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

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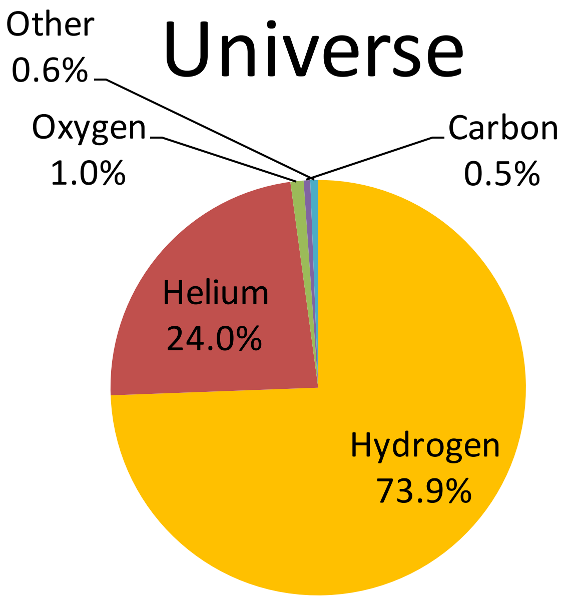
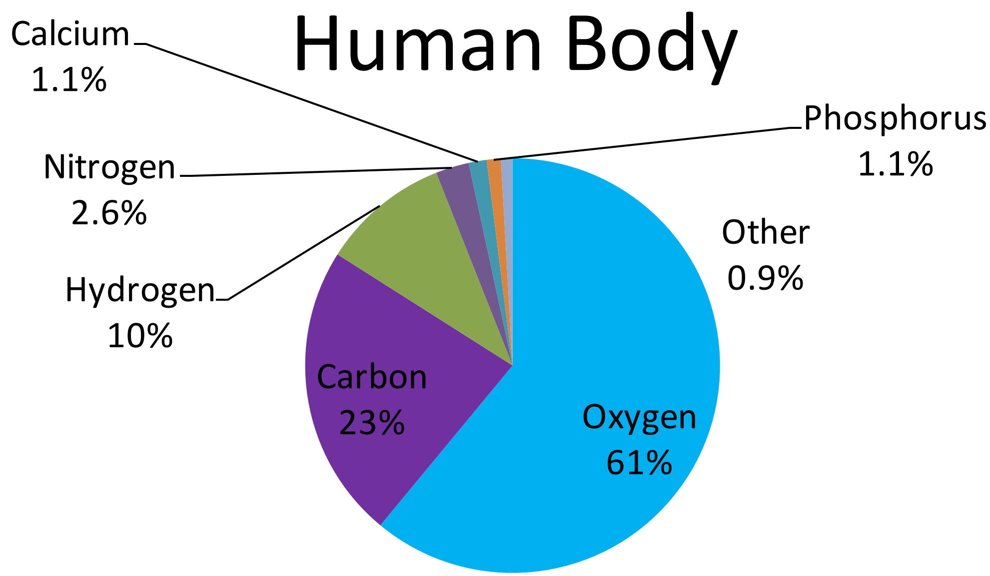
https://wiki.jlab.org/ciswiki/index.php/Bubble_Chamber

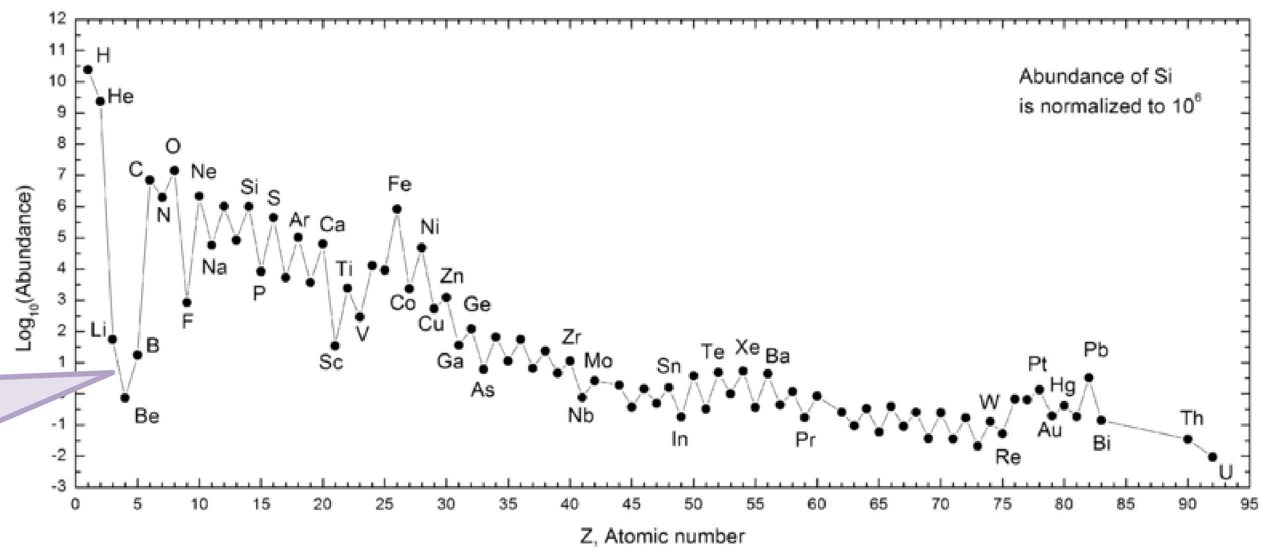
OUTLINE

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

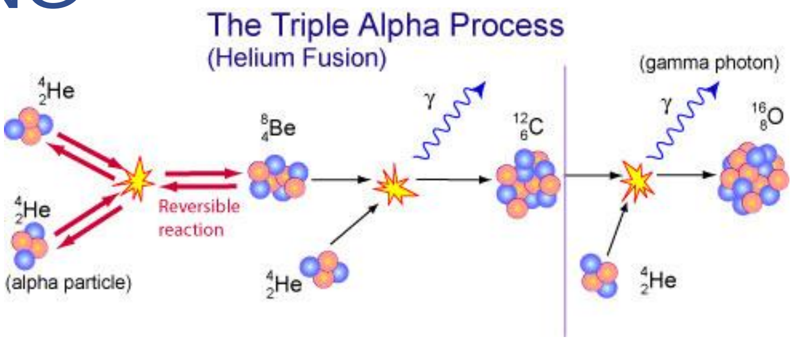






This region is bypassed by 3α process

Stellar Helium Burning



- Helium Reactions:
  - I. $\alpha + \alpha \leftrightarrow {}^{8}Be$
    (Q = -0.092 MeV, $T_{1/2} \approx 10^{-16}$ s)
  - II. $\alpha + {}^{8}Be \rightarrow {}^{12}C + \gamma$ (Q = +7.367 MeV, Hoyle State = 7.654 MeV)
  - III. $\alpha + {}^{12}C \rightarrow {}^{16}O + \gamma$ (Q = +7.162 MeV)
    (slow, otherwise no ^{12}C remains)
  - IV. $\alpha + {}^{16}O \rightarrow {}^{20}Ne + \gamma$ (very slow)
- $\alpha + {}^{12}C$ burning at very small cross section $\sigma \approx 10^{-17}$ barn
  ➡ Currently, reaction rate error is large (±35%)

Goal <±10%

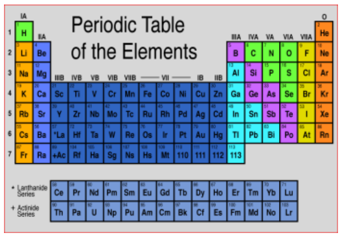
- Thermonuclear reaction rate involving two nuclei is:

Only narrow energy range is important (Gamow Peak)

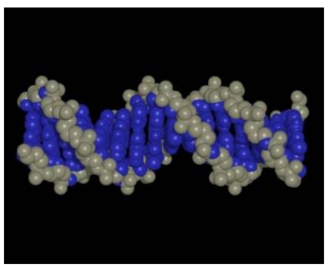
$$R = \sqrt{\frac{8}{\pi m (k_B T)^3}} \int_0^\infty E \sigma_{tot}(E) e^{-\frac{E}{k_B T}} dE$$

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

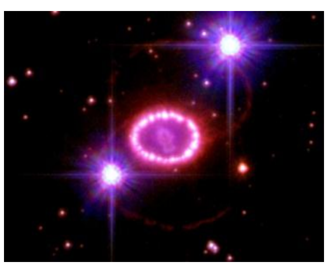
- The *holy grail* of nuclear astrophysics



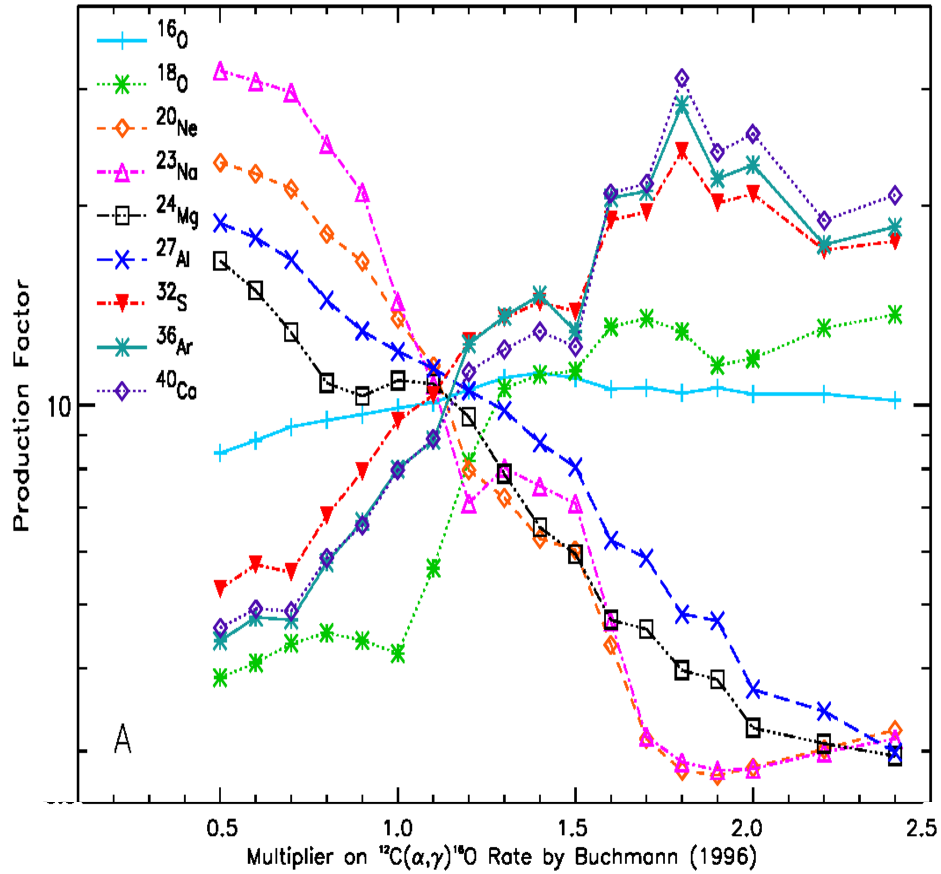
Affects the synthesis of most of the elements of the periodic table



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



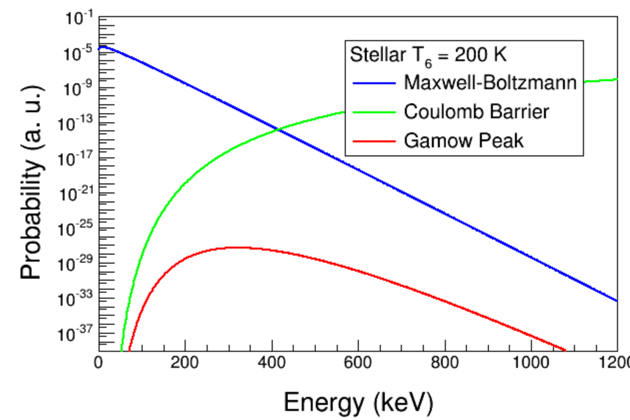
Determines the minimum mass a star requires to become a supernova



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

The Gamow Peak (Window)

- 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 $e^{-b/E^{1/2}}$



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

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

- For α + ^{12}C (Z_1=2, Z_2=6, A=3),

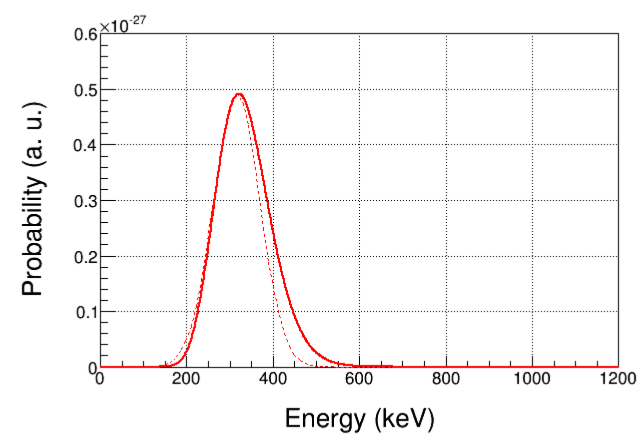
and stellar T=200 10^6 K:

  - **Gamow Peak, E_0 ≈ 300 keV, W ≈ 50 keV**

  (in Center-of-Mass (CM) of α + ^{12}C system)

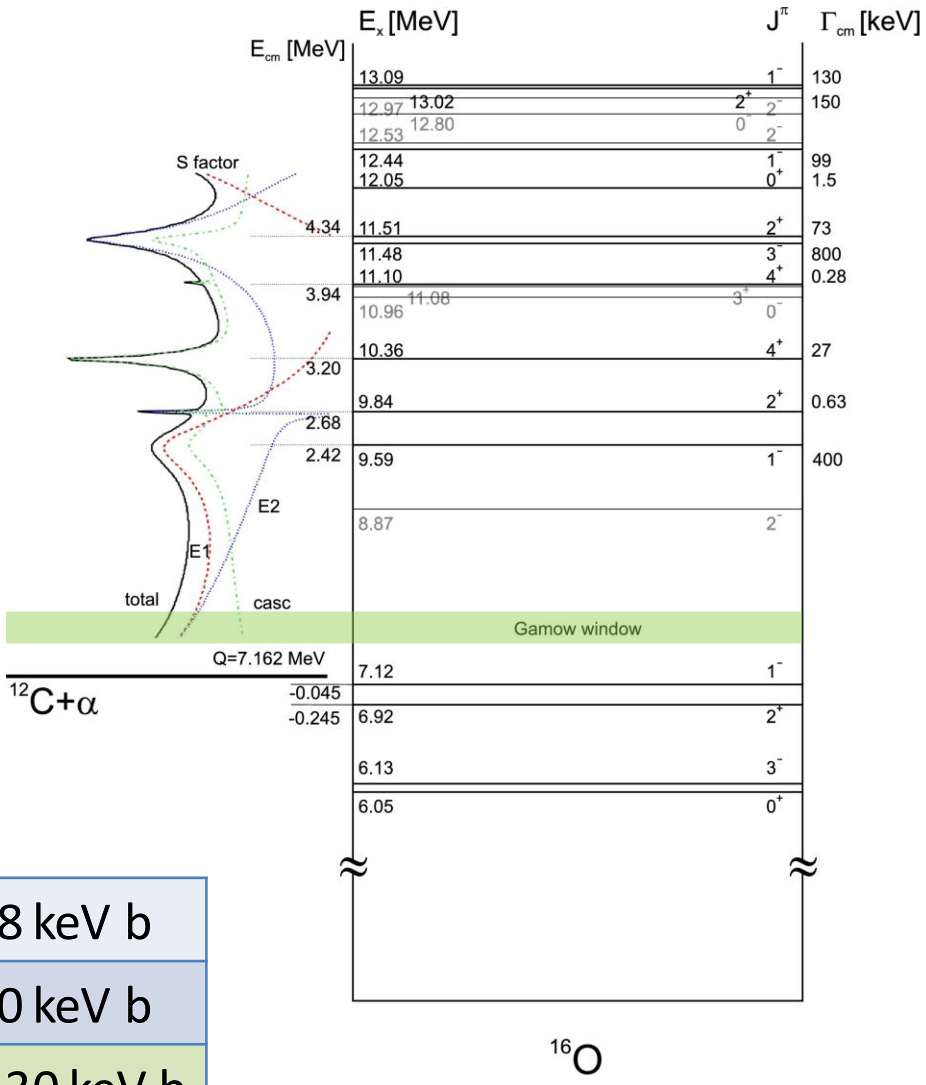
  - Maximum of Maxwell–Boltzmann

  energy distribution, k_BT = 17 keV



α+^{12}C Reaction

- α ($J^{\pi}=0^{+}$) + ^{12}C ($J^{\pi}=0^{+}$) cross section, $\sigma(E_0)$, is dominated by *p*–wave (E1) and *d*–wave (E2) radiative capture to ^{16}O ground state ($J^{\pi}=0^{+}$)
- 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 $1^{-} \rightarrow 0^{+}$ (E1)	$S_{E1}(300)$ = 1–288 keV b
Transition $2^{+} \rightarrow 0^{+}$ (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 Measurements:

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

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

Experiment	Beam Current (mA)	Target (nuclei/cm²)	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 Measurements:

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

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

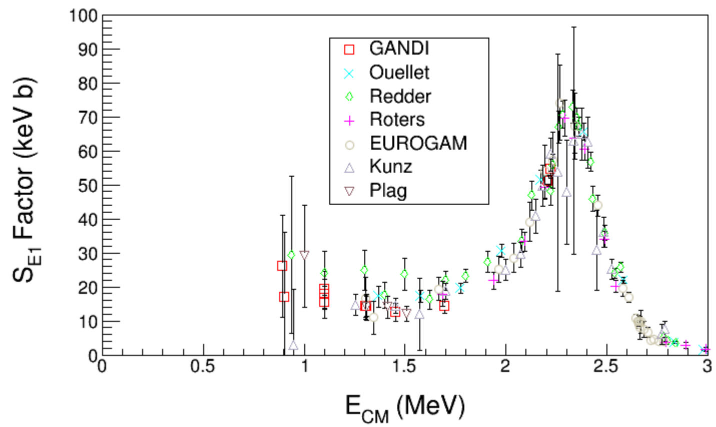
Astrophysical S-Factor $^{12}C(\alpha,\gamma)^{16}O$

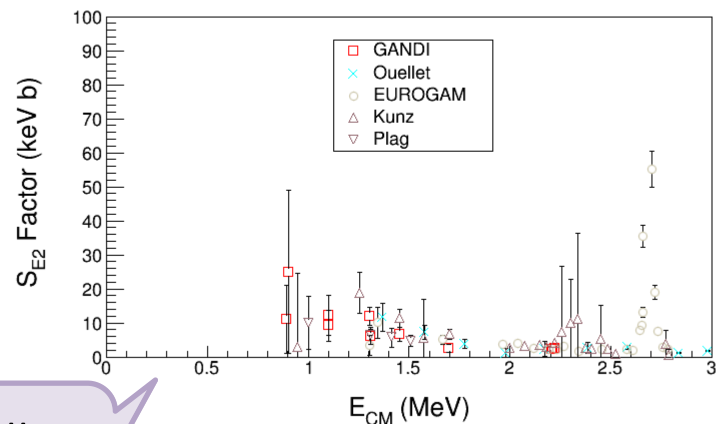
- Define *S-Factor* to remove both 1/E dependence of nuclear cross sections and Coulomb barrier transmission probability:

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

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

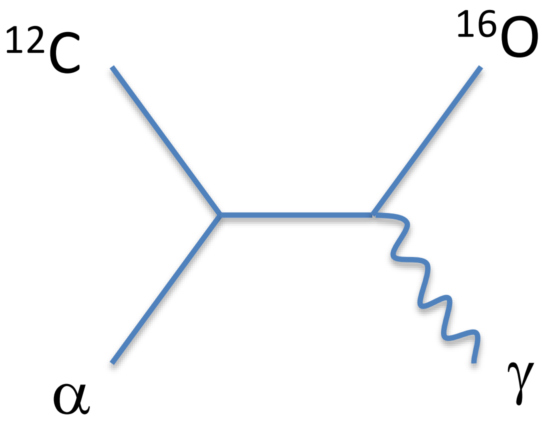
Author	$S_{tot}(300)$ (keV b)
Hammer (2005)	162±39
Kunz (2001)	165±50



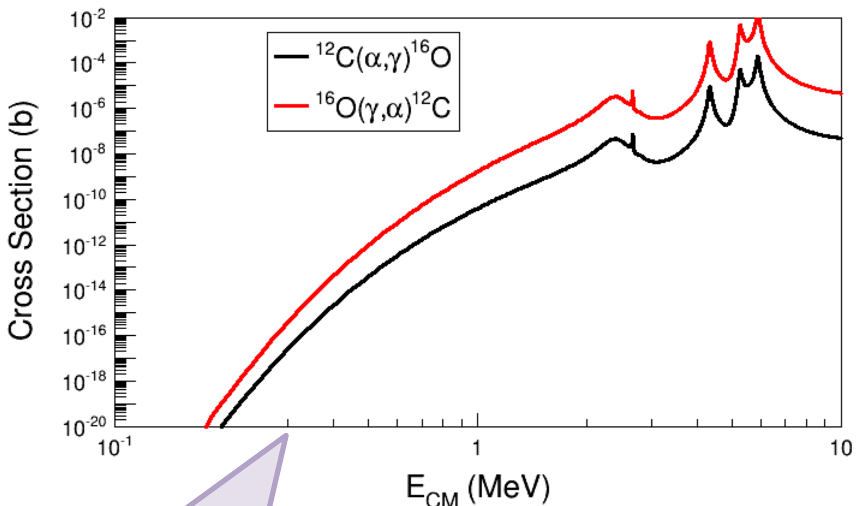


R-matrix Extrapolation to stellar helium burning at E = 300 keV

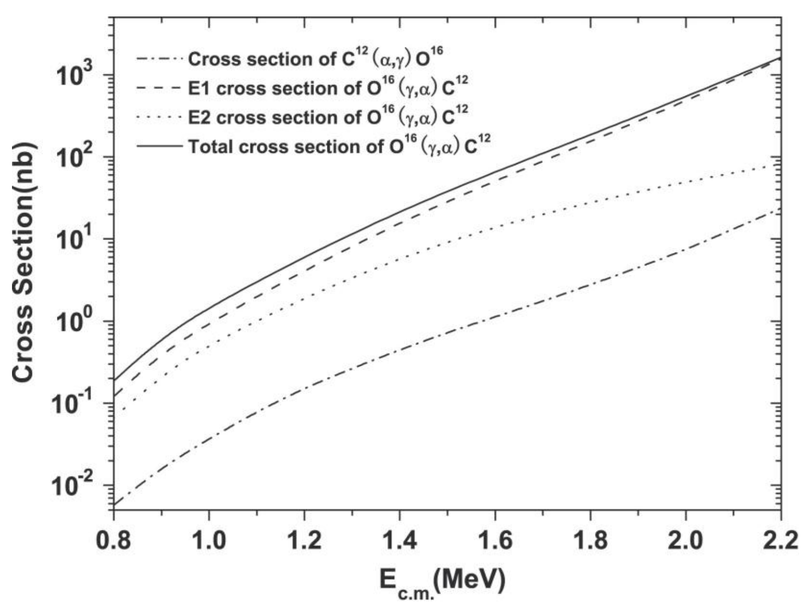
Time Reversal Reaction



- 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



Reciprocity Relation: (γ,α) and (α,γ)

- A(α, γ)B:

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

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

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

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

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

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

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

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

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

New Approach: Reversal Reaction + Bubble Chamber

beam | target | signal

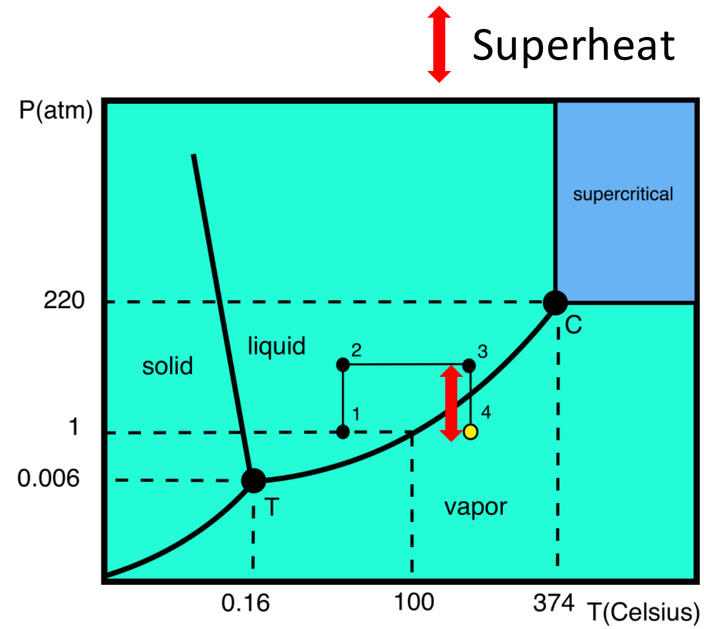
$$\gamma + {}^{16}\mathrm{O} \rightarrow {}^{12}\mathrm{C} + \alpha$$

- 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)
- Measures total cross section σ_{tot} (or S_{tot})
- Solid Angle and Detector Efficiency = 100%
- 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 $\approx 10^{7-8}$ γ/s
- Bremsstrahlung at JLab $\approx 10^9$ γ/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), still liquid but now superheated

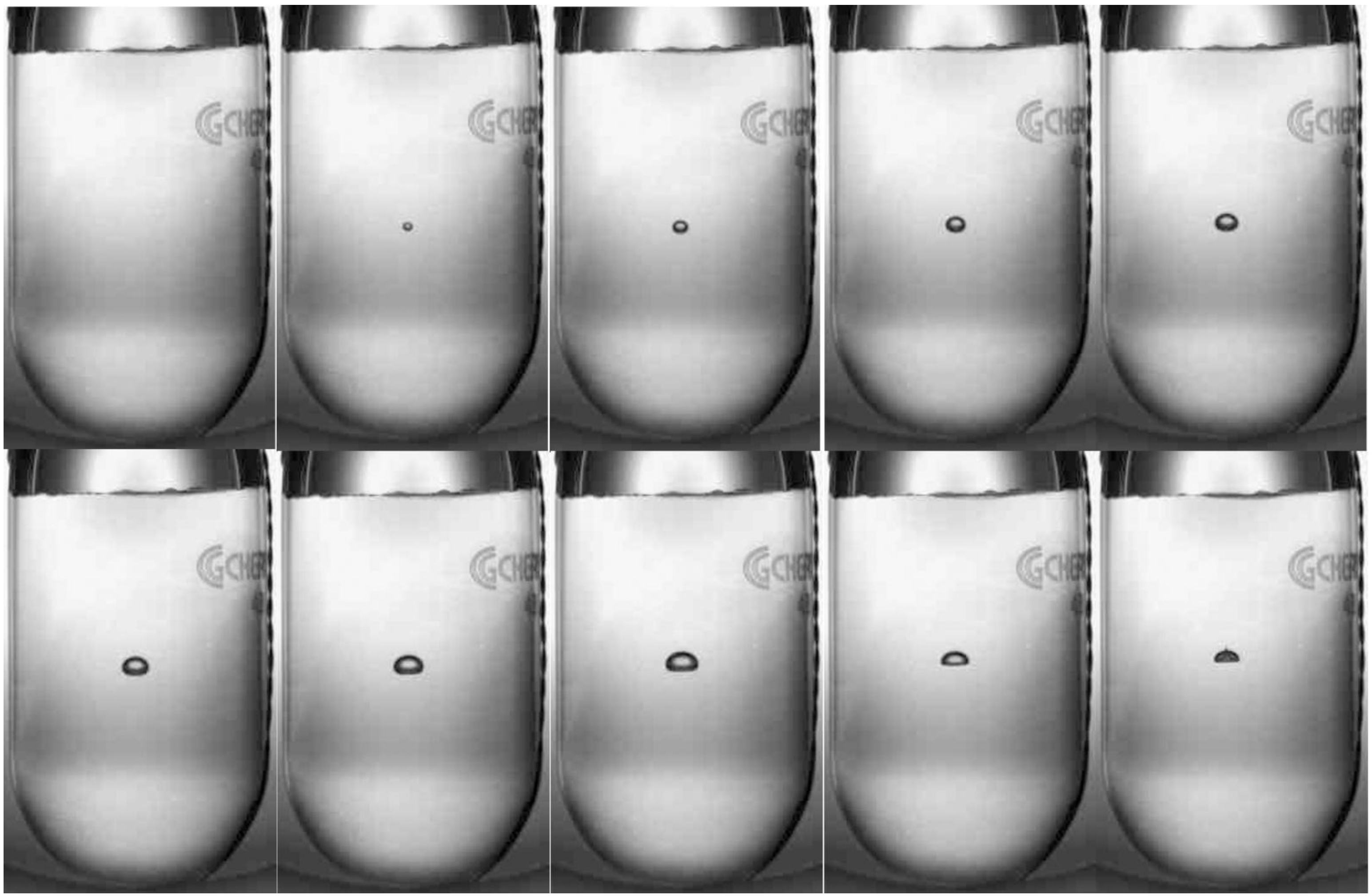


- Bubble Formation:
  - Particle energy loss will induce vaporization
  - Resultant vapor bubble is observable either **visibly** or **audibly**
  - Bubble growth is captured by a digital camera
  - Pressure is increased (4 to 3) to quench bubble. It takes about few seconds for liquid to return to a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

Bubble Growth and Quenching

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

100 Hz Digital Camera: $\Delta t = 10$ ms



3.0 cm

Bubble Chamber Principle

I. For bubble formation, particle must be over thresholds in both **E** and **dE/dx**

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

II. Only bubbles with r > R_c grow to be macroscopic

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

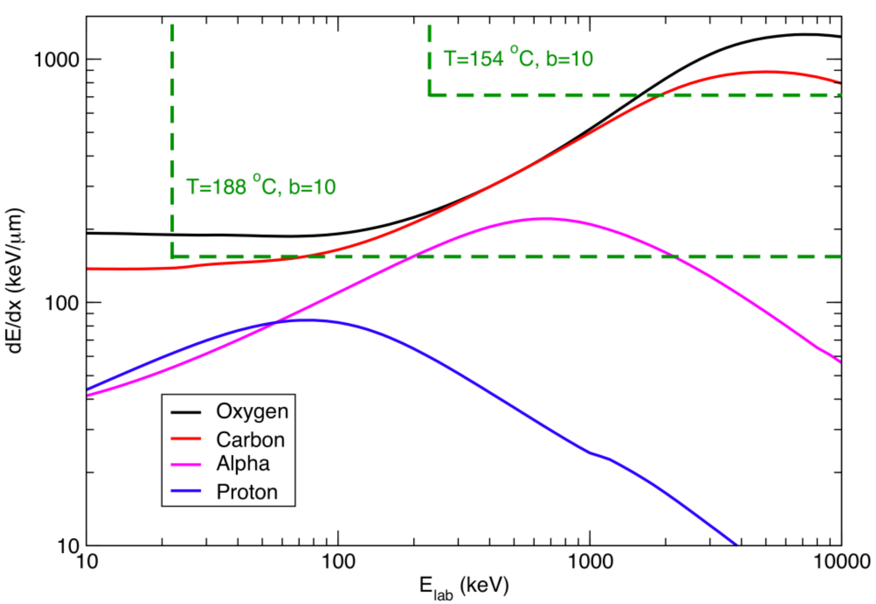
s: Surface tension

III. Bubble requires minimum deposited energy (E_c) within minimum distance L_c (=aR_c , 10s of nm to a few μm)

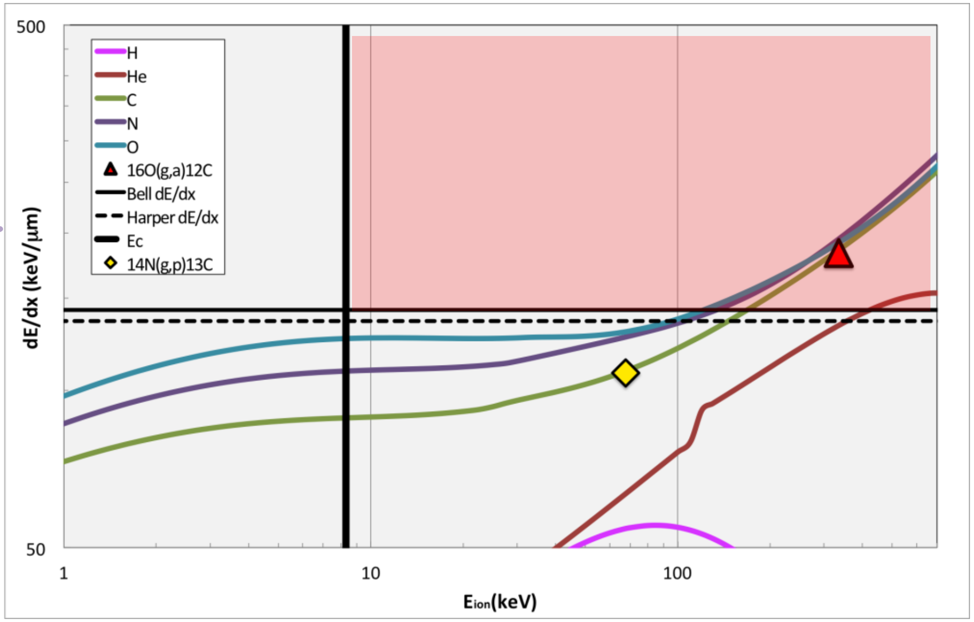
$$\frac{dE}{dx} > \left(\frac{dE}{dx}\right)_c = \frac{E_c}{aR_c}$$

a: free parameter (to determined experimentally)

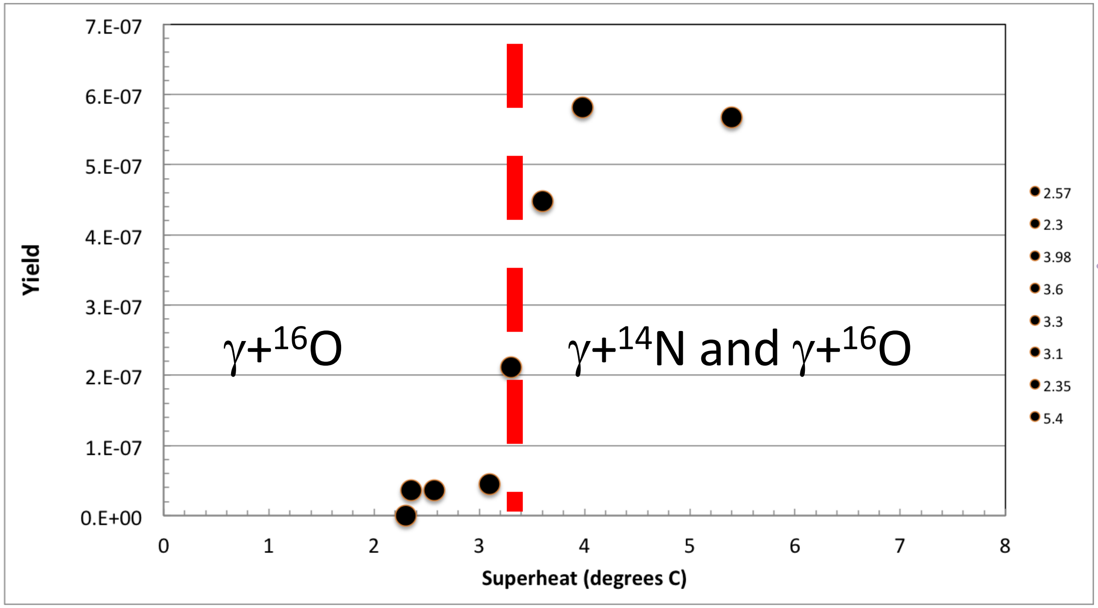
Nucleation thresholds (Water)



Efficiency Curve



N_2O thresholds
Superheat = 3.3˚C



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

Acoustic Signal Discrimination

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

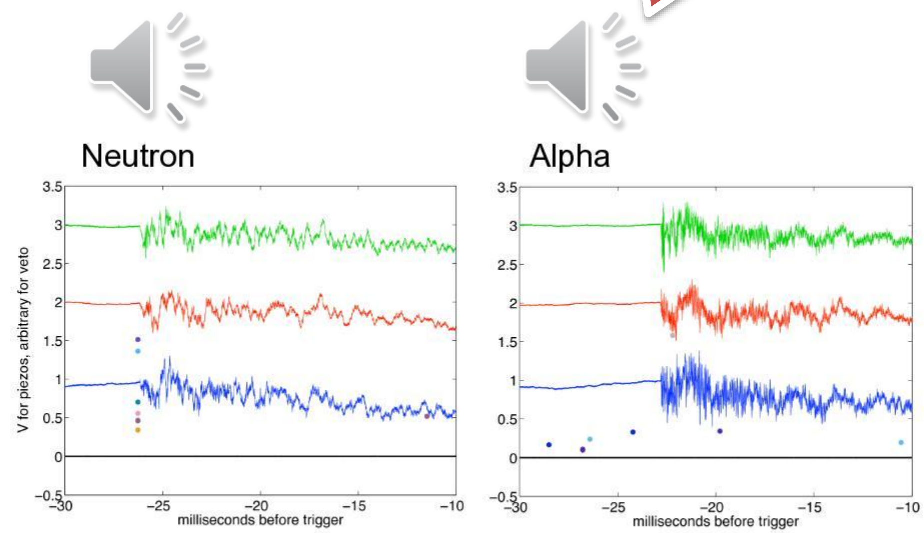
II. Neutron Events:
  - I. $^{17}O(\gamma,n)^{16}O$
  - II. Neutron–nucleus elastic scattering: $^{16}O(n,n)$, $^{14}N(n,n)$

<u>Ions ^{16}O or ^{14}N will generate a single bubble</u>

III. Alpha Events:
  - I. $^{16}O(\gamma,\alpha)^{12}C$
  - II. $^{17}O(\gamma,\alpha)^{13}C$
  - III. $^{18}O(\gamma,\alpha)^{14}C$

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

Higher Pitch



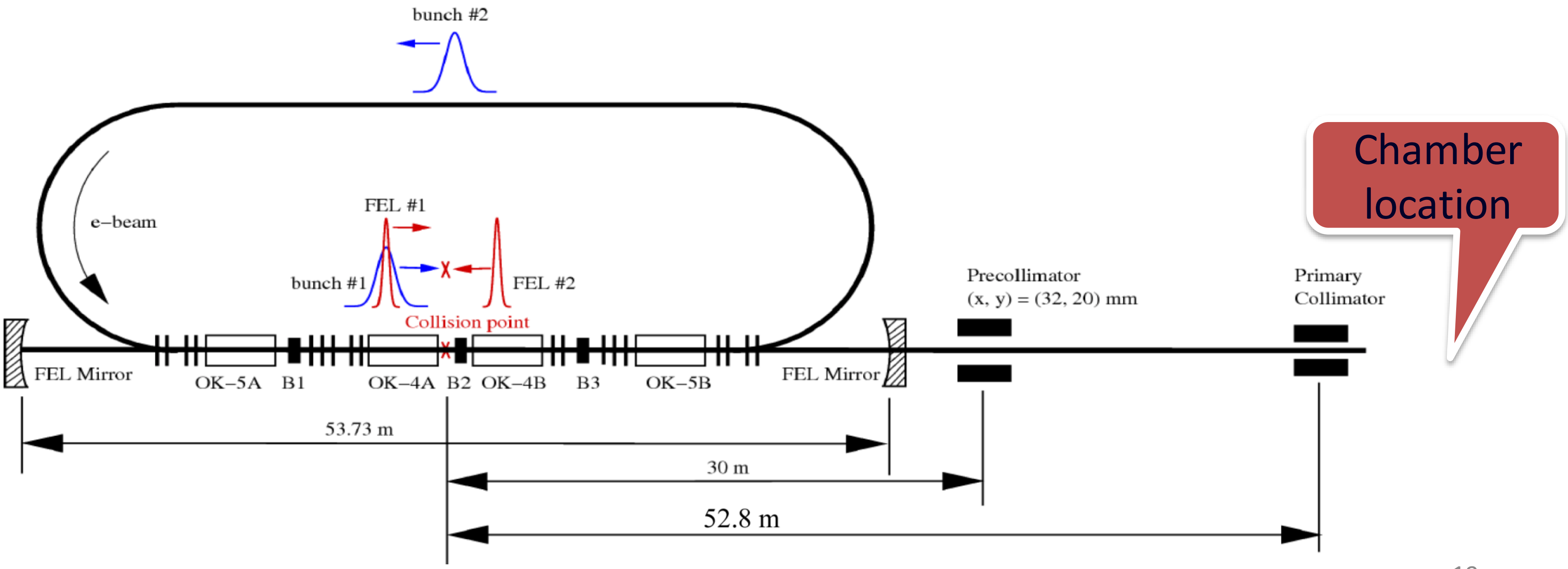
COUPP, FNAL, courtesy of A. Sonnenschein

Suppress neutron events by 100 using acoustic signal

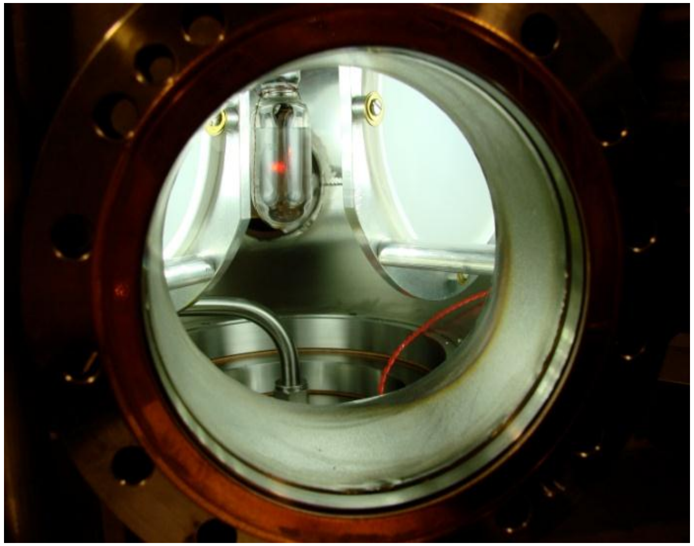
Bubble Chamber at HIGS

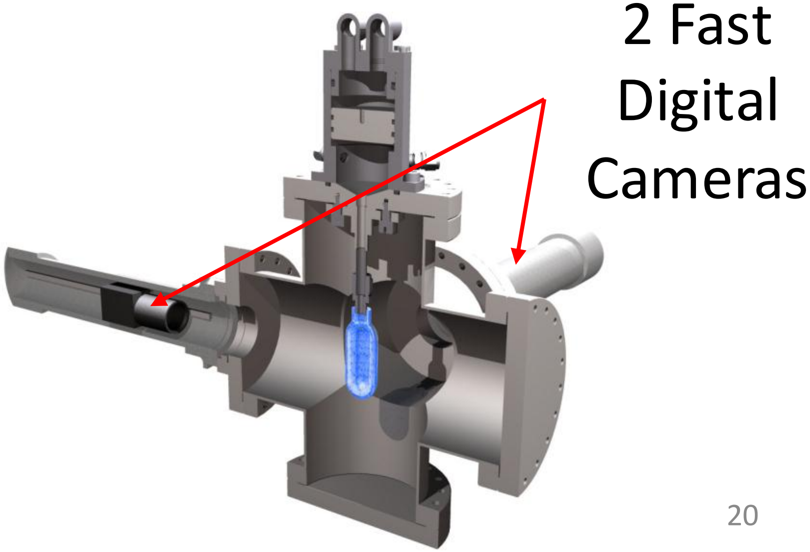
I. High Intensity Gamma Source (HIGS) at Duke University

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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Physics Letters B

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

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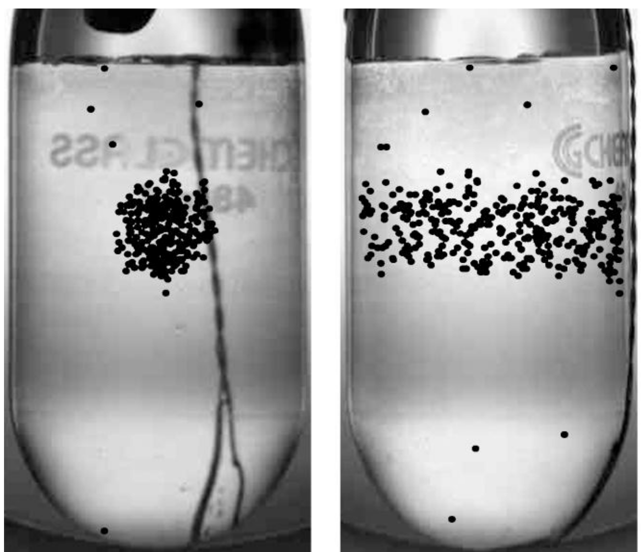
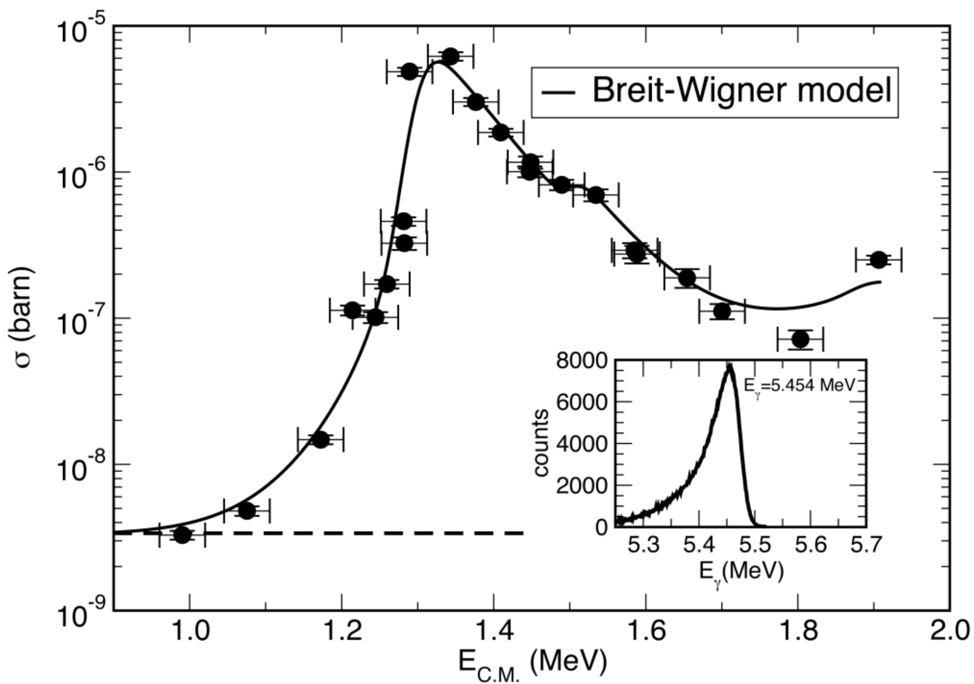
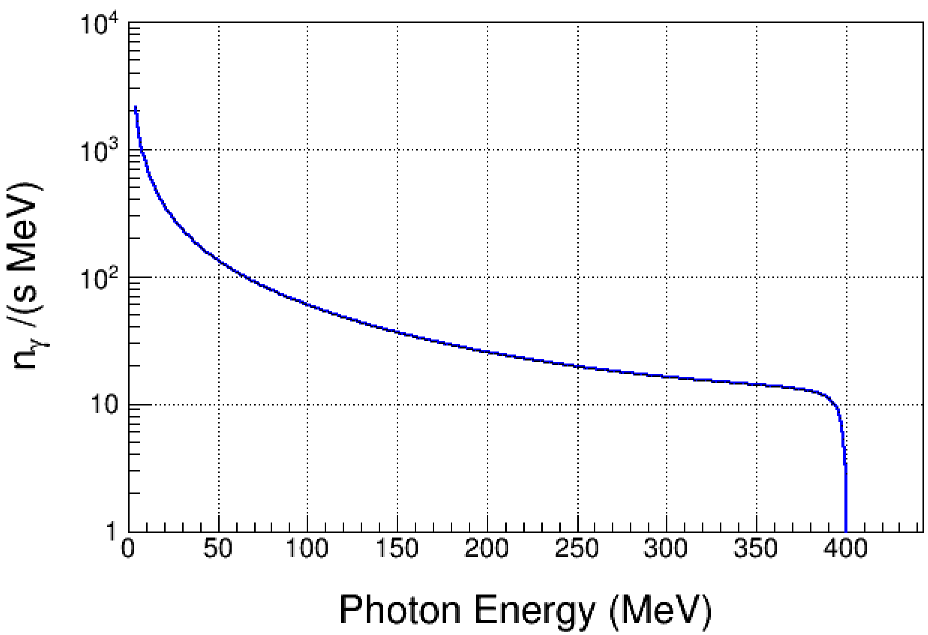




BREMSSTRAHLUNG BACKGROUND AT HIGS

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

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

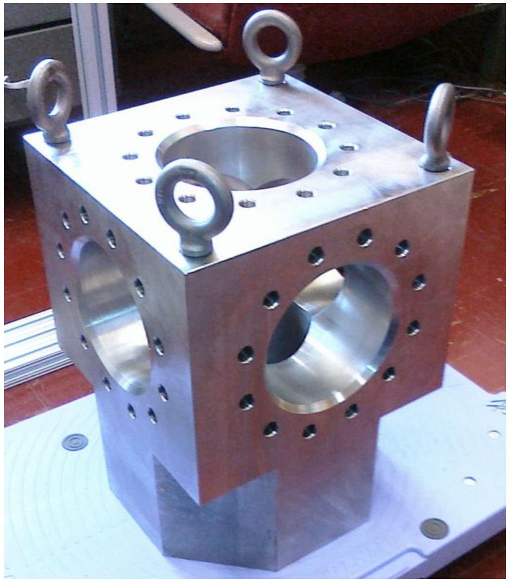


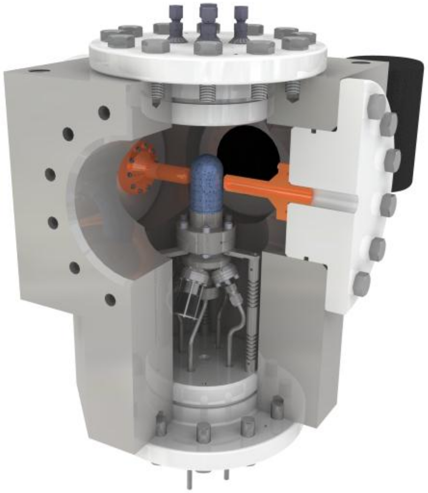
Recent Work

N_2O Bubble Chamber

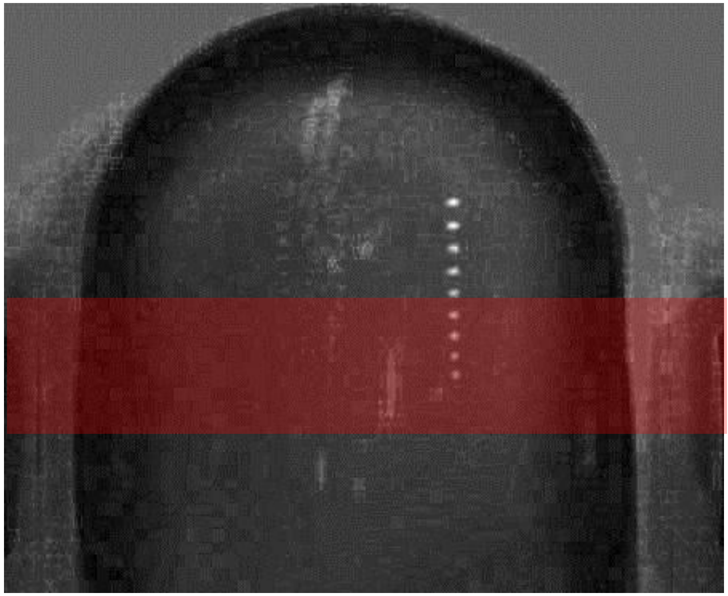
$T = 5^{\circ}C$

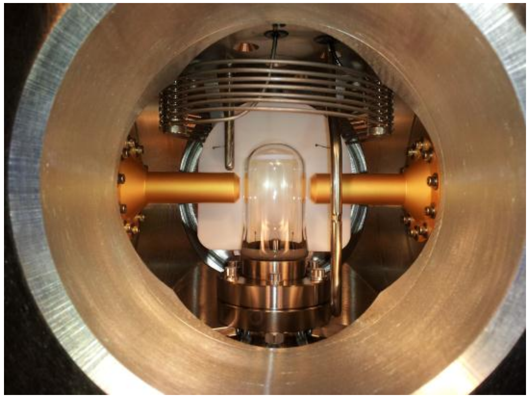
$P = 60$ atm





First γ+O→α+C bubble
April 2013





SUPERHEATED TARGETS

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

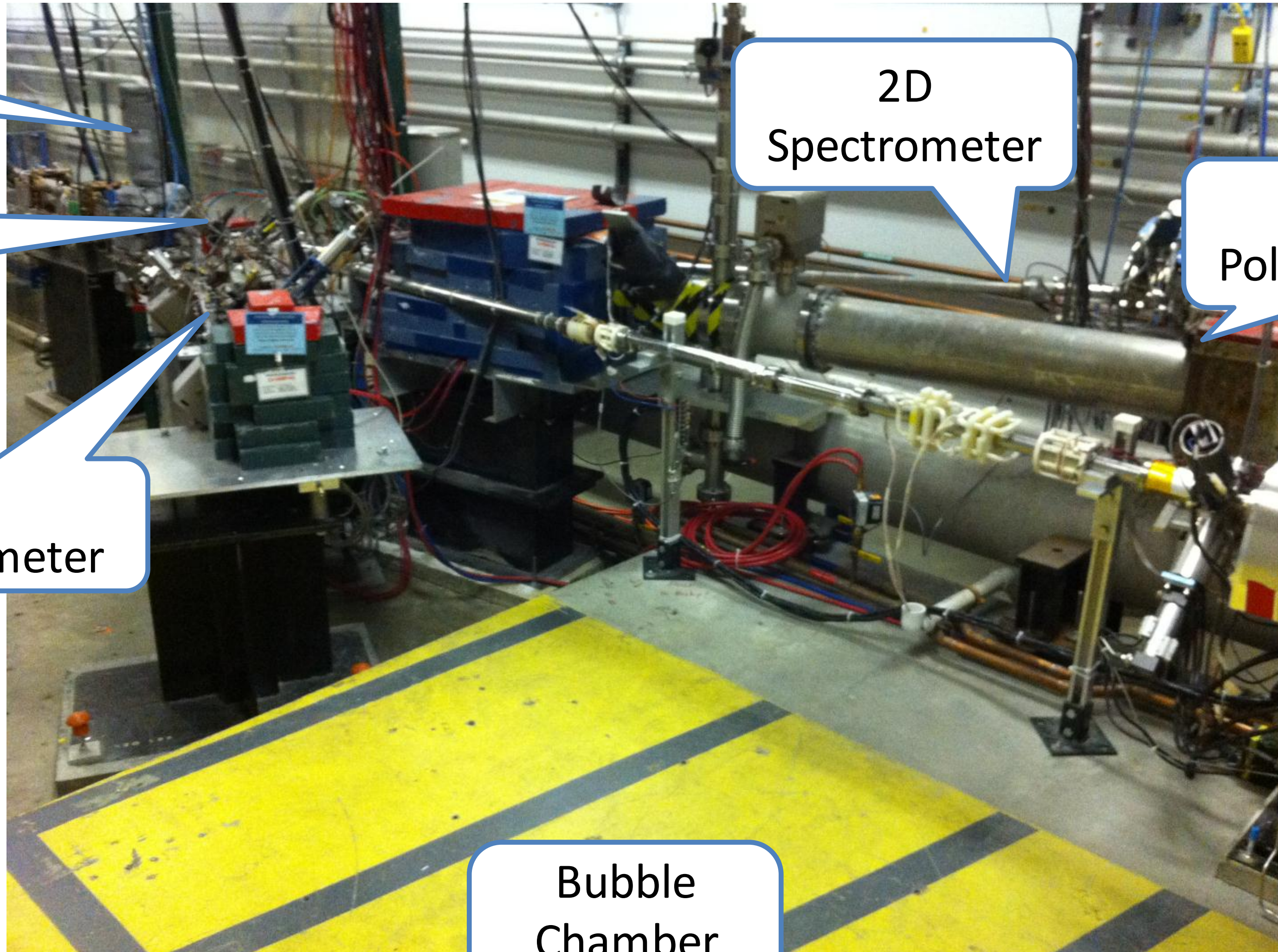
N_2O Targets	^{16}O	^{17}O	^{18}O
Natural Target	99.757%	0.038%	0.205%
^{16}O Target		Depleted > 5,000	Depleted > 5,000
^{17}O Target		Enriched > 80%	<1.0%
^{18}O Target		<1.0%	Enriched > 80%

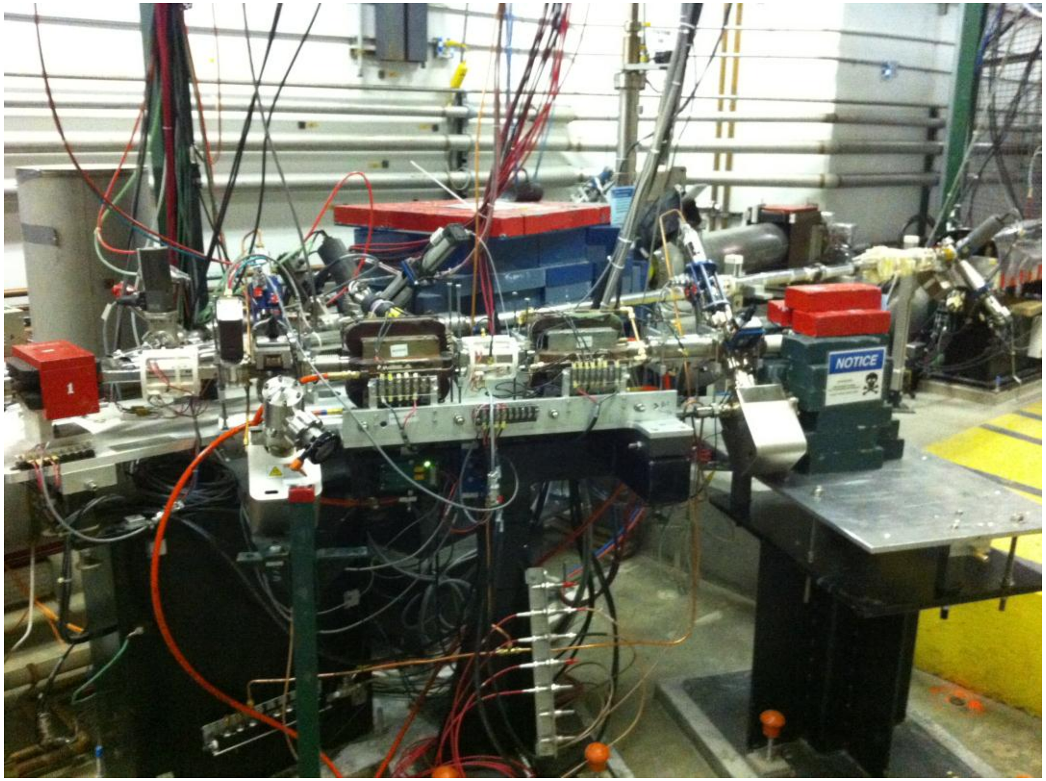
Physics

Measure Backgrounds

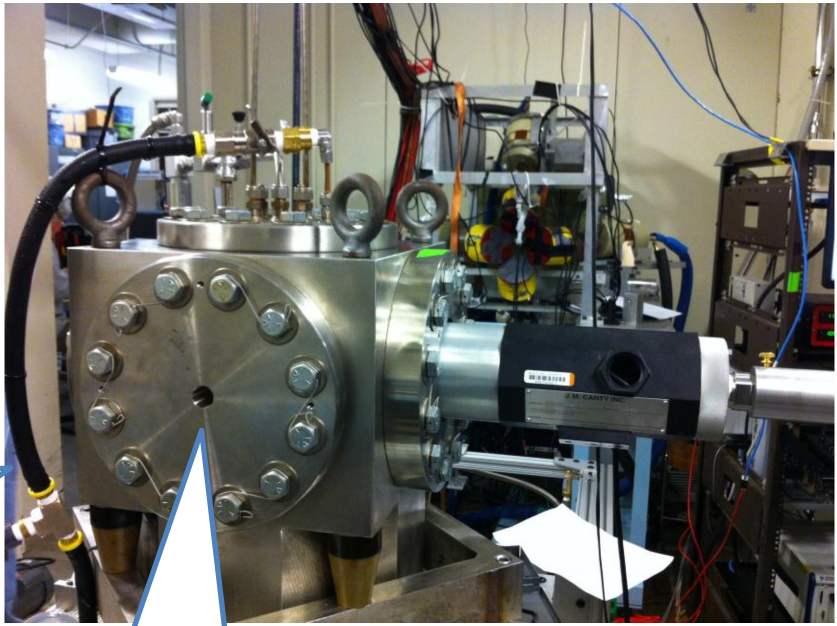
II. Readout:
   I. Fast Digital Camera
   II. Acoustic Signal to discriminate between neutron and alpha events

EXPERIMENTAL SETUP AT JLAB INJECTOR





5D Spectrometer

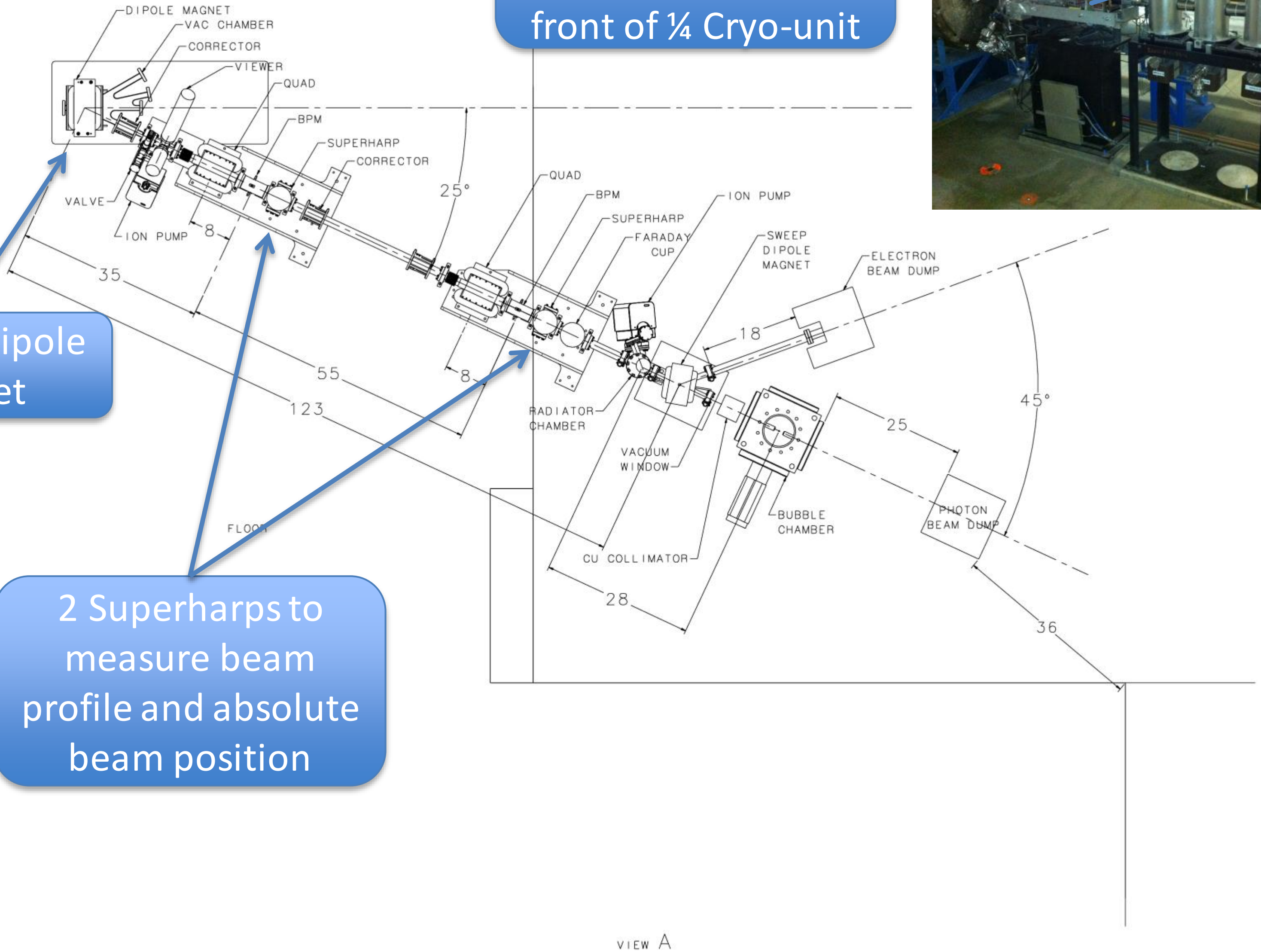


Bubble Chamber at HIGS April 2013

Photon Beam Entrance

BEAMLINE

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



Replace Dipole Magnet

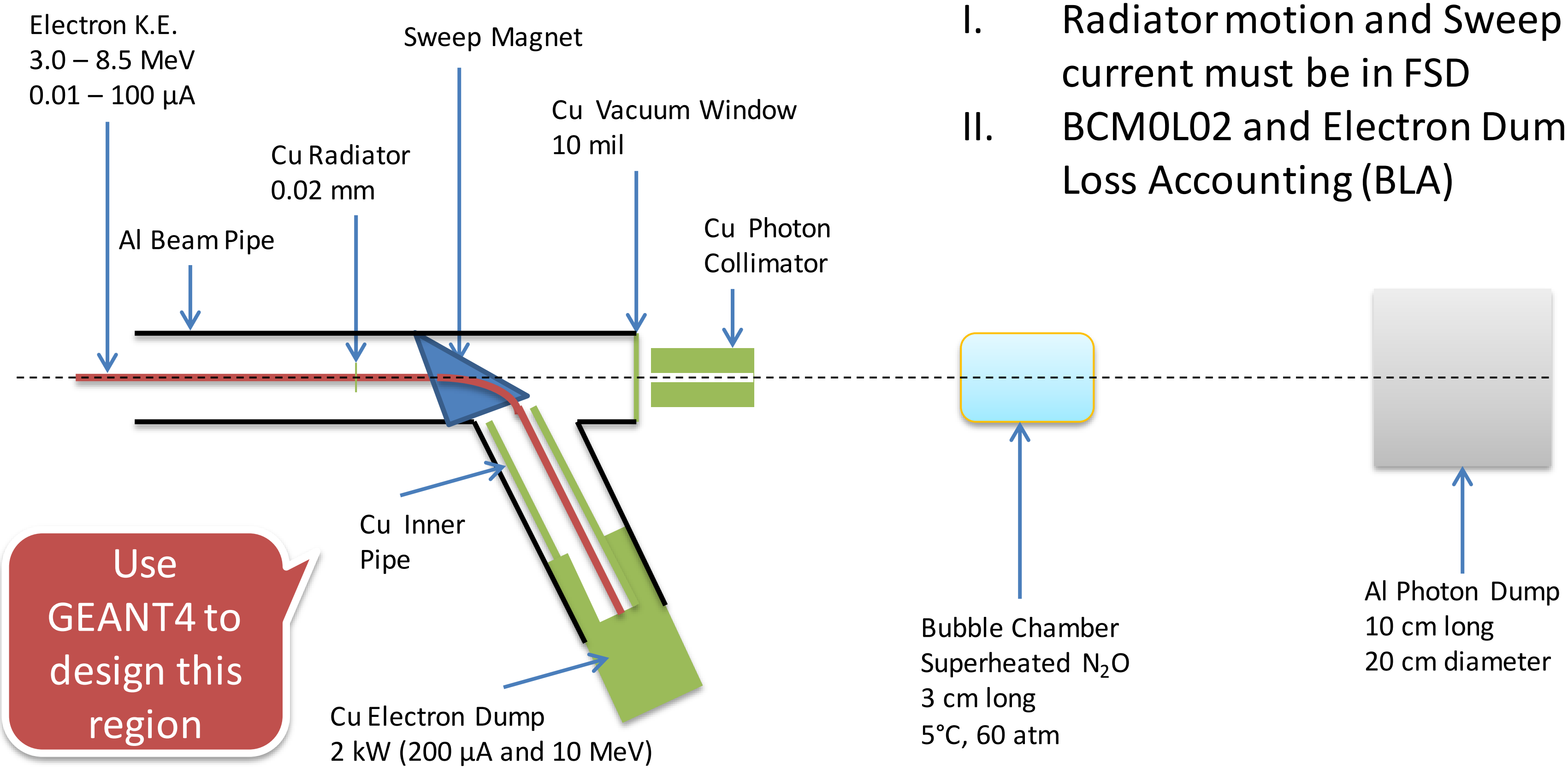
2 Superharps to measure beam profile and absolute beam position

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:

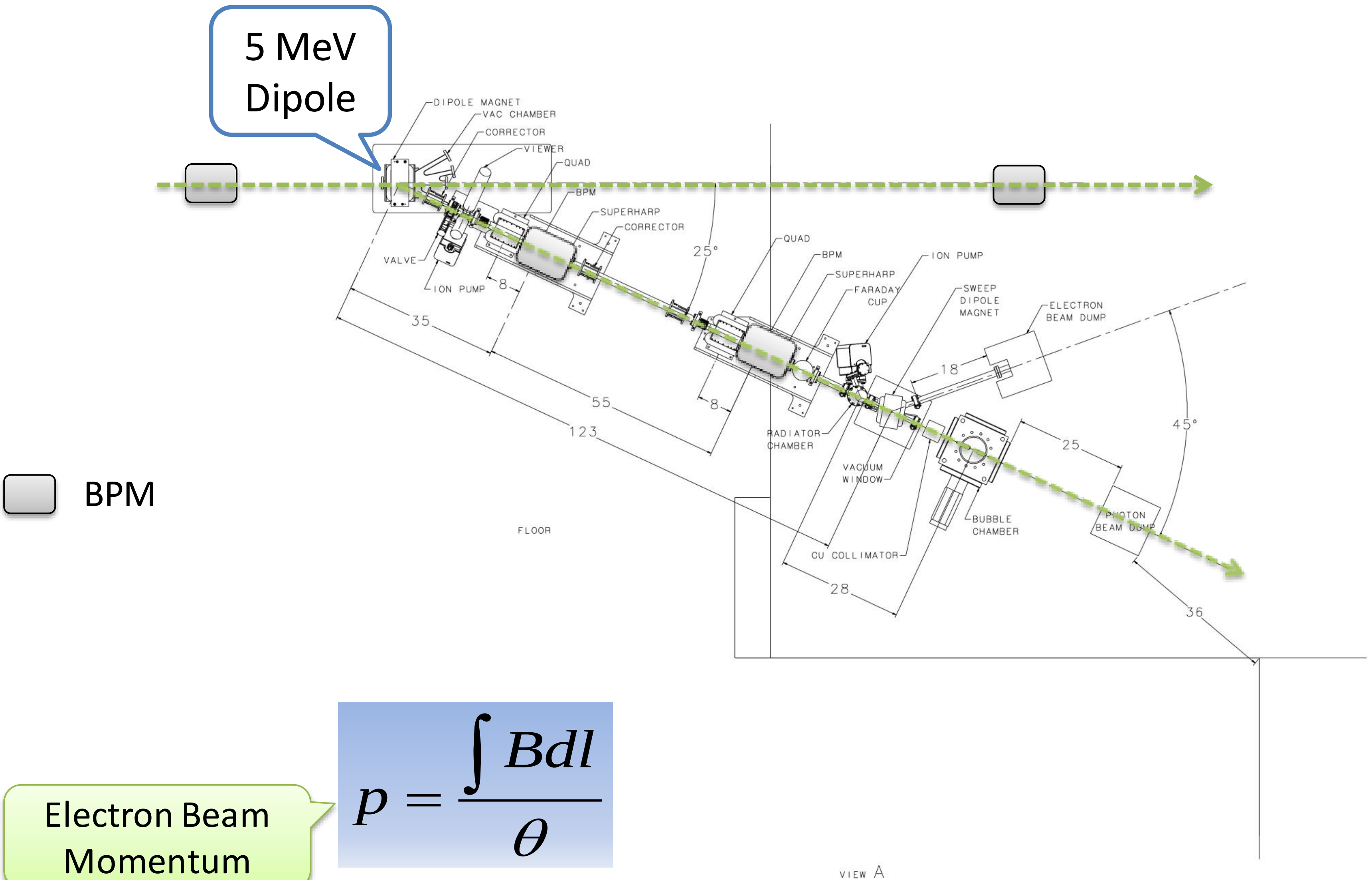
Beam Kinetic Energy, (MeV)	7.9–8.5
Beam Current (μA)	0.01–100
Absolute Beam Energy Uncertainty	<0.1%
Relative Beam Energy Uncertainty	<0.02%
Energy Resolution (Spread), σ_T/T	<0.06%
Beam Size, $\sigma_{x,y}$ (mm)	1–2

II. PEPPo achieved p=8.25 MeV/c or K.E.=7.75 MeV

III. January 2014, achieved p=9.1 MeV/c or K.E.=8.6 MeV for one hour. Still, suffer from trips due to wave guide vacuum faults; may improve with more processing.

IV. We may also need to helium process the ¼-cryounit

Measuring Absolute Beam Energy



Electron Beam Momentum

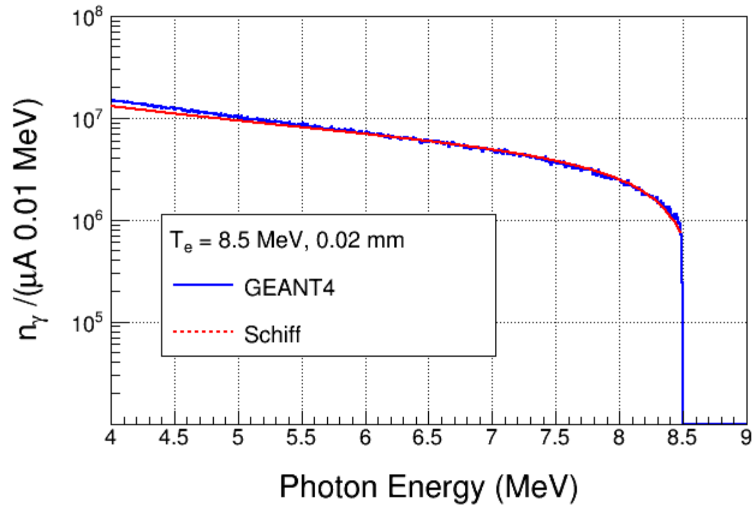
$$p = \frac{\int Bdl}{\theta}$$

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%**

I. Jay Benesch designed and is now working with Engineering to fabricate a more uniform and higher field dipole
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. Additional goal: Relative beam energy uncertainty **<0.02%**

Bremsstrahlung Beam

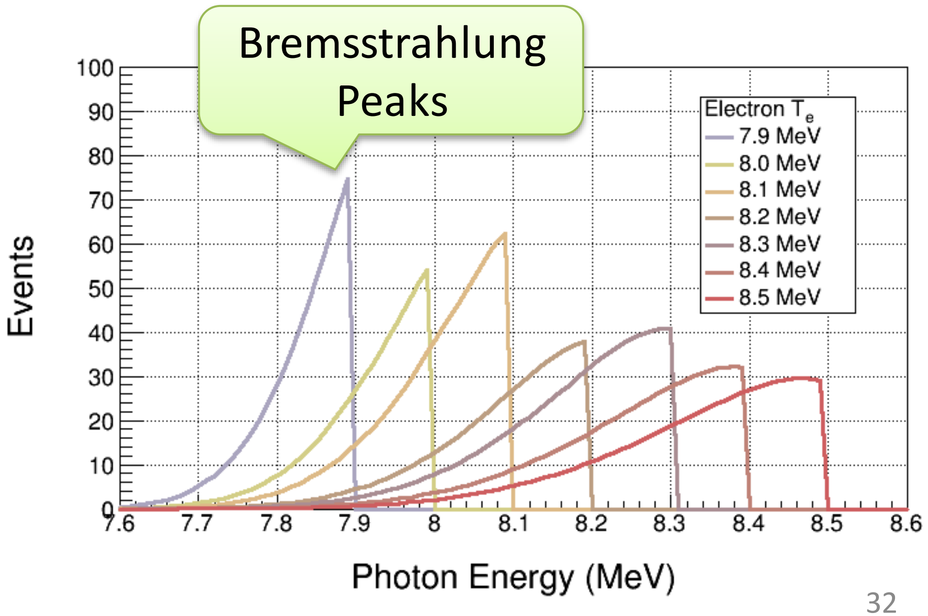
- Use both GEANT4 and FLUKA to calculate Bremsstrahlung spectra (we will not measure Bremsstrahlung spectra)
- Monte Carlo simulation of Bremsstrahlung at radiotherapy energies is well studied, accuracy: ±5%



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

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

II. No-structure (resonances)

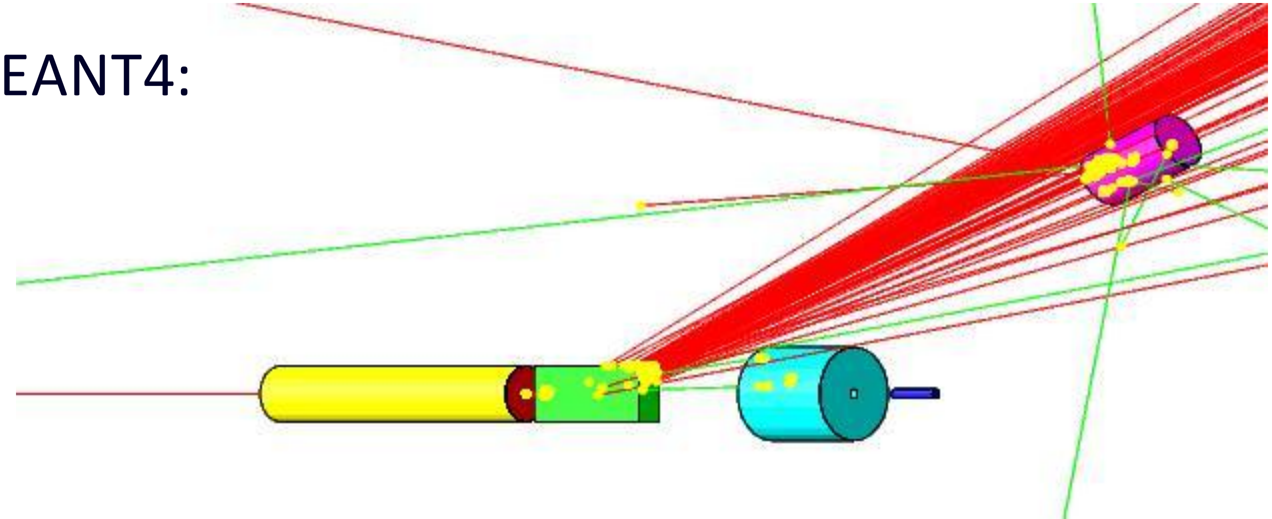


GEANT4 SIMULATION

- Both GEANT4 and FLUKA use models that calculate wrong photo–nuclear cross sections. Both do not allow for user's cross sections. 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: $E = E_1, E_2, \ldots, E_n$ where,
  $E_i - E_{i-1} = \Delta, i = 2, n$

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

Volterra Integral Equation of First Kind

Method of Quadratures: numerical solution of integral equation based on replacement of integral by finite sum

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

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

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 photon 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 10^{22} /cm^2

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

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

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

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

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

- 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 (ρ_{ij}) =1

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

No energy-to-energy change in systematic error

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

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

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

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

Systematic Error Propagation

No energy-to-energy change in systematic error

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

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

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%

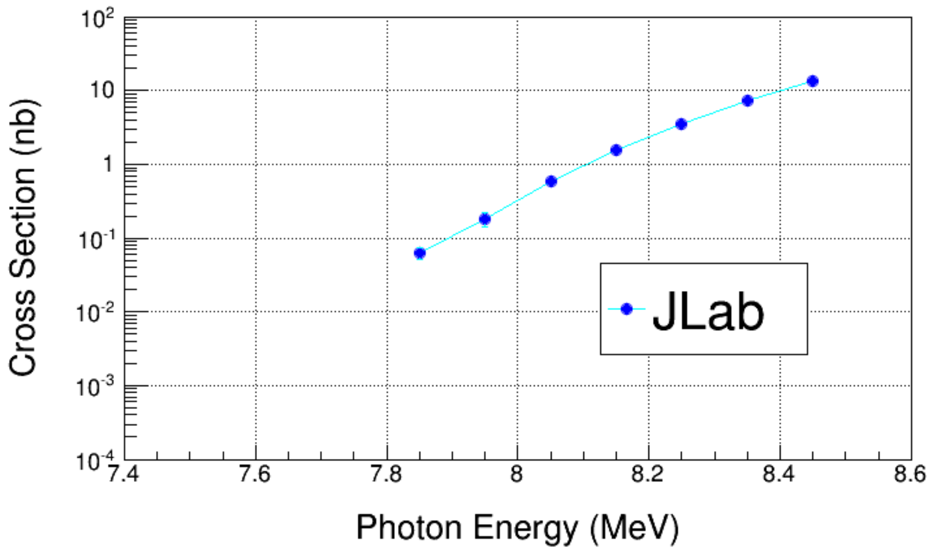
Simulation

- 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



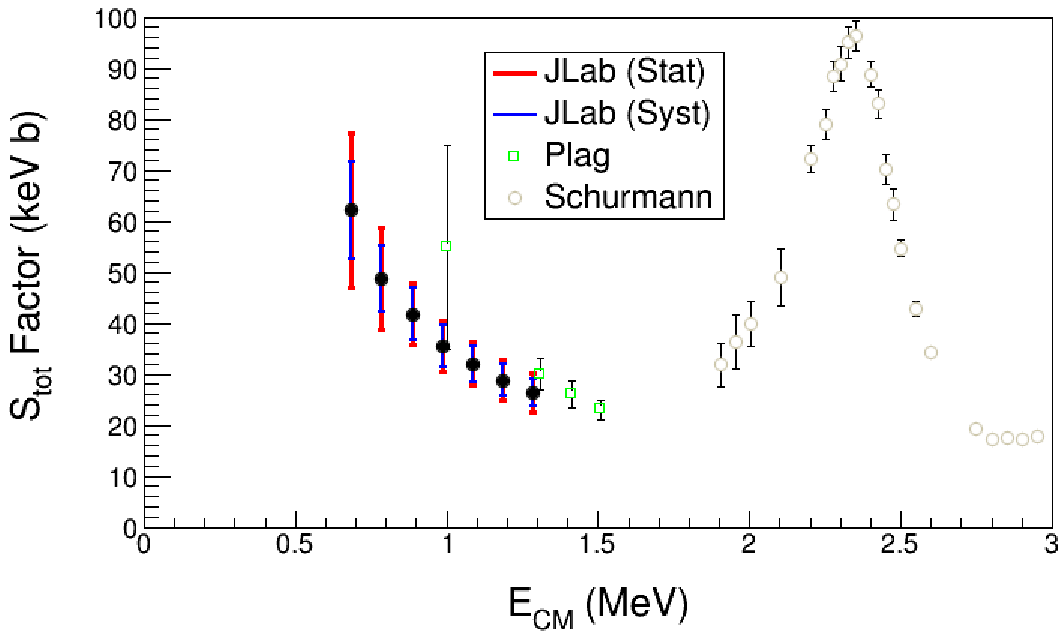
Electron Beam K. E.	Cross Section (nb)	Sys Error (Energy, %)	Sys Error (Total, %)
7.9	0.046	12.5	15.3
8.0	0.185	10.2	13.5
8.1	0.58	8.3	12.2
8.2	1.53	7.0	11.4
8.3	3.49	6.0	10.7
8.4	7.2	5.3	10.5
8.5	13.6	4.7	10.1

<u>Note</u>: Relative systematic errors do not get magnified 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%

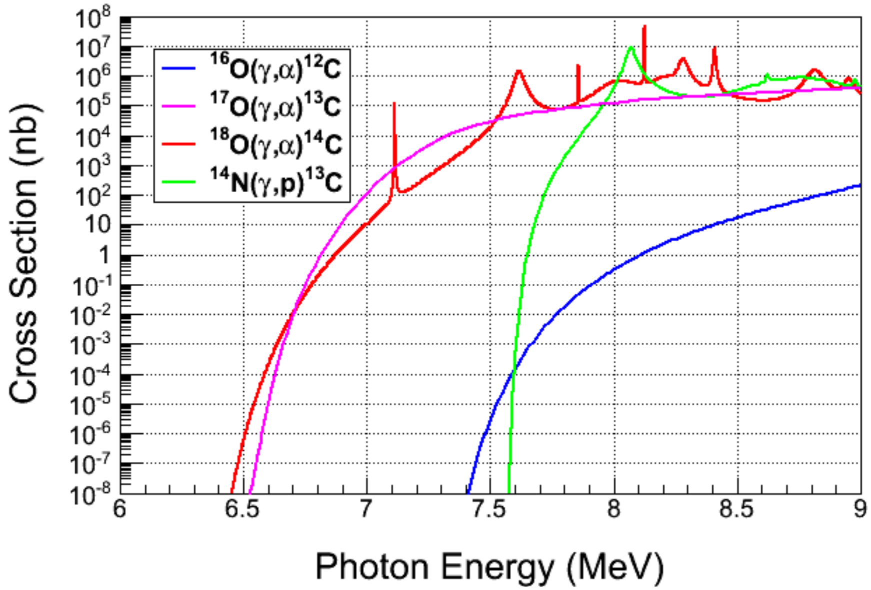
II. ^{18}O: 0.205%

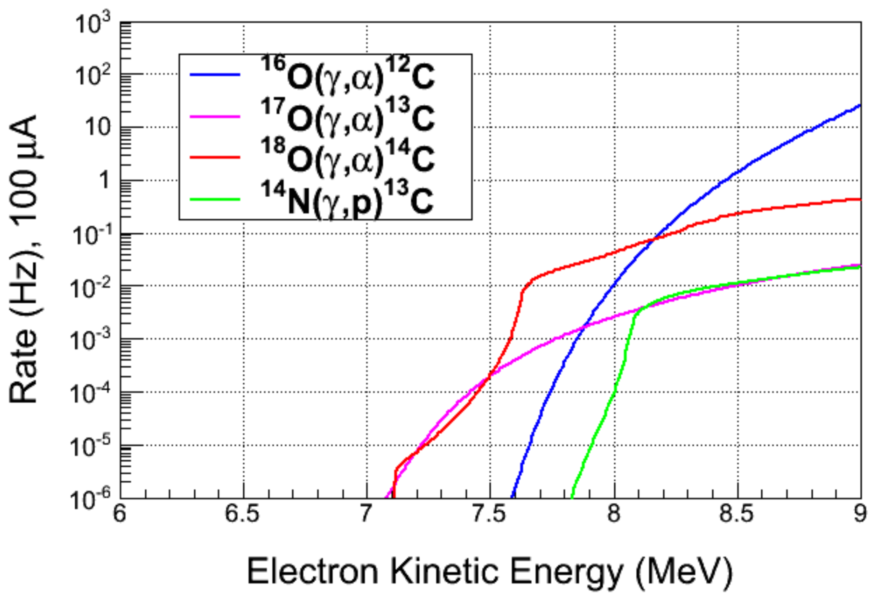
➢ Expected Rates:

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

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

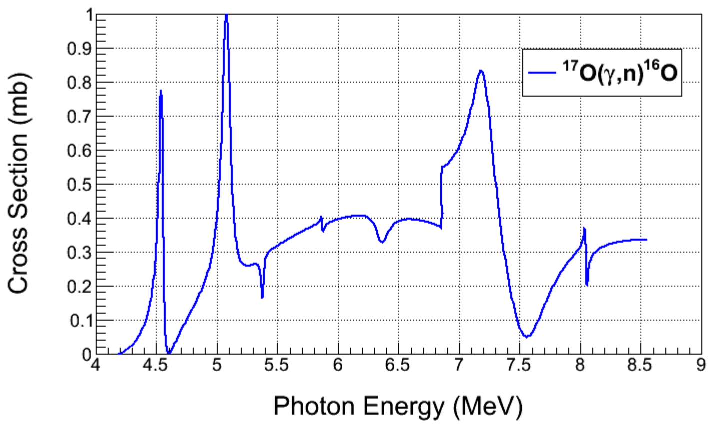
III. $^{14}N(\gamma,p)^{13}C$, Chamber eff.= 10^{-8}





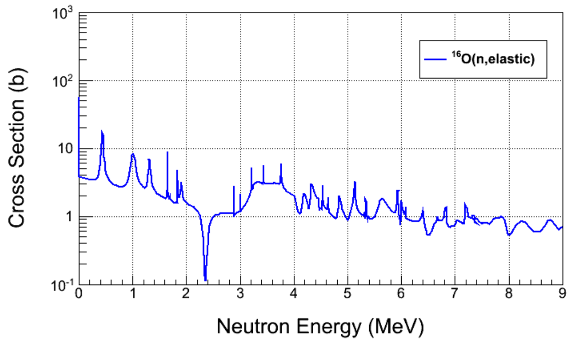
II. Background from:

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



III. Background from Chamber glass:

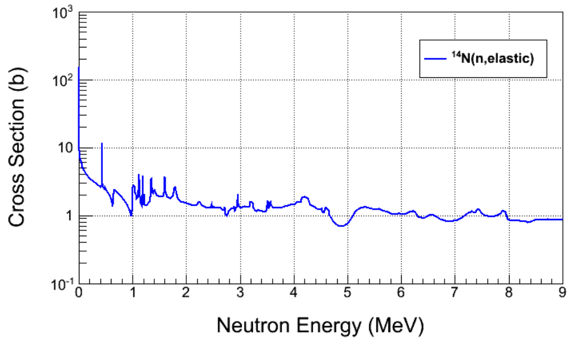
– Neutron–nucleus elastic scattering from $^{29}Si(\gamma,n)^{28}Si$



IV. Cosmic–ray background:

– $\mu^{\pm}$–nuclear

– neutron–nuclear elastic scattering



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

Ion Energy Distributions

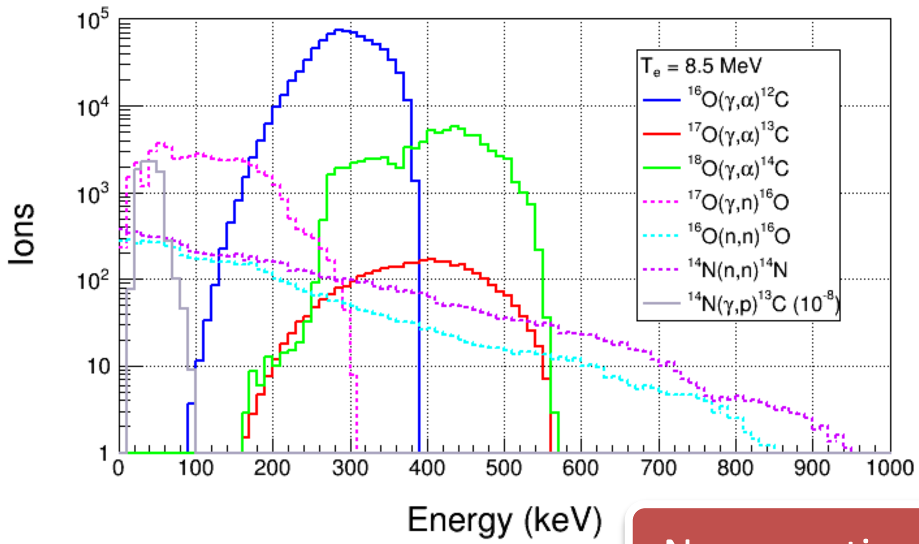
- Use depleted N_2O:
  I. ^{17}O depletion = 5,000
  II. ^{18}O depletion = 5,000
- Suppress background with Bubble Chamber thresholds

$$E_{CM} \cong E_{\gamma} - Q \qquad E_{CM} = T_{\alpha} + T_{C}$$

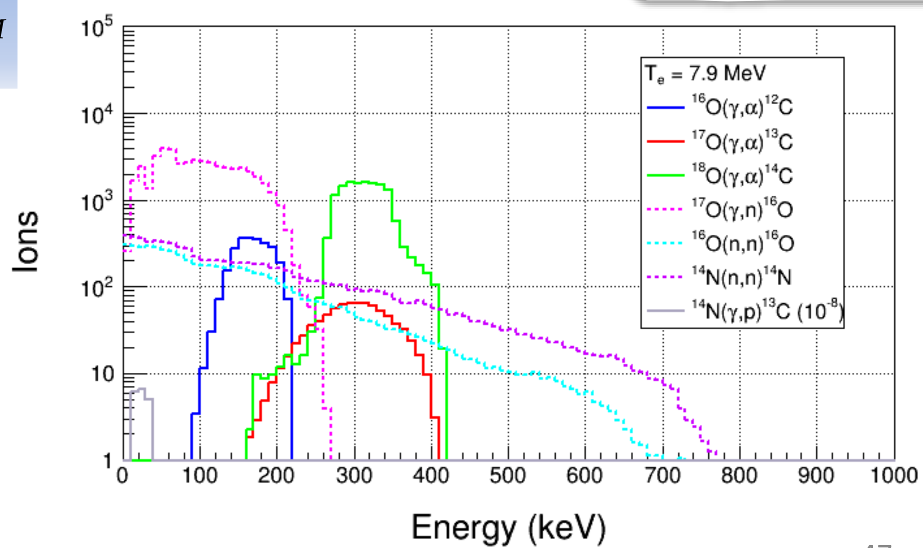
$$T_{\alpha,lab} \cong \frac{m_c}{m_\alpha + m_c} E_{CM} \qquad T_{C,lab} \cong \frac{m_\alpha}{m_\alpha + m_c} E_{CM}$$

- Threshold Efficiency (function of superheat):

Particle	Efficiency
$e^{\pm}$	$<10^{-11}$
γ	$<10^{-11}$
$^{14}N(\gamma,p)^{13}C$	$<10^{-8}$

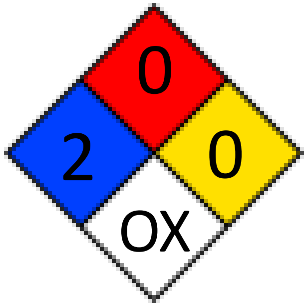


No acoustic cut



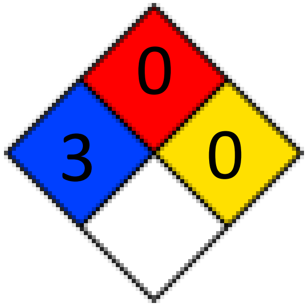
SAFETY

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



- High pressure system:
  I. Design Authority: Dave Meekins
  II. T = 5˚C
  III. P = 60 atm

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



SUMMARY AND OUTLOOK

- More testing of N_2O Bubble Chamber at HIGS (Spring 2014)
- Measure cross sections of $^{18}O(\gamma,\alpha)^{14}C$ and $^{17}O(\gamma,\alpha)^{13}C$ at HIGS (Fall 2014)
- Test Bubble Chamber at JLab with Bremsstrahlung beam (2015)
- Run depleted N_2O bubble chamber at JLab to measure $^{16}O(\gamma,\alpha)^{12}C$
- 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

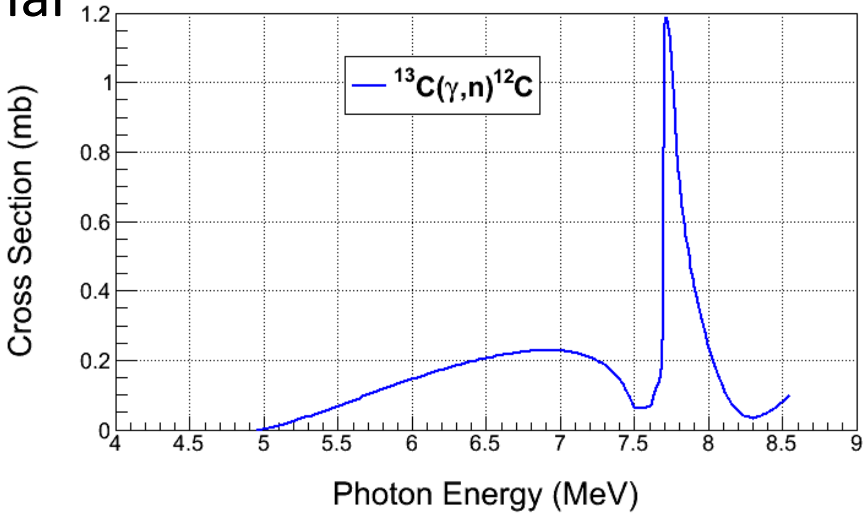
I. New beamline components:
   I. New Dipole Magnet and Hall Probe
   II. 2 Super Harps
   III. Fast Valve
II. Summary of labor cost by group:

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

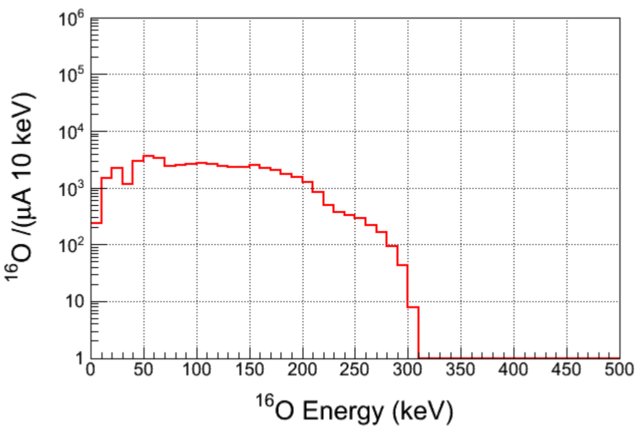
Item	Material Procurement	Shop	Labor
New Dipole Magnet	Dipole Magnet ($8,000) Hall Probe System ($10,000)		Design (2 week) Mapping (1 week) EESDC (1 week) Alignment (2 days)
New Beamline	2 Super Harps (20,000) Fast Valve ($23,000)	Pipes + Pedestals ($20,000)	Design (6 weeks) Alignment (1 week) Software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

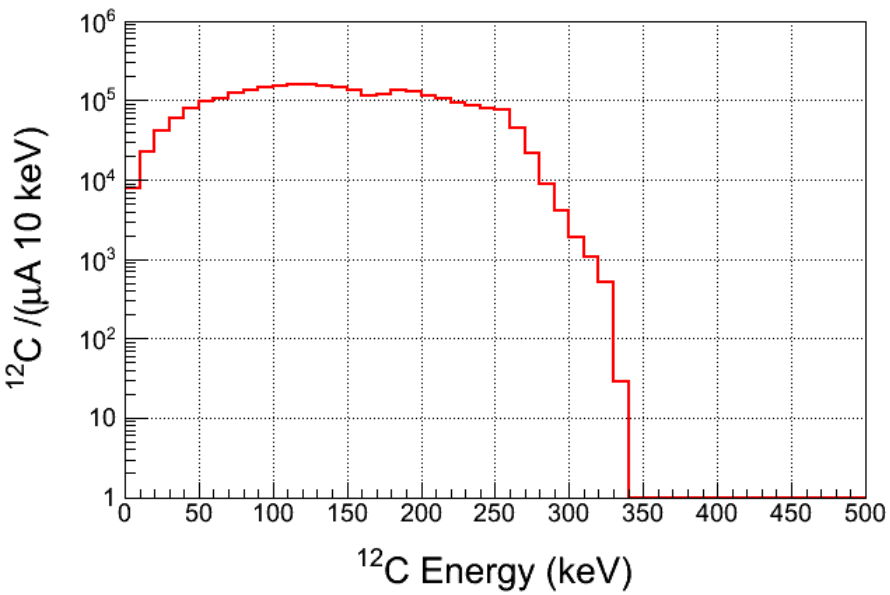
CO_2 SUPERHEATED LIQUID?

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

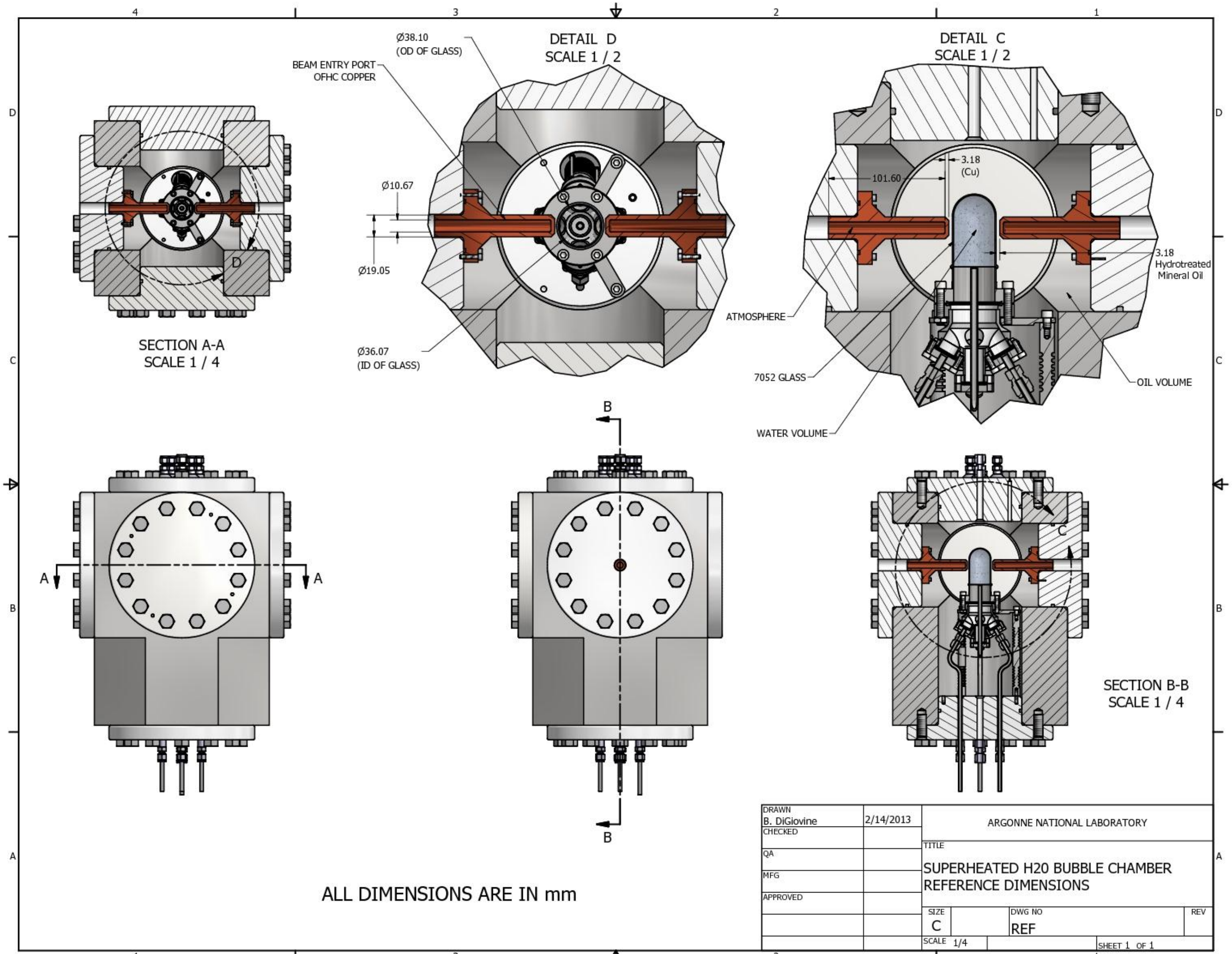


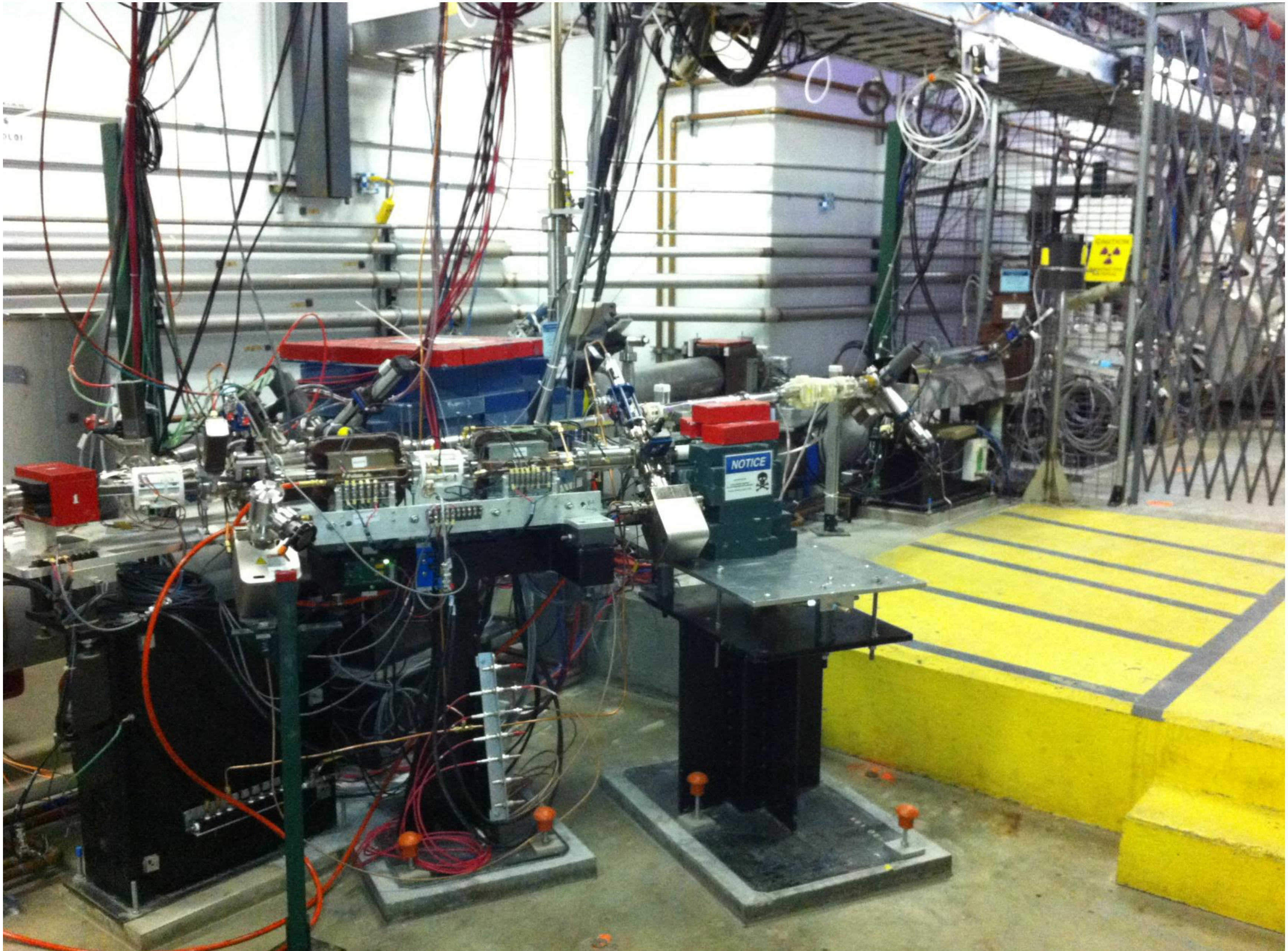


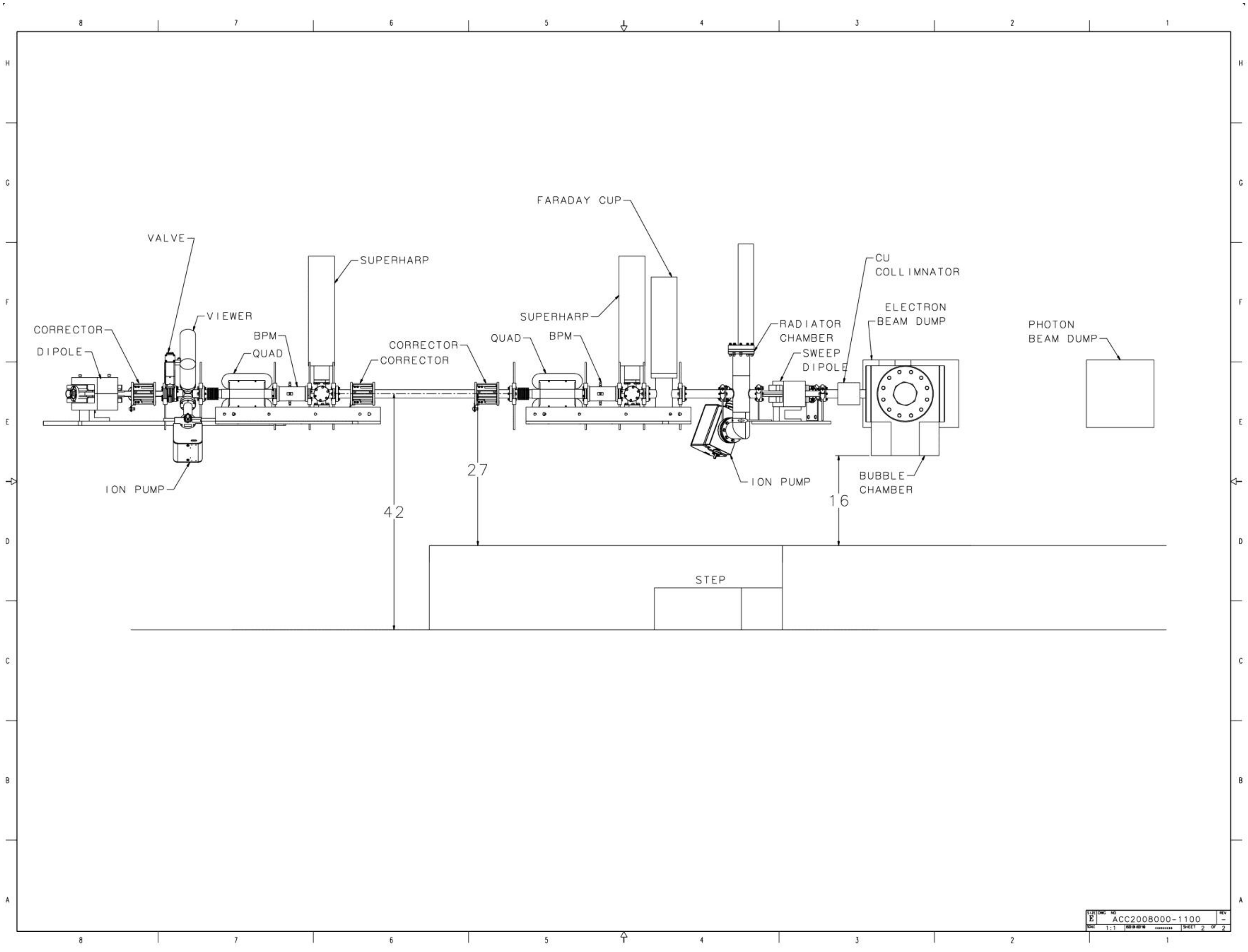
- $^{12}C(\gamma,2\alpha)\alpha$ Background

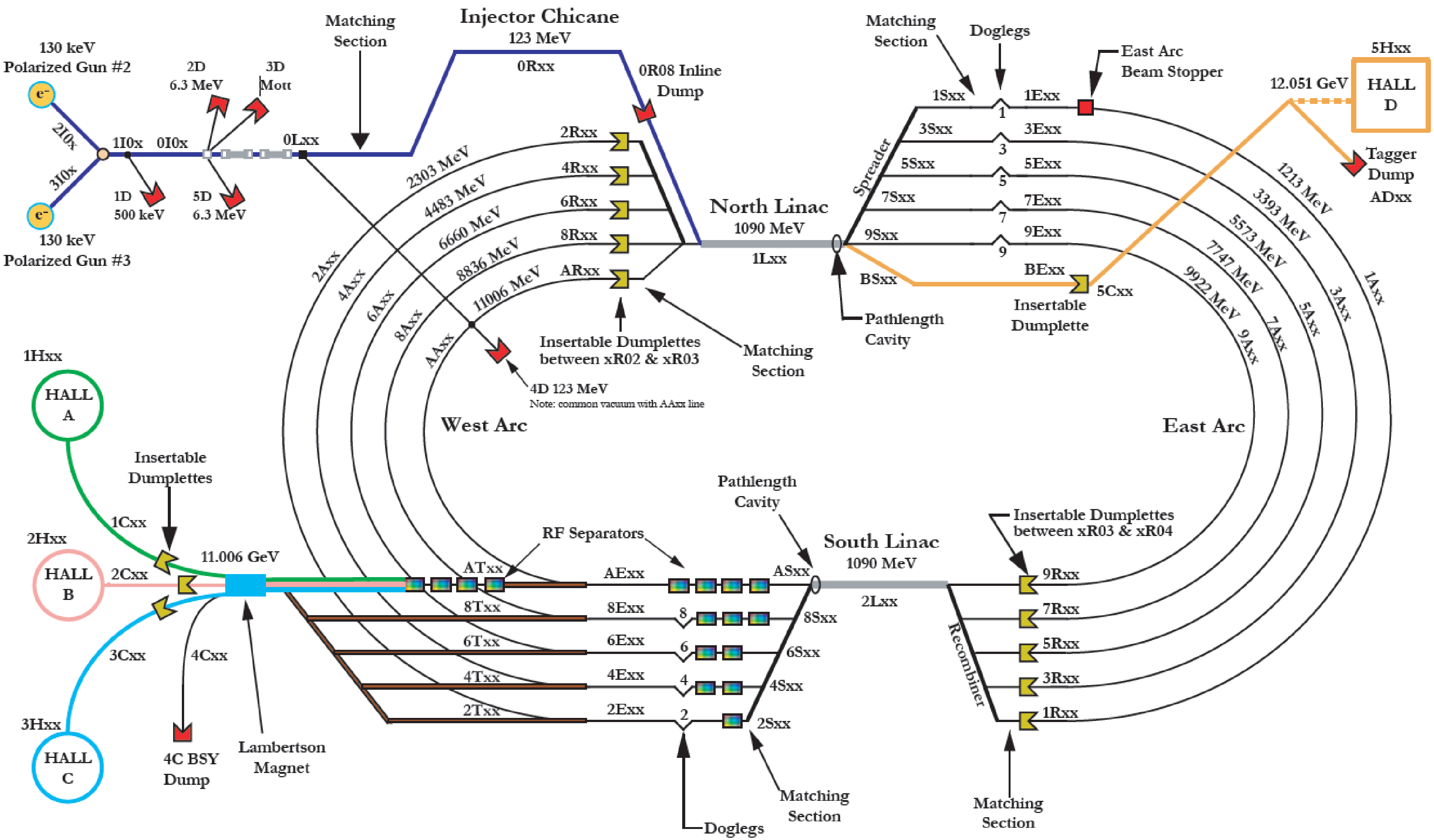
WATER SUPERHEATED LIQUID?

- Etching of glass vessel by superheated H_2O
- $T = 250^{\circ}C$
- $P = 75$ atm
- Background from secondary neutron–nucleus elastic scattering by neutrons from $d(\gamma,n)p$

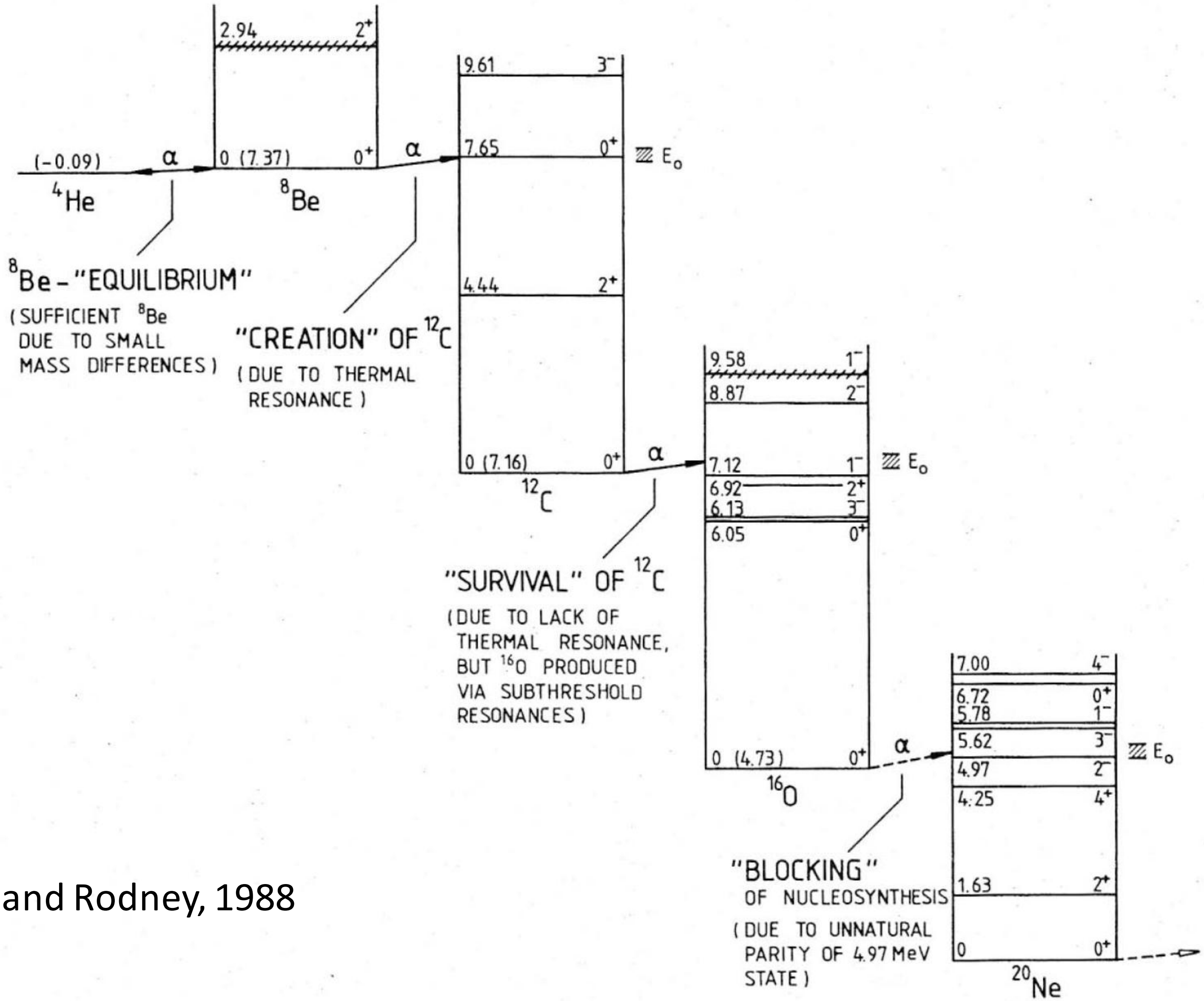

DETAIL D
SCALE 1 / 2
DETAIL C
SCALE 1 / 2
Ø38.10
(OD OF GLASS)
BEAM ENTRY PORT
OFHC COPPER
Ø10.67
Ø19.05
Ø36.07
(ID OF GLASS)
3.18
(Cu)
101.60
3.18
Hydrotreated
Mineral Oil
ATMOSPHERE
7052 GLASS
WATER VOLUME
OIL VOLUME
SECTION A-A
SCALE 1 / 4
SECTION B-B
SCALE 1 / 4
ALL DIMENSIONS ARE IN mm
DRAWN
B. DiGiovine
2/14/2013
CHECKED
QA
MFG
APPROVED
ARGONNE NATIONAL LABORATORY
TITLE
SUPERHEATED H20 BUBBLE CHAMBER
REFERENCE DIMENSIONS
SIZE
C
DWG NO
REF
REV
SCALE 1/4
SHEET 1 OF 1


NOTICE


FARADAY CUP
VALVE
SUPERHARP
CU
COLLIMNATOR
VIEWER
SUPERHARP
ELECTRON
BEAM DUMP
CORRECTOR
BPM
QUAD
BPM
RADIATOR
CHAMBER
PHOTON
BEAM DUMP
DIPOLE
QUAD
CORRECTOR
CORRECTOR
SWEEP
DIPOLE
27
ION PUMP
BUBBLE
CHAMBER
ION PUMP
42
16
STEP
ACC2008000-1100



130 keV
Polarized Gun #2
2I0x
3I0x
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
5Cxx
Insertable
Dumplette
Pathlength
Cavity
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
Insertable
Dumplettes
1Cxx
2Hxx
HALL
B
2Cxx
11.006 GeV
3Cxx
4Cxx
3Hxx
HALL
C
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