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

Riad Suleiman

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U.S. DEPARTMENT OF ENERGY JSA Jefferson Lab

Argonne NATIONAL LABORATORY

B. DiGiovine
D. Henderson
R. J. Holt
K. E. Rehm

THE UNIVERSITY OF CHICAGO

A. Robinson
C. Ugalde

Fermilab

A. Sonnenschein

Jefferson Lab

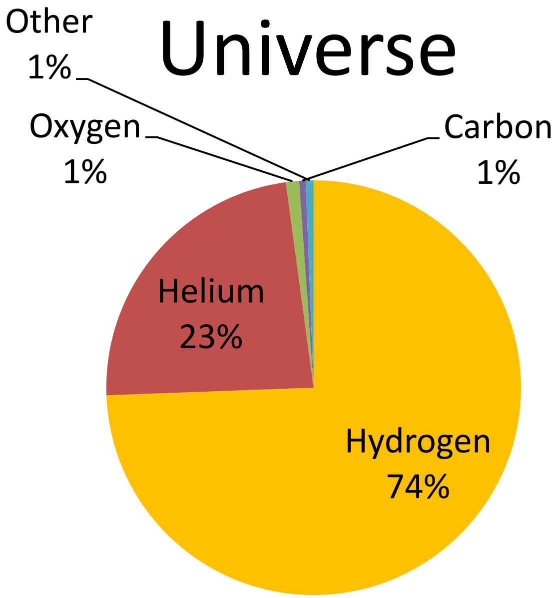
J. Benesch
P. Degtiarenko
A. Freyberger
J. Grames
G. Kharashvili
D. Meekins
M. Poelker
Y. Roblin
R. Suleiman
C. Tennant
V. Vylet

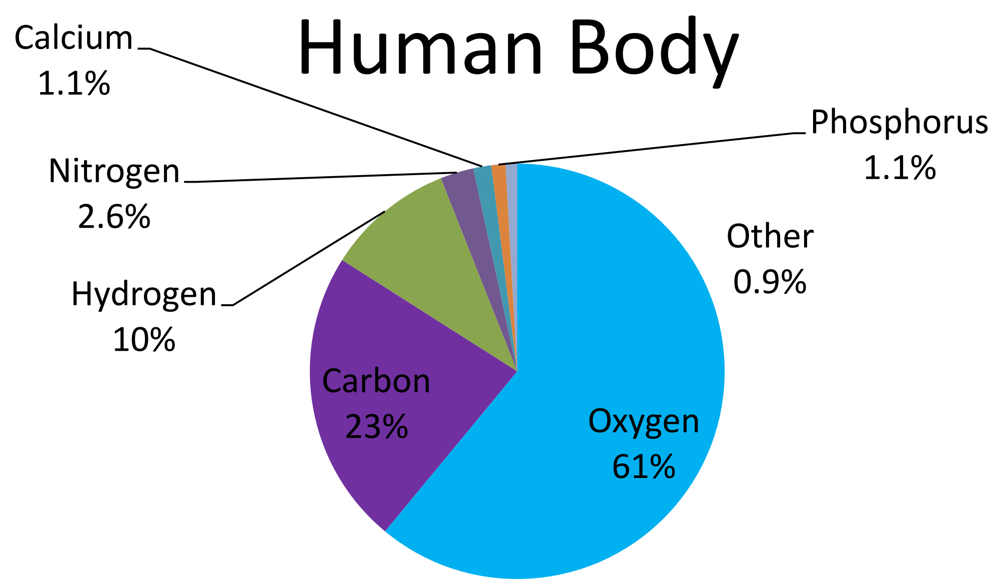
https://wiki.jlab.org/ciswiki/index.php/Bubble_Chamber

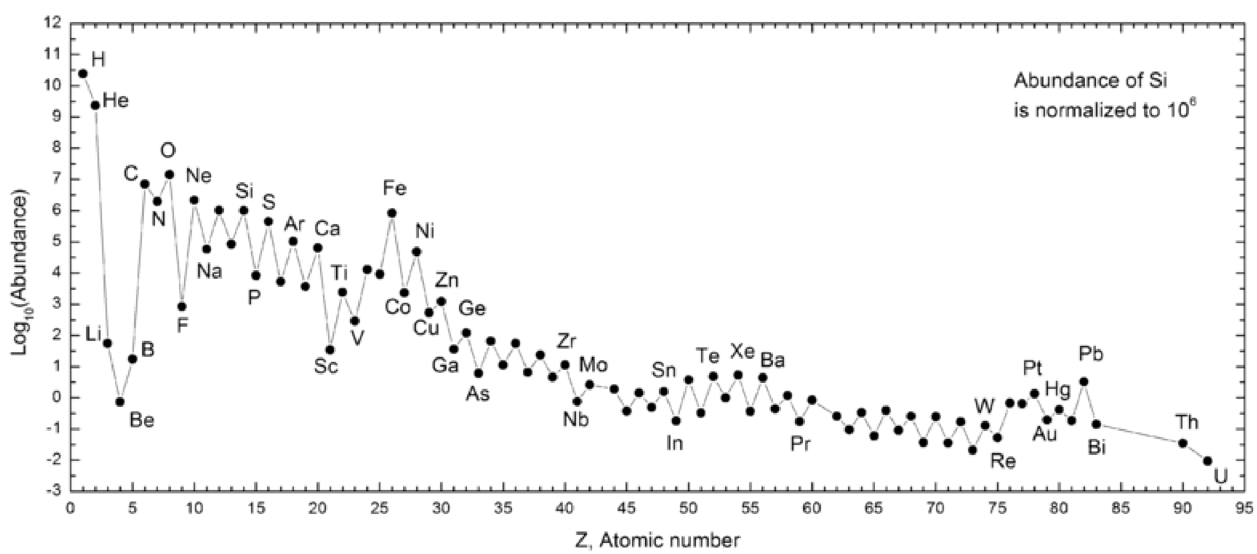
Outline

- Nucleosynthesis and the $^{12}C(\alpha,\gamma)^{16}O$ Reaction
- Time-reversal Reaction: $^{16}O(\gamma,\alpha)^{12}C$
- 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

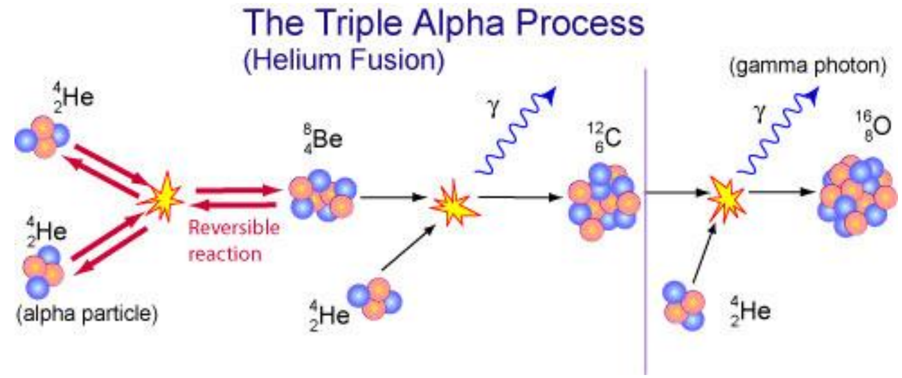






Stellar Helium Burning

- Helium Reactions:
  I. $\alpha + \alpha \leftrightarrow {}^{8}\text{Be}$ ($T_{1/2} \approx 10^{-16}$ s)
  II. $\alpha + {}^{8}\text{Be} \rightarrow {}^{12}\text{C} + \gamma$
  III. $\alpha + {}^{12}\text{C} \rightarrow {}^{16}\text{O} + \gamma$
  (slow, otherwise no ^{12}C remains)
  III. $\alpha + {}^{16}\text{O} \rightarrow {}^{20}\text{Ne} + \gamma$ (very slow)



- $\alpha + {}^{12}\text{C}$ burning at very small cross section $\sigma \approx 10^{-17}$ barn
  ➡ Currently, reaction rate error is large (±35%)

Goal <±10%

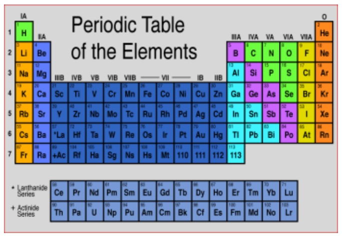
- Thermonuclear reaction rate involving two nuclei is:

Only narrow energy range is important (Gamow Peak)

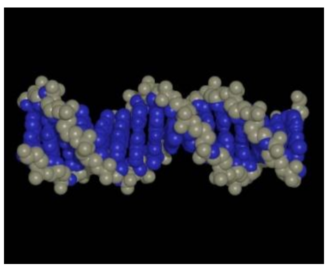
$$R = \sqrt{\frac{8}{\pi m (k_B T)^3}} \int_0^\infty E \sigma_{tot}(E) e^{-\frac{E}{k_B T}} dE$$

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

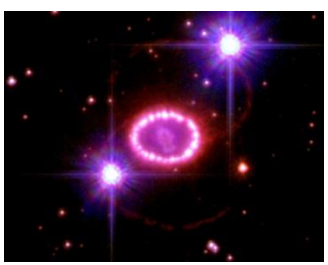
- The *holy grail* of nuclear astrophysics



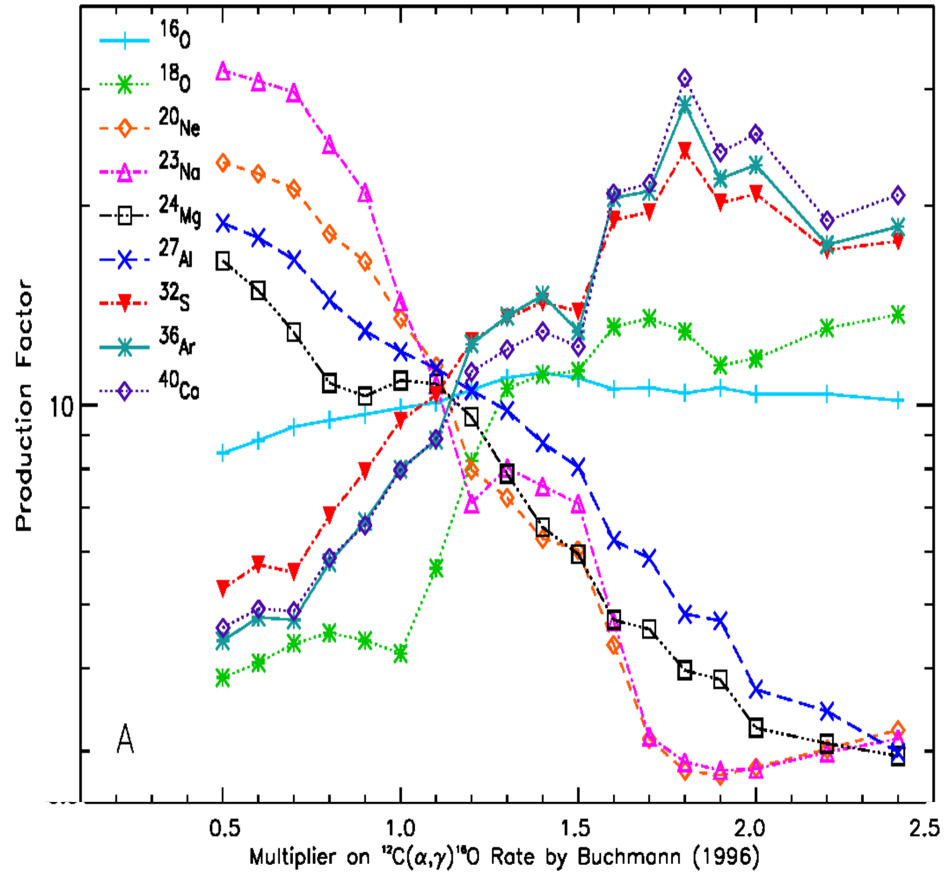
Affects the synthesis of most of the elements of the periodic table



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



Determines the minimum mass a star requires to become a supernova



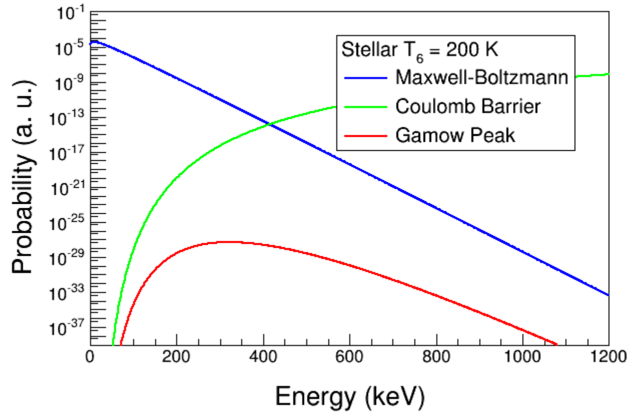
S. Woosley, A. Heger, Phys. Rep. **442** (2007) 269

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_BT}
  II. Penetration through Coulomb barrier with $e^{-b/E^{½}}$

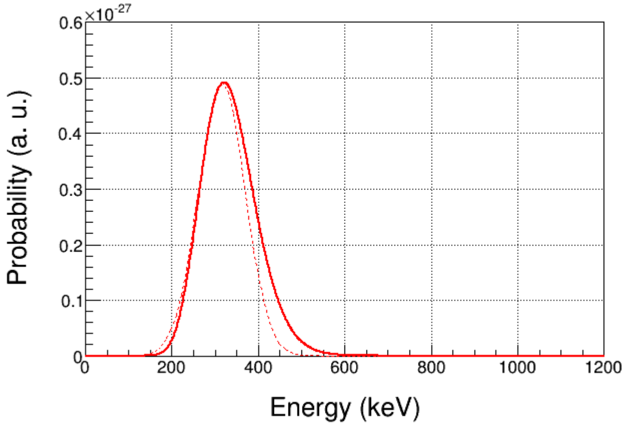
$$E_0 = 1.220\left(Z_1^2 Z_2^2 A T_6^2\right)^{\frac{1}{3}}\ \text{keV}$$

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



- For α + ^{12}C (Z_1=2, Z_2=6, A=3), and stellar T=200 10^6 K:

  - **Gamow Peak, E_0 ≈ 300 keV, W ≈ 50 keV**
  - Maximum of Maxwell–Boltzmann energy distribution, k_BT = 17 keV

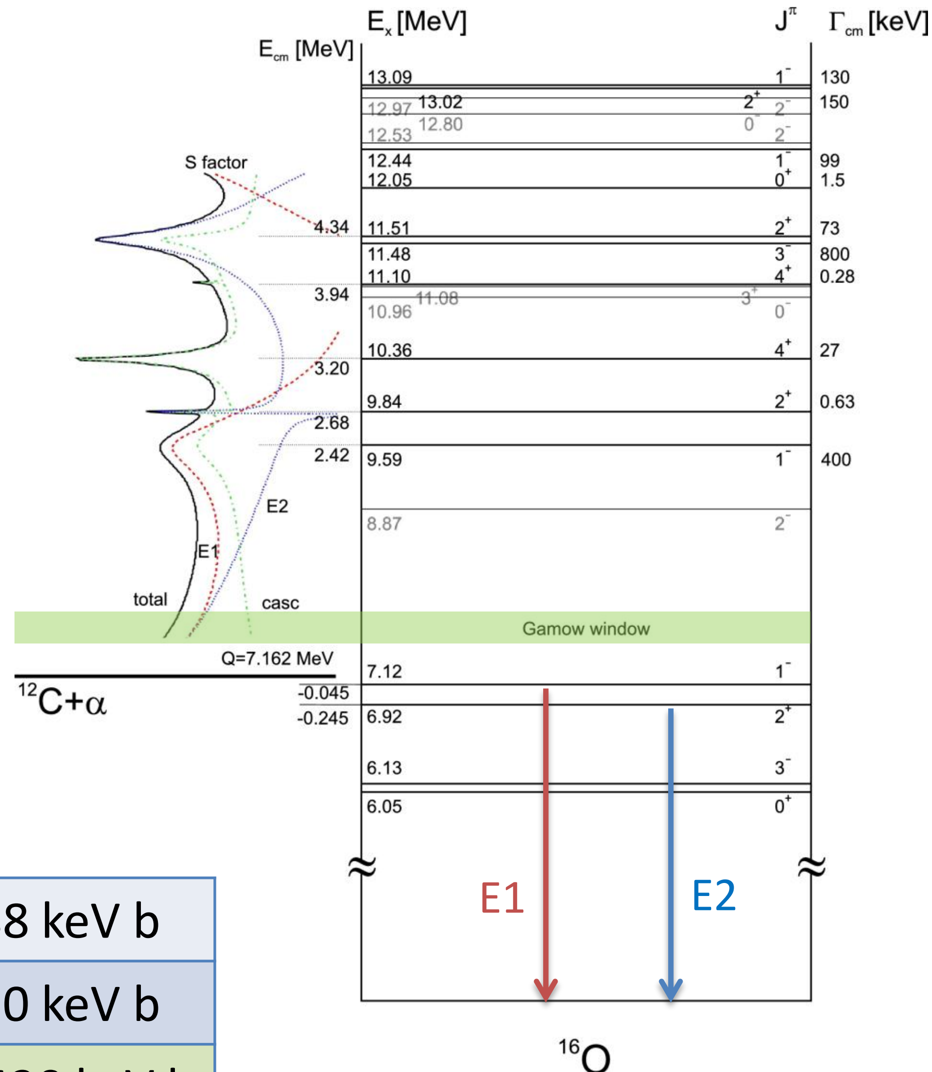


α + ^{12}C Radiative Capture

- $\sigma(E_0)$ is dominated by *p*–wave (E1) and *d*–wave (E2) radiative capture to ($J^\pi=0^+$) ^{16}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 → 0 (E1)	$S_{E1}(300)$ = 1–288 keV b
Transition → 0 (E2)	$S_{E2}(300)$ = 7–120 keV b
Total	$S_{tot}(300)$ = 40–430 keV b

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

- Previous Experiments:

A. Direct Techniques:

I. Helium ions on carbon target: $^{12}C(\alpha,\gamma)^{16}O$

II. Carbon ions on helium gas: $^{4}He(^{12}C,^{16}O)\gamma$

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

B. Indirect Methods:

I. β–delayed α decay of ^{16}N ($J^{\pi}=2^{-}$, $T_{1/2}=7.13$ s, BR=0.12%)

$^{16}N \rightarrow \beta^{-} + {}^{16}O^{*}$ ($J^{\pi}=1^{-}$) $\rightarrow \alpha + {}^{12}C$

II. Elastic α – ^{12}C scattering

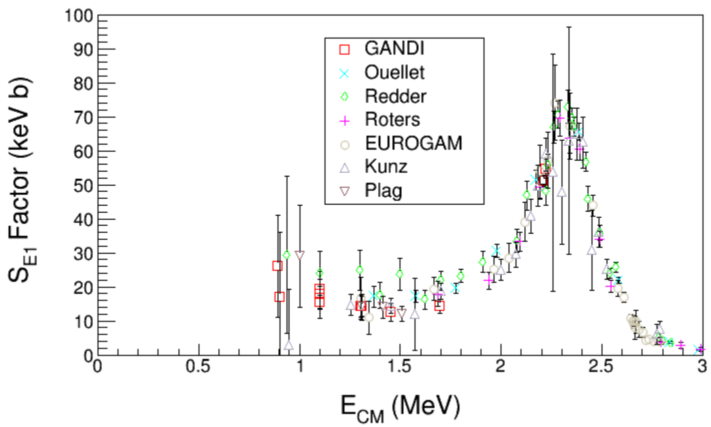
Astrophysical S-Factor $^{12}C(\alpha,\gamma)^{16}O$

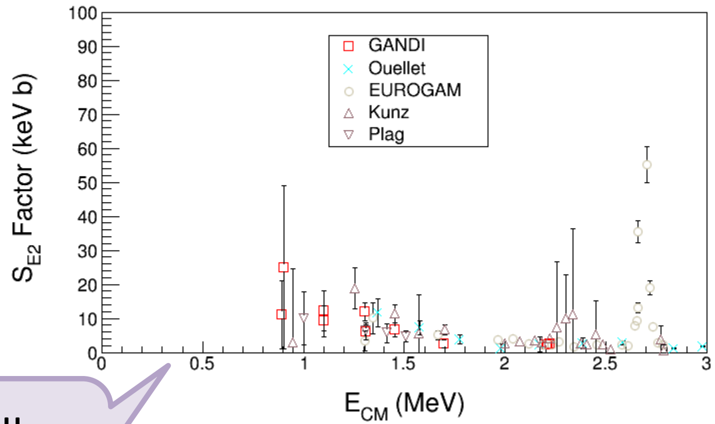
- Define *S-Factor* to remove both 1/E dependence of nuclear cross sections and Coulomb barrier transmission probability:

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

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

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





<u>R-matrix Extrapolation</u> to stellar helium burning at E = 300 keV

RECIPROCITY RELATION: (γ,α) and (α,γ)

- A(α, γ)B:

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

$$m_{A\alpha}c^2 = \frac{M(^{12}C)\cdot M(\alpha)}{M(^{12}C)+M(\alpha)} = 2796\ \text{MeV}$$

$$J_i = 0, J_j = 0, J_\alpha = 0$$

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

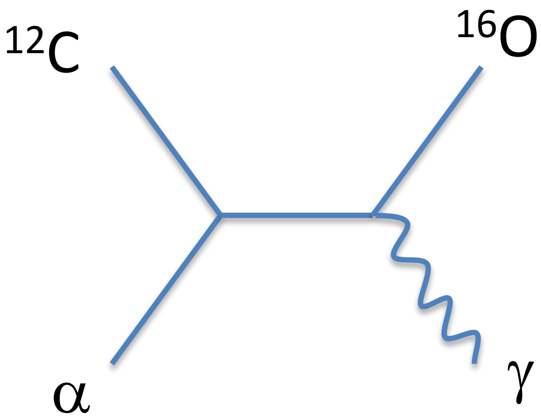
$$Q = m_A + m_\alpha - m_B = 7.162\ \text{MeV}$$

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

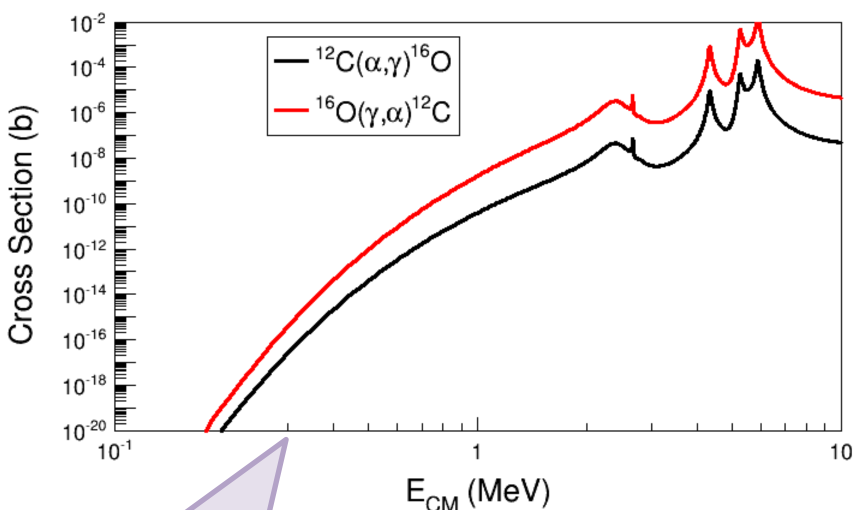
$$\sigma_{(\gamma,\alpha)}(E_\gamma) = \frac{m_{A\alpha}c^2E_{CM}}{E_\gamma^2}\sigma_{(\alpha,\gamma)}(E_{CM})$$

- σ(γ,α) is over <u>two orders</u> of magnitude larger than σ(α, γ)

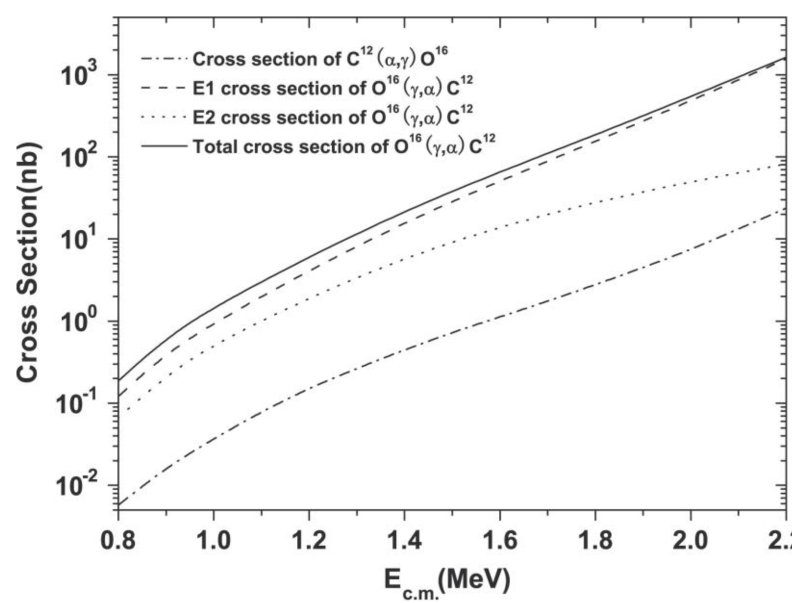
Time Reversal Reaction



- 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

beam | target | signal

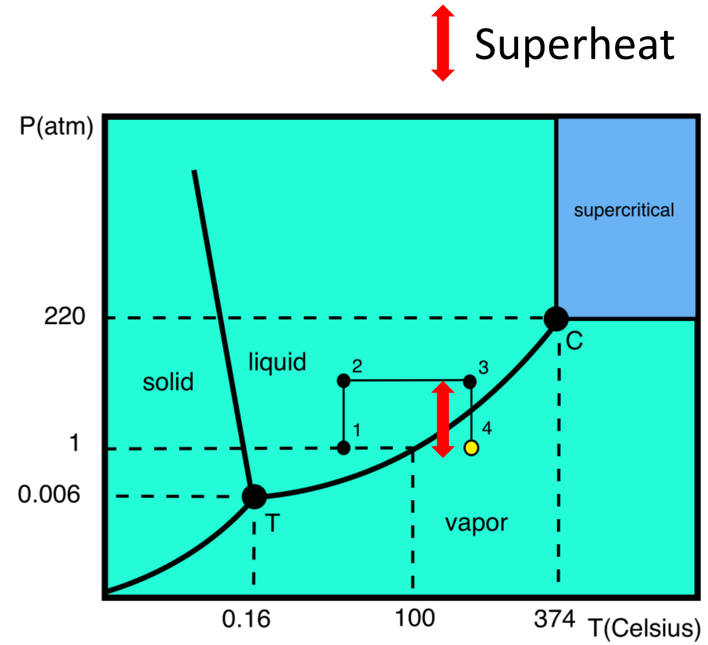
$$\gamma + {}^{16}O \rightarrow {}^{12}C + \alpha$$

- 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 = $3.5\ 10^{22}\ /cm^2$ (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 ≈ $10^{7\text{-}8}\ \gamma/s$
- Bremsstrahlung at JLab ≈ $10^9\ \gamma/s$ (top 250 keV)

The Bubble Chamber

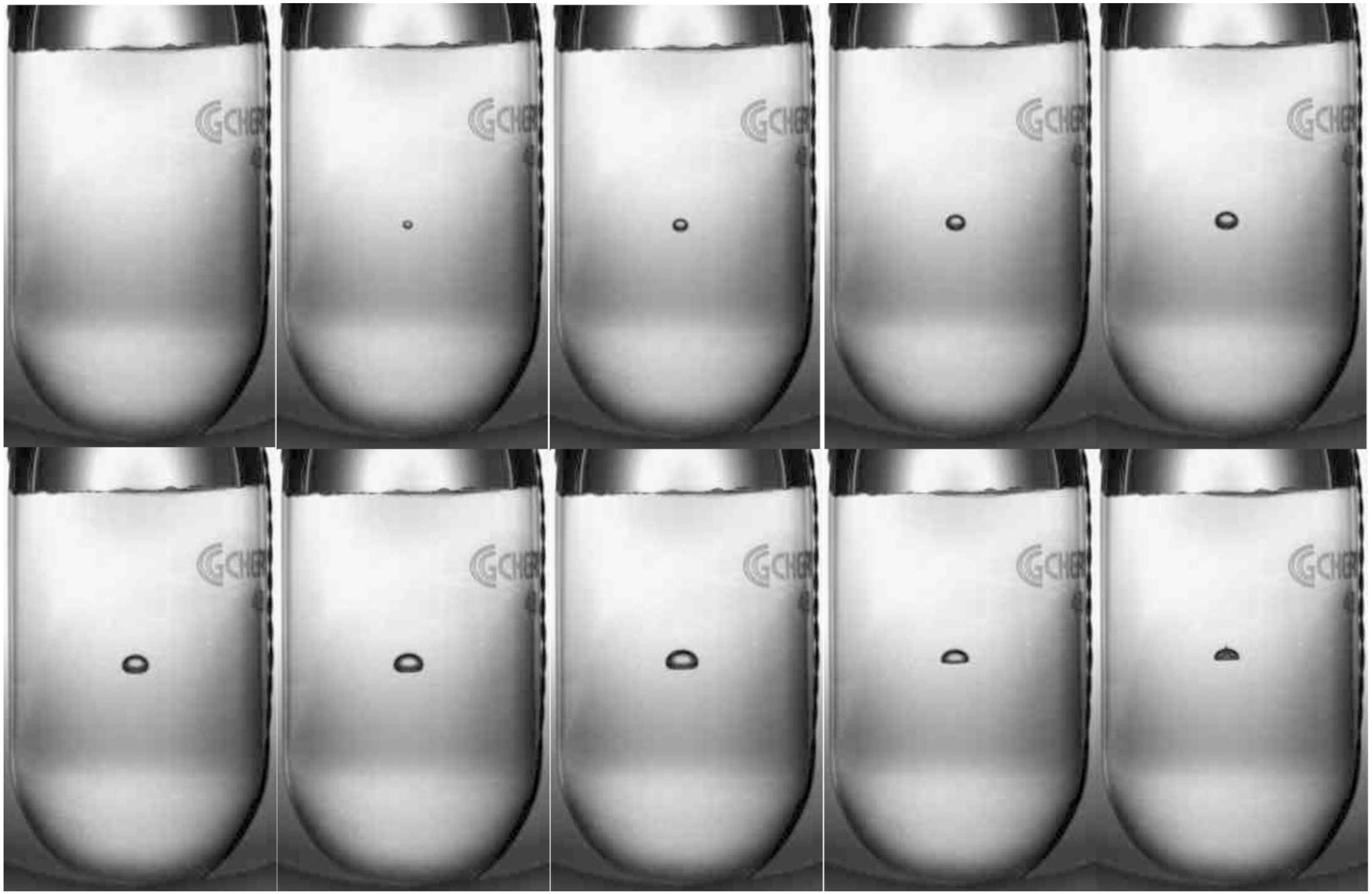
- Donald Glaser won Nobel Prize for inventing chamber to detect particles (1960)
- Now being used in Dark Matter Search Experiments: COUPP, PICASSO, SIMPLE
- Superheat Preparation:
  - Liquid is pressurized at ambient temperature (1 to 2)
  - Then pressure is kept constant while temperature is increased 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 Growth and Quenching:
  - A small disturbance will induce vaporization
  - When this happens , bubble growth process needs to be controlled by increasing pressure (4 to 3). It takes about 10 seconds for liquid to return to a stable state
  - Superheat is then returned into system by releasing pressure again (3 to 4), and cycle is repeated for each bubble event



Bubble Growth and Quenching

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

Fast Camera: Δt = 10 ms



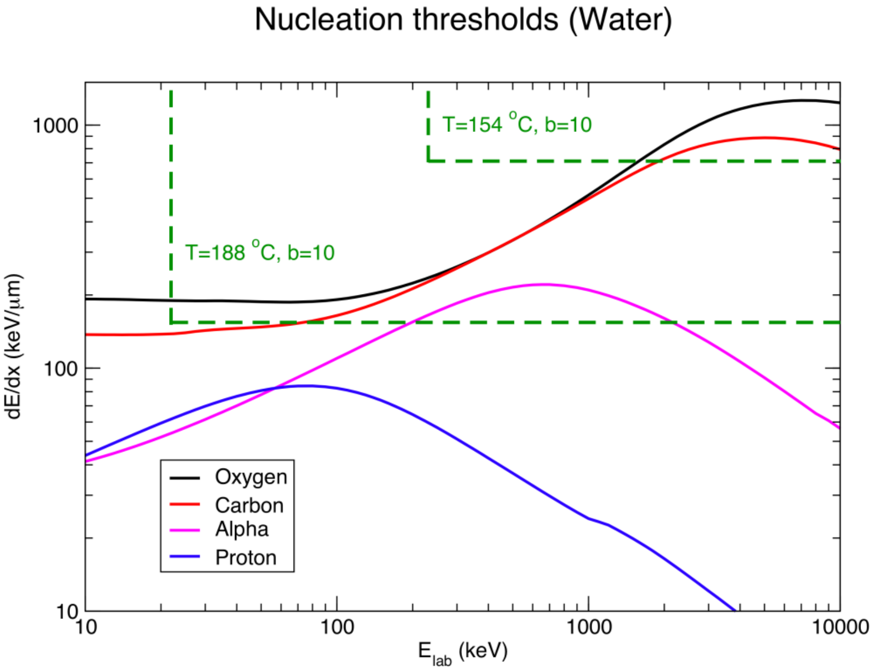
Bubble Chamber Principle

- Gamma suppression of 10^{11}
- Nuclear recoil threshold

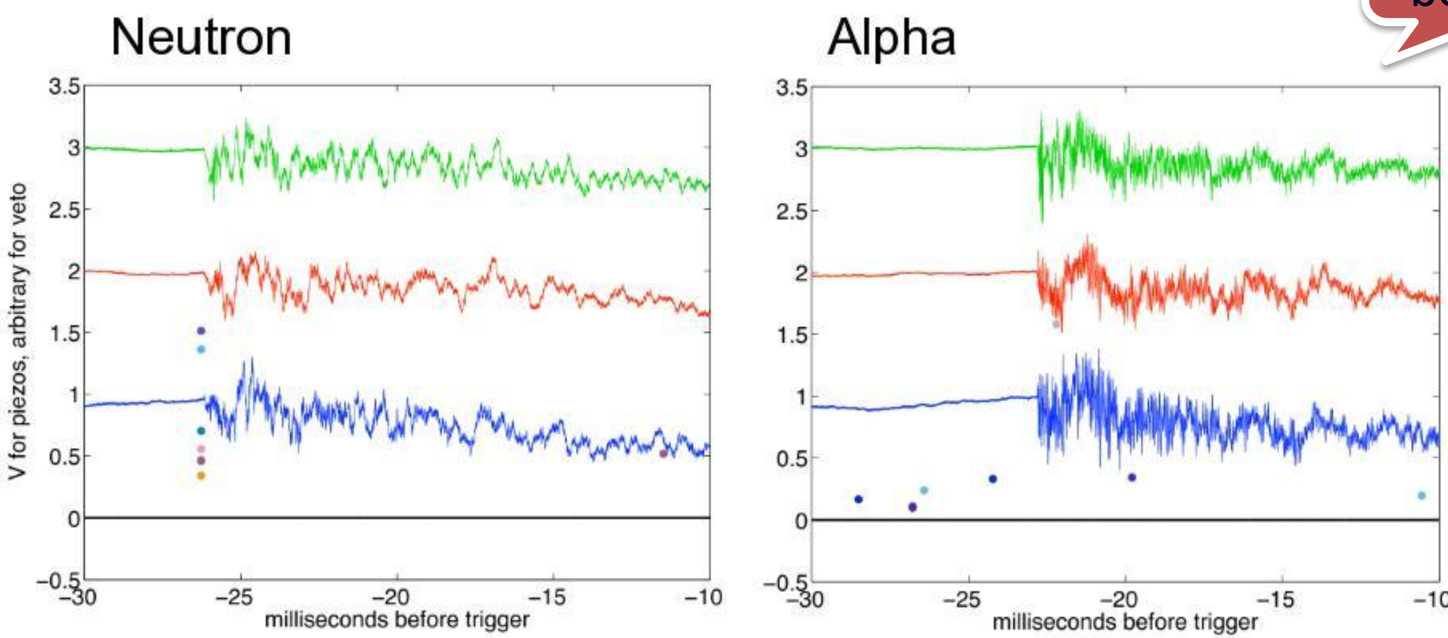
$$R_c = 2s/(P_v - P)$$

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

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



ACOUSTIC SIGNAL: PARTICLE ID



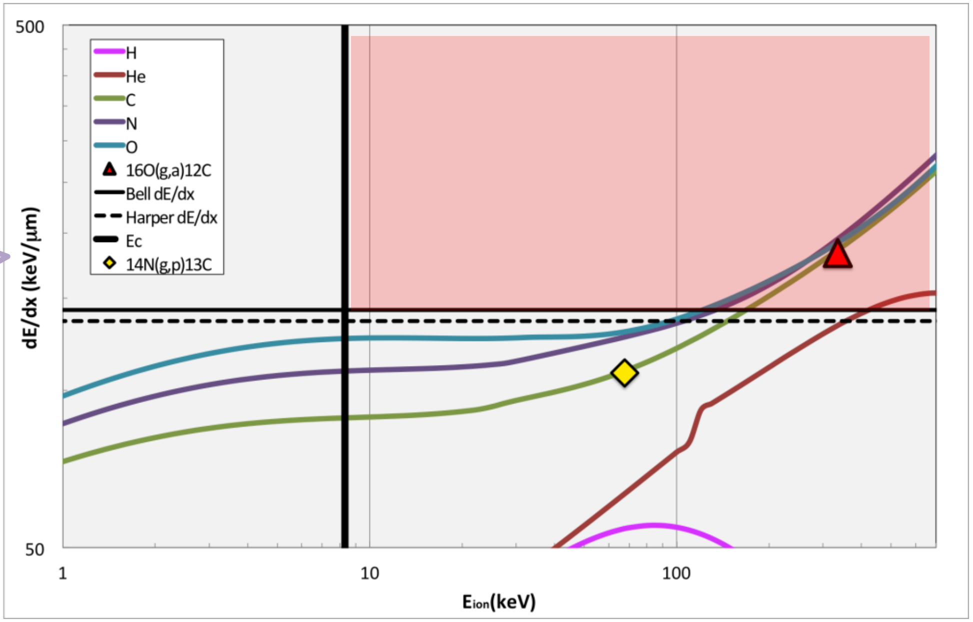
α should be louder

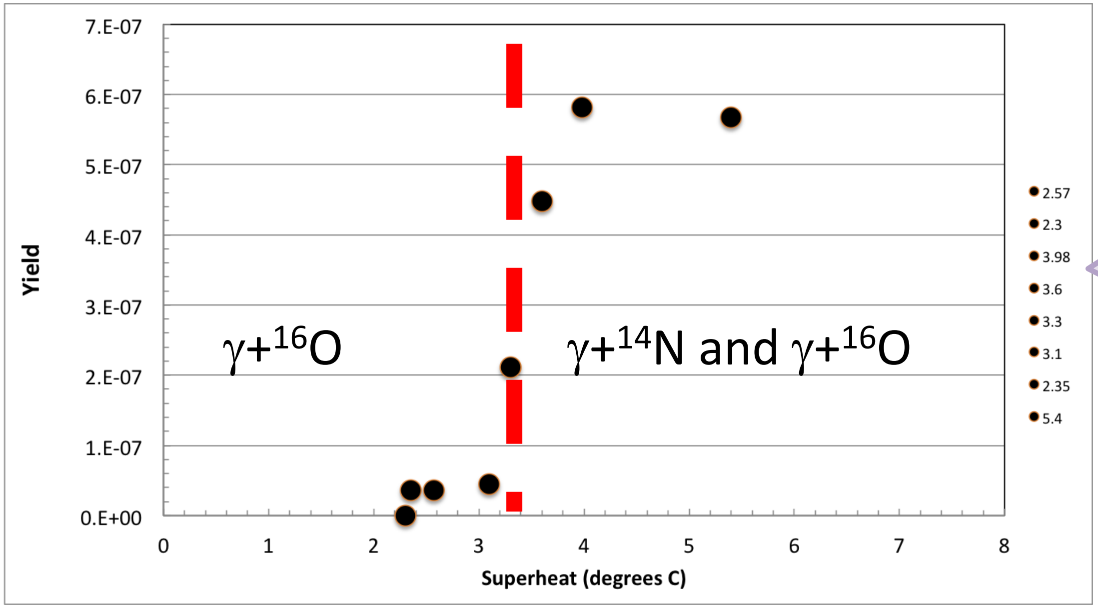
Suppress neutron events by x500 from acoustic signal

COUPP, FNAL, courtesy of A. Sonnenschein

EFFICIENCY CURVE

N_2O thresholds,
Superheat = 3.3˚C,
E_γ=8.5 MeV



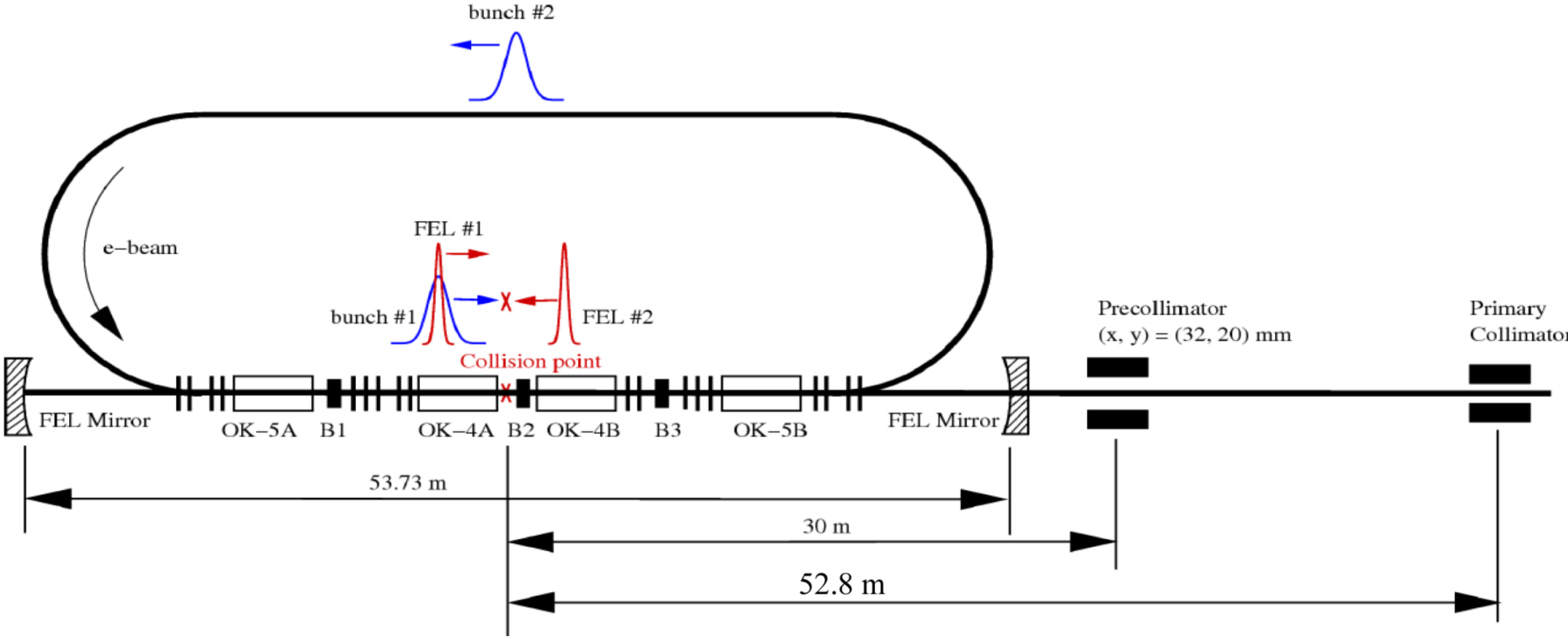


N_2O efficiency curve,
HIGS April 2013,
E_γ = 9.7 MeV

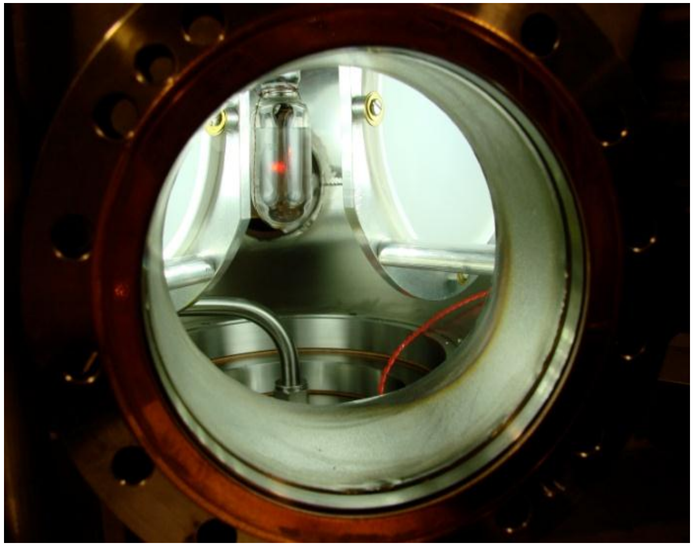
Bubble Chamber at HIGS

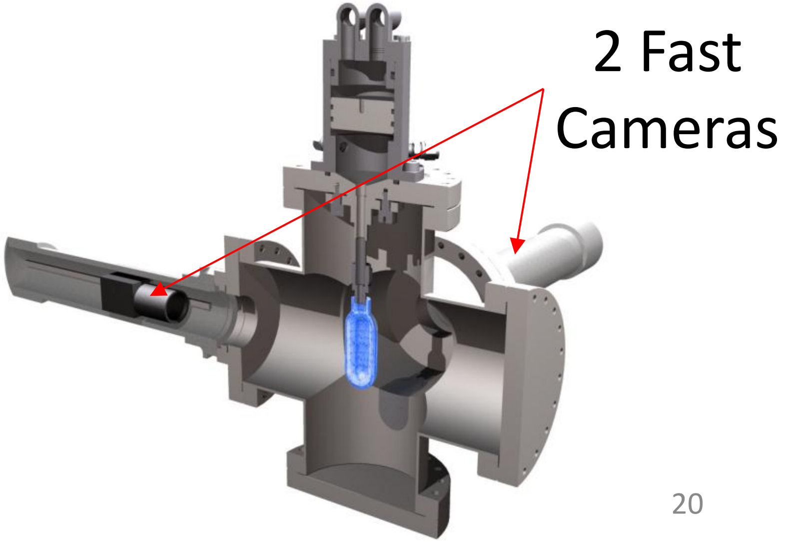
I. High Intensity Gamma Source (HIGS) at Duke University

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



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





C_4F_{10} Bubble Chamber

T = 30˚C

P = 3 atm

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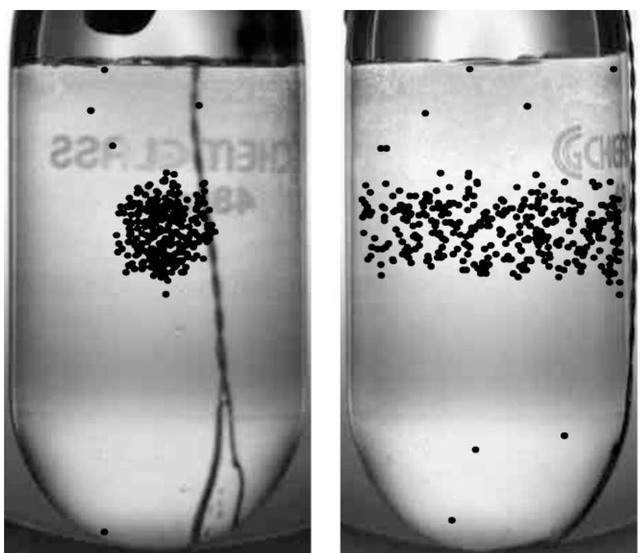
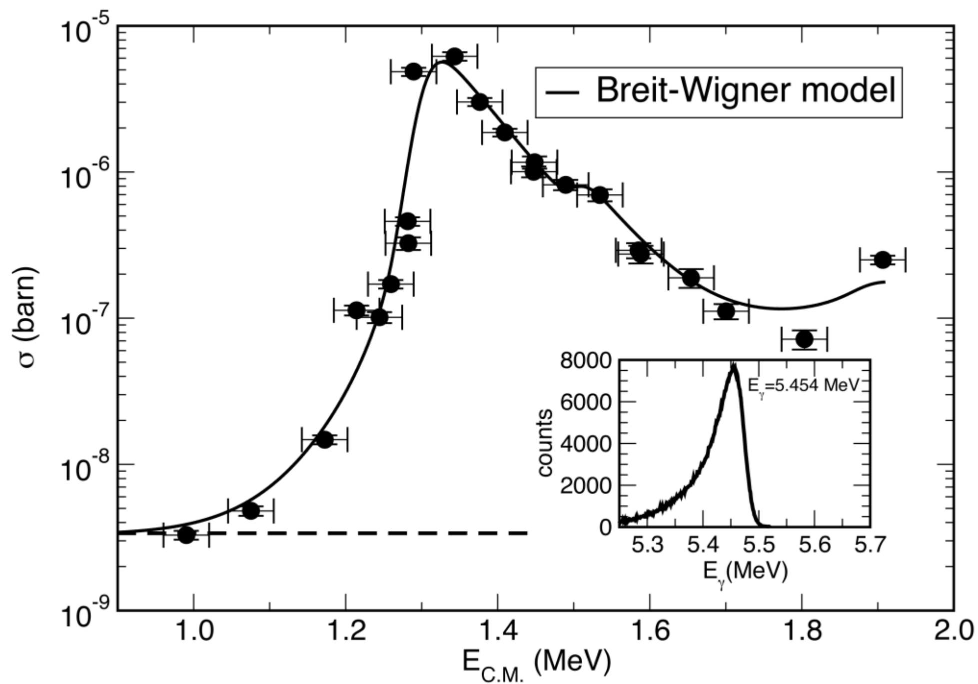
First determination of an astrophysical cross section with a bubble chamber: The $^{15}N(\alpha,\gamma)^{19}F$ reaction

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

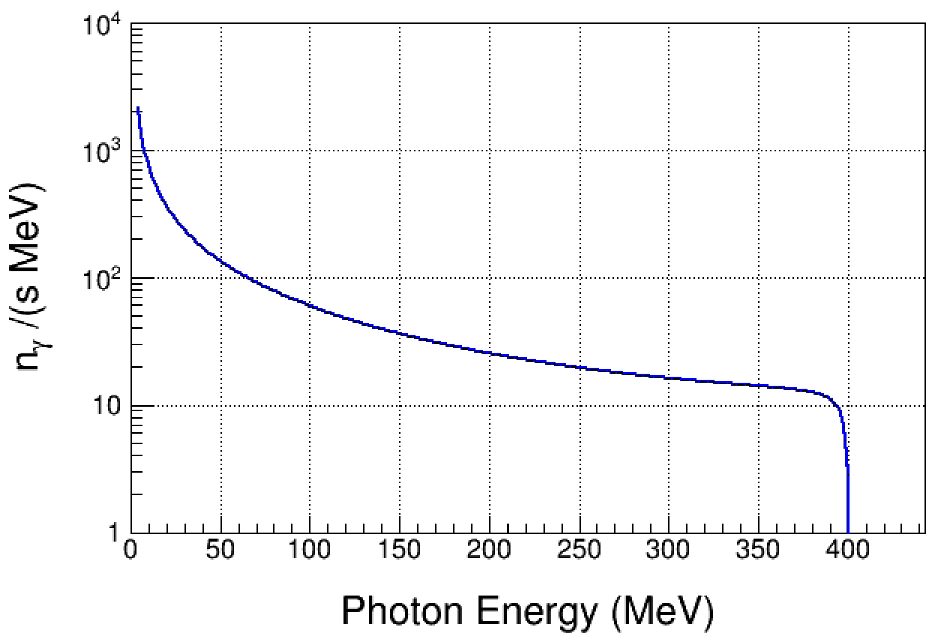




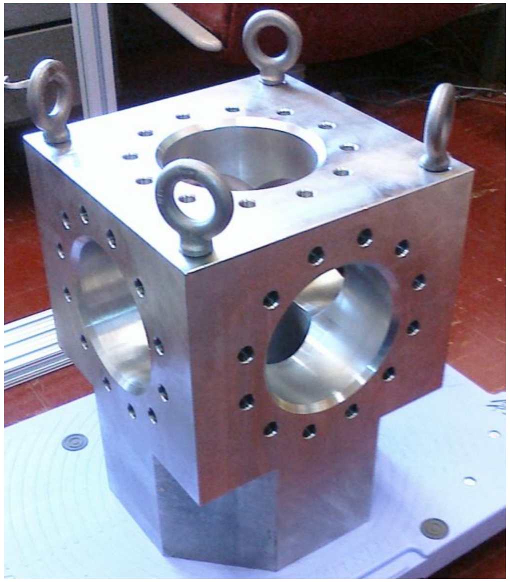
BREMSSTRAHLUNG BACKGROUND AT HIGS

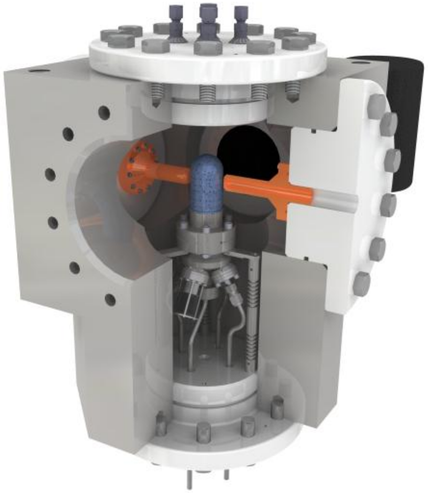
Vacuum: $2x10^{-10}$ Torr
Residual Gas: Z = 10
Electron Beam Energy: 400 MeV
Electron Beam Current: 41 mA
Interaction Length: 35 m

Strong Bremsstrahlung Background

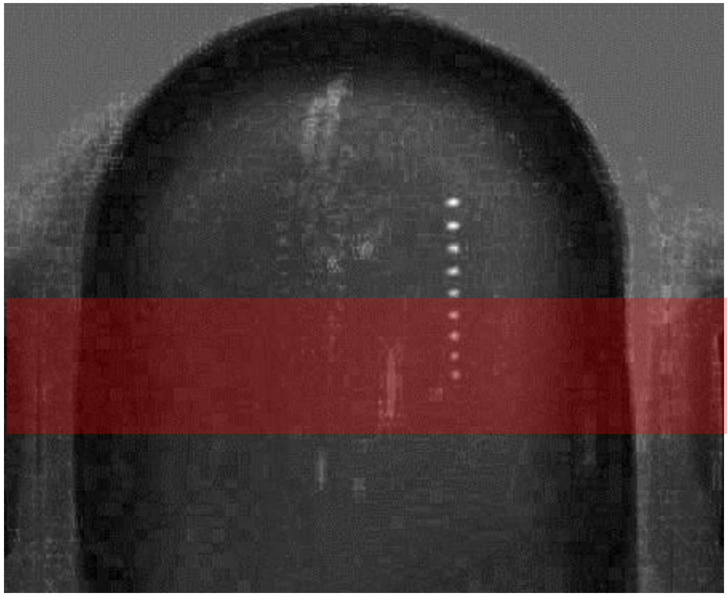


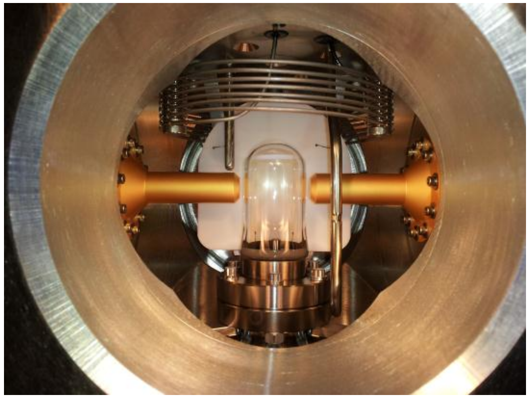
Recent Work





N_2O Bubble Chamber:
first γ+O→α+C bubble
April 2013





SUPERHEATED TARGETS

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

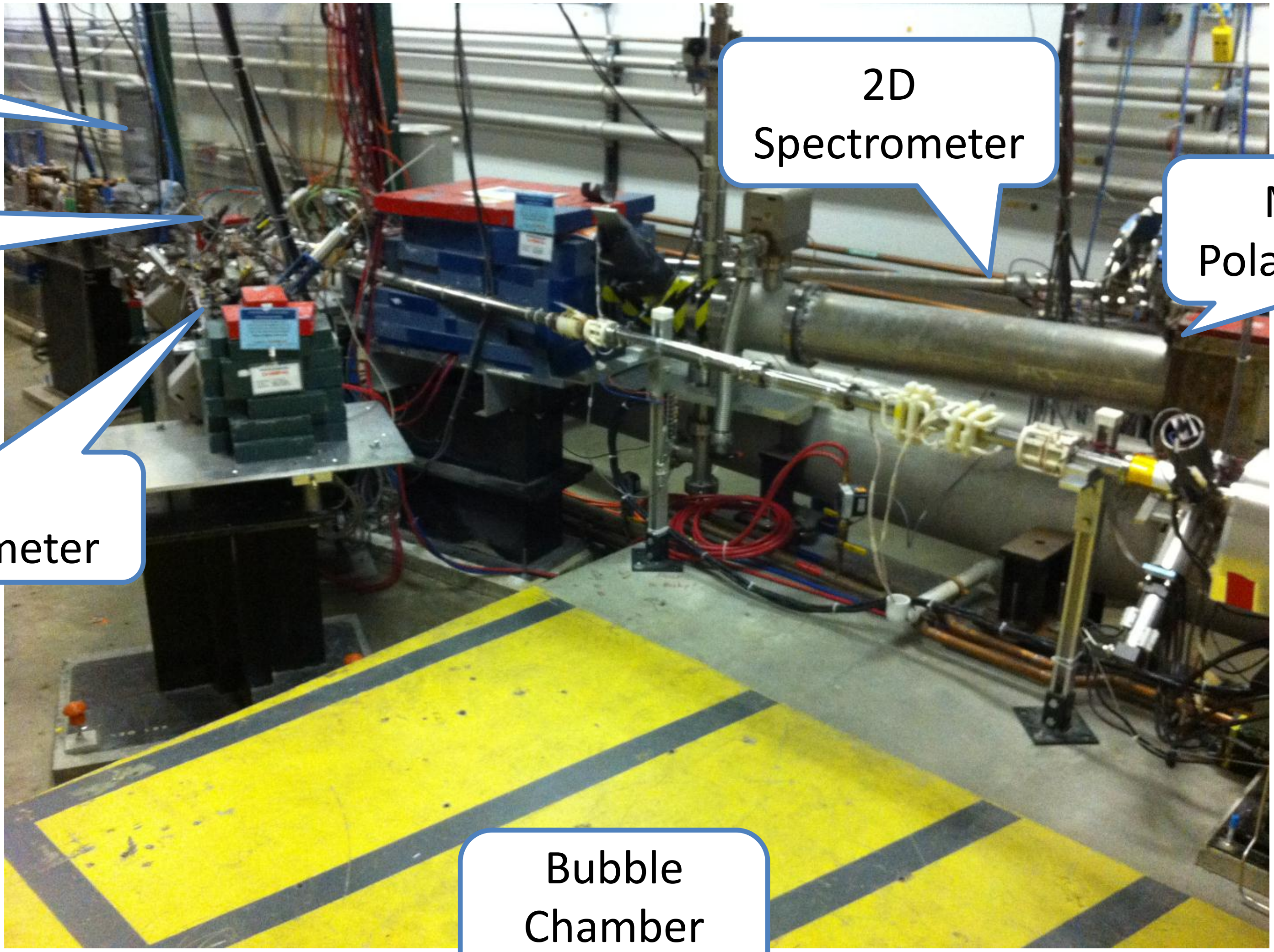
N_2O Targets	^{16}O	^{17}O	^{18}O
Natural Target	99.757%	0.038%	0.205%
^{16}O Target		Depleted > 5,000	Depleted > 5,000
^{17}O Target		Enriched > 80%	<1.0%
^{18}O Target		<1.0%	Enriched > 80%

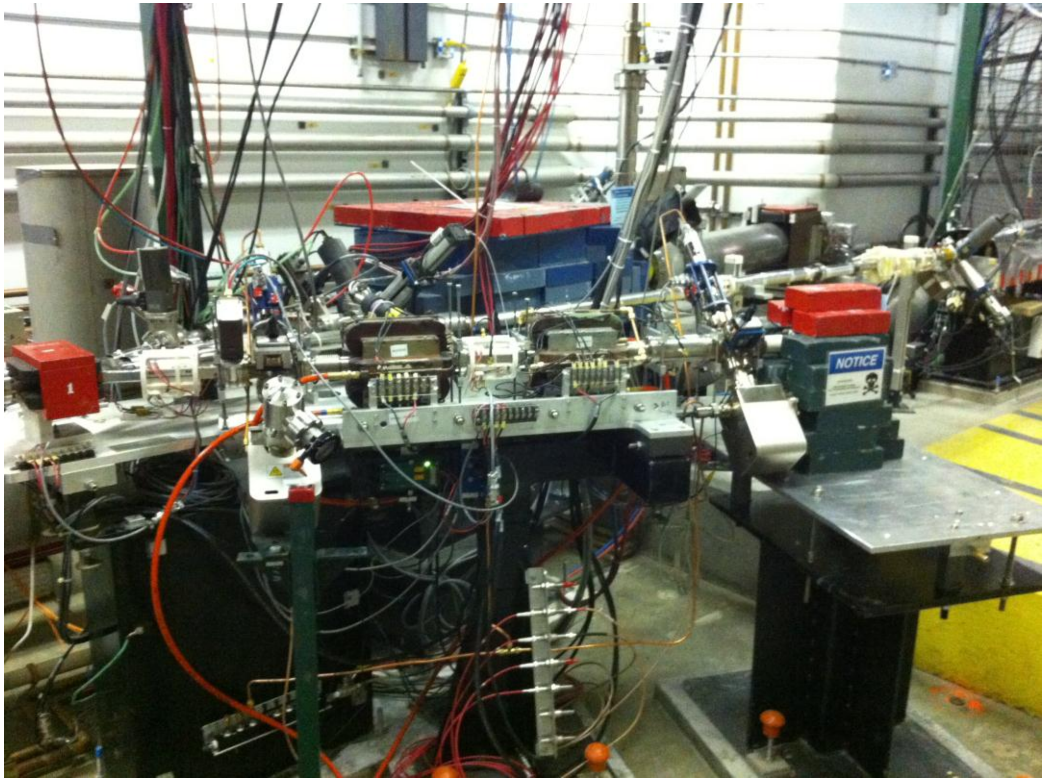
II. Readout:

   I. Optical Camera

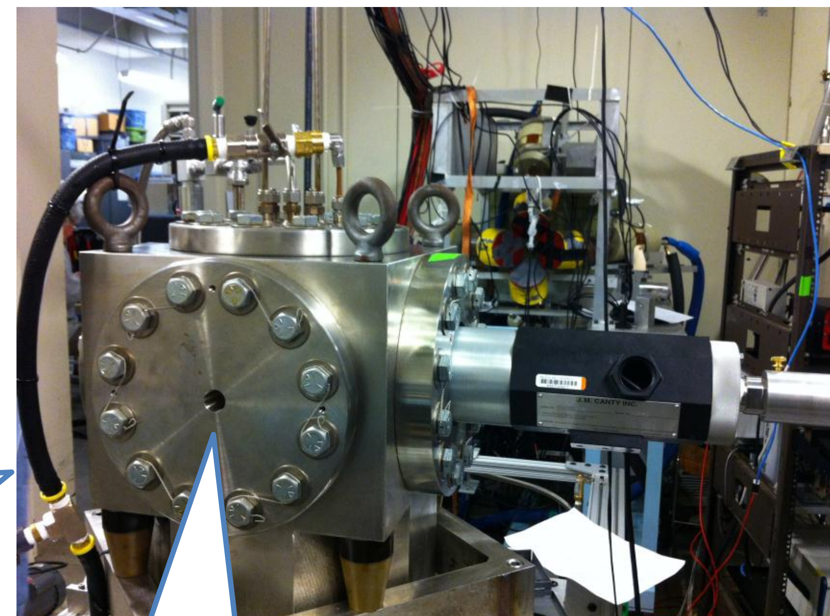
   II. Acoustic Signal to discriminate between (γ,α) and (γ,n) events

EXPERIMENTAL SETUP AT JLAB INJECTOR





5D Spectrometer



Bubble Chamber at HIGS

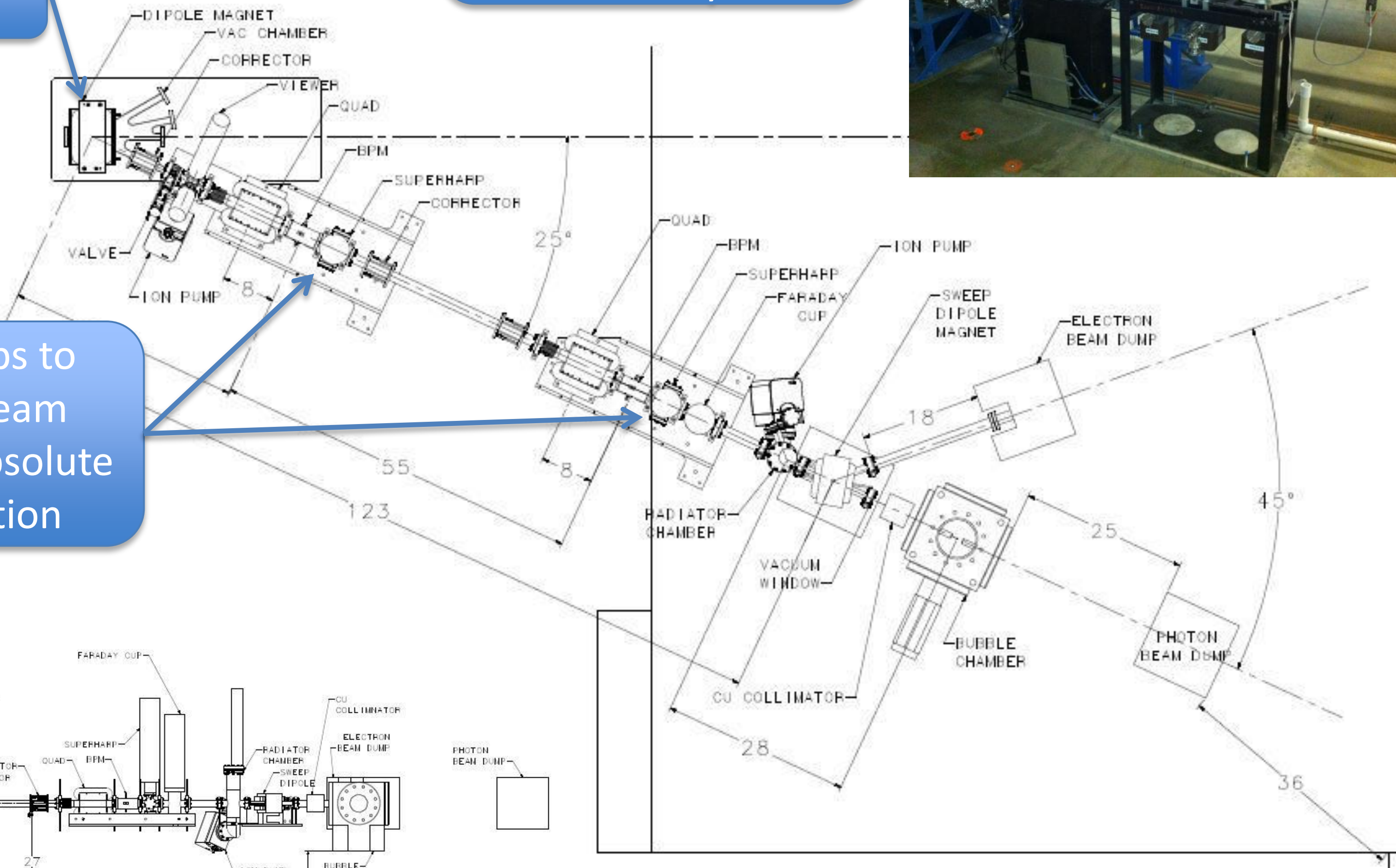
Photon Beam Entrance

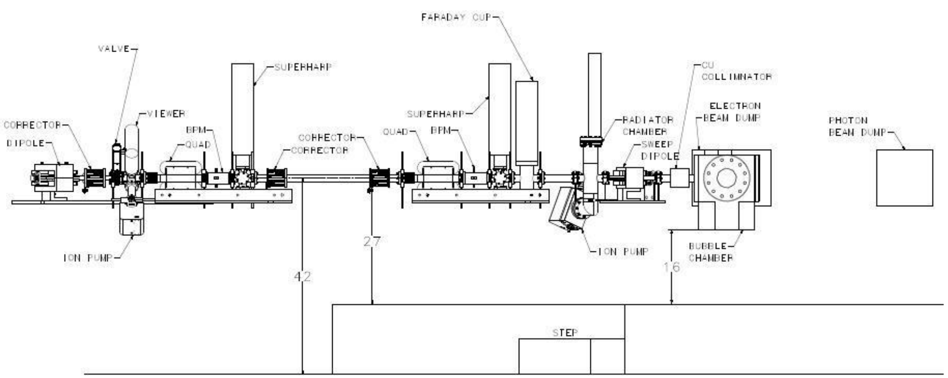
Beamline

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

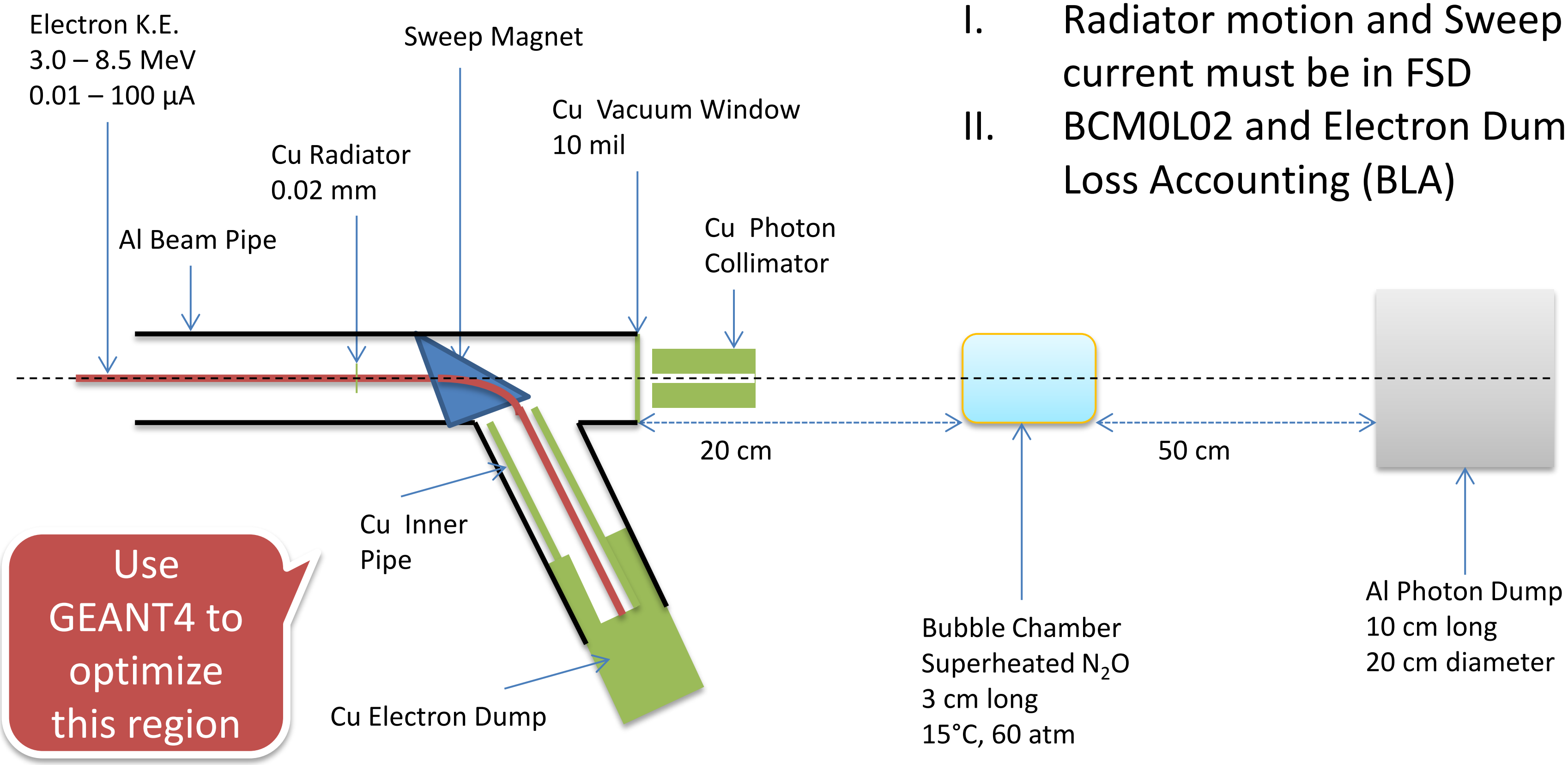




SCHEMATICS

- Power deposited in radiator (100 μA 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}C(γ,n) threshold = 10.86 MeV
  II. ^{27}Al(γ,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:

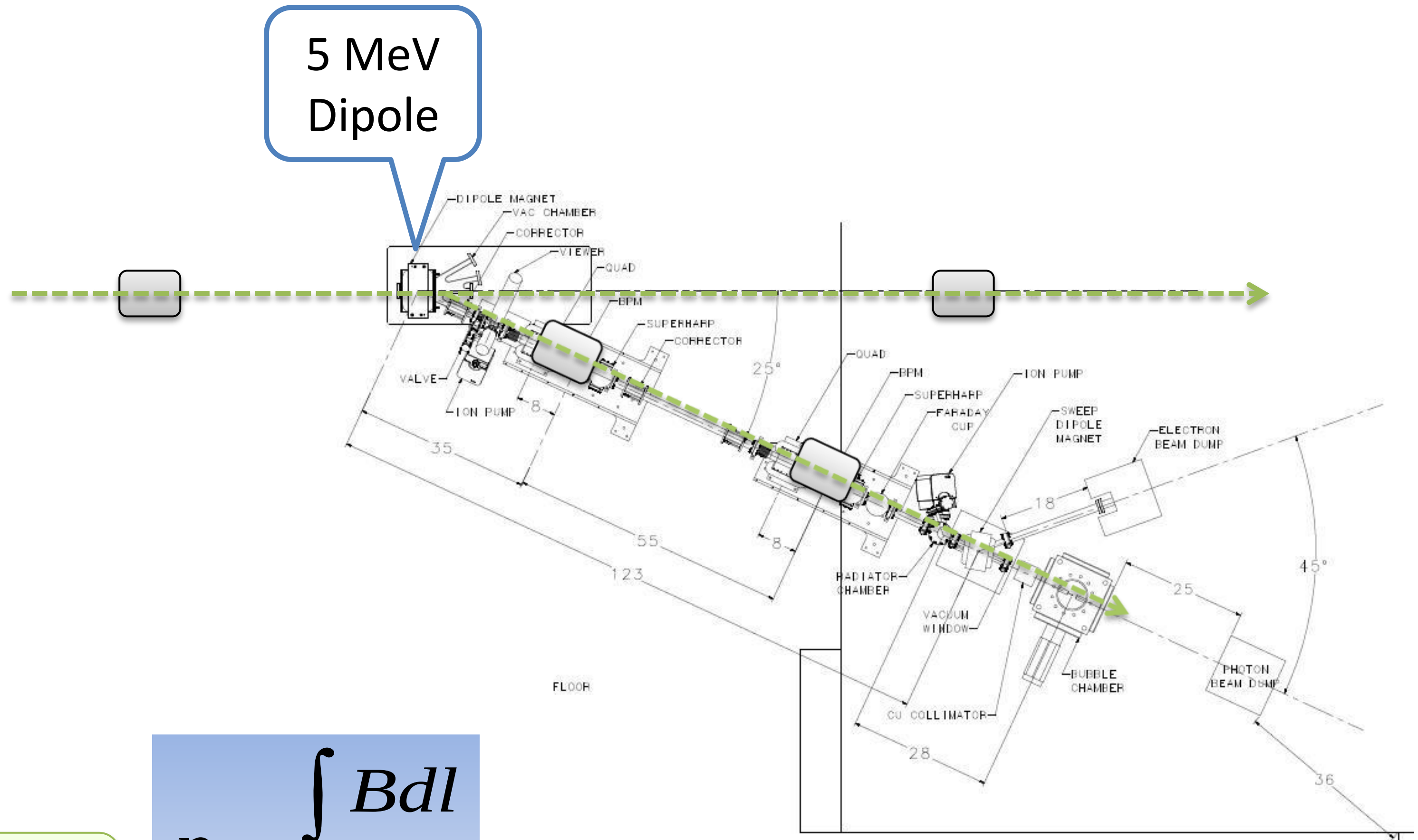
Beam Kinetic Energy, (MeV)	7.9 – 8.5
Beam Current (μA)	0.01 – 100
Absolute Beam Energy	<0.1%
Relative Beam Energy	<0.02%
Energy Resolution (Spread), σ_T /T	0.06%
Beam Size, $\sigma_{x,y}$ (mm)	1 – 2

II. PEPPo achieved p=8.25 MeV/c or K.E.=7.75 MeV. Maximum stable ¼- 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 ¼-cryounit

Absolute Beam Energy

BPM



Electron Beam Momentum

$$p = \frac{\int B dl}{\theta}$$

Parameter	Term	Now	Goal
Dipole – linearity	δB/B	0.25%	0.02%
Dipole – spatial	δBL/BL	0.10%	0.02%
Dipole – reproduce	δB/B	0.10%	0.02%
Dipole – power supply	δI/I	0.20%	0.02%
Position – surveys	δθ/θ	0.01%	0.01%
Position – BPM calibration	δθ/θ	0.05%	0.05%
Stray magnetic field	δθ/θ	0.05%	0.05%
TOTAL	**δP/P**	**0.36%**	**<0.10%**

Goal:

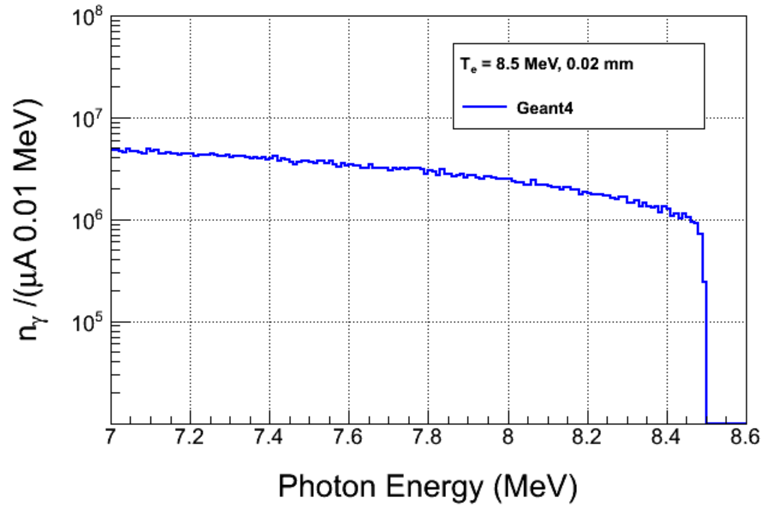
I. Jay Benesch designed and now fabricating higher quality dipole (more uniformity, higher field)

II. New Hall Probe: 0.01% accuracy, resolution to 2 ppm, and a temperature stability of 10 ppm/°C

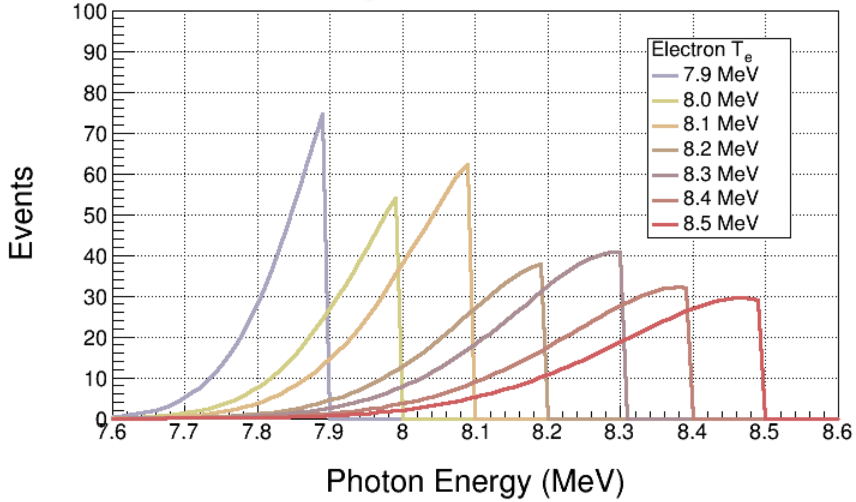
III. Relative beam energy error: <0.02%

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



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

I. Very steep; only photons near endpoint contribute to yield
II. 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 superheated liquid.

II. Fold the above photon spectrum 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: $E = E_1, E_2, \ldots, E_n$ 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:

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

- 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:

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

- Where:

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

$\mathrm{var}(y_i, y_i) = y_i$

$\mathrm{cov}(y_i, y_j) = 0$

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

Although,

$\mathrm{cov}(y_i, y_j) = 0,$

$\mathrm{cov}(\sigma_i, \sigma_j) \neq 0$

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

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 = 3.474e22 /cm^2

III. Background subtraction of $^{18}O(\gamma,\alpha)^{14}C$. $^{17}O(\gamma,n)^{16}O$: 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 (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:

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

$$E_0 = 7.8 + \delta E$$

$$E_i = E_0 + i\Delta$$

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

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

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

- With:

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

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

- Then:

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

- Where:

Note: Correlation Coefficient =1

$$\mathrm{var}(y_i, y_i) = (dy_i)^2$$
$$\mathrm{cov}(y_i, y_j) = \rho_{ij} dy_i dy_j$$

No point-to-point systematic

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

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

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

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

SYSTEMATIC ERROR PROPAGATION

$$(d\sigma_i)^2 \cong \frac{1}{N_{ii}^2}\left[dy_i^2 - 2dy_i \sum_{j=1}^{i-1} N_{ij}\, d\sigma_j \right.$$

$$+ \sum_{j=1}^{i-1} \left(N_{ij}\, d\sigma_j\right)^2 + \sum_{k=1}^{i-1}\sum_{l=1}^{i-1} N_{ik}\, \mathrm{cov}(\sigma_k, \sigma_l) N_{il}$$

$$\left. + \sum_{j=1}^{i-1} \left(dN_{ij}\,\sigma_j\right)^2 + \left(dN_{ii}\,\sigma_i\right)^2 \right]$$

No point-to-point systematic

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

Other Systematic Errors

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

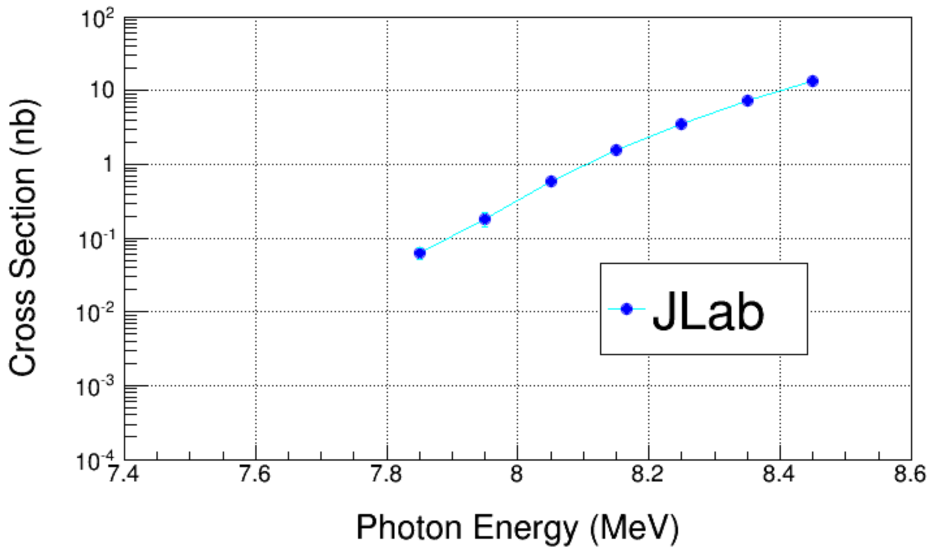
Simulation

- Then:

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

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

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



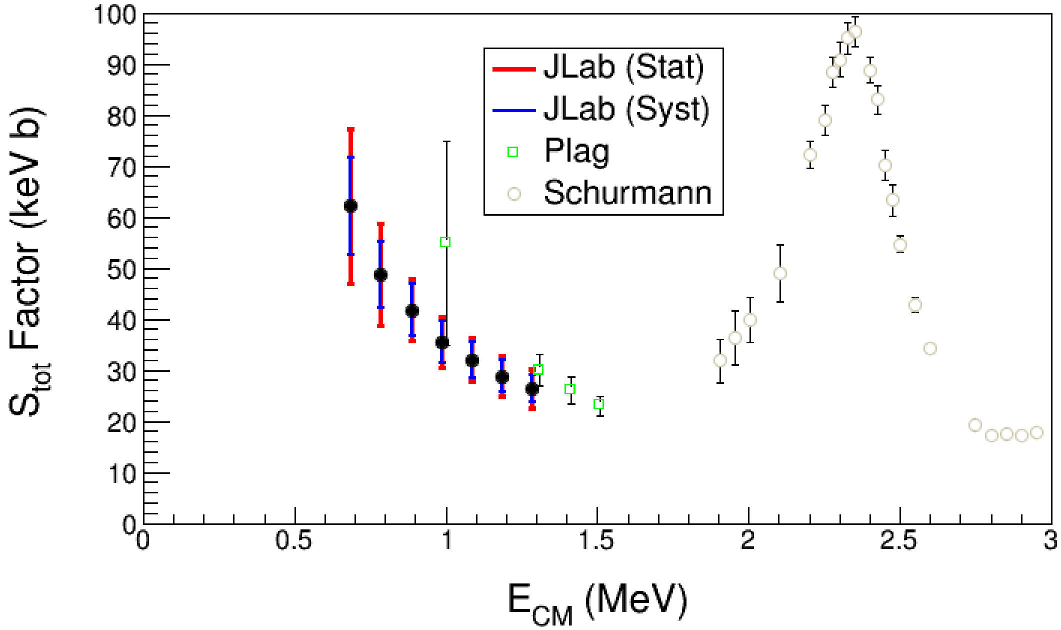
Electron Beam K. E.	Cross Section (nb)	Sys Error (Energy, %)	Sys Error (Total, %)
7.9	0.046	12.5	15.3
8.0	0.185	10.2	13.5
8.1	0.58	8.3	12.2
8.2	1.53	7.0	11.4
8.3	3.49	6.0	10.7
8.4	7.2	5.3	10.5
8.5	13.6	4.7	10.1

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

JLAB PROJECTED $^{12}C(\alpha,\gamma)^{16}O$ S-Factor

- Statistical Error: dominated by background subtraction from $^{18}O(\gamma,\alpha)^{14}C$ (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_2O:

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

➢ Natural Abundance:

I. ^{17}O: 0.038%

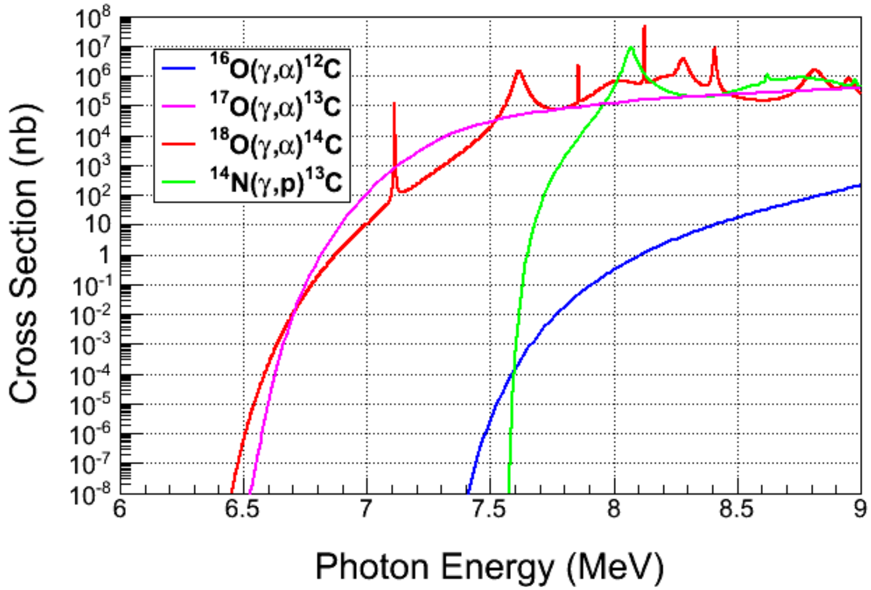
II. ^{18}O: 0.205%

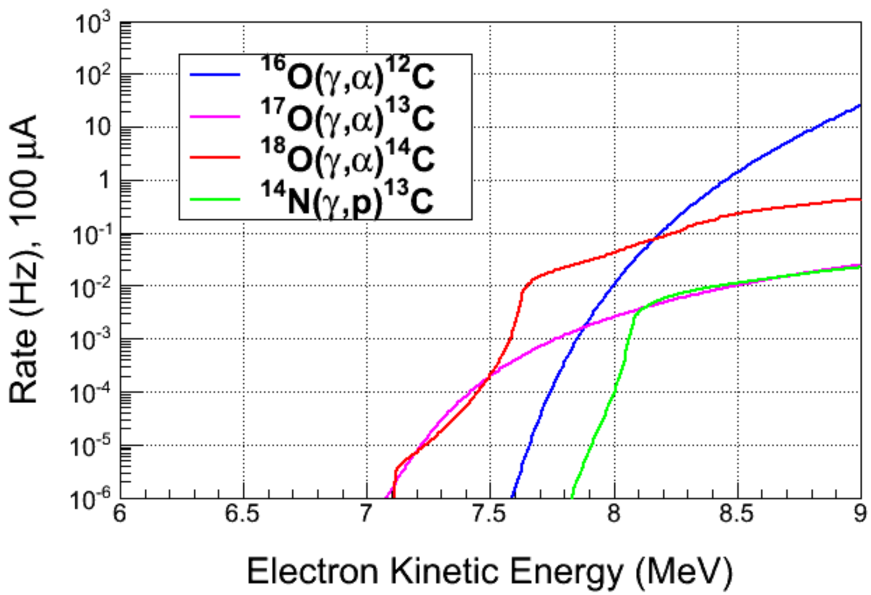
➢ Expected Rates:

I. $^{17}O(\gamma,\alpha)^{13}C$, depletion=5,000

II. $^{18}O(\gamma,\alpha)^{14}C$, depletion=5,000

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





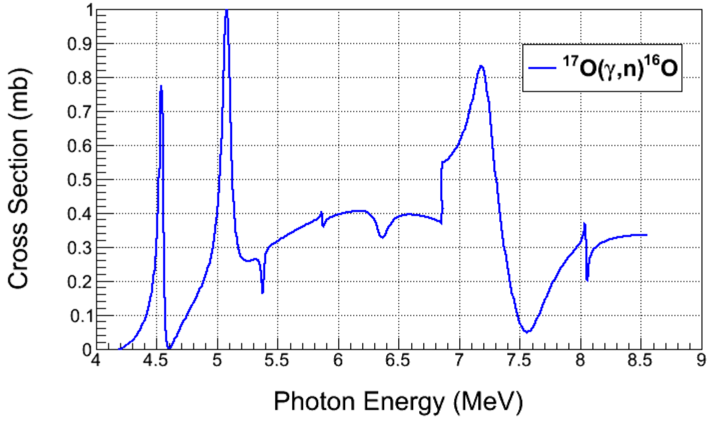
II. Background from:

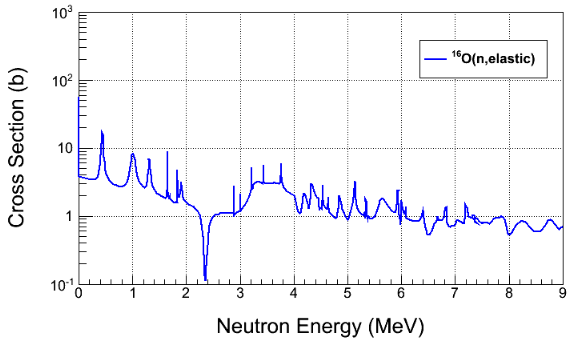
- $^{17}O(\gamma,n)^{16}O$ and secondary (n,n) neutron–nucleus elastic scattering

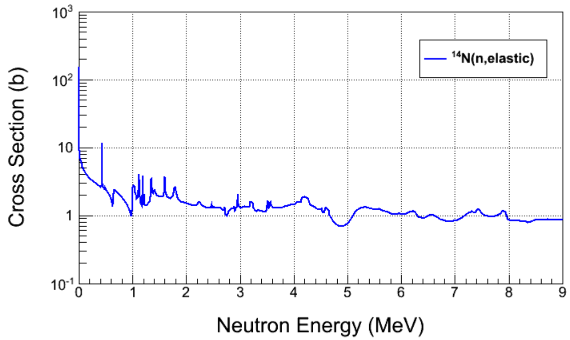
III. Cosmic–ray background:

- $\mu^{\pm}$–nuclear
- neutron–nuclear elastic scattering

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







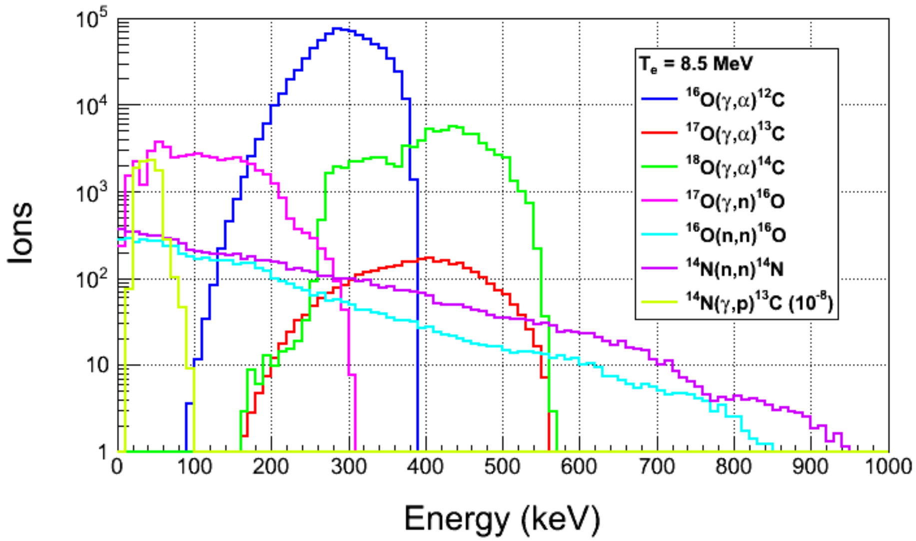
Ion Energy Distributions

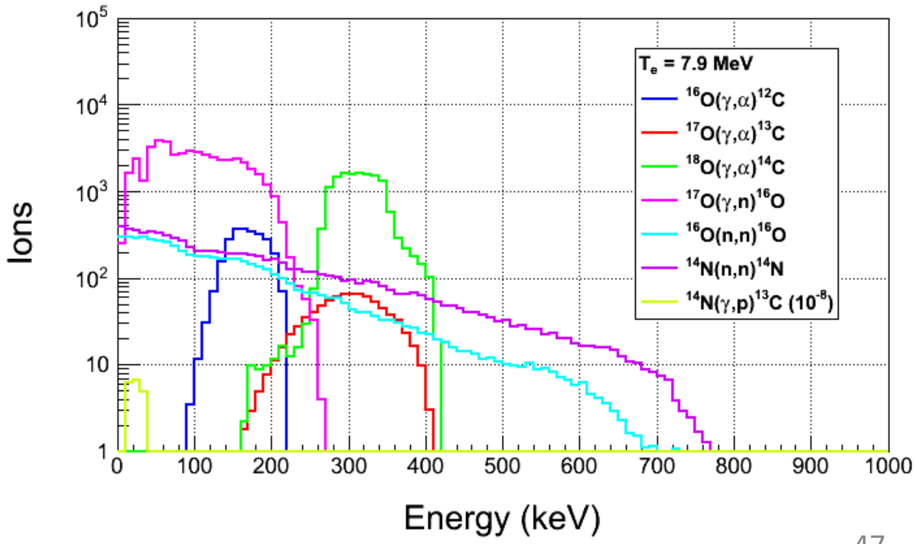
- Suppress background with Bubble Chamber threshold

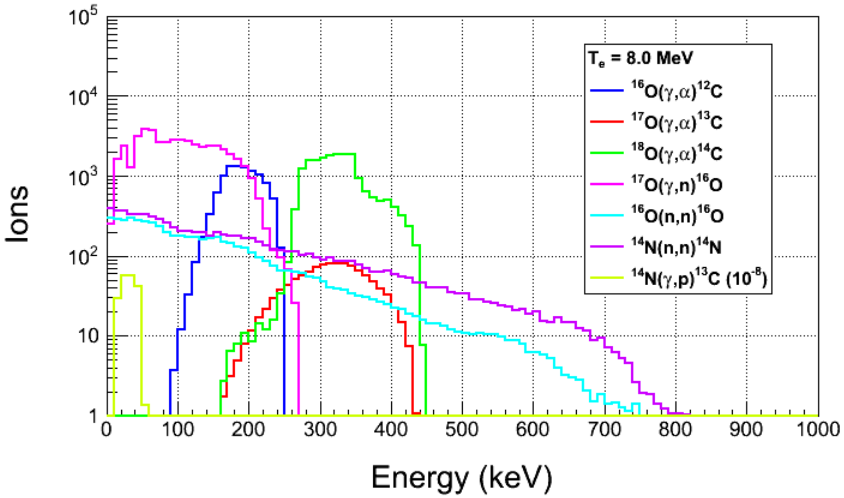
- Calculated with Depletion:
  I. ^{17}O depletion = 5,000
  II. ^{18}O depletion = 5,000

- Threshold Efficiency (function of superheat):

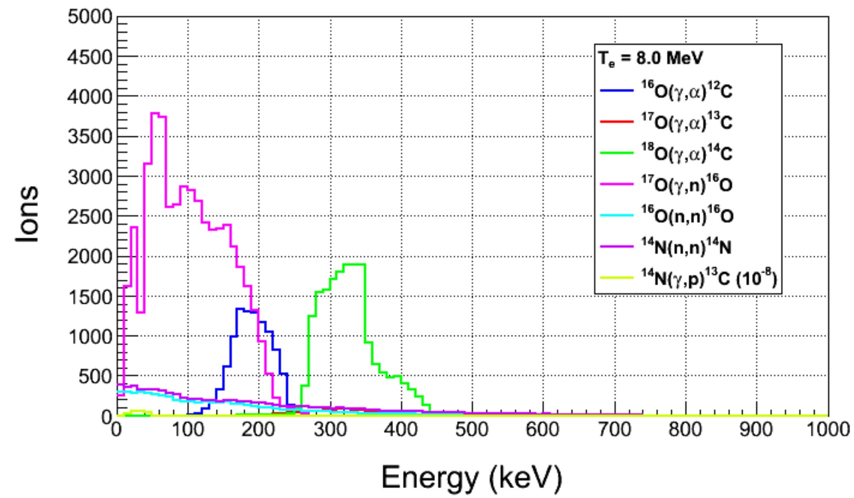
Particle	Efficiency
$e^{\pm}$	$<10^{-11}$
γ	$<10^{-11}$
(γ,n)	2×10^{-3}



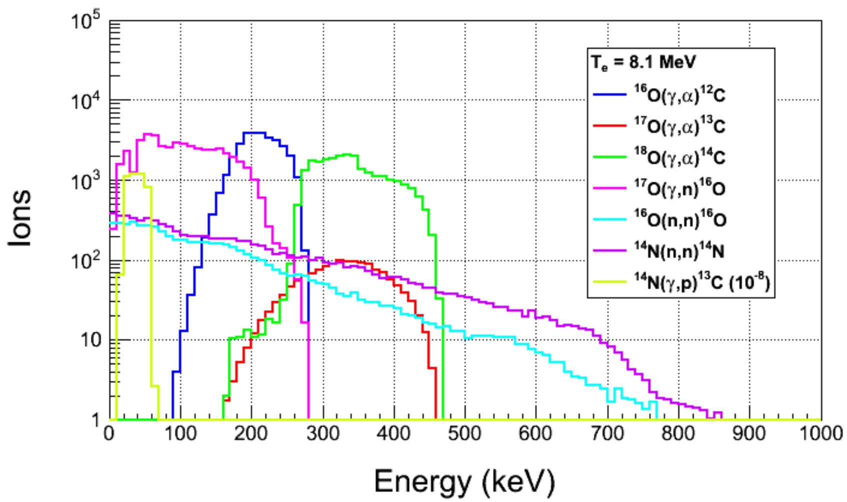




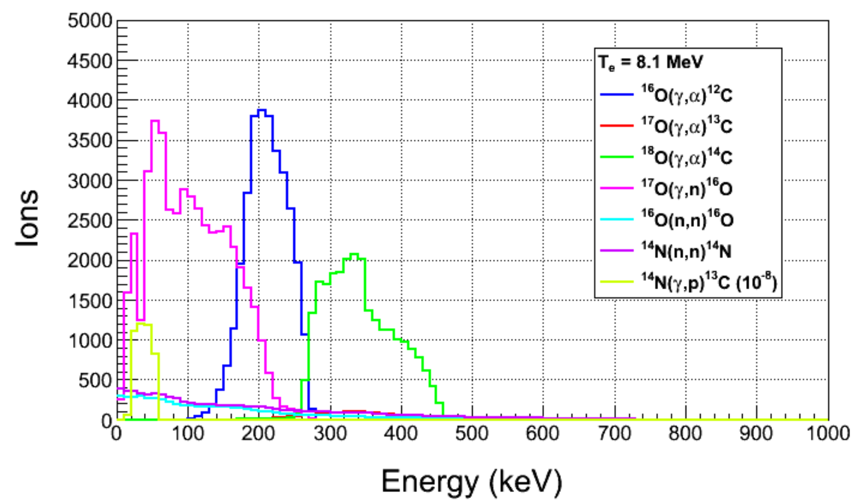
Ions
Energy (keV)
T_e = 8.0 MeV
$^{16}O(\gamma,\alpha)^{12}C$
$^{17}O(\gamma,\alpha)^{13}C$
$^{18}O(\gamma,\alpha)^{14}C$
$^{17}O(\gamma,n)^{16}O$
$^{16}O(n,n)^{16}O$
$^{14}N(n,n)^{14}N$
$^{14}N(\gamma,p)^{13}C$ (10^{-8})



Ions
Energy (keV)
T_e = 8.0 MeV
$^{16}O(\gamma,\alpha)^{12}C$
$^{17}O(\gamma,\alpha)^{13}C$
$^{18}O(\gamma,\alpha)^{14}C$
$^{17}O(\gamma,n)^{16}O$
$^{16}O(n,n)^{16}O$
$^{14}N(n,n)^{14}N$
$^{14}N(\gamma,p)^{13}C$ (10^{-8})



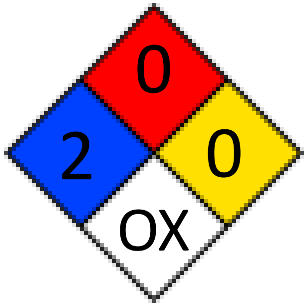
Ions
Energy (keV)
T_e = 8.1 MeV
$^{16}O(\gamma,\alpha)^{12}C$
$^{17}O(\gamma,\alpha)^{13}C$
$^{18}O(\gamma,\alpha)^{14}C$
$^{17}O(\gamma,n)^{16}O$
$^{16}O(n,n)^{16}O$
$^{14}N(n,n)^{14}N$
$^{14}N(\gamma,p)^{13}C$ (10^{-8})



Ions
Energy (keV)
T_e = 8.1 MeV
$^{16}O(\gamma,\alpha)^{12}C$
$^{17}O(\gamma,\alpha)^{13}C$
$^{18}O(\gamma,\alpha)^{14}C$
$^{17}O(\gamma,n)^{16}O$
$^{16}O(n,n)^{16}O$
$^{14}N(n,n)^{14}N$
$^{14}N(\gamma,p)^{13}C$ (10^{-8})

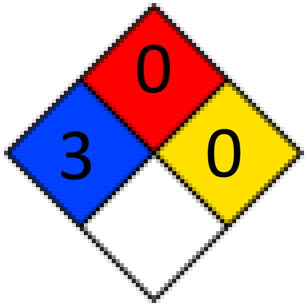
SAFETY

- 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 = 5˚C
    III. P = 5 atm

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



SUMMARY AND OUTLOOK

- Test N_2O Bubble Chamber at HIGS (February 2014)
- Measure cross sections of $^{18}O(\gamma,\alpha)^{14}C$ and $^{17}O(\gamma,\alpha)^{13}C$ at HIGS (Summer 2014)
- Test Bubble Chamber at JLab with Bremsstrahlung beam (October 2014)
- If successful, run depleted N_2O bubble chamber at JLab $^{16}O(\gamma,\alpha)^{12}C$
- Beam issues:
  - Design radiator, collimator, and dumps with GEANT4
  - Simulate Photon Spectrum
  - Deliver 8.5 MeV K.E. electron beam to 5D Spectrometer with $<0.1\%$ energy error
- Bubble Chamber issues:
  - Study acoustic signal
  - Deadtime measurement (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

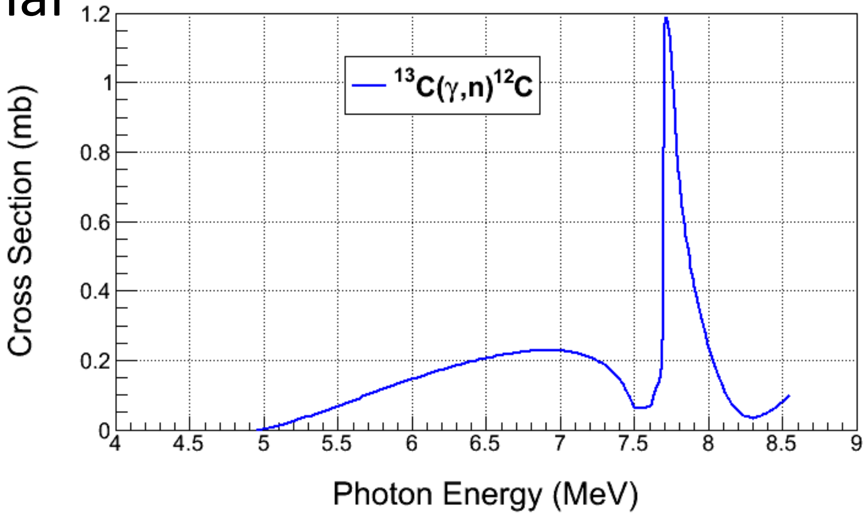
I. New beamline components:
   I. New Dipole Magnet and Hall Probe
   II. 2 Super Harps
   III. Fast Valve
II. Summary of labor cost by group:

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

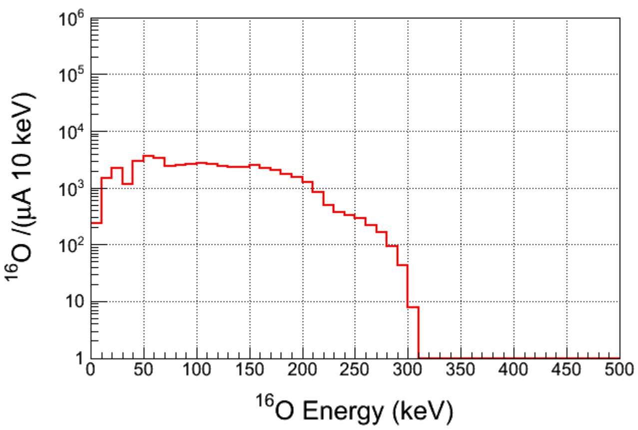
Item	Material Procurement	Shop	Labor
New Dipole Magnet	Dipole Magnet ($8,000) Hall Probe System ($10,000)		Design (2 week) Mapping (1 week) EESDC (1 week) Alignment (2 days)
New Beamline	2 Super Harps (20,000) Fast Valve ($23,000)	Pipes + Pedestals ($20,000)	Design (6 weeks) Alignment (1 week) Software (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)
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**

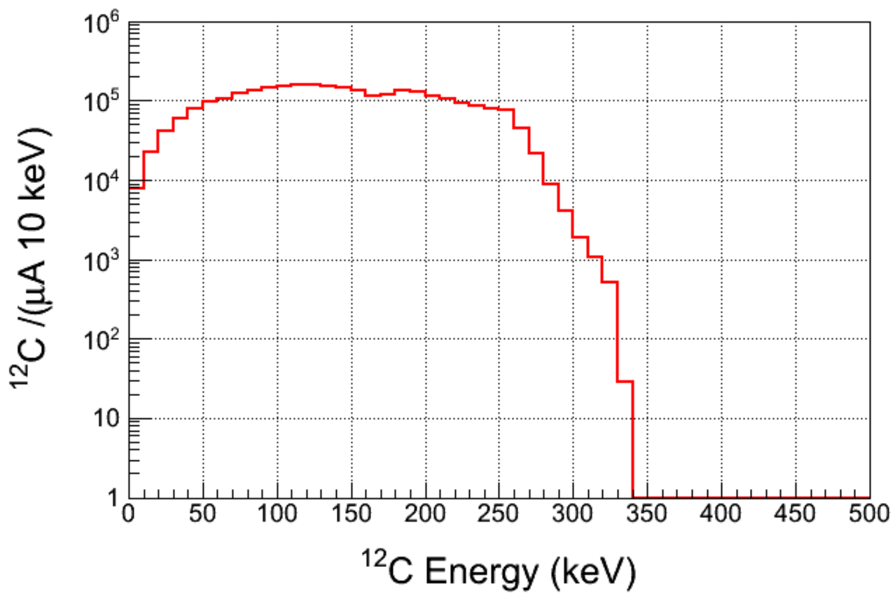
CO_2 SUPERHEATED LIQUID?

- Similar Bubble Chamber operational parameters as N_2O
- Natural Abundance: ^{13}C: 1.07%
- Depletion: ^{13}C depletion=1,000
- $^{13}C(\gamma,n)^{12}C$ Background



For comparison, $^{17}O(\gamma,n)^{16}O$

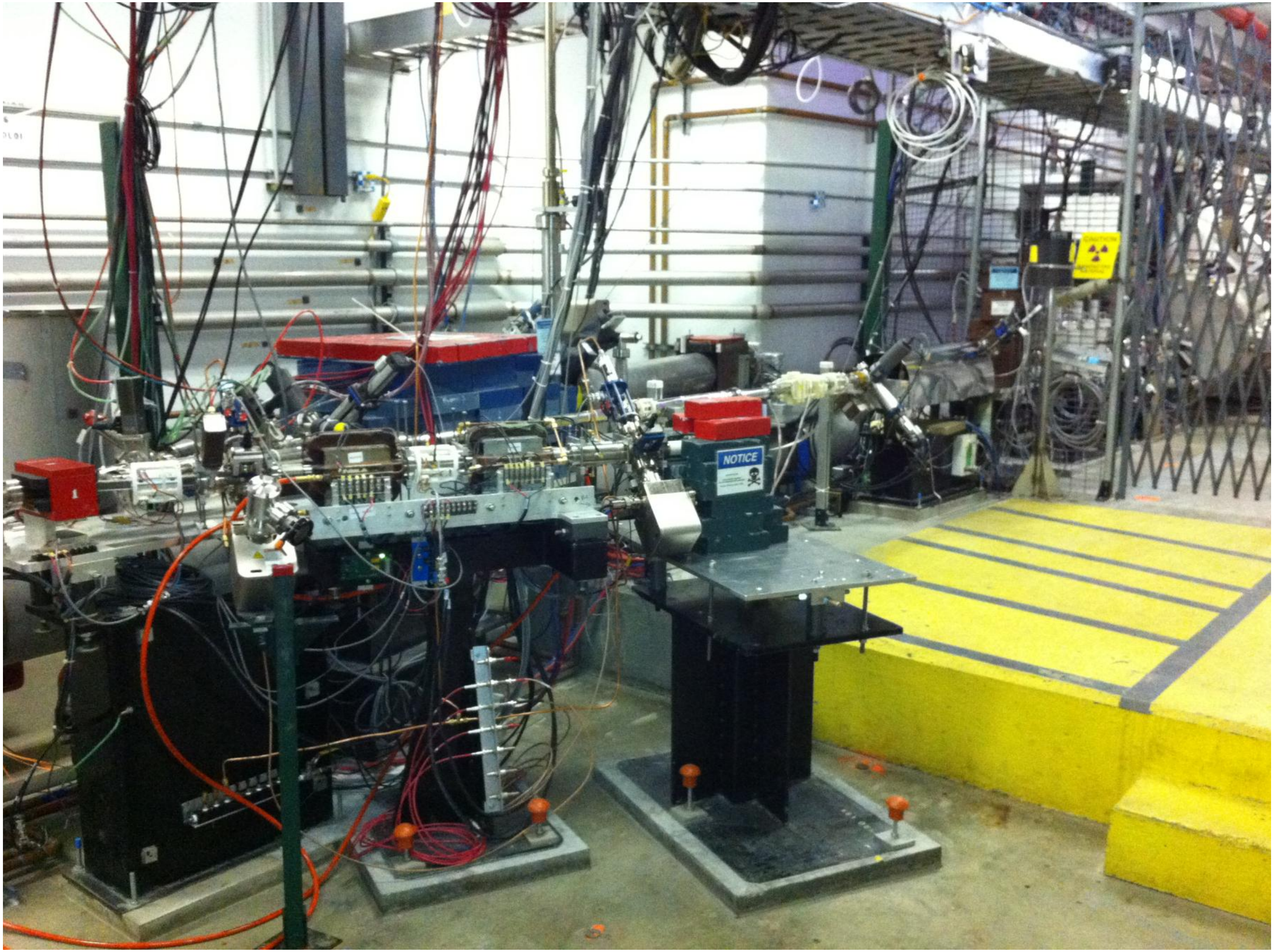


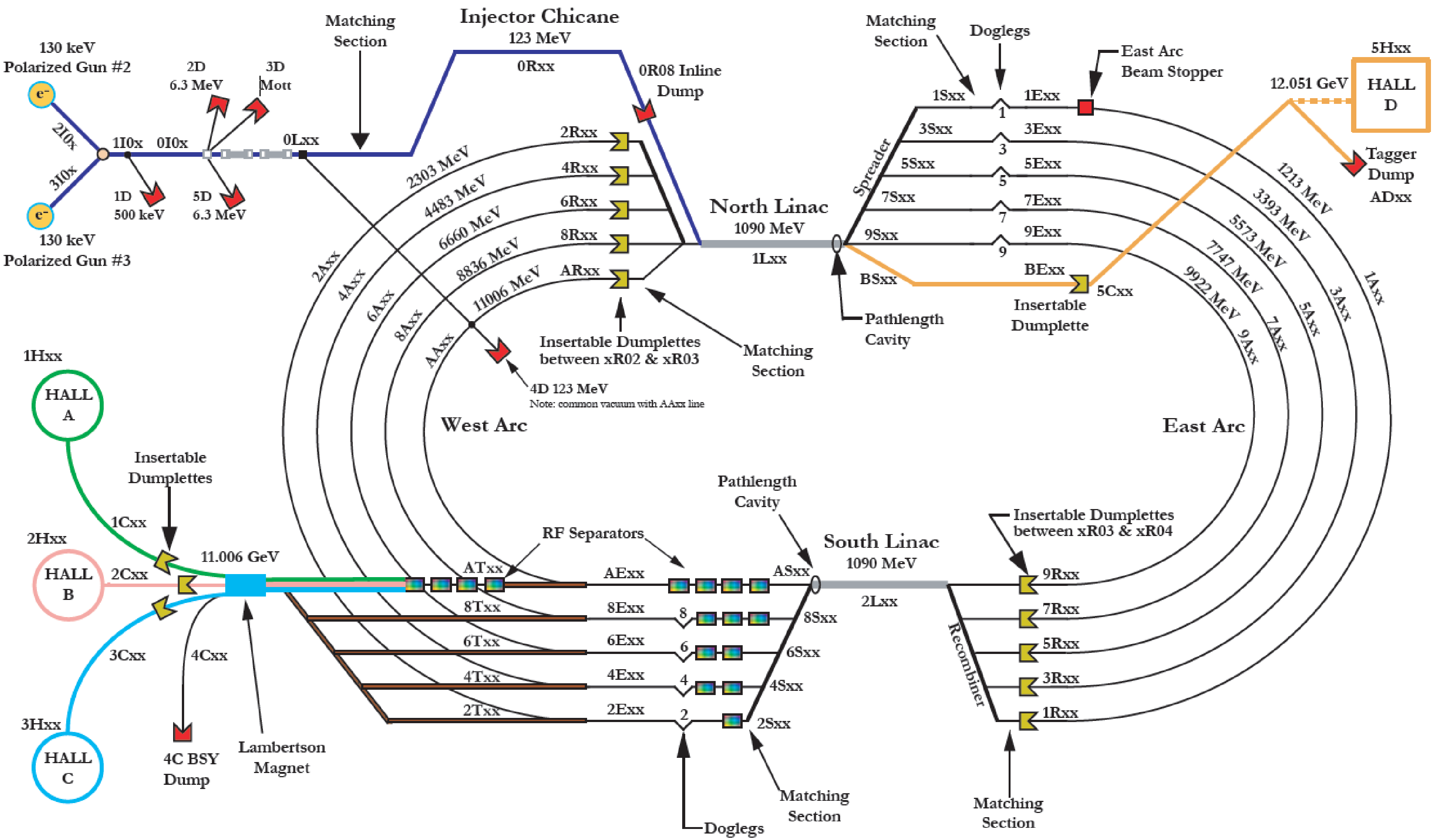


- $^{12}C(\gamma,2\alpha)\alpha$ Background

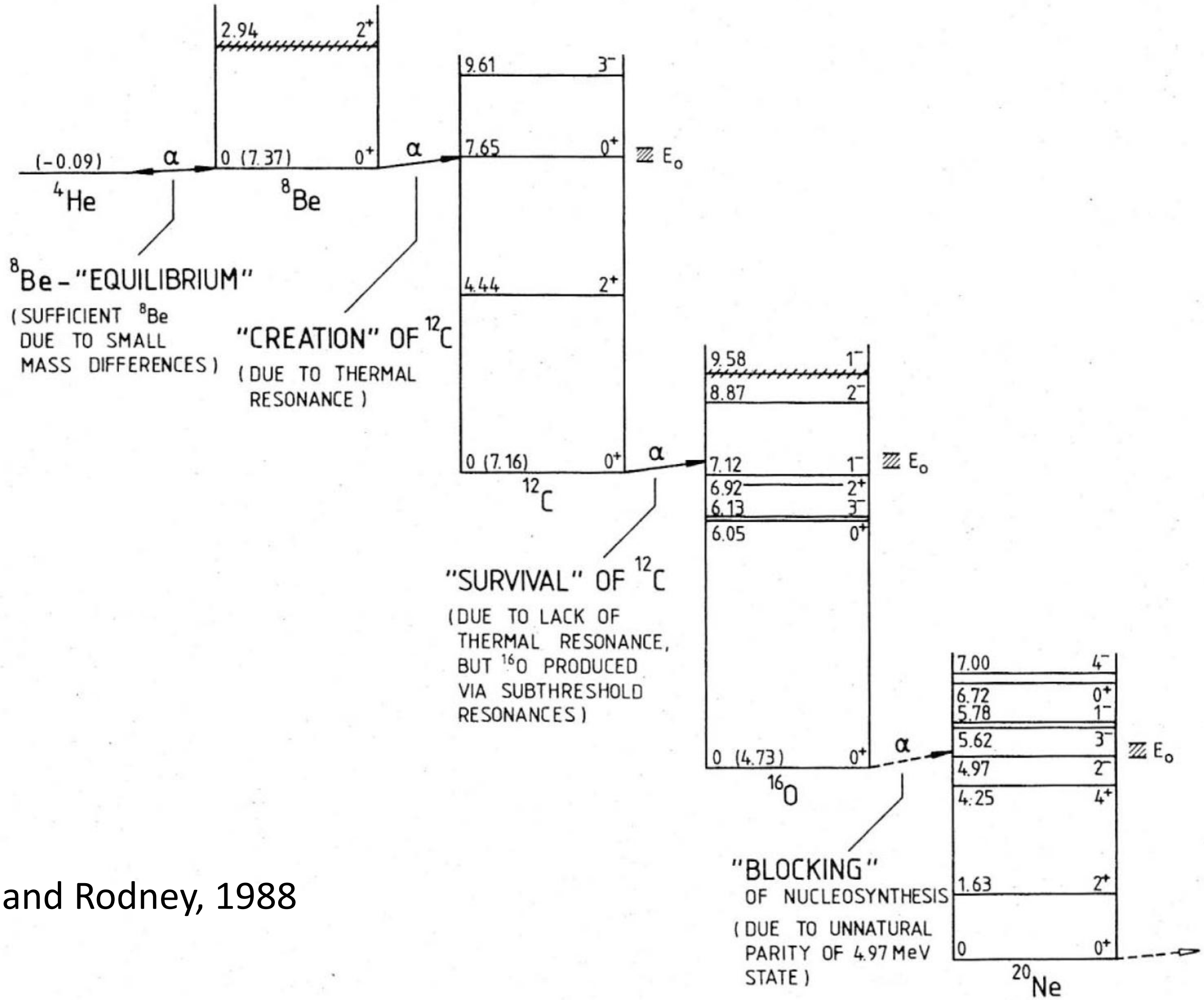
WATER SUPERHEATED LIQUID?

- Etching of glass vessel by superheated H_2O
- T = 250˚C
- P = 75 atm
- Background from secondary neutron–nucleus elastic scattering by neutrons from d(γ,n)p


NOTICE



130 keV
Polarized Gun #2
e⁻
2I0x
3I0x
e⁻
130 keV
Polarized Gun #3
1I0x
0I0x
1D
500 keV
2D
6.3 MeV
3D
Mott
5D
6.3 MeV
0Lxx
Matching
Section
Injector Chicane
123 MeV
0Rxx
0R08 Inline
Dump
2Rxx
4Rxx
6Rxx
8Rxx
ARxx
2303 MeV
4483 MeV
6660 MeV
8836 MeV
11006 MeV
2Axx
4Axx
6Axx
8Axx
AAxx
Insertable Dumplettes
between xR02 & xR03
Matching
Section
4D 123 MeV
Note: common vacuum with AAxx line
West Arc
North Linac
1090 MeV
1Lxx
Matching
Section
Doglegs
Spreader
1Sxx
3Sxx
5Sxx
7Sxx
9Sxx
BSxx
1Exx
3Exx
5Exx
7Exx
9Exx
BExx
East Arc
Beam Stopper
Pathlength
Cavity
Insertable
Dumplette
5Cxx
12.051 GeV
5Hxx
HALL
D
Tagger
Dump
ADxx
1213 MeV
3393 MeV
5573 MeV
7747 MeV
9922 MeV
1Axx
3Axx
5Axx
7Axx
9Axx
East Arc
1Hxx
HALL
A
2Hxx
HALL
B
3Hxx
HALL
C
Insertable
Dumplettes
1Cxx
2Cxx
3Cxx
4Cxx
11.006 GeV
4C BSY
Dump
Lambertson
Magnet
RF Separators
ATxx
8Txx
6Txx
4Txx
2Txx
AExx
8Exx
6Exx
4Exx
2Exx
Pathlength
Cavity
ASxx
8Sxx
6Sxx
4Sxx
2Sxx
South Linac
1090 MeV
2Lxx
Recombiner
Insertable Dumplettes
between xR03 & xR04
9Rxx
7Rxx
5Rxx
3Rxx
1Rxx
Doglegs
Matching
Section
Matching
Section



Rolfs and Rodney, 1988