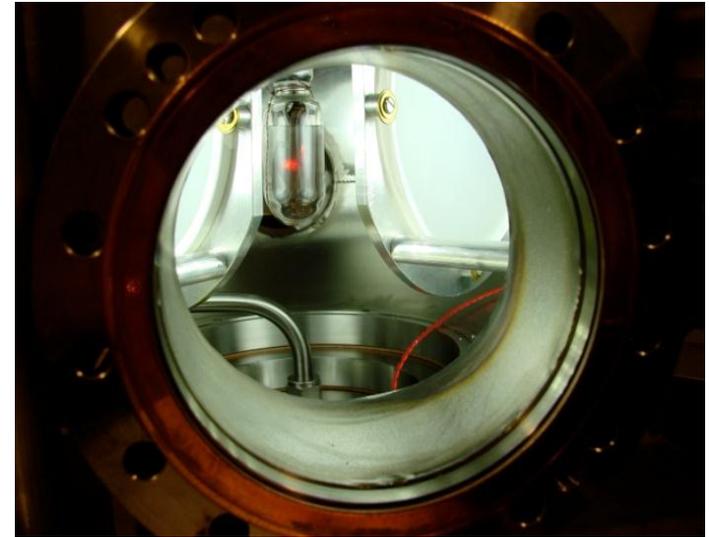
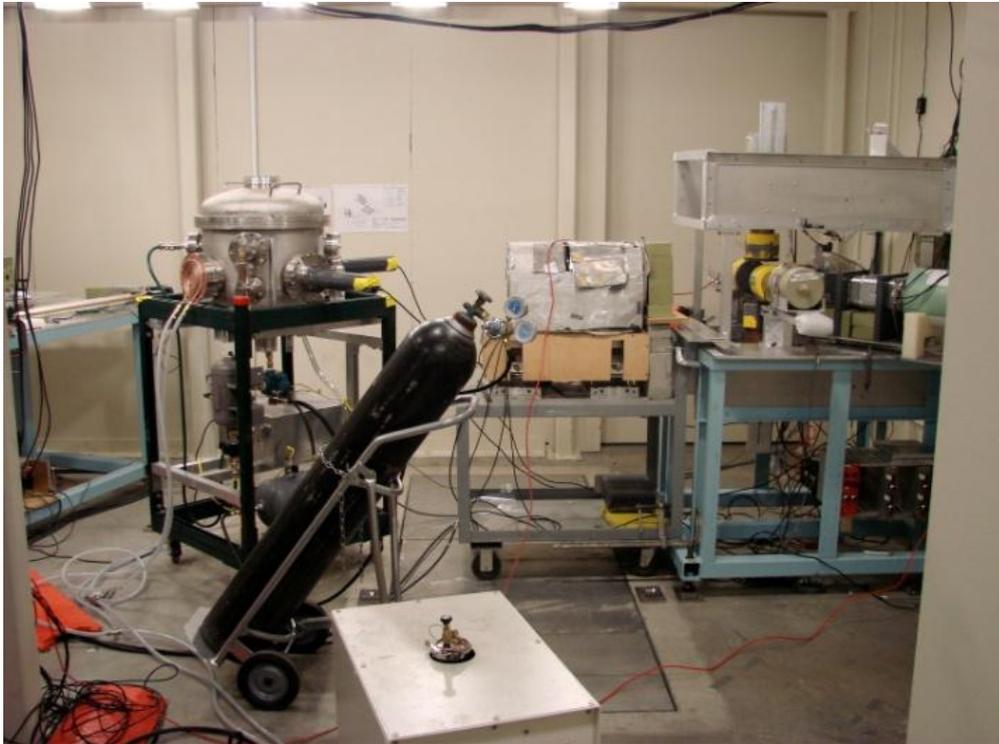
N₂O efficiency curve,
 HIGS April 2013,
 E_γ = 9.7 MeV

BUBBLE CHAMBER AT HIGS

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



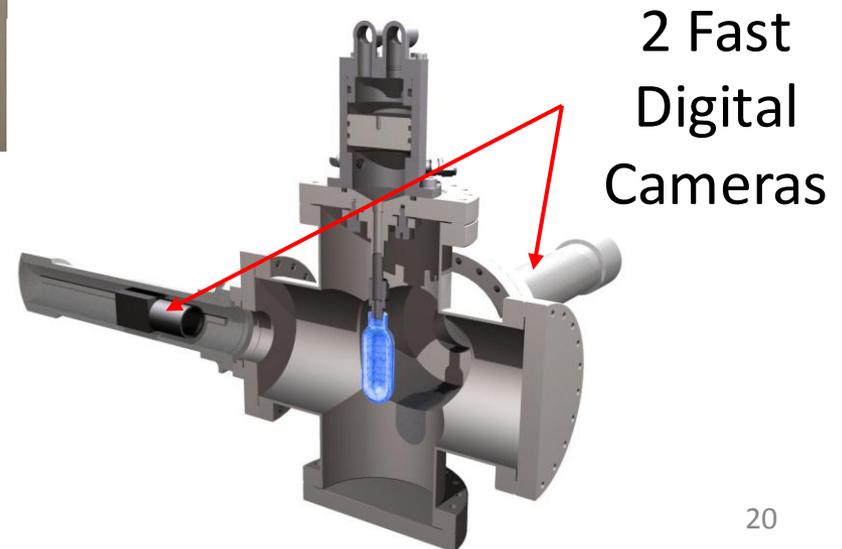
MEASURING $^{19}\text{F}(\gamma, \alpha)^{15}\text{N}$ AT HIGS



C_4F_{10} Bubble Chamber

$T = 30^\circ\text{C}$

$P = 3 \text{ atm}$





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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

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R. Raut ^{e,f,1}, G. Rusev ^{e,f,2}, A.P. Tonchev ^{e,f,3}

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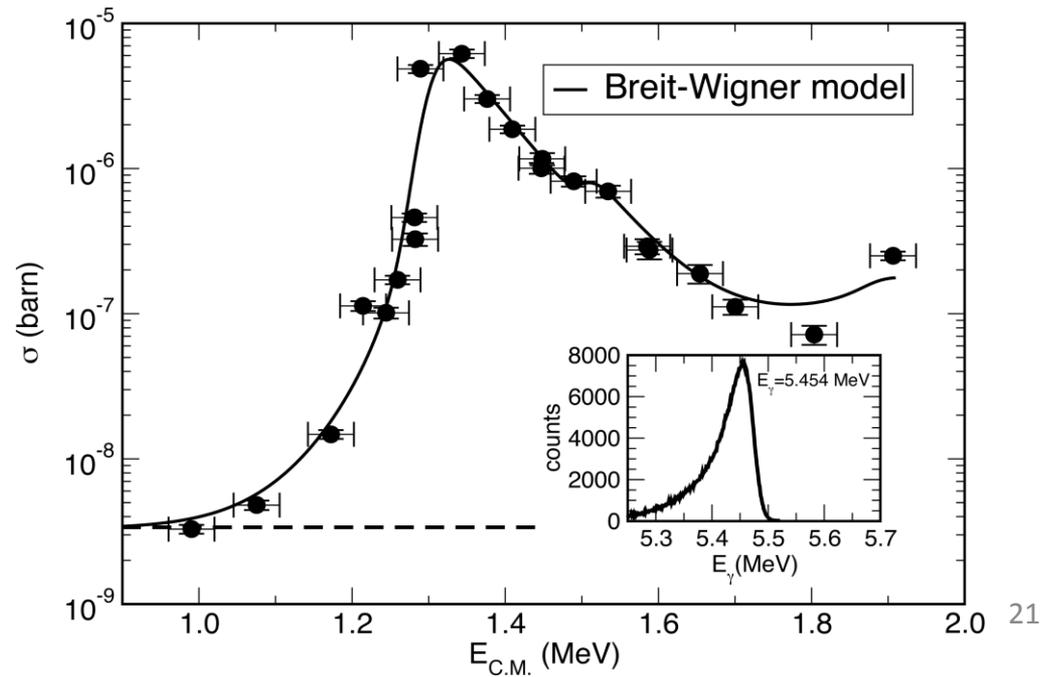
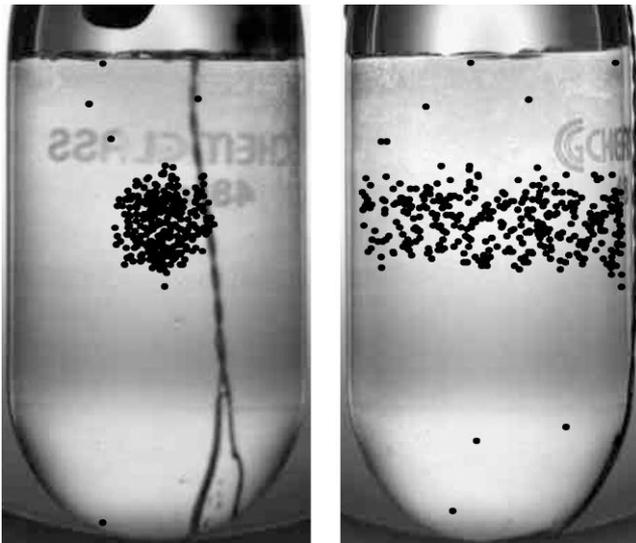
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^f Triangle Universities Nuclear Laboratory, Durham, NC 27708, USA



BREMSSTRAHLUNG BACKGROUND AT HIGS

Vacuum: 2×10^{-10} Torr

Residual Gas: $Z = 10$

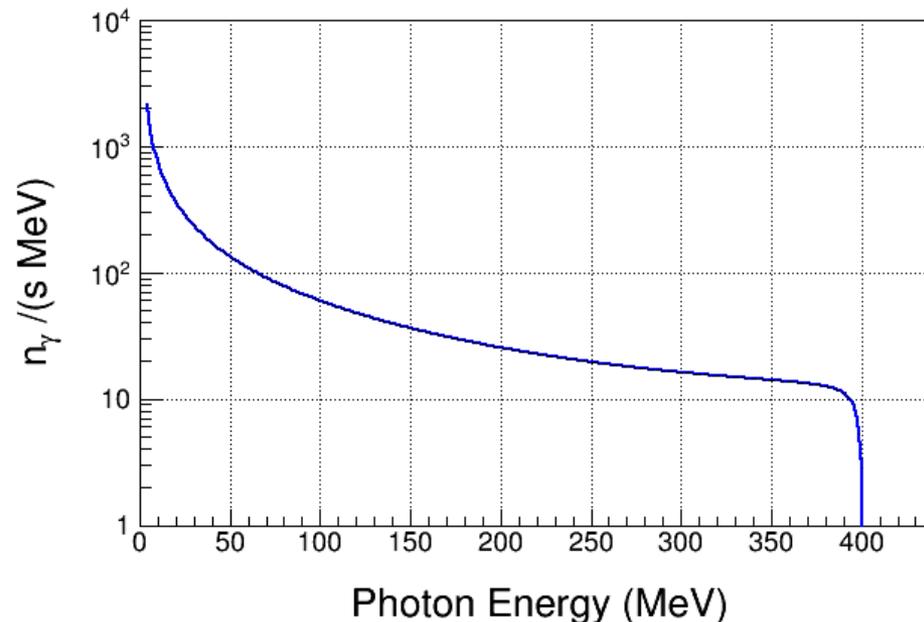
Electron Beam Energy: 400 MeV

Electron Beam Current: 41 mA

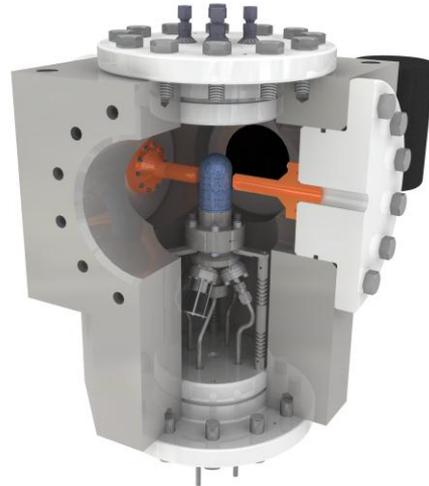
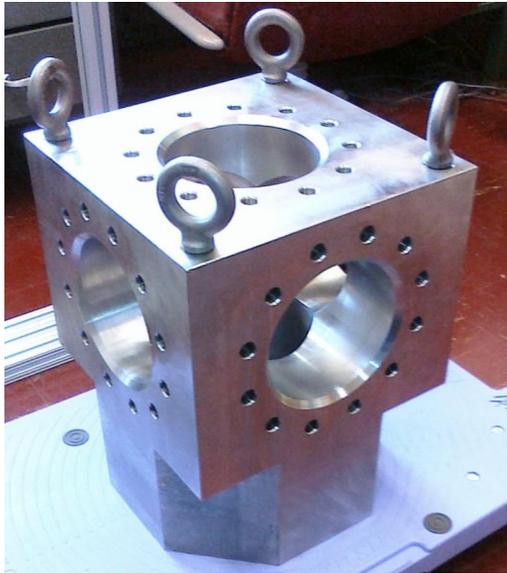
Interaction Length: 35 m



Strong Bremsstrahlung
Background
(when coupled with large
cross sections at high energies)



RECENT WORK



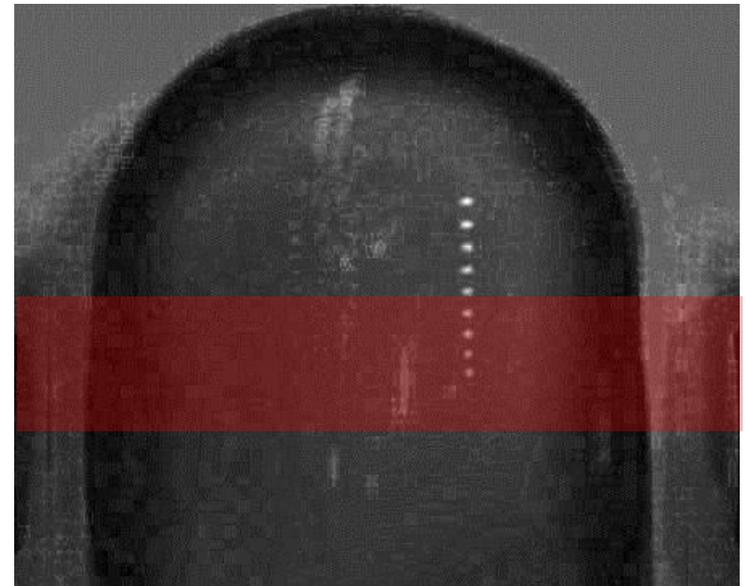
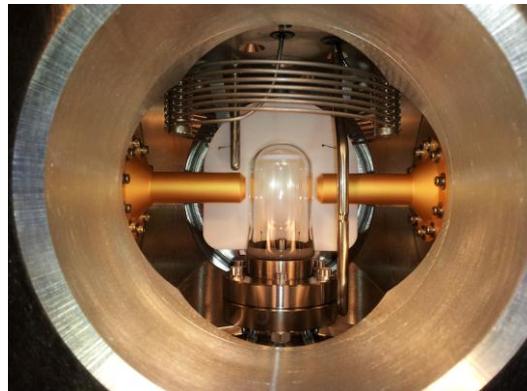
N₂O Bubble Chamber

T = 5°C

P = 60 atm

First $\gamma+O \rightarrow \alpha+C$ bubble

April 2013



SUPERHEATED TARGETS

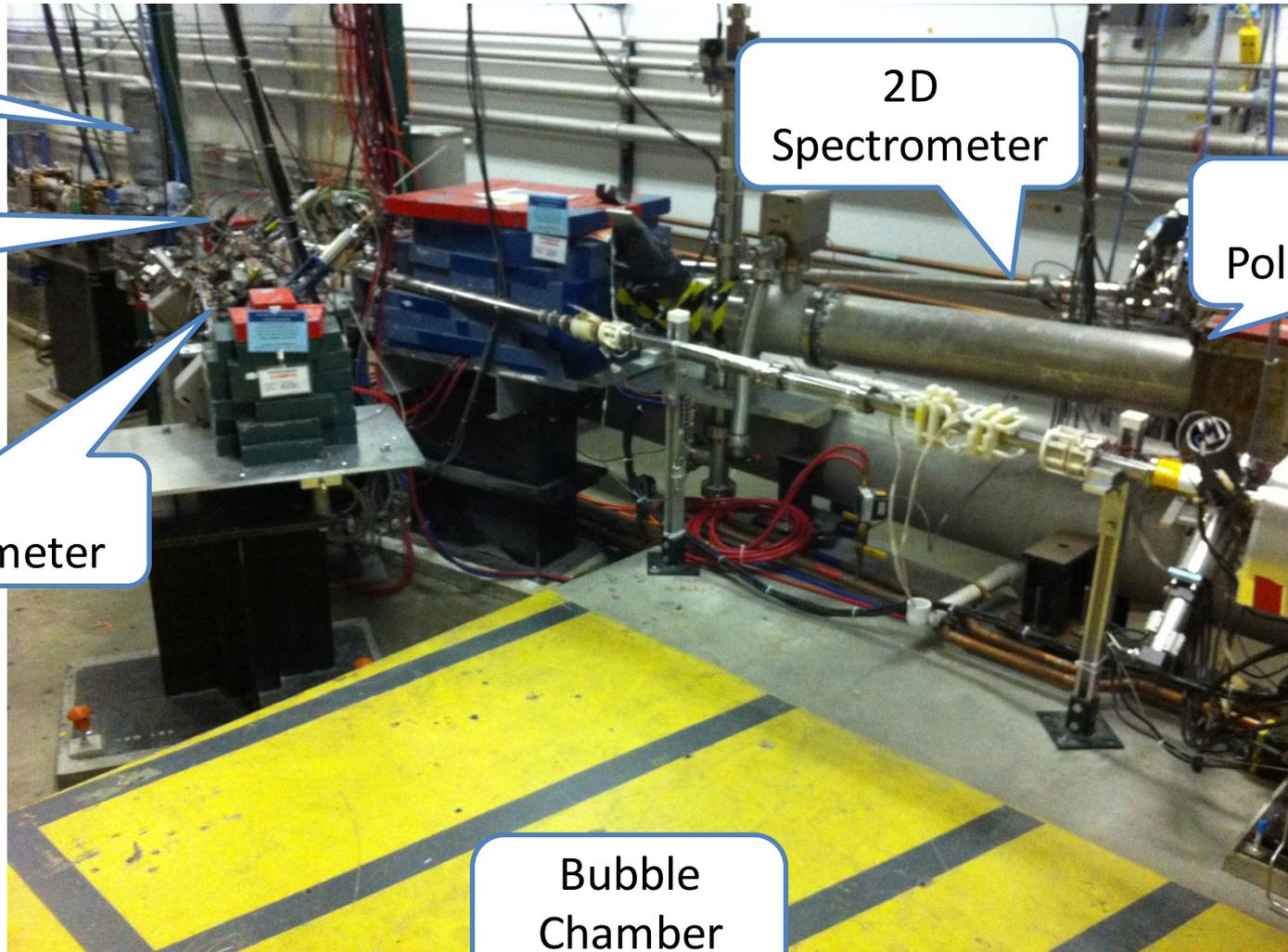
I. List of superheated liquids to be used in experiment:

| N₂O Targets | ¹⁶O | ¹⁷O | ¹⁸O |
|-------------------------------|-----------------------|-----------------------|-----------------------|
| Natural Target | 99.757% | 0.038% | 0.205% |
| ¹⁶ O Target | | Depleted > 5,000 | Depleted > 5,000 |
| ¹⁷ O Target | | Enriched > 80% | <1.0% |
| ¹⁸ O Target | | <1.0% | Enriched > 80% |

II. Readout:

- I. Fast Digital Camera
- II. Acoustic Signal to discriminate between neutron and alpha events

EXPERIMENTAL SETUP AT JLAB INJECTOR



BCM

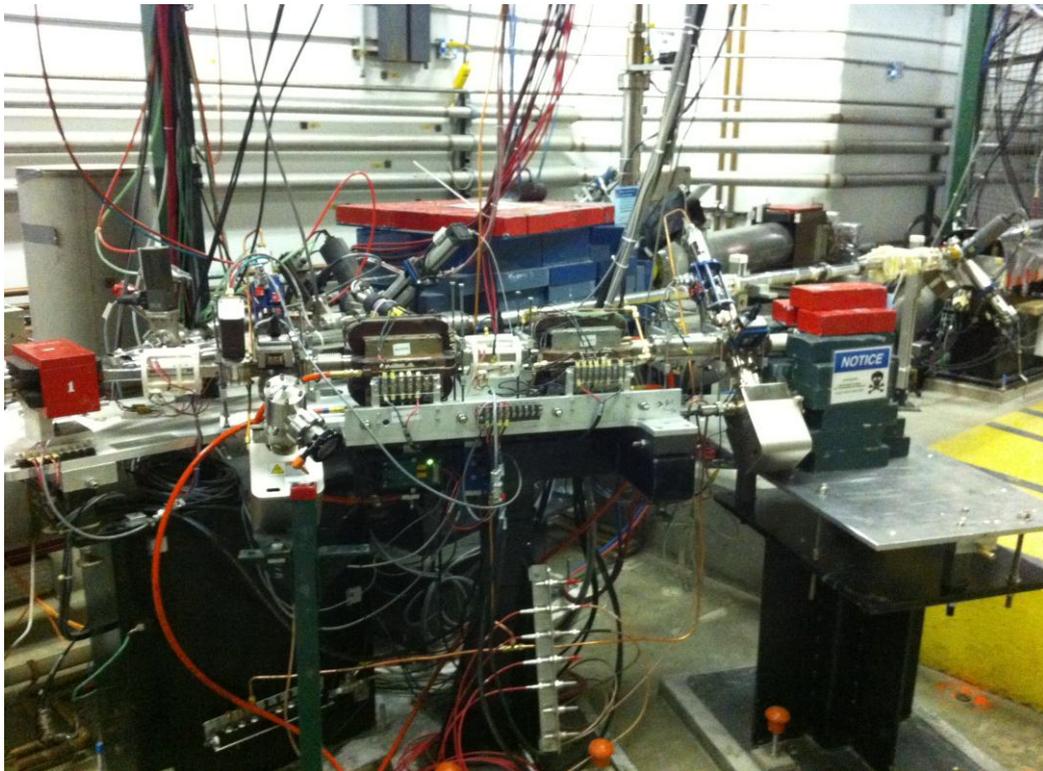
5 MeV
Dipole

5D
Spectrometer

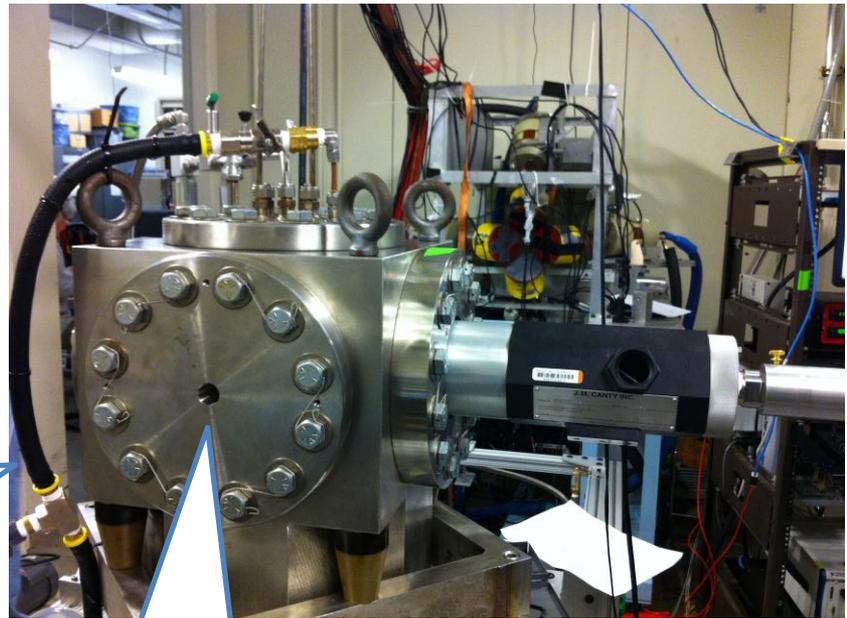
2D
Spectrometer

Mott
Polarimeter

Bubble
Chamber
location



5D
Spectrometer



Bubble Chamber
at HIGS
April 2013

Photon Beam
Entrance

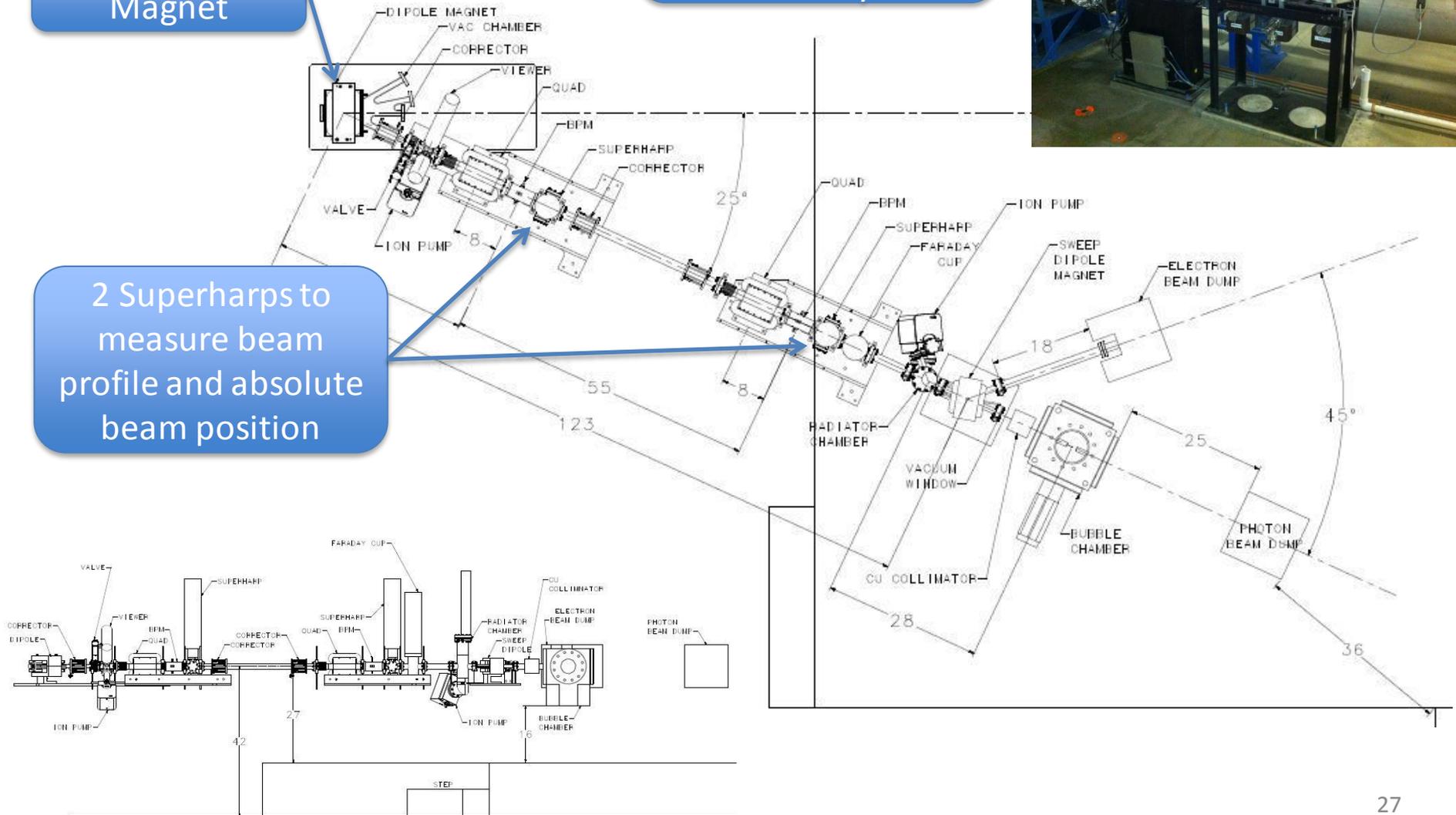
BEAMLINE

Replace Dipole Magnet

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

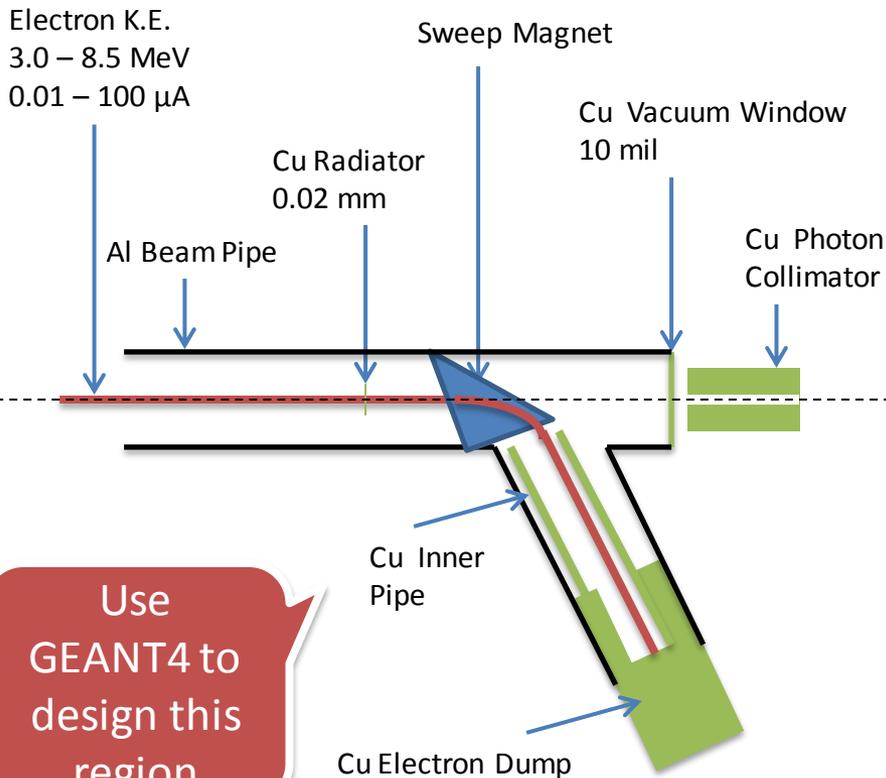


2 Superharp to measure beam profile and absolute beam position

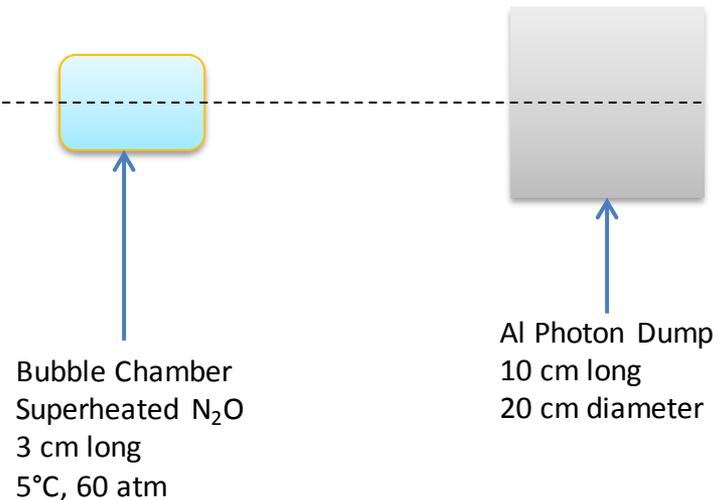


SCHEMATICS

- Power deposited in radiator (100 μ 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



- I. Radiator motion and Sweep Dipole current must be in FSD
- II. BCM0L02 and Electron Dump in Beam Loss Accounting (BLA)



BEAM REQUIREMENTS

I. Beam Properties at Radiator:

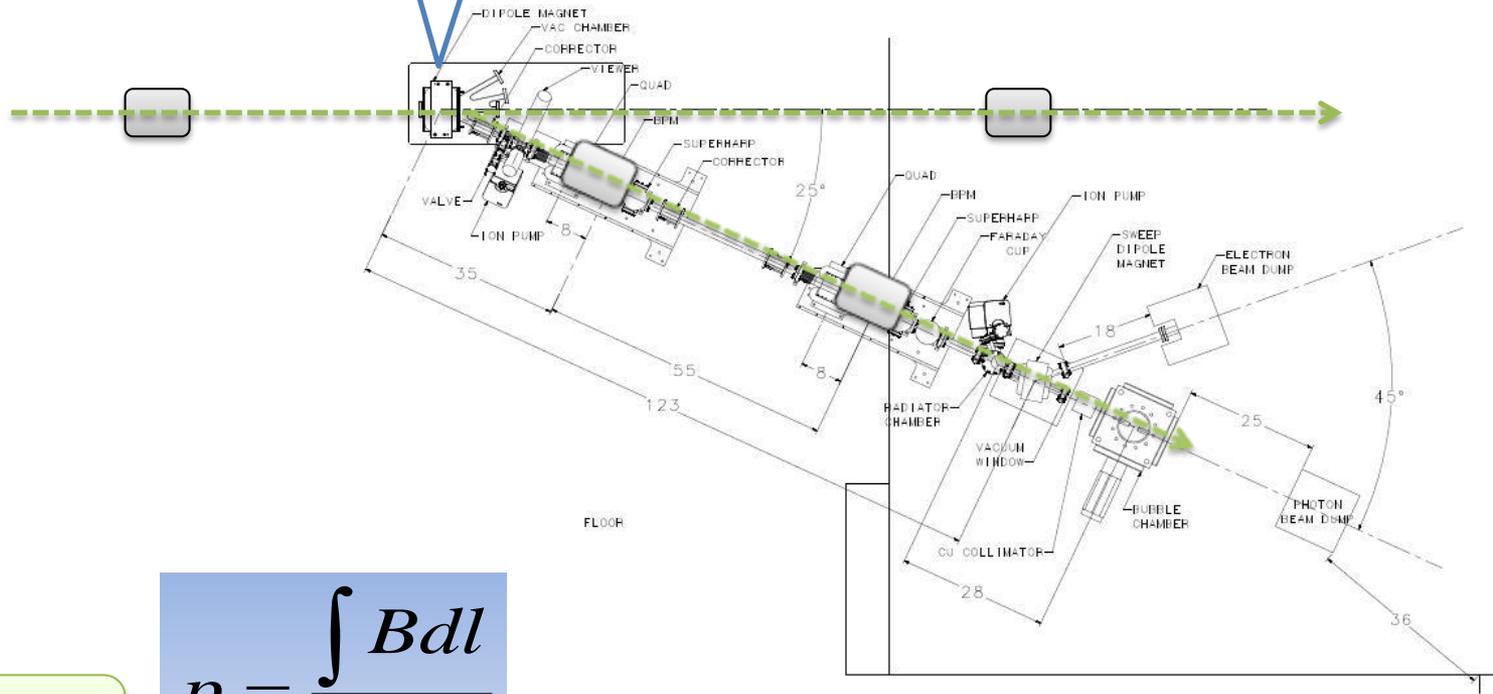
| | |
|--|----------|
| Beam Kinetic Energy, (MeV) | 7.9–8.5 |
| Beam Current (μA) | 0.01–100 |
| Absolute Beam Energy | <0.1% |
| Relative Beam Energy | <0.02% |
| Energy Resolution (Spread), σ_T/T | 0.06% |
| Beam Size, $\sigma_{x,y}$ (mm) | 1–2 |

- 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. We may need to helium process the $\frac{1}{4}$ -cryounit

MEASURING ABSOLUTE BEAM ENERGY

□ BPM

5 MeV Dipole



Electron Beam Momentum

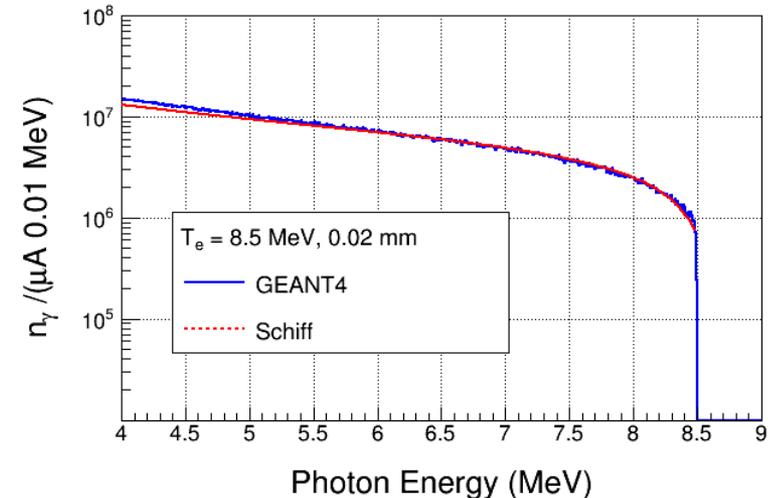
$$p = \frac{\int Bdl}{\theta}$$

| 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% |
| Total | $\delta P/P$ | 0.36% | <0.10% |

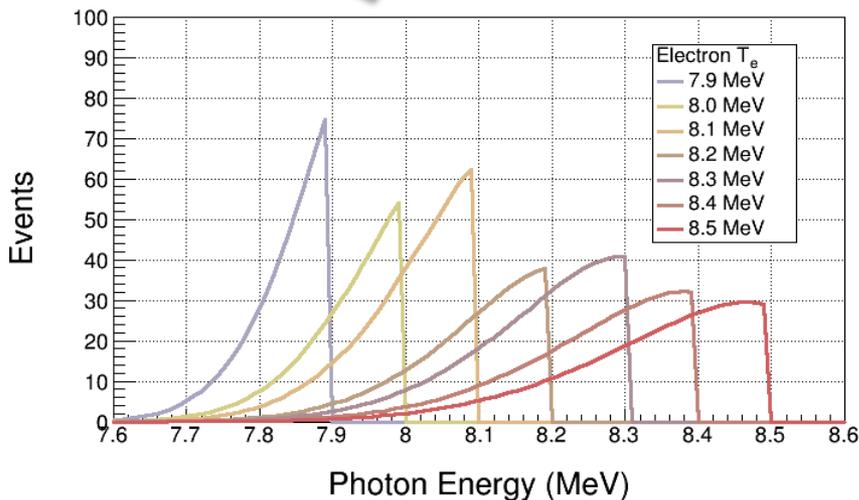
- I. Jay Benesch designed and now fabricating higher quality dipole (more uniformity, higher field)
- II. New Hall Probe: 0.01% accuracy, resolution to 2 ppm, and a temperature stability of 10 ppm/°C
- III. Better shielding of stray magnetic fields
- IV. Relative beam energy error: **<0.02%**

BREMSSTRAHLUNG BEAM

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



Bremsstrahlung
Peaks

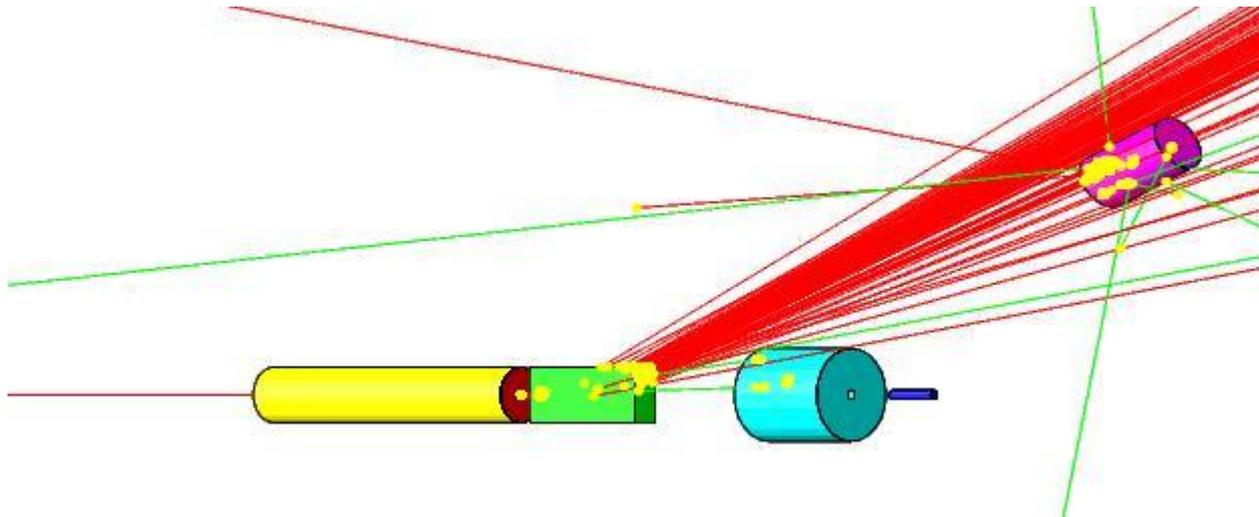


$^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ is ideal case for Bremsstrahlung beam and Penfold–Leiss Unfolding :

- 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. What to do?
 - I. Use GEANT4 and FLUKA to produce the photon spectra impinging on the superheated liquid.
 - II. Fold the above photon spectra with our cross sections in stand-alone codes.
- Use GEANT4 to design radiator, collimator, and dumps
- 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}O nuclei = $3.474 \cdot 10^{22} / \text{cm}^2$
- III. Background subtraction of $^{18}\text{O}(\gamma, \alpha)^{14}\text{C}$

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

| Electron Beam K. E. | Beam Current (μA) | 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 δE ($= 0.1\%$) 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

$$\text{var}(y_i, y_i) = (dy_i)^2$$

$$\text{cov}(y_i, y_j) = \rho_{ij} dy_i dy_j$$

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

No energy-to-energy change in systematic error

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

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

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

SYSTEMATIC ERROR PROPAGATION

No energy-to-energy change in systematic error

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

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

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, ε | 5% |

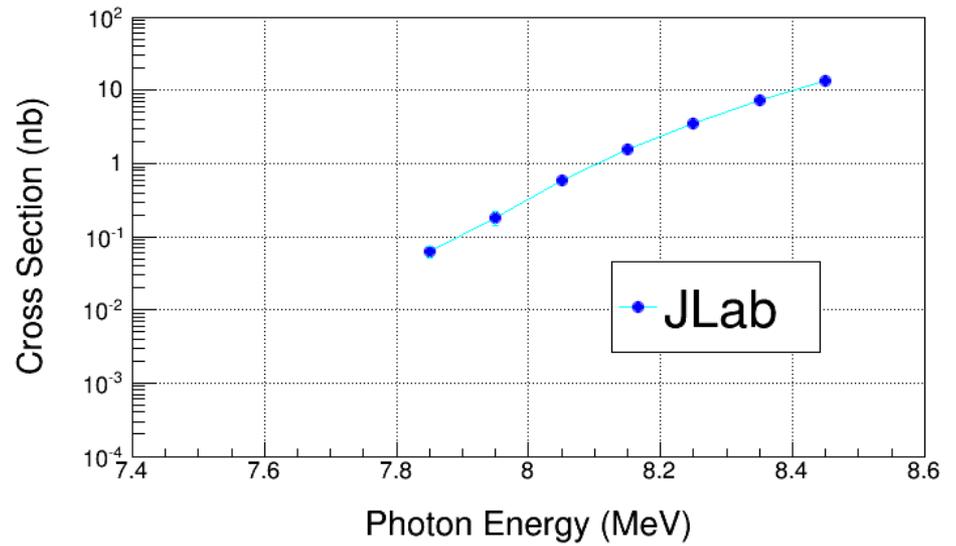
Simulation

- 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 |



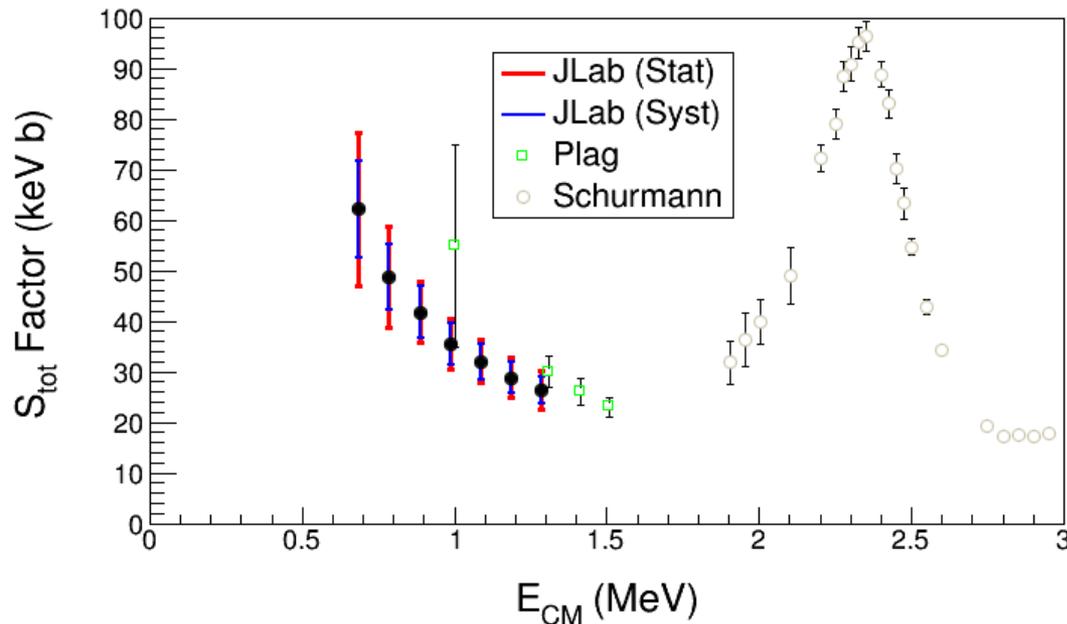
| Electron Beam K. E. | Cross Section (nb) | Sys Error (Energy, %) | Sys Error (Total, %) |
|---------------------|--------------------|-----------------------|----------------------|
| 7.9 | 0.046 | 12.5 | 15.3 |
| 8.0 | 0.185 | 10.2 | 13.5 |
| 8.1 | 0.58 | 8.3 | 12.2 |
| 8.2 | 1.53 | 7.0 | 11.4 |
| 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 magnified in PL Unfolding

JLAB PROJECTED $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ 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 N₂O:

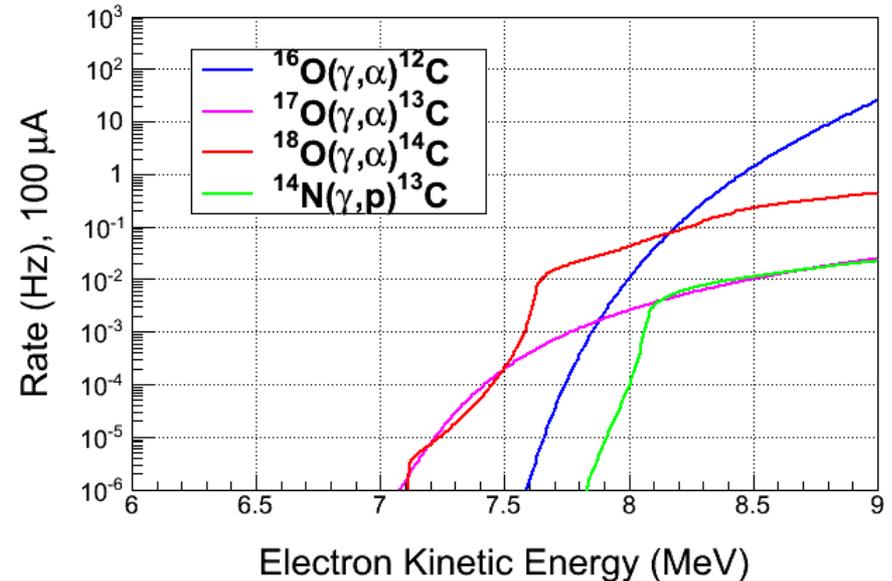
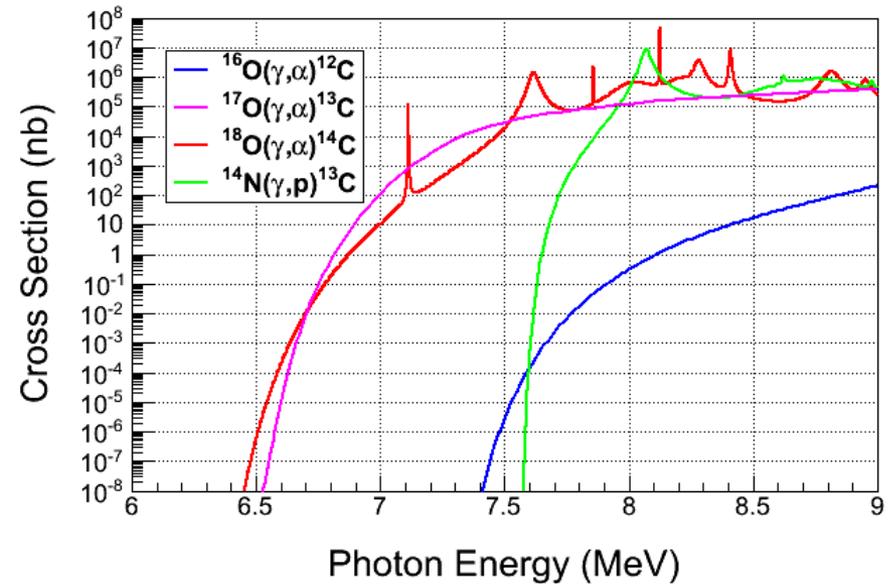
- $^{18}\text{O}(\gamma, \alpha)^{14}\text{C}$
- $^{17}\text{O}(\gamma, \alpha)^{13}\text{C}$
- $^{14}\text{N}(\gamma, p)^{13}\text{C}$

➤ Natural Abundance:

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

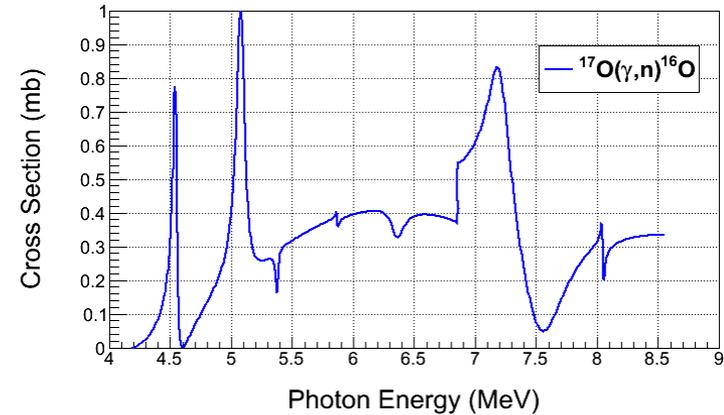
➤ Expected Rates:

- 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. $^{14}\text{N}(\gamma, p)^{13}\text{C}$, Chamber eff.= 10^{-8}



II. Background from:

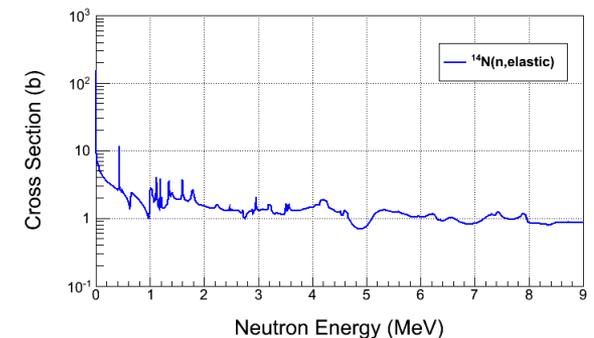
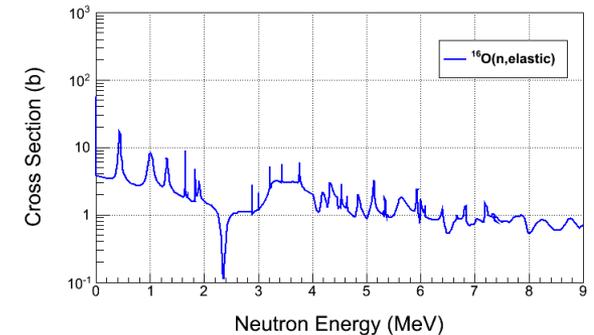
- $^{17}\text{O}(\gamma,n)^{16}\text{O}$ and secondary (n,n) neutron–nucleus elastic scattering



III. Cosmic–ray background:

- μ^\pm –nuclear
- neutron–nuclear elastic scattering

➤ Reject neutron events using acoustic signal (100 suppression factor)



ION ENERGY DISTRIBUTIONS

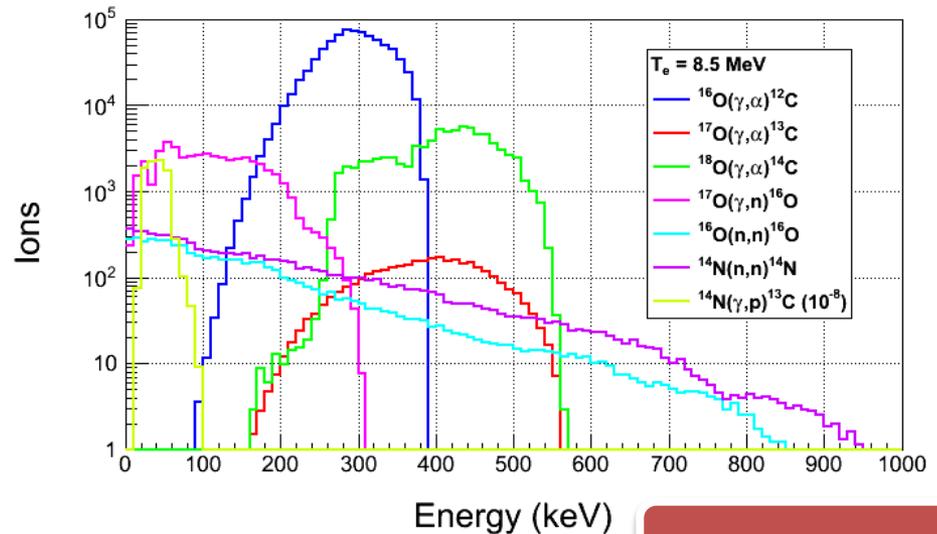
➤ Suppress background with Bubble Chamber thresholds

➤ Calculated with Depletion:

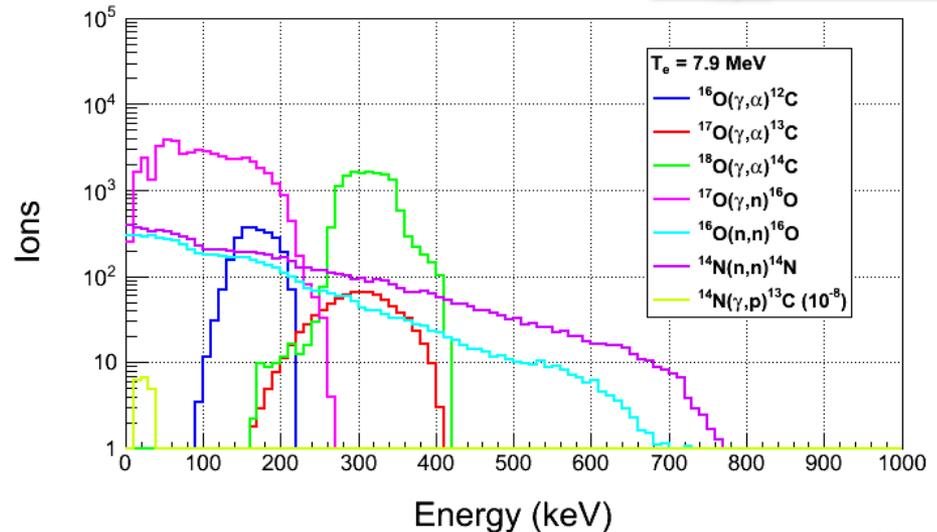
- I. ^{17}O depletion = 5,000
- II. ^{18}O depletion = 5,000

➤ Threshold Efficiency (function of superheat):

| Particle | Efficiency |
|----------|-------------|
| e^\pm | $<10^{-11}$ |
| γ | $<10^{-11}$ |

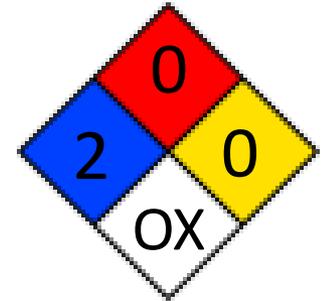


No acoustic cut



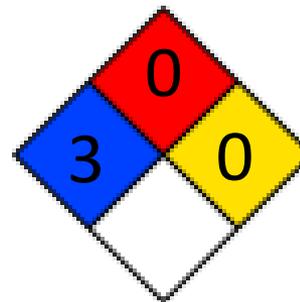
SAFETY

- Superheated 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. $T = 5^\circ\text{C}$
 - III. $P = 60 \text{ atm}$

- Buffer liquid: Mercury
 - I. Closed system
 - II. Volume: 135 mL



SUMMARY AND OUTLOOK

- More testing of N₂O Bubble Chamber at HIGS (February 2014)
- Measure cross sections of $^{18}\text{O}(\gamma, \alpha)^{14}\text{C}$ and $^{17}\text{O}(\gamma, \alpha)^{13}\text{C}$ at HIGS (Summer 2014)
- Test Bubble Chamber at JLab with Bremsstrahlung beam (October 2014)
- If successful, run depleted N₂O bubble chamber at JLab to measure $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$
- Beam issues:
 - Design radiator, collimator, and dumps with GEANT4
 - Simulate photon spectra with GEANT4 and FLUKA
 - Deliver 8.5 MeV K.E. beam to 5D Spectrometer with <0.1% absolute energy uncertainty
- Bubble Chamber issues:
 - Study acoustic signal and measure neutron events suppression factor
 - Deadtime measurements (now $\tau \pm d\tau = 10.0 \pm 0.9$ sec)
 - Measure O-isotopes depletion
- Background tests:
 - Measure cosmic-ray background
 - Study chamber thresholds efficiency vs. superheat and measure γ -rays suppression factor

BACKUP SLIDES

COST ESTIMATE

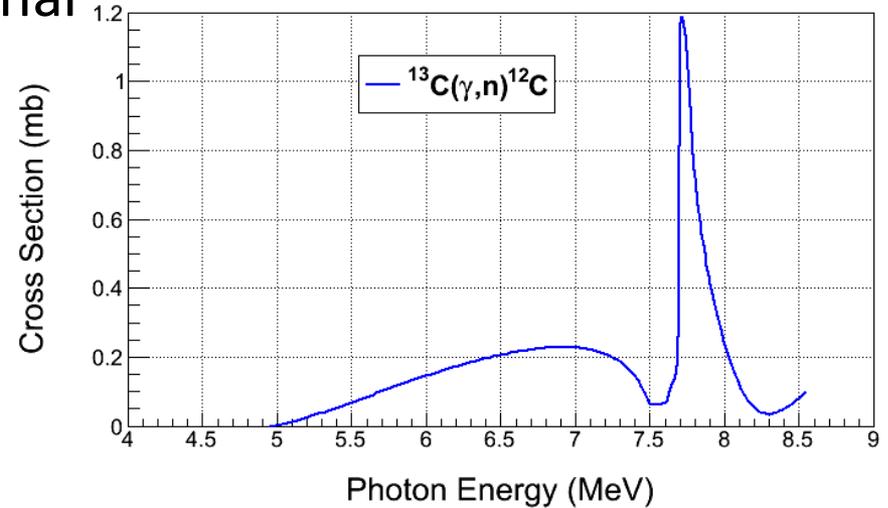
- I. New beamline components:
 - I. New Dipole Magnet and Hall Probe
 - II. 2 Super Harps
 - III. Fast Valve
- II. Summary of labor cost by group:

| 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 |

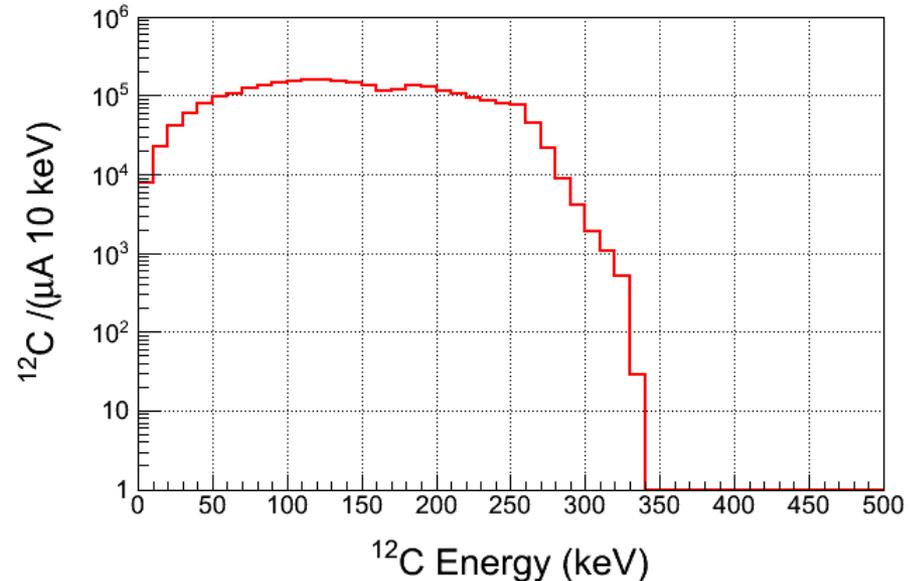
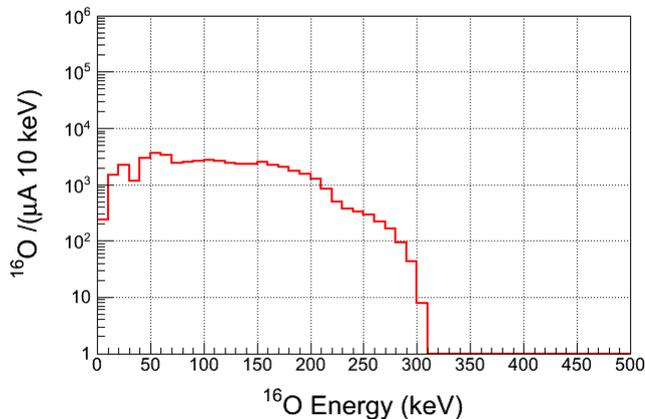
| Item | Material Procurement | Shop | Labor |
|---------------------------------|---|------------------------------|---|
| New Dipole Magnet | Dipole Magnet (\$8,000) Hall Probe System (\$10,000) | | Design (2 week) Mapping (1 week) EESDC (1 week) Alignment (2 days) |
| New Beamline | 2 Super Harps (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) |
| Total | \$76,000 | \$48,000 | \$80,000 |
| Indirect G&A (55.65%) | \$42,300 | \$26,400 | \$42,500 |
| Indirect Stat & Fringe (57.15%) | | | \$45,700 |
| Total | \$118,300 | \$74,400 | \$168,200 |

CO₂ SUPERHEATED LIQUID?

- Similar Bubble Chamber operational parameters as N₂O
- Natural Abundance: ¹³C: 1.07%
- Depletion: ¹³C depletion=1,000
- ¹³C(γ,n)¹²C Background



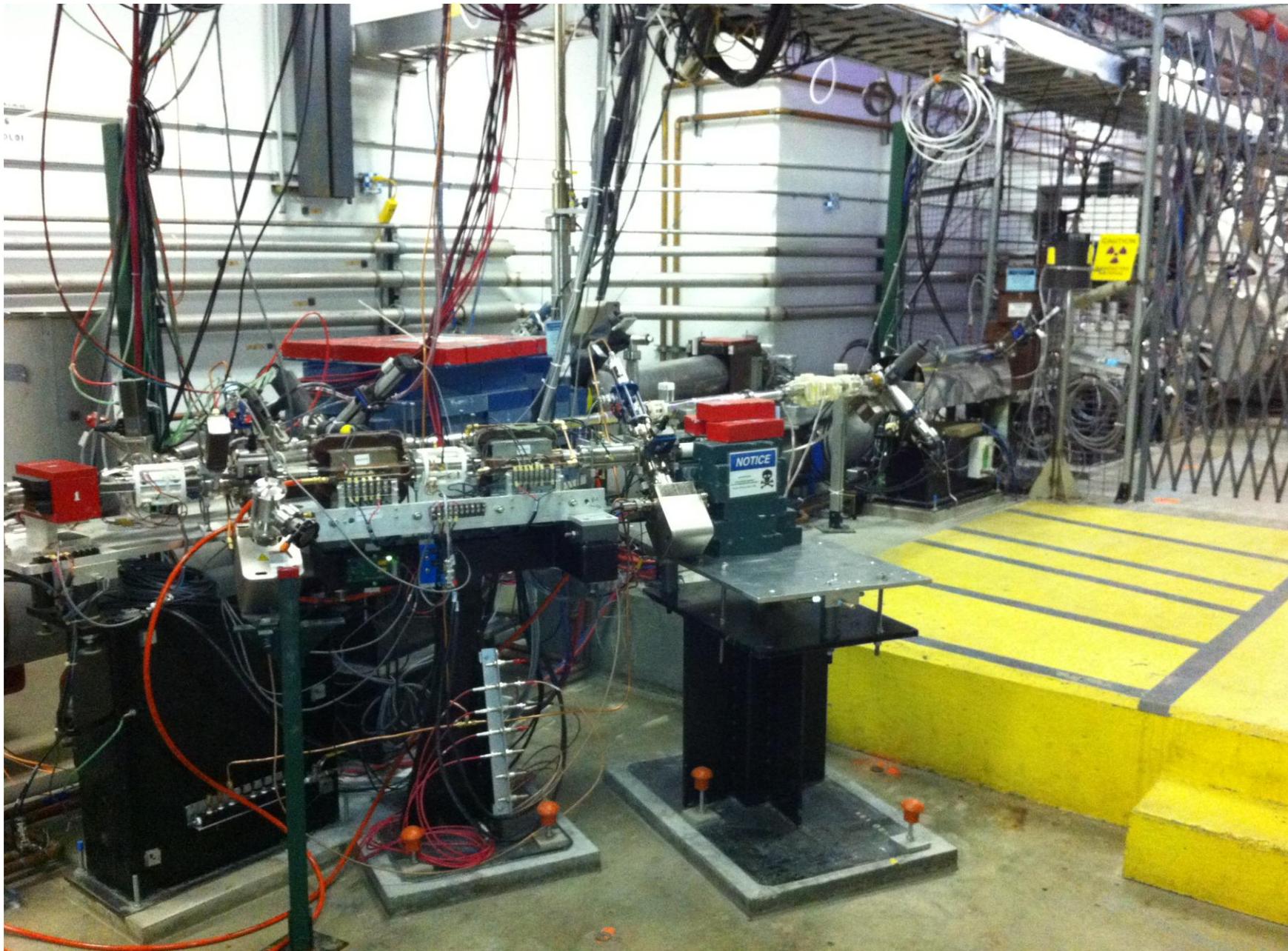
For comparison, ¹⁷O(γ,n)¹⁶O

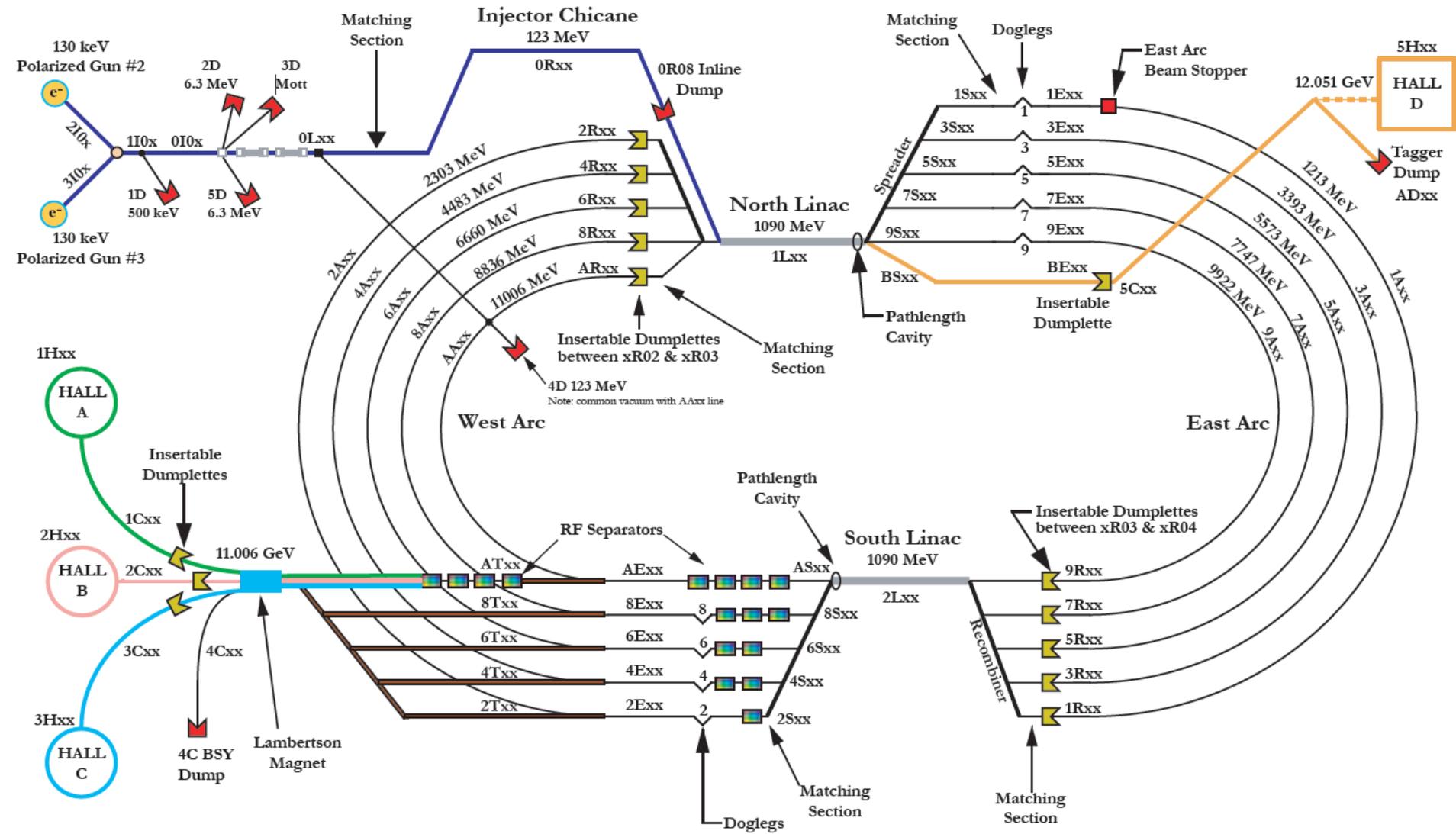


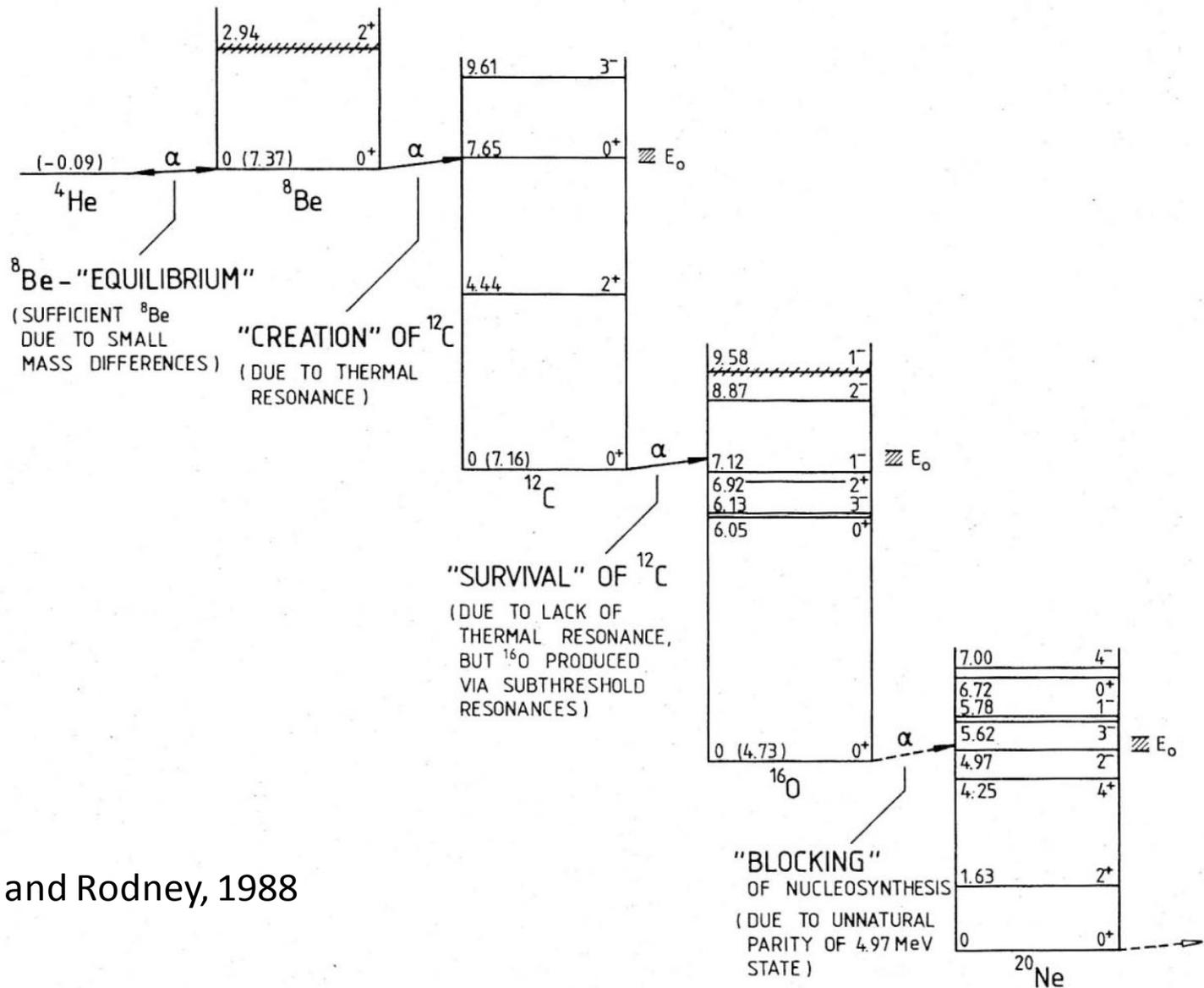
- ¹²C(γ,2α)α Background

WATER SUPERHEATED LIQUID?

- Etching of glass vessel by superheated H₂O
- T = 250°C
- P = 75 atm
- Background from secondary neutron–nucleus elastic scattering by neutrons from $d(\gamma,n)p$







Rolfs and Rodney, 1988