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

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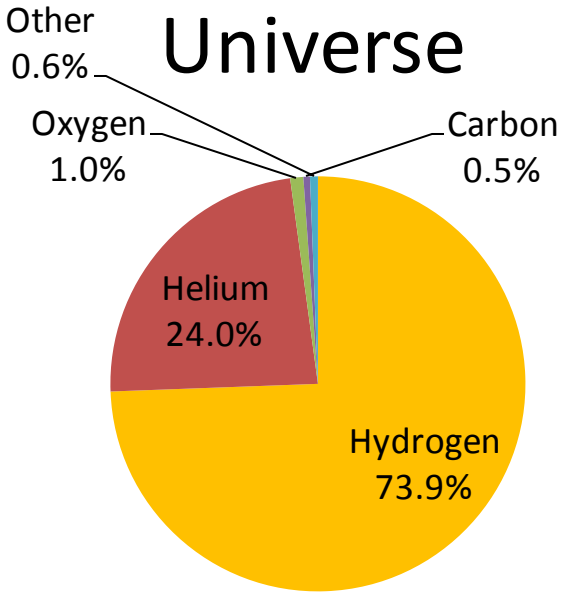
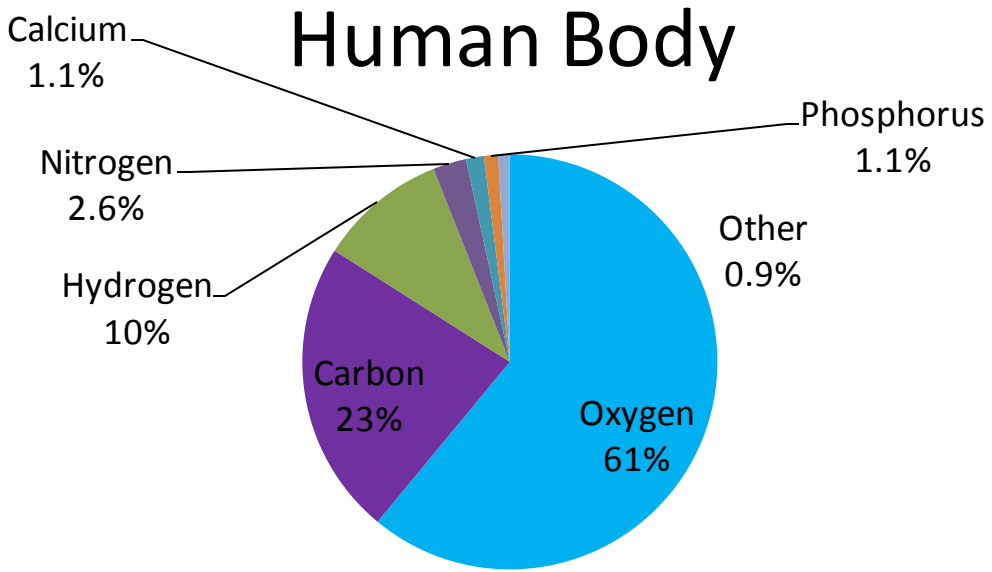
https://wiki.jlab.org/ciswiki/index.php/Bubble_Chamber

OUTLINE

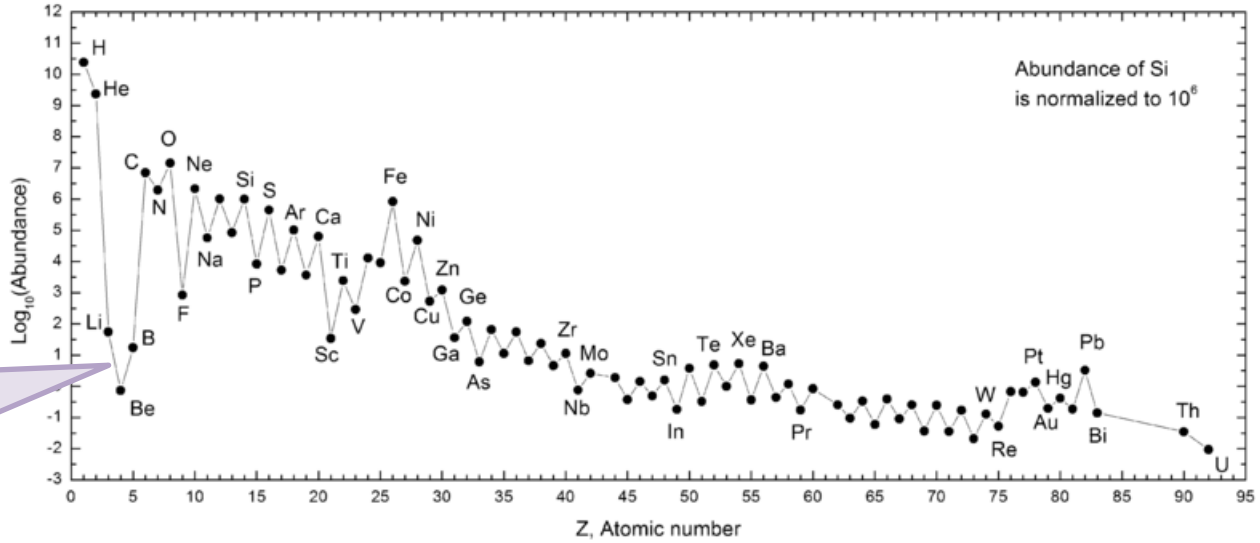
- Nucleosynthesis and the $^{12}C(\alpha,\gamma)^{16}O$ Reaction
- Time Reversal Reaction: $^{16}O(\gamma,\alpha)^{12}C$
- The Bubble Chamber
- Experimental Setup at Jefferson Lab Injector
- Bremsstrahlung Beam and Penfold-Leiss Unfolding
- Statistical and Systematic Errors
- Backgrounds and Ion Energy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

Relative Abundance of Elements by Weight



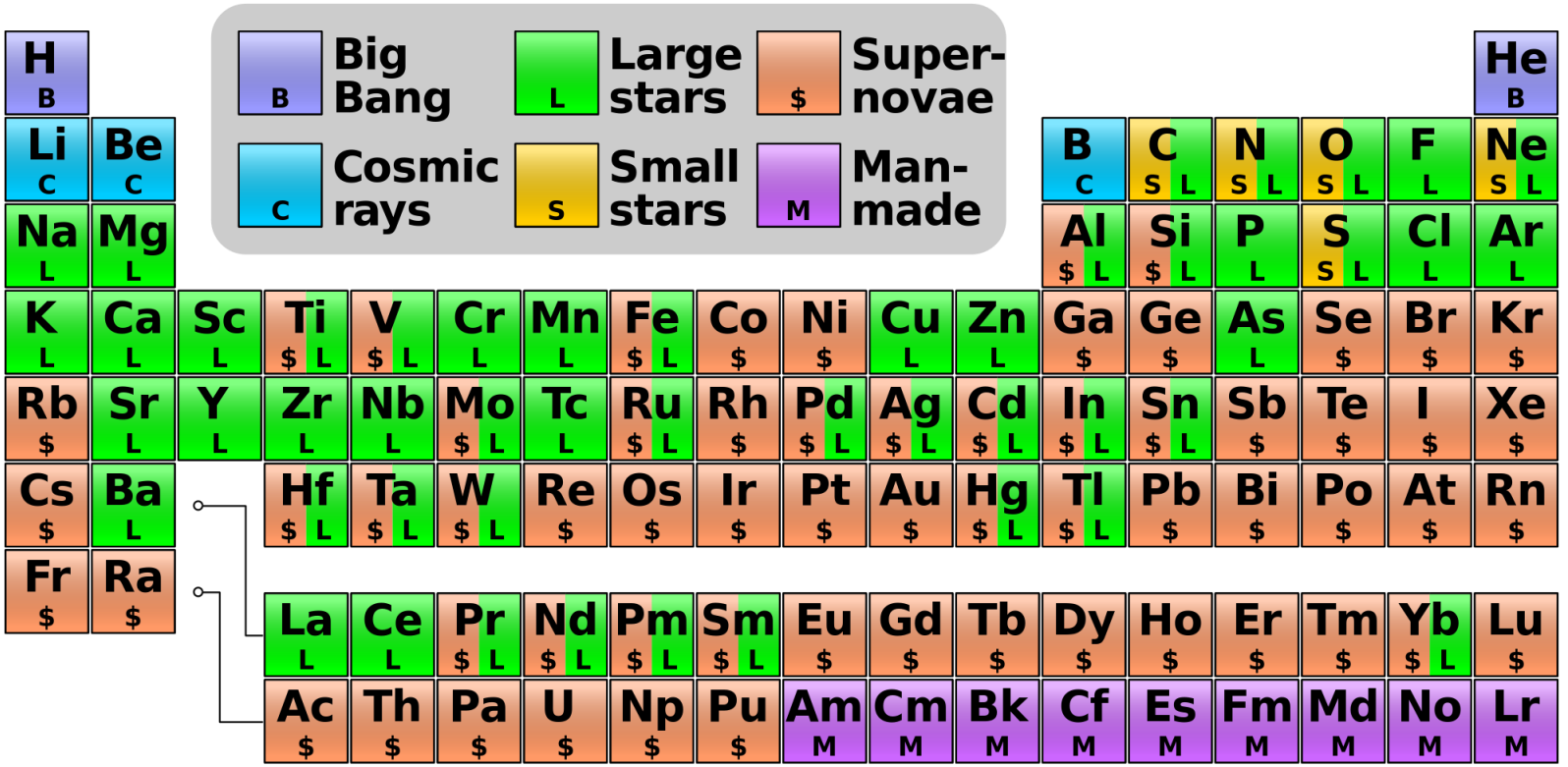


This region is bypassed by 3α process

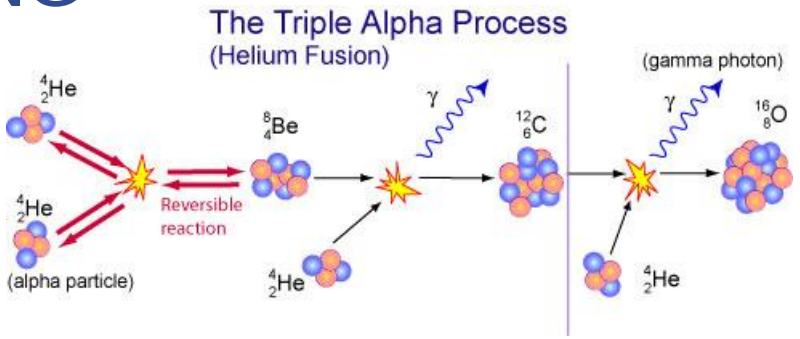


NUCLEOSYNTHESIS

- **Big Bang Nucleosynthesis:** quark–gluon plasma → p, n, He
- **Stellar Nucleosynthesis:** H burning, He burning, NCO cycle
- **Supernovae Nucleosynthesis:** Si burning
- **Cosmic Ray Spallation**



Stellar Helium Burning



- Helium Reactions:
  - I. $\alpha + \alpha \leftrightarrow {}^{8}Be$
  - ($Q = -0.092$ MeV, $T_{½} \approx 10^{-16}$ 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 – due to parity conservation)
- $\alpha + {}^{12}C$ burns at very small cross section $\sigma \approx 10^{-17}$ barn (10^{-41} cm^2)
  - ➡ Currently, reaction rate error is large (±35%)

Goal <±10%

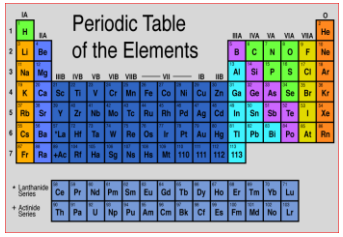
- Thermonuclear reaction rate involving two nuclei is:

Only narrow energy range is relevant (Gamow Peak)

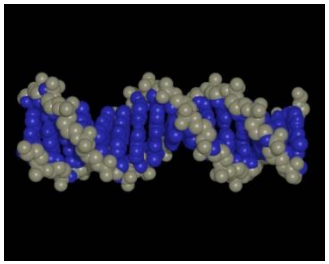
$$R = \sqrt{\frac{8}{\pi m (k_B T)^3}} \int_0^\infty E \sigma_{tot}(E) e^{-\frac{E}{k_B T}} dE$$

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

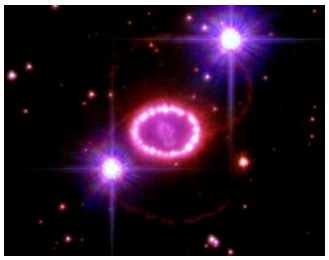
- The *holy grail* of nuclear astrophysics



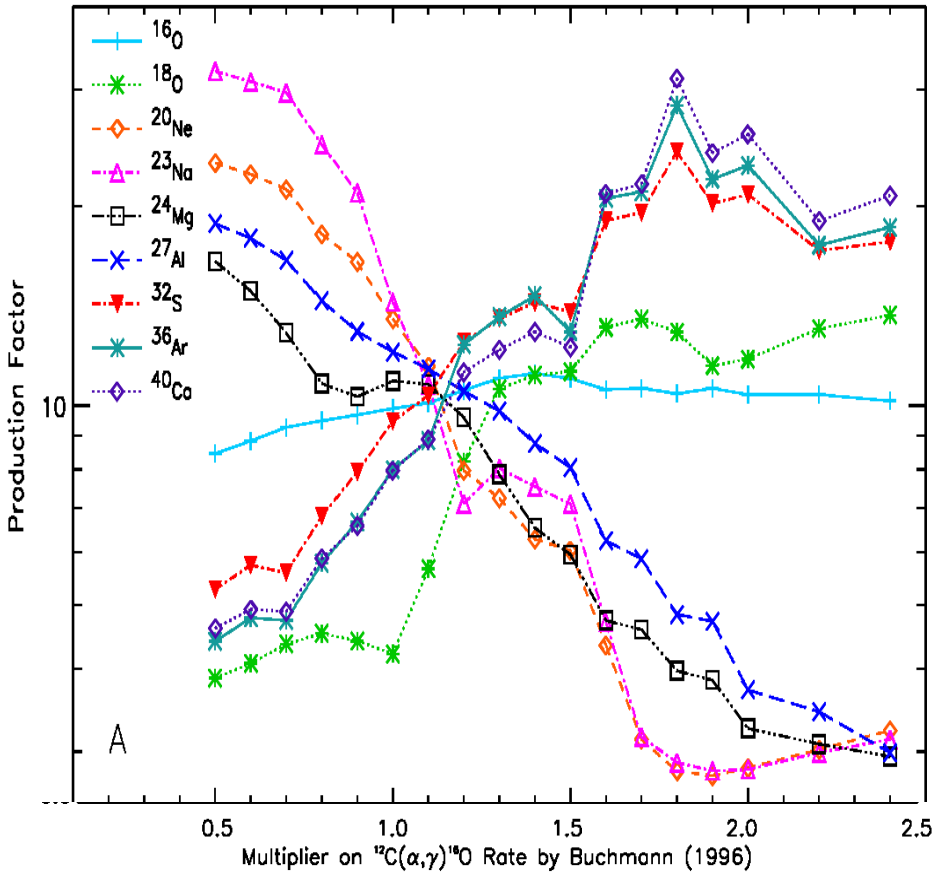
Affects the synthesis of most of the elements of the periodic table



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



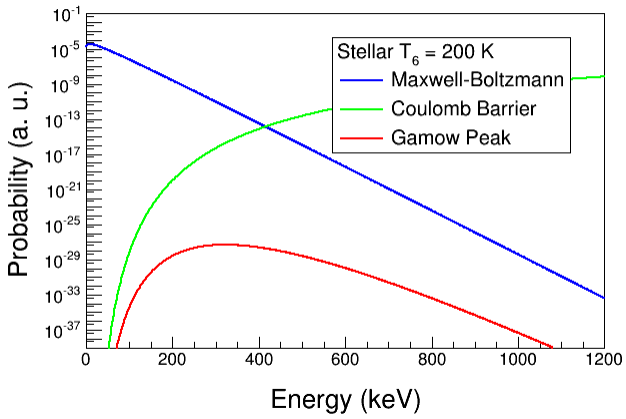
S. Woosley, A. Heger, Phys. Rep. **442** (2007) 269

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}

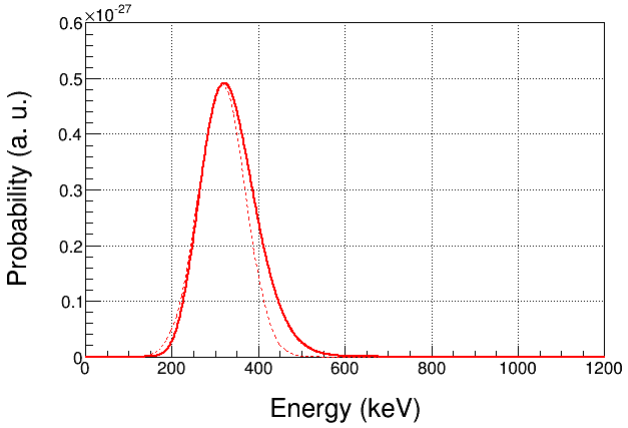
  II. Penetration through Coulomb barrier with $e^{-b/E^{1/2}}$



- For α + ^{12}C, and stellar T=200 10^6 K:

  ➢ **Gamow Peak, E_0 ≈ 300 keV, Width ≈ 50 keV (in Center-of-Mass (CM) of α + ^{12}C system)**

  ➢ Maximum of Maxwell–Boltzmann energy distribution, k_BT = 17 keV

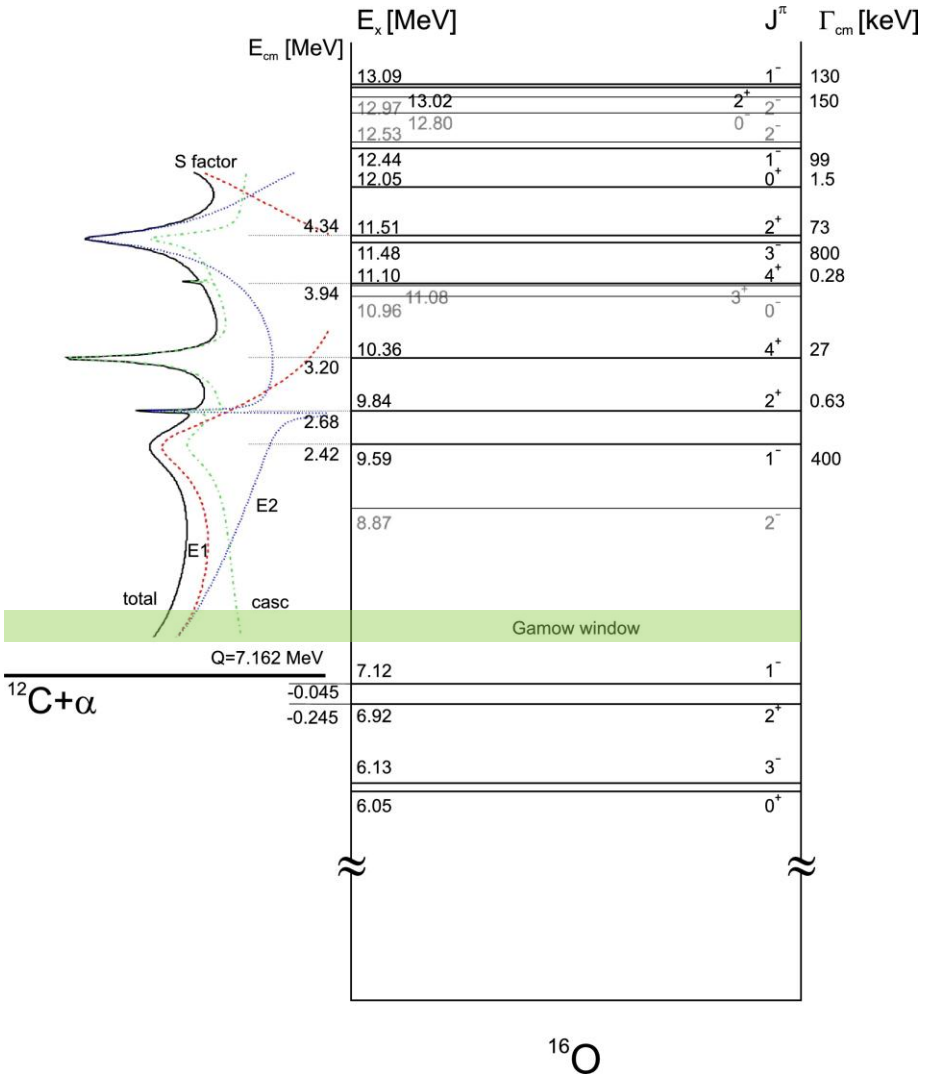


α+^{12}C Reaction

- 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



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/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 Measurements:

I. β–delayed α decay of ^{16}N ($J^{\pi}=2^{-}$, $T_{½}=7.13$ s, BR=0.12%)

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

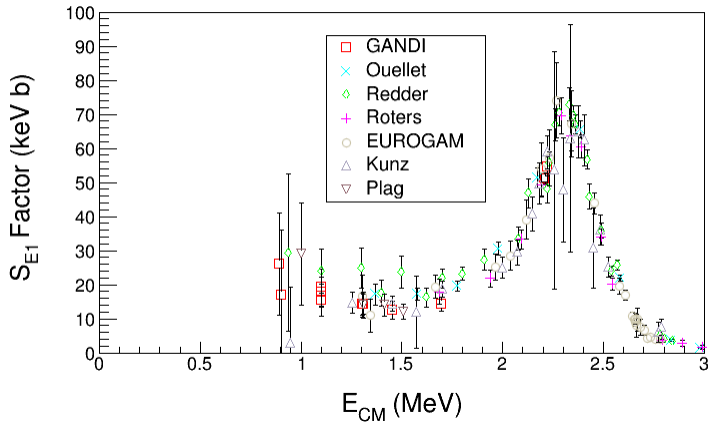
Astrophysical S-Factor $^{12}C(\alpha,\gamma)^{16}O$

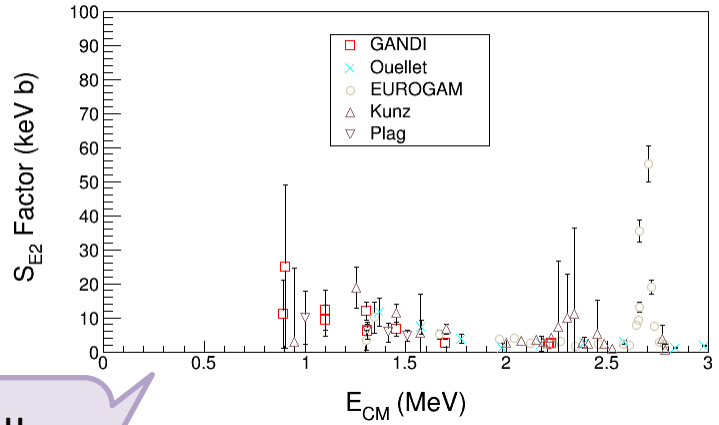
- Define *S-Factor* to remove both 1/E dependence of nuclear cross sections and Coulomb barrier transmission probability:

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

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

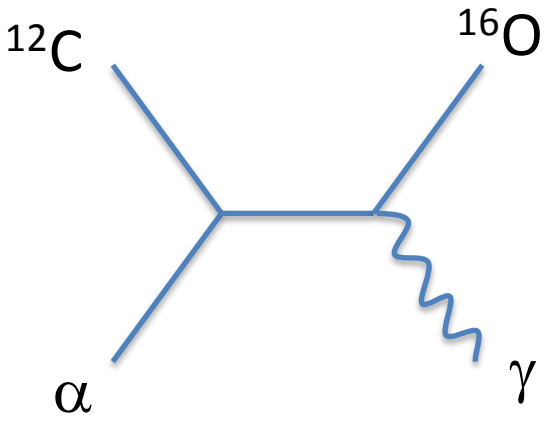
Author	S_{tot}(300) (keV b)
Hammer (2005)	162±39
Kunz (2001)	165±50

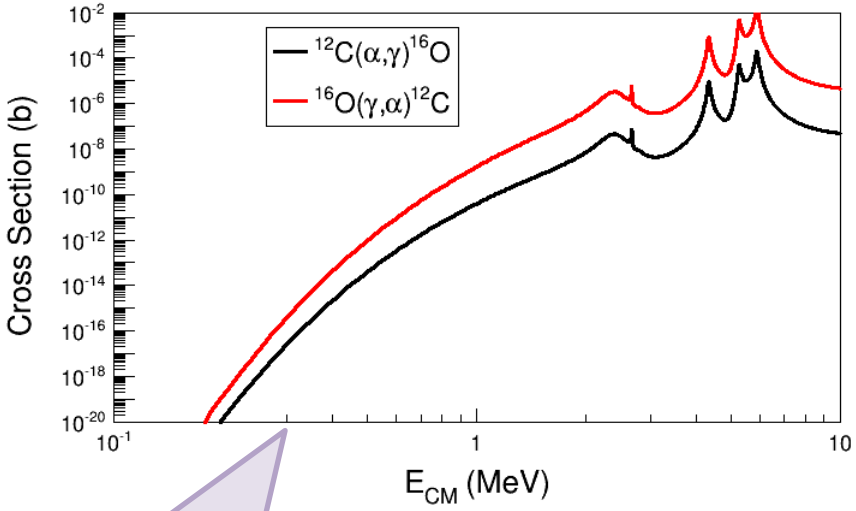




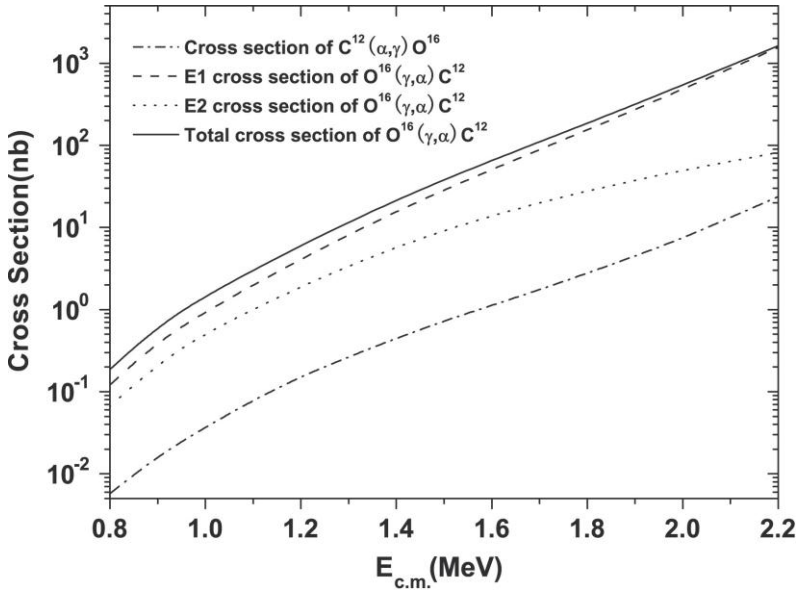
R-matrix Extrapolation to stellar helium burning at E = 300 keV

Time Reversal Reaction





Stellar helium burning at E = 300 keV



Reciprocity Relation: (γ,α) and (α,γ)

- A(α, γ)B:

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

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

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

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

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

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

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

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

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

New Approach: Reversal Reaction + Bubble Chamber

beam | target | signal

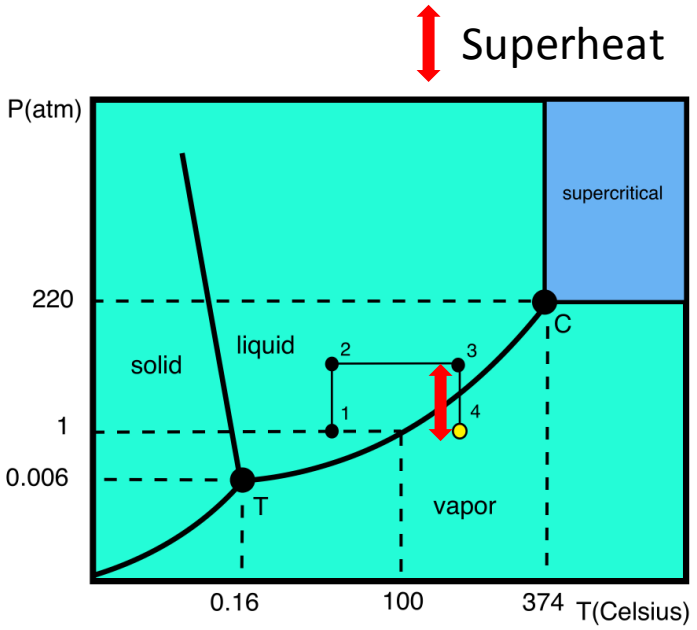
$$\gamma + {}^{16}O \rightarrow {}^{12}C + \alpha$$

- 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)
- 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}).

Bremsstrahlung at JLab ≈ 10^9 γ/s (top 250 keV)

The Bubble Chamber

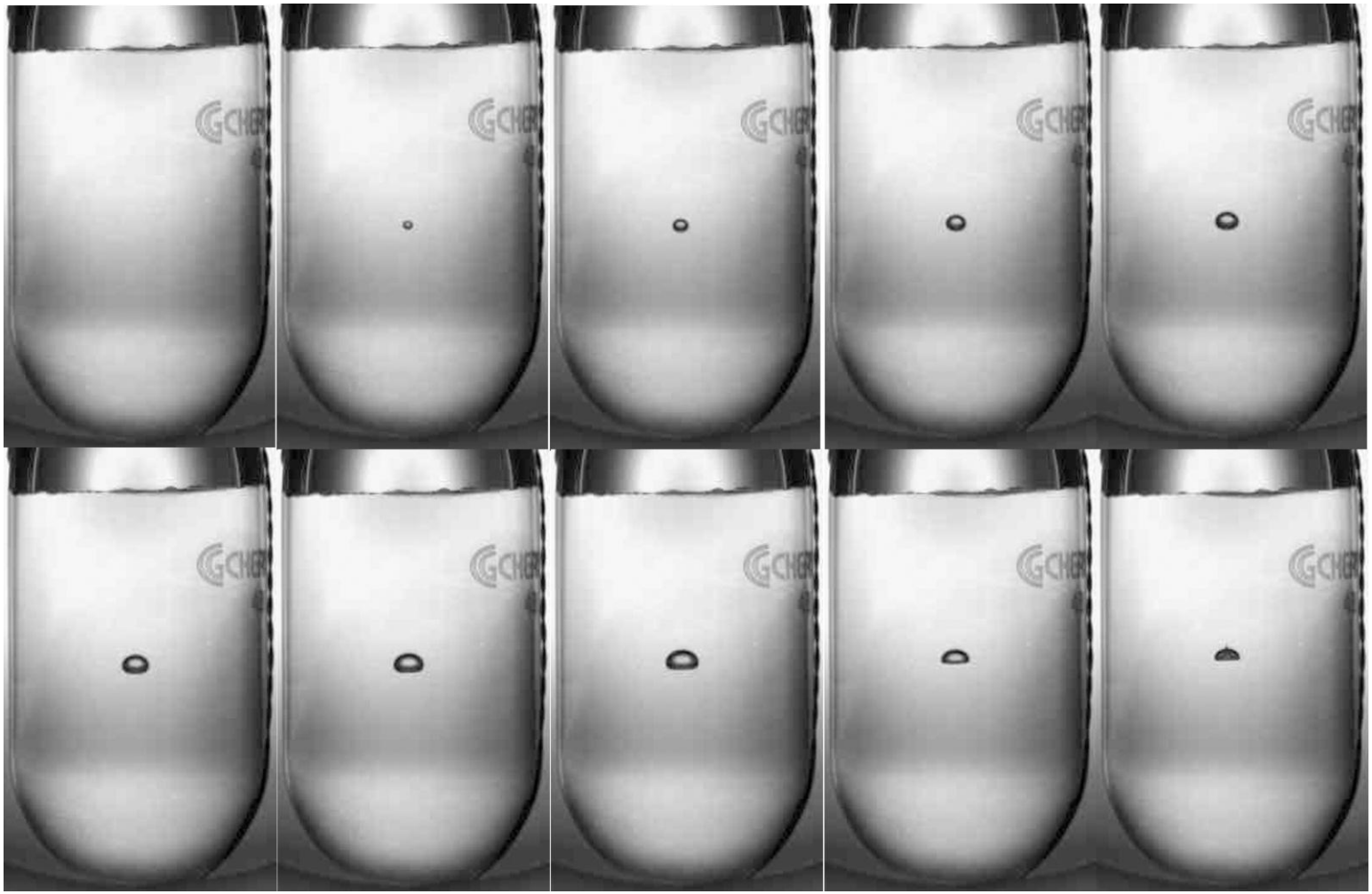
- Donald Glaser won Nobel Prize for inventing chamber to detect particles (1960)
- Now being used in Dark Matter Search Experiments: COUPP, PICASSO, SIMPLE
- Superheat Preparation:
  - Liquid is pressurized at ambient temperature (1 to 2)
  - Then pressure is kept constant while temperature is increased 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 a second 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} at HIGS



3.0 cm

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

Acoustic Signal Discrimination

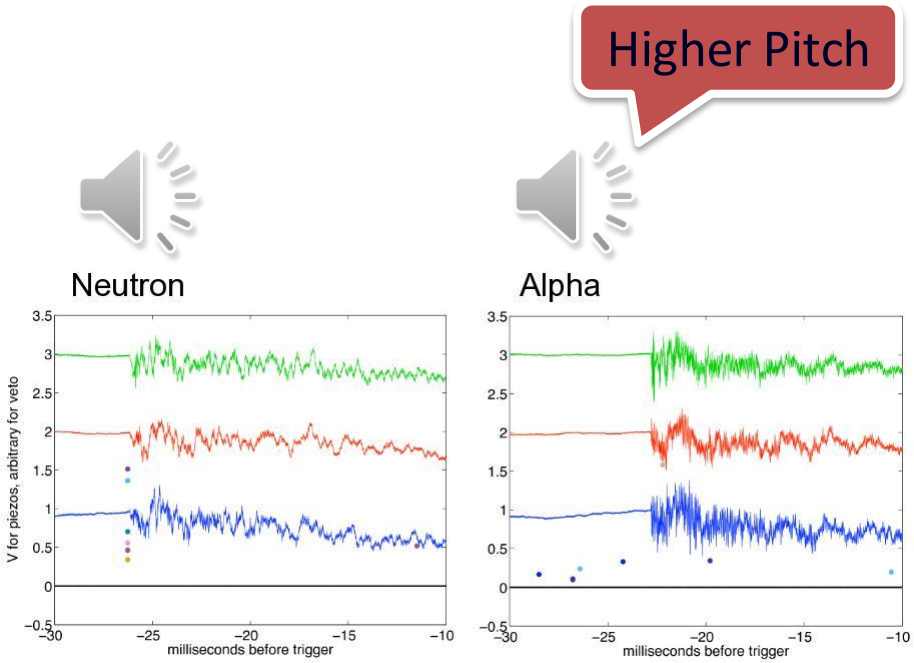
I. Bubble growth produces an audible click which is recorded by piezo-electric transducers

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

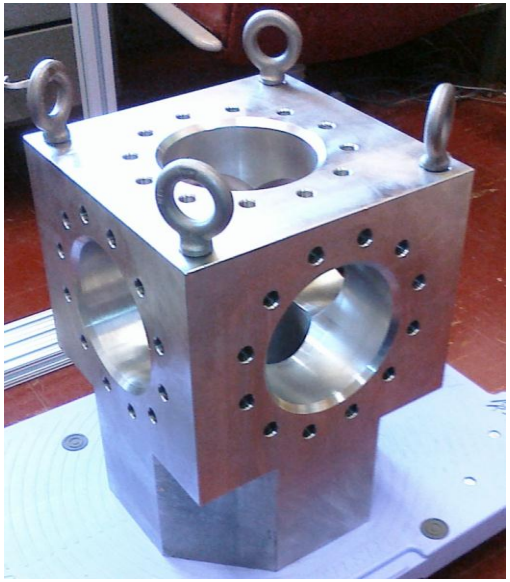
<u>Ions $^{12}C+\alpha$ or $^{13}C+\alpha$ or $^{14}C+\alpha$ will generate a combined multi-bubble</u>

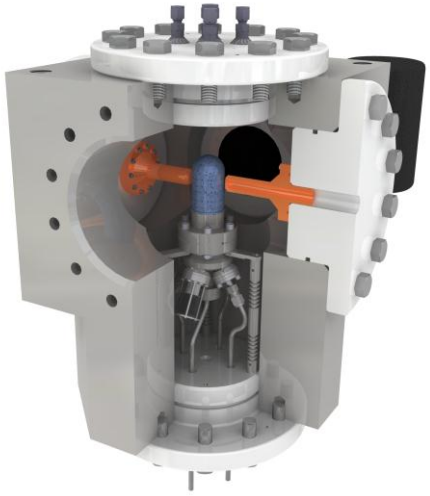


COUPP, FNAL, courtesy of A. Sonnenschein

Suppress neutron events by 100 using acoustic signal

N_2O (Laughing Gas) Bubble Chamber

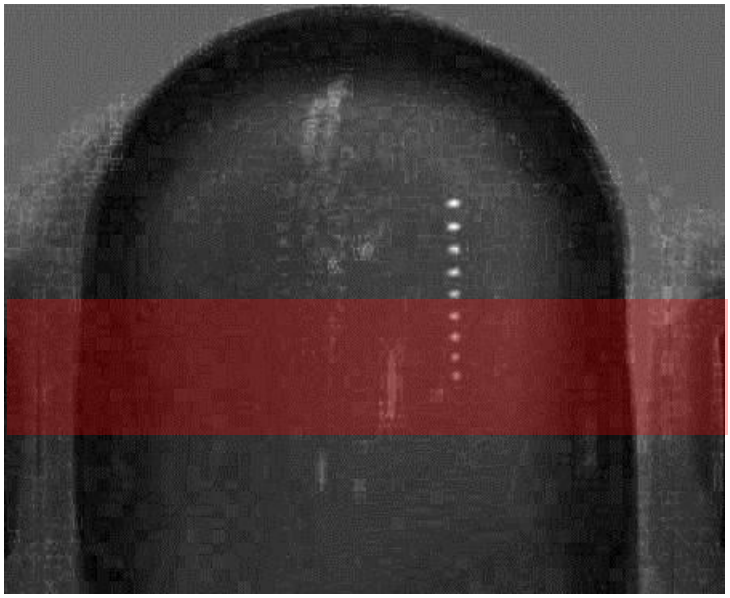


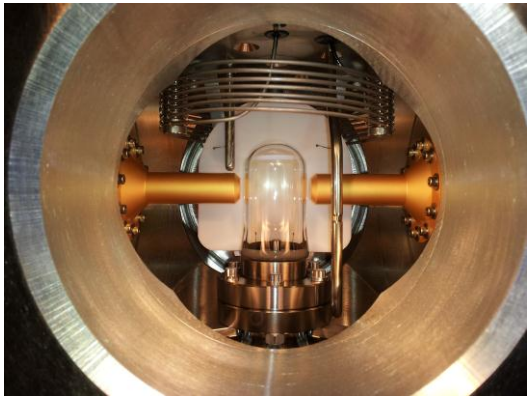


T = -5˚C

P = 60 atm

First γ+O→α+C bubble
HIGS, April 2013





Bubble Chamber Principle

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

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

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

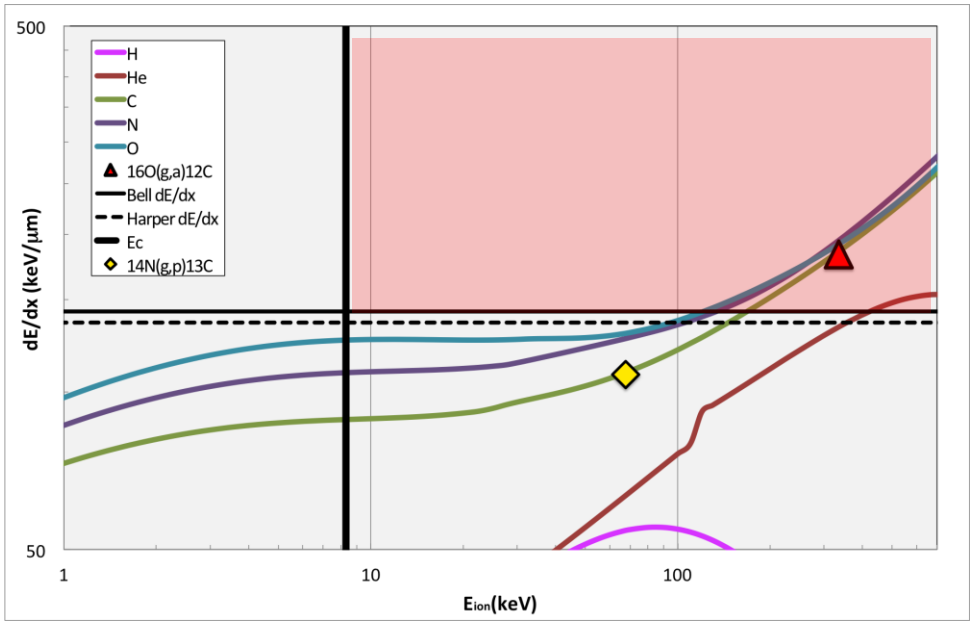
$$R_c = 2s/(P_v - P_l)$$

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)

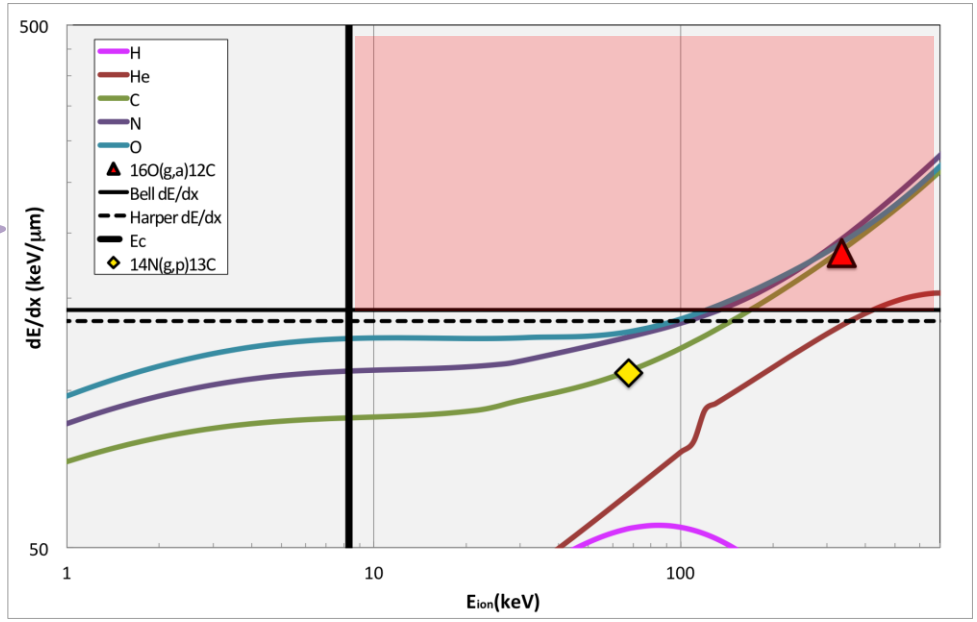
$$\frac{dE}{dx} > \left(\frac{dE}{dx}\right)_c = \frac{E_c}{aR_c}$$

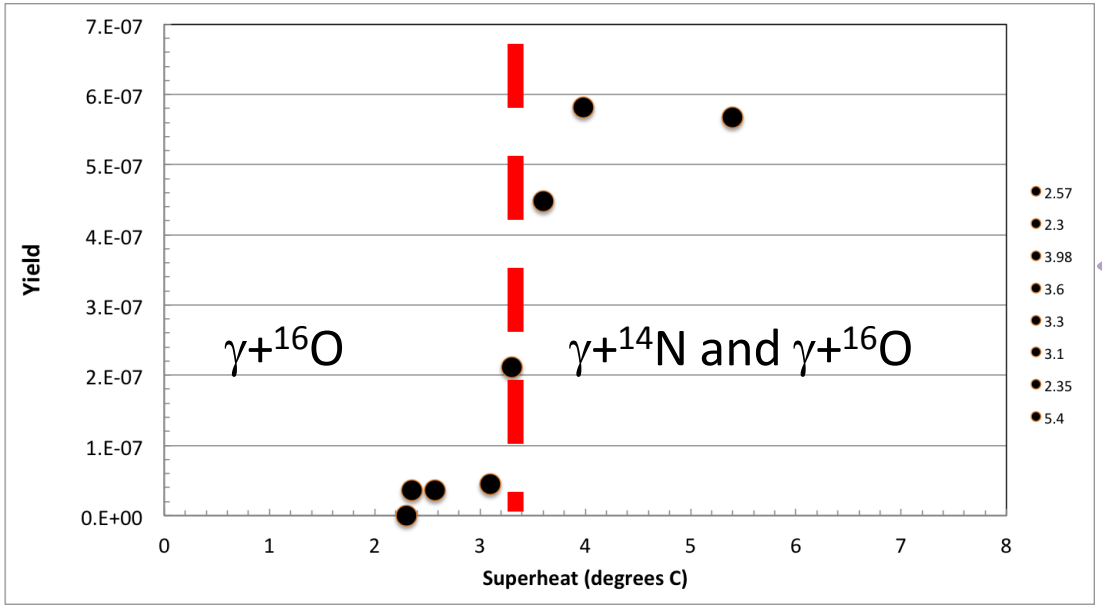
a: free parameter (to determined experimentally)



Efficiency Curve

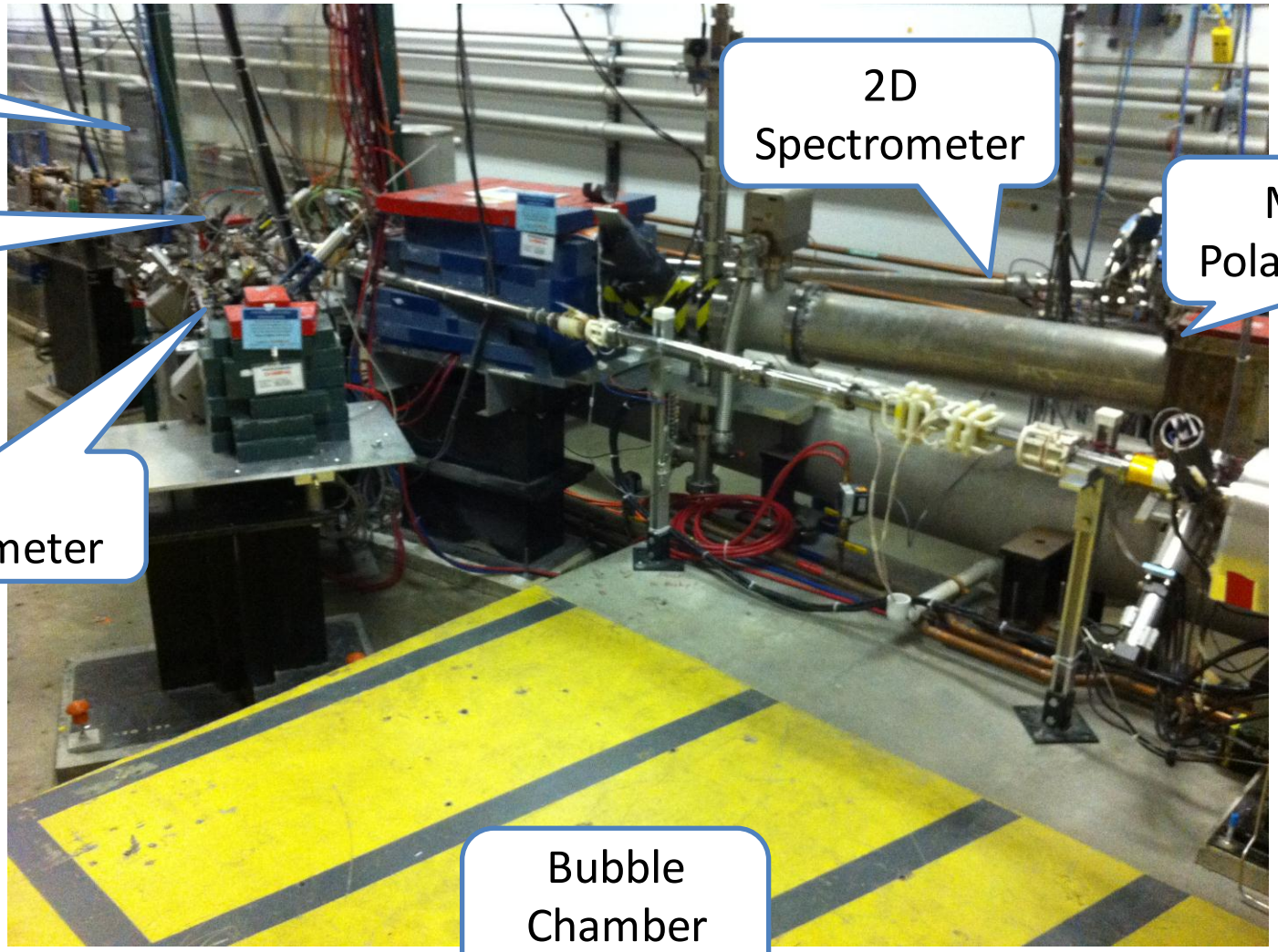
N_2O thresholds
Superheat = 3.3˚C

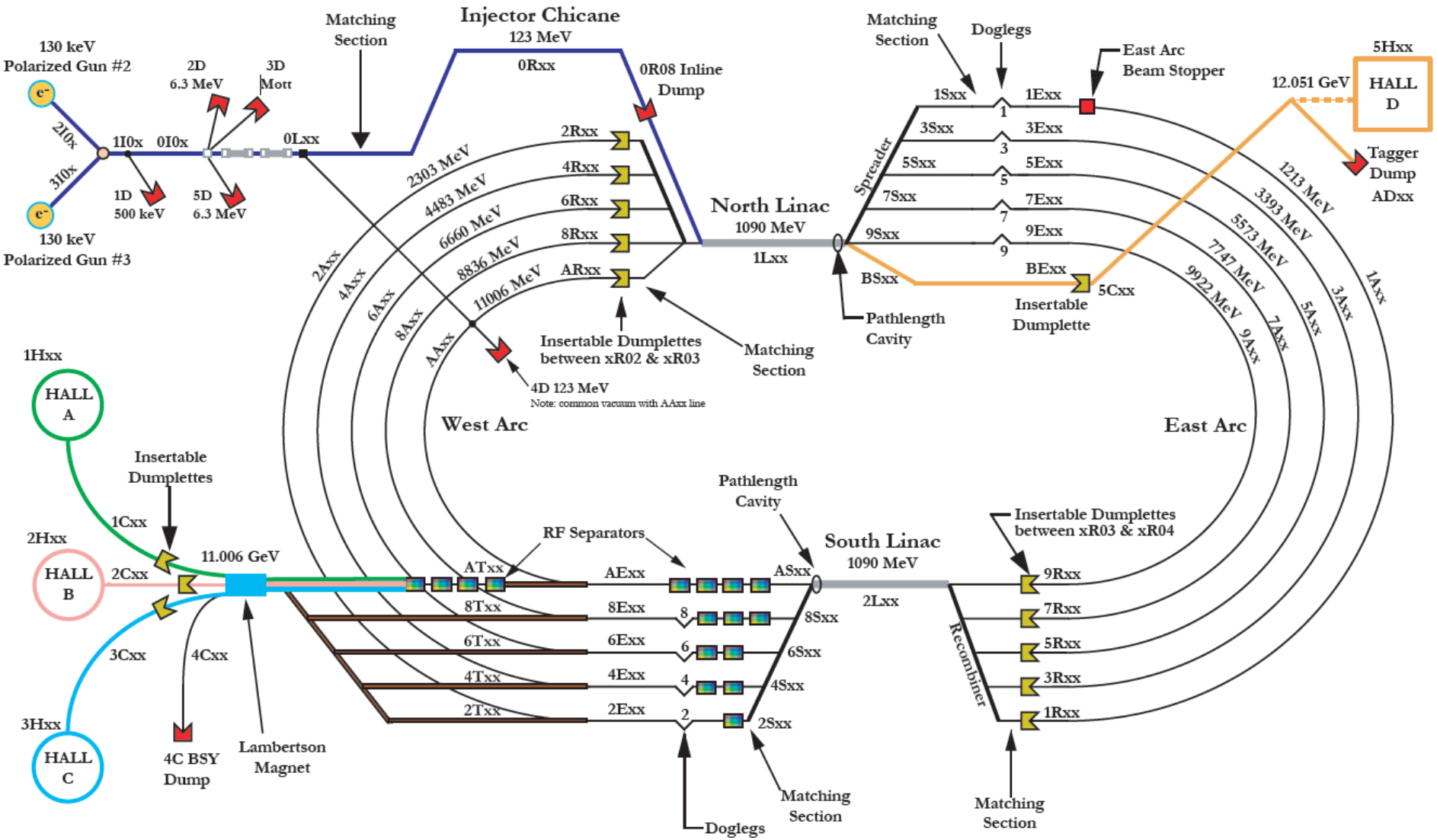




N_2O efficiency curve,
HIGS April 2013,
E_γ = 9.7 MeV

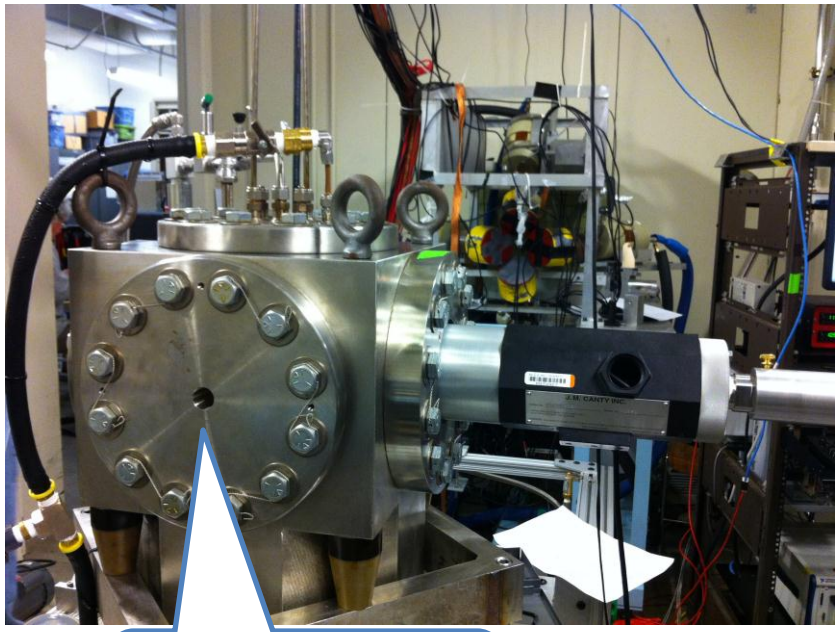
Experimental Setup at JLab Injector



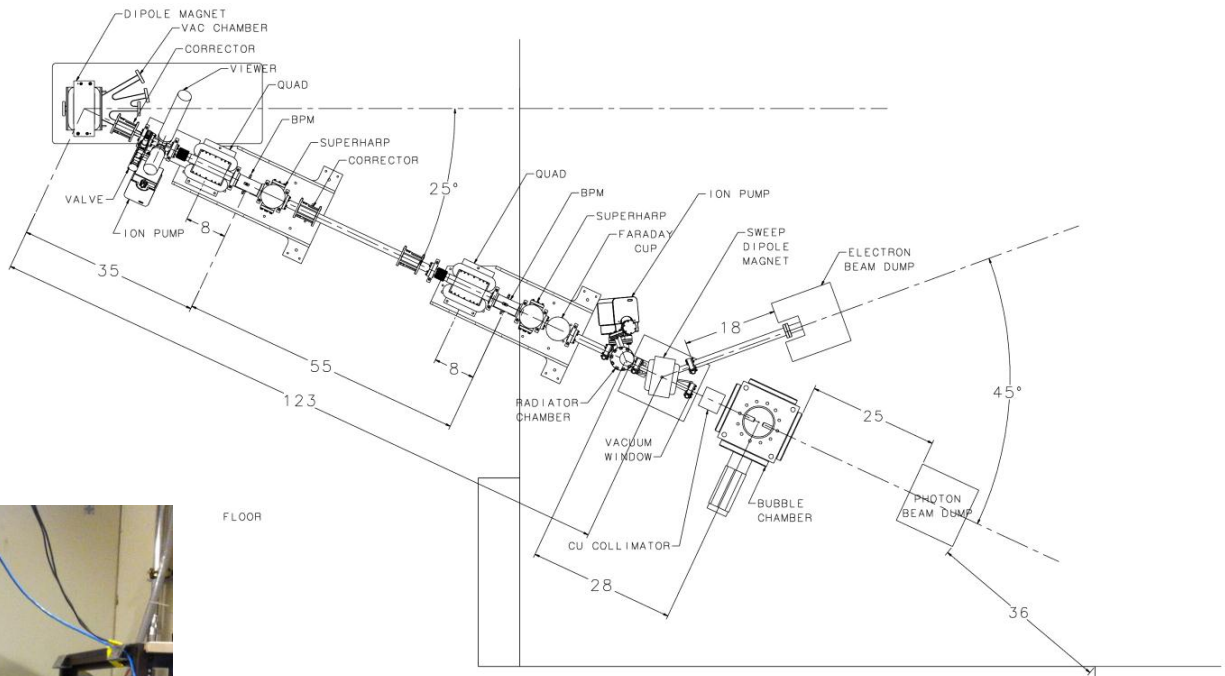

130 keV
Polarized Gun #2
130 keV
Polarized Gun #3
2I0x
3I0x
1I0x
0I0x
0Lxx
1D
500 keV
2D
6.3 MeV
3D
Mott
5D
6.3 MeV
Matching
Section
Injector Chicane
123 MeV
0Rxx
0R08 Inline
Dump
2303 MeV
4483 MeV
6660 MeV
8836 MeV
11006 MeV
2Axx
4Axx
6Axx
8Axx
AAxx
2Rxx
4Rxx
6Rxx
8Rxx
ARxx
Insertable Dumplettes
between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

BEAMLINE

Bubble Chamber at HIGS April 2013



Photon Beam Entrance

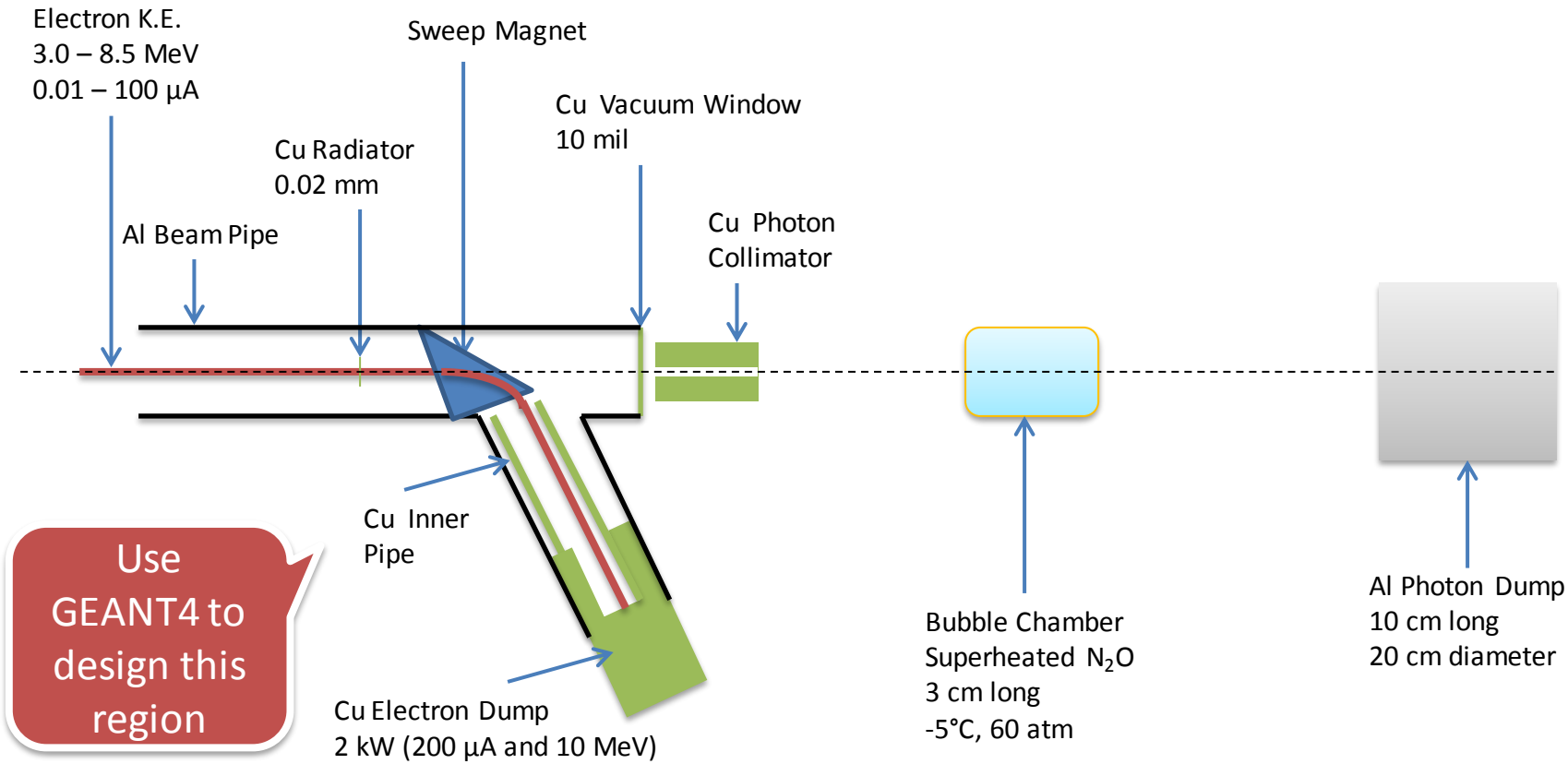


Beam Kinetic Energy, (MeV)	7.9–8.5
Beam Current (μA)	0.01–100
Absolute Beam Energy Uncertainty	<0.1%
Relative Beam Energy Uncertainty	<0.02%
Energy Resolution (Spread), σ_T/T	<0.06%
Beam Size, $\sigma_{x,y}$ (mm)	1–2

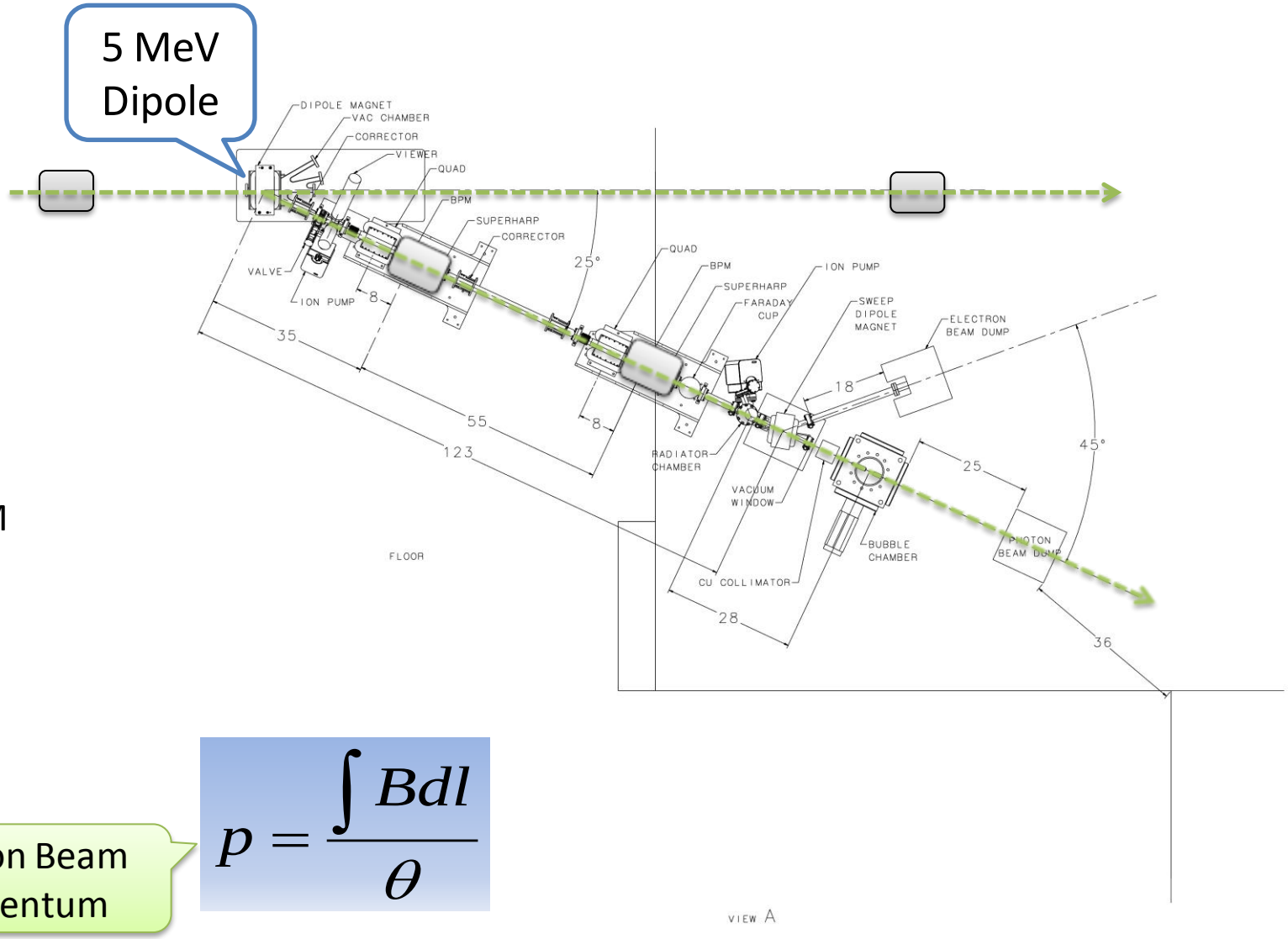
Electron Beam Requirements at Radiator

SCHEMATICS

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



Measuring Absolute Beam Energy



BPM

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

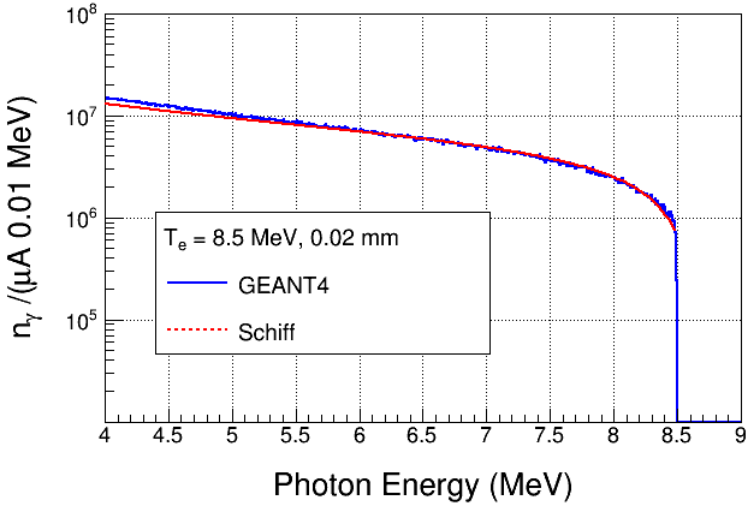
II. New Hall Probe: 0.01% accuracy, resolution to 2 ppm, and a temperature stability of 10 ppm/°C

III. Better shielding of Earth's and other stray magnetic fields

IV. Additional goal: Relative beam energy uncertainty **<0.02%**

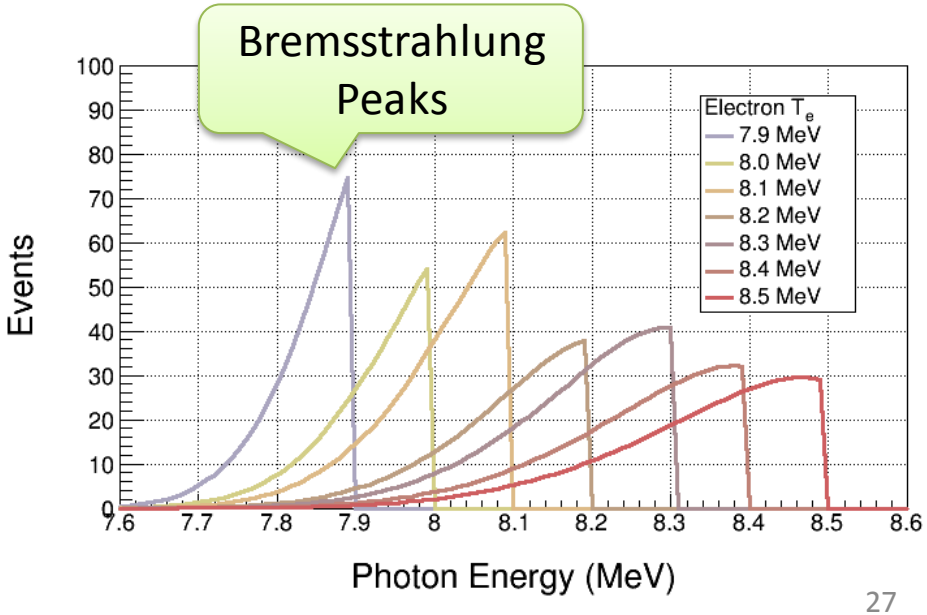
BREMSSTRAHLUNG BEAM

- 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)

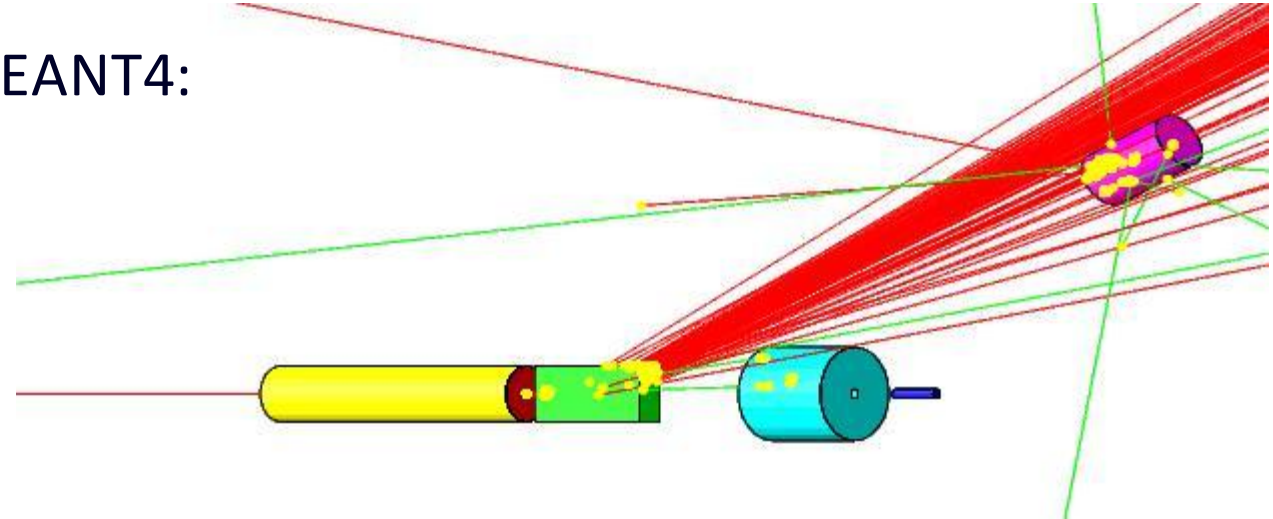


GEANT4 SIMULATION

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

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

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,

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

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

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

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

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

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

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

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

Systematic Error Propagation

No energy-to-energy change in systematic error

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

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

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

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

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

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%

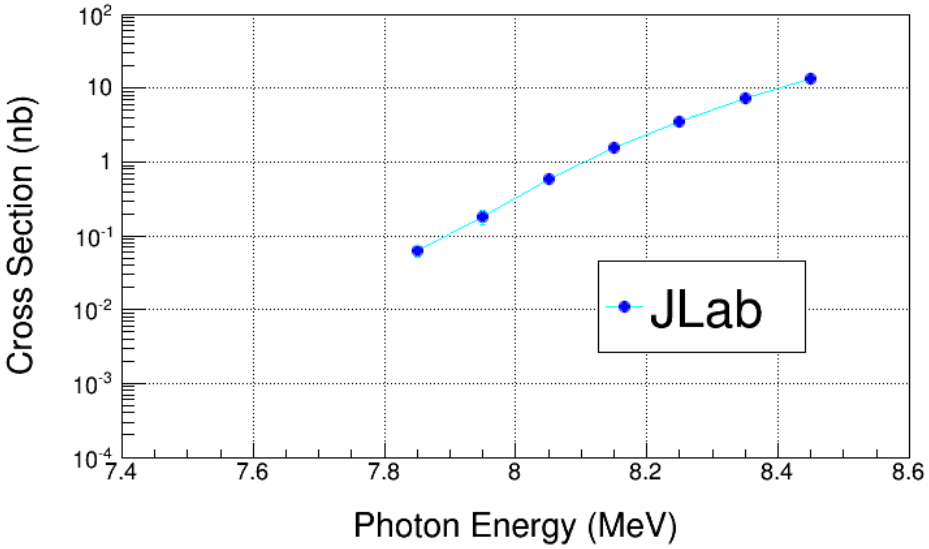
Simulation

- 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



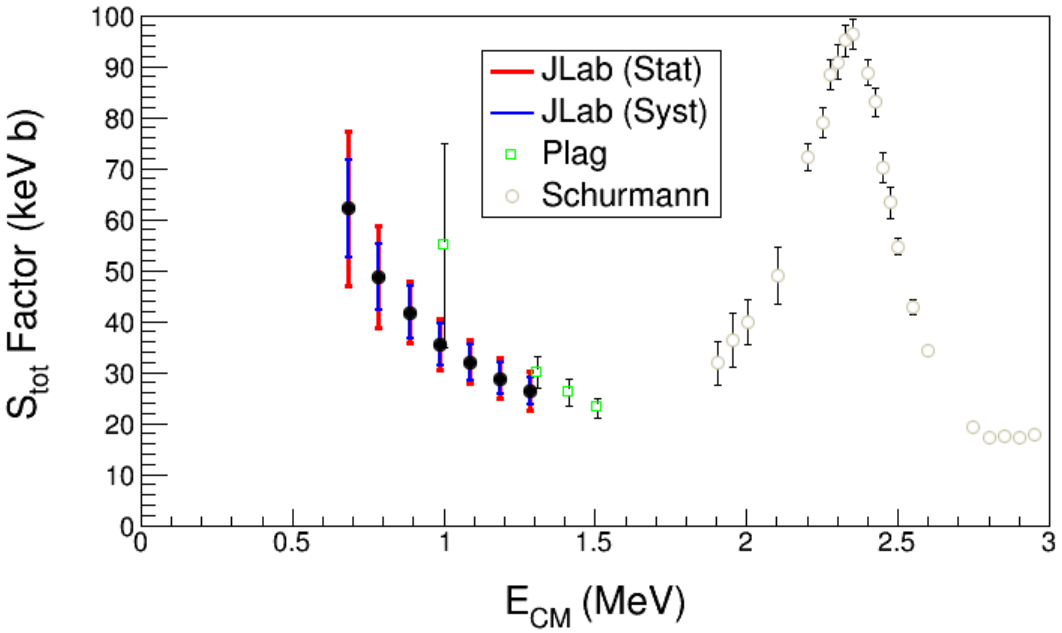
Electron Beam K. E.	Cross Section (nb)	Sys Error (Energy, %)	Sys Error (Total, %)
7.9	0.046	12.5	15.3
8.0	0.185	10.2	13.5
8.1	0.58	8.3	12.2
8.2	1.53	7.0	11.4
8.3	3.49	6.0	10.7
8.4	7.2	5.3	10.5
8.5	13.6	4.7	10.1

Note: Absolute 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)

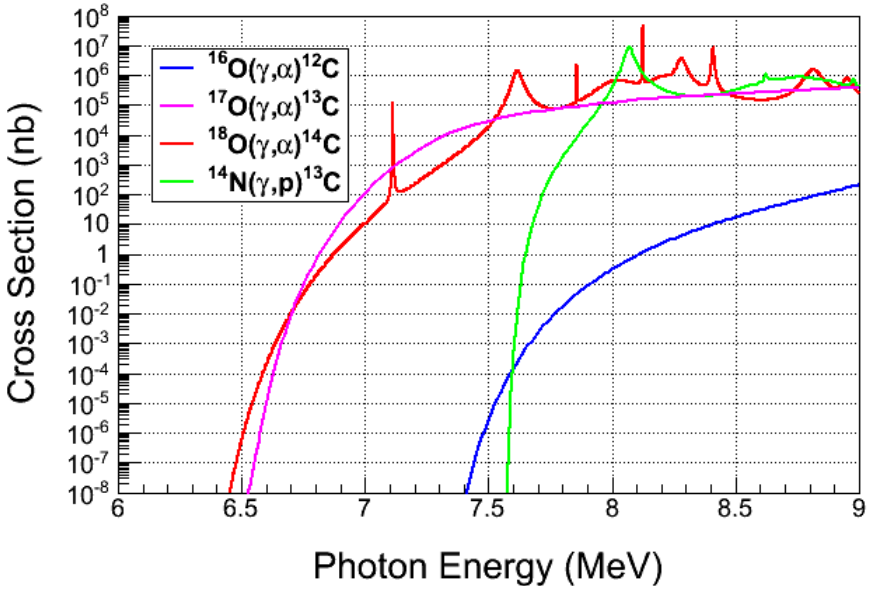
Electron Beam K. E.	Gamma Energy (MeV)	E_{CM} (MeV)	Cross Section (nb)	S_{tot} Factor (keV b)	Stat Error (%)	Sys Error (Total, %)
7.9	7.85	0.69	0.046	62.2	24.5	15.3
8.0	7.95	0.79	0.185	48.7	20.7	13.5
8.1	8.05	0.89	0.58	41.8	14.7	12.2
8.2	8.15	0.99	1.53	35.5	13.8	11.4
8.3	8.25	1.09	3.49	32.0	13.3	10.7
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, $S_{E1} + S_{E2}$

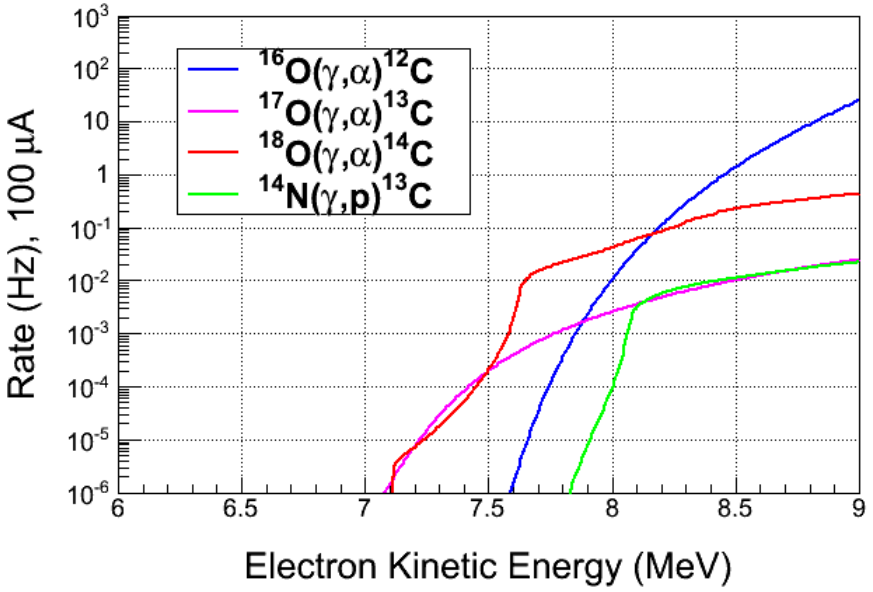
BACKGROUNDS

I. Background from oxygen isotopes and nitrogen in N_2O:
   - $^{18}O(\gamma,\alpha)^{14}C$
   - $^{17}O(\gamma,\alpha)^{13}C$
   - $^{14}N(\gamma,p)^{13}C$



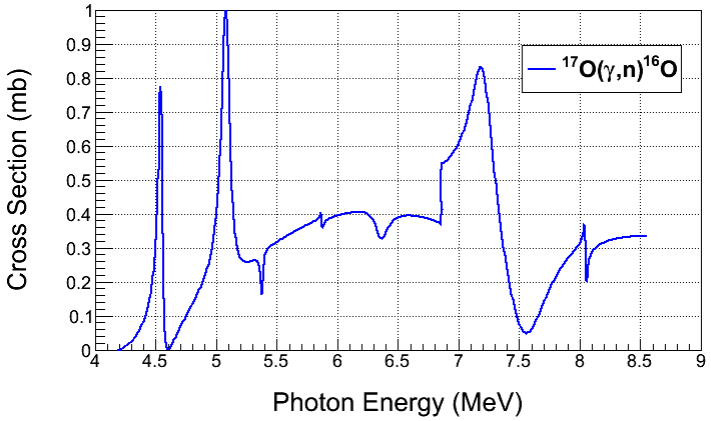
- Natural Abundance:
  I. ^{17}O: 0.038%
  II. ^{18}O: 0.205%

- 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}



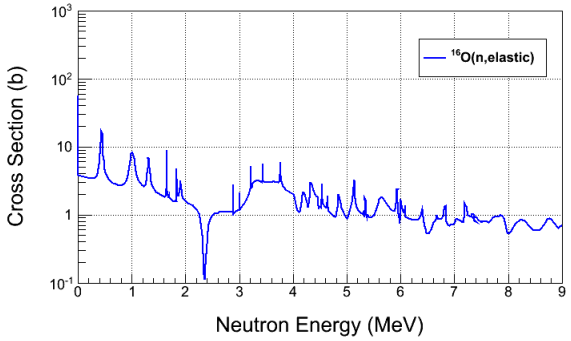
II. Background from:

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



III. Background from Chamber glass:

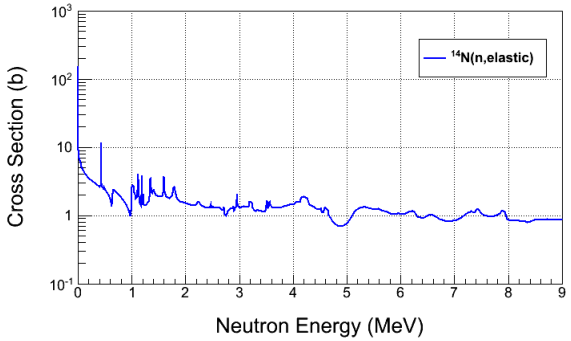
– Neutron–nucleus elastic scattering from $^{29}Si(\gamma,n)^{28}Si$



IV. Cosmic–ray background:

– $\mu^{\pm}$–nuclear

– neutron–nuclear elastic scattering



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

Ion Energy Distributions

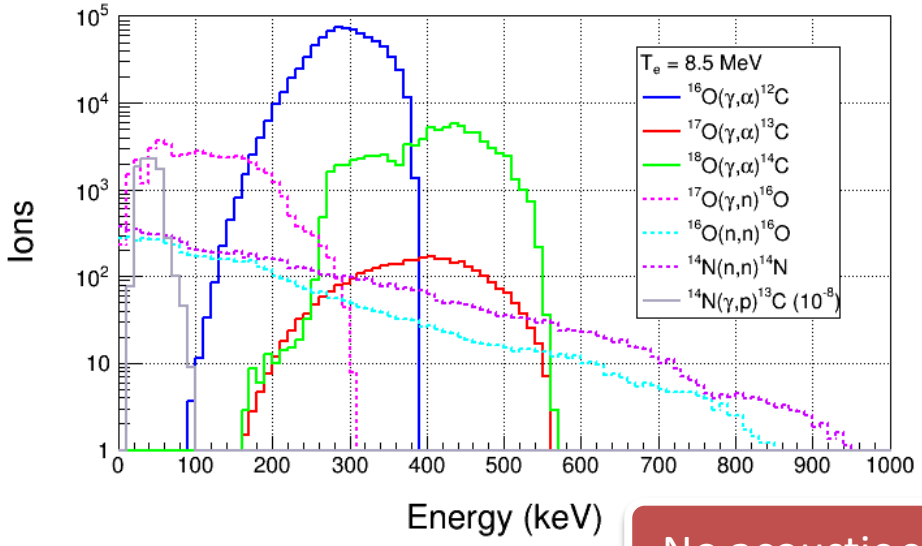
- Use depleted N_2O:
  - I. ^{17}O depletion = 5,000
  - II. ^{18}O depletion = 5,000
- Suppress background with Bubble Chamber thresholds

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

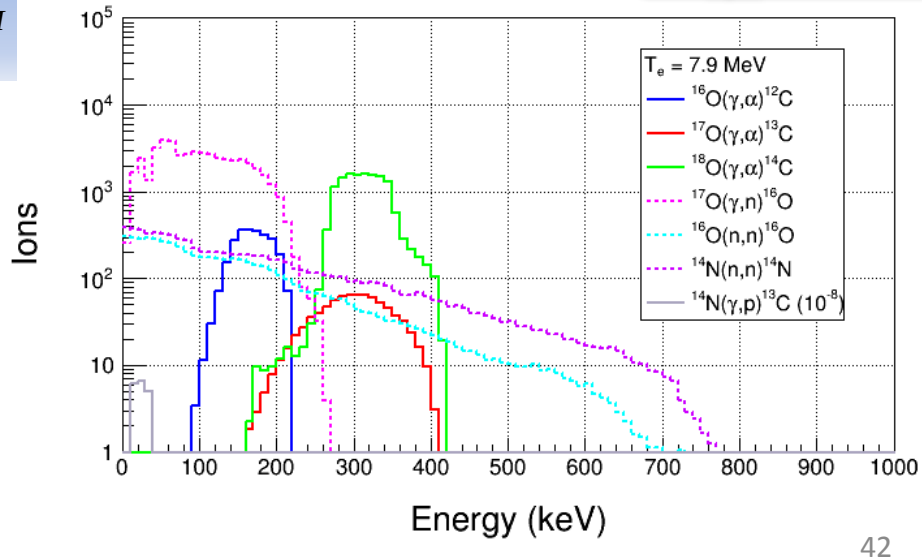
$$T_{\alpha,lab} \cong \frac{m_c}{m_\alpha + m_c} E_{CM} \qquad T_{C,lab} \cong \frac{m_\alpha}{m_\alpha + m_c} E_{CM}$$

- 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



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

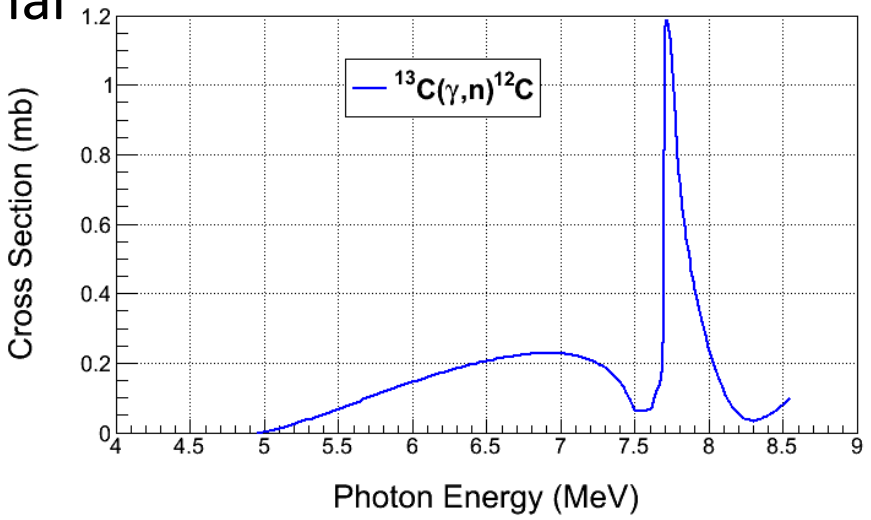
Summary and Outlook

- Test N_2O Bubble Chamber at HIGS (Summer 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 (October 2014, January 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: use laser shutter to stop beam while chamber is not ready
  - Measure O-isotopes depletion
- Background tests:
  - Measure cosmic–ray background
  - Study chamber thresholds efficiency vs. superheat and measure γ-rays suppression factor

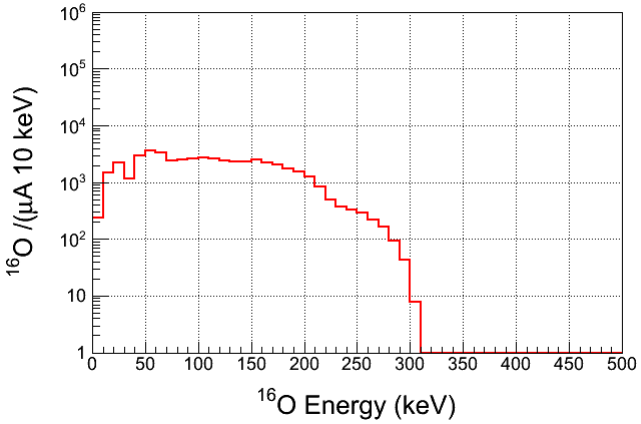
BACKUP SLIDES

CO_2 Superheated Liquid?

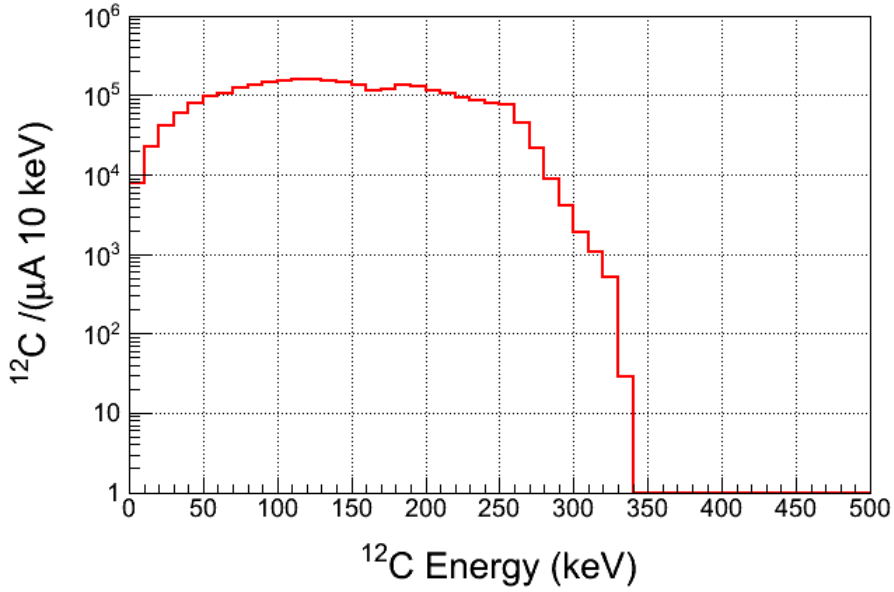
- Similar Bubble Chamber operational parameters as N_2O
- Natural Abundance: ^{13}C: 1.07%
- Depletion: ^{13}C depletion=1,000
- $^{13}C(\gamma,n)^{12}C$ Background



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

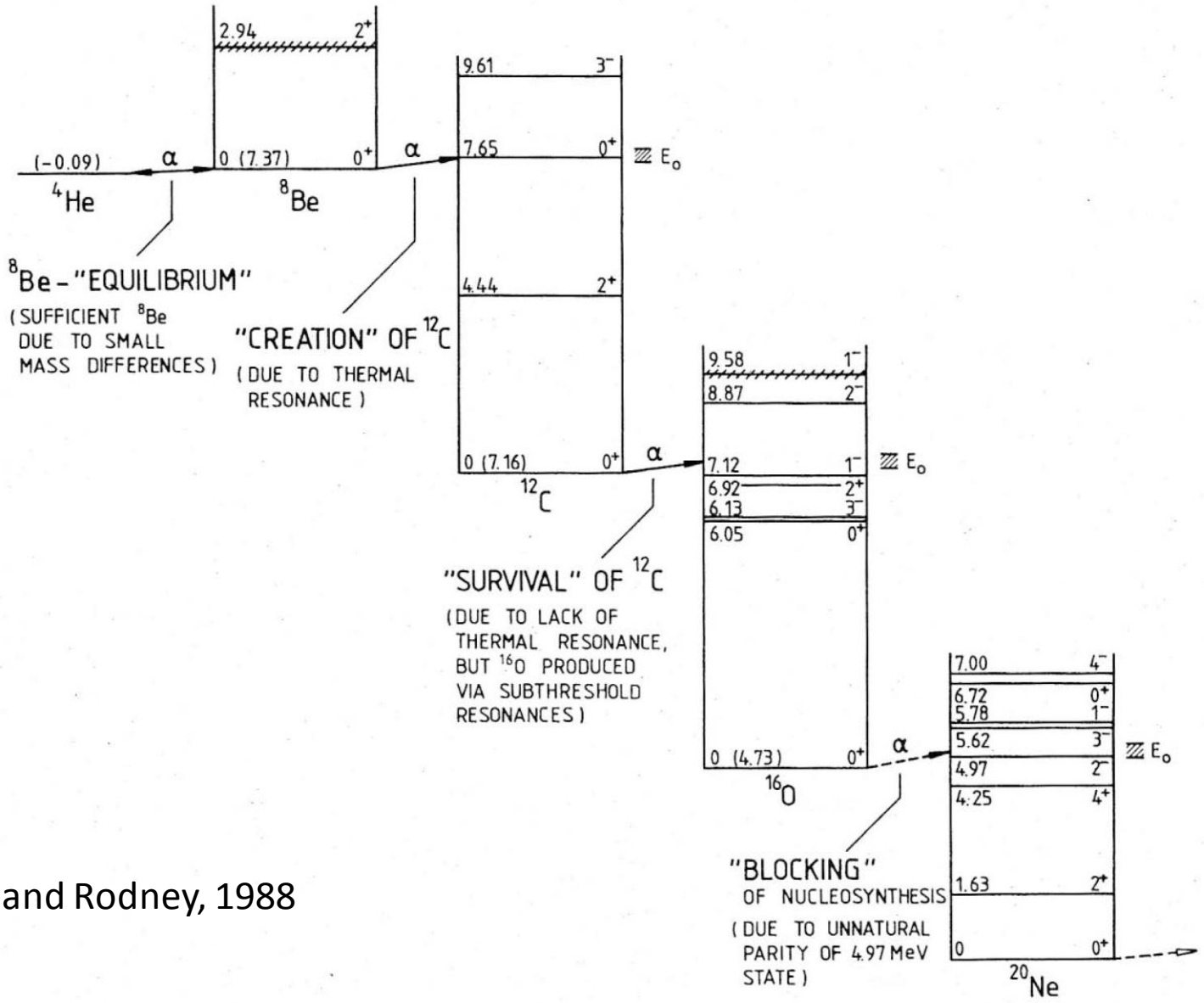


- $^{12}C(\gamma,2\alpha)\alpha$ Background



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



Rolfs and Rodney, 1988