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

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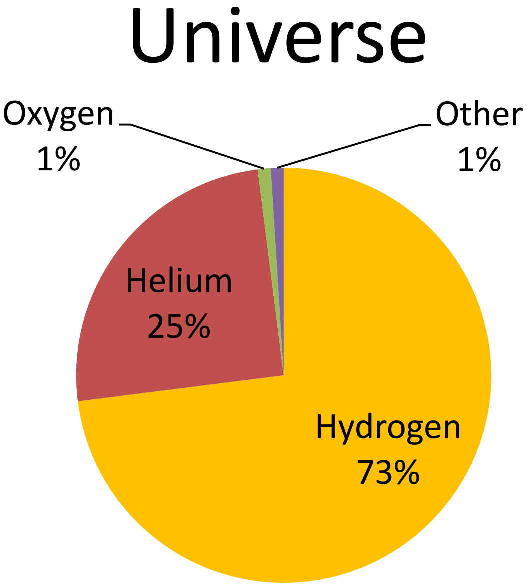
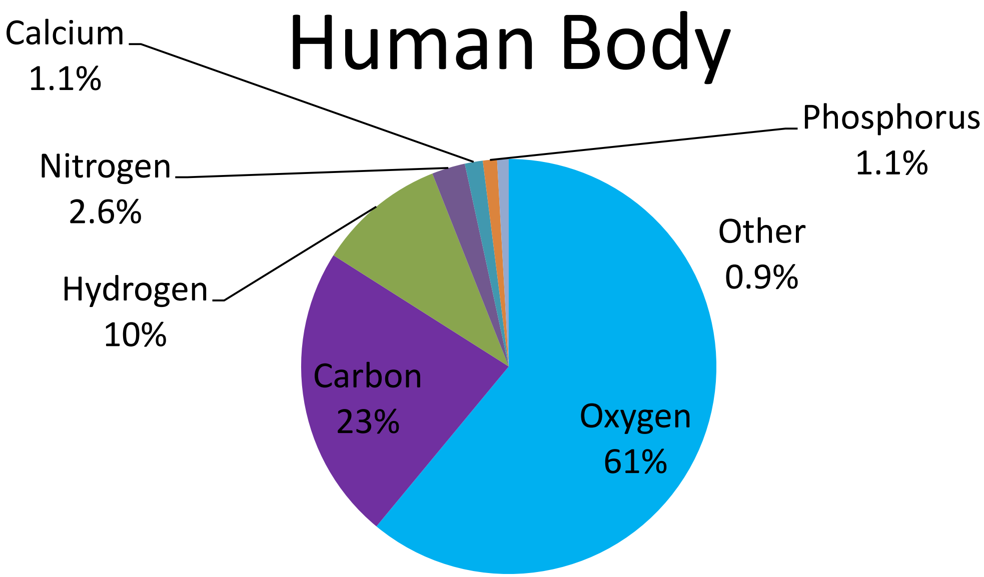
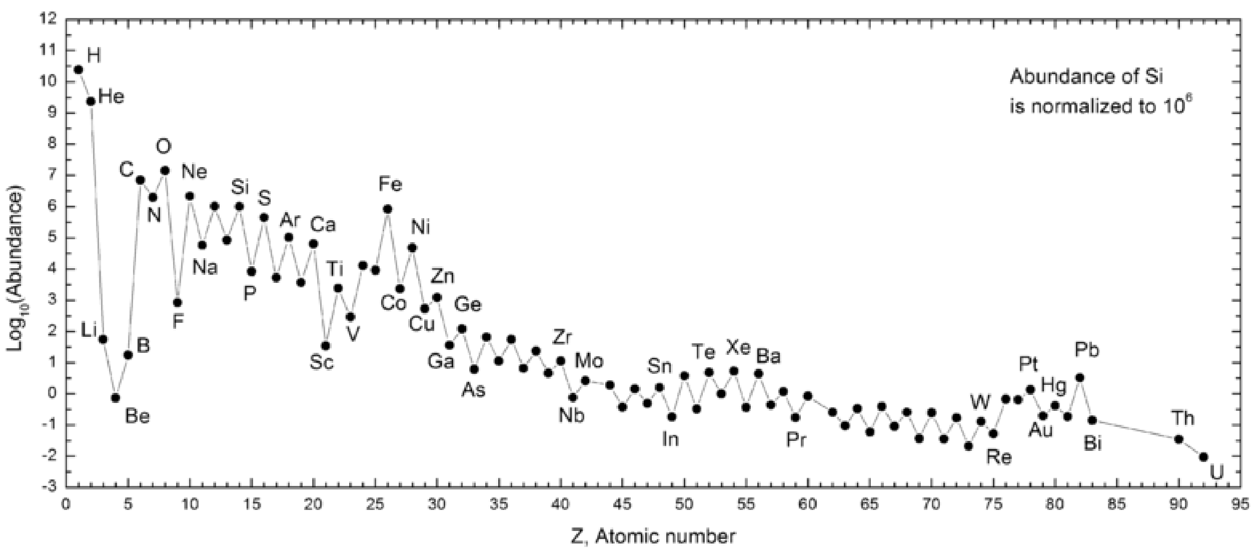
Outline

- 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

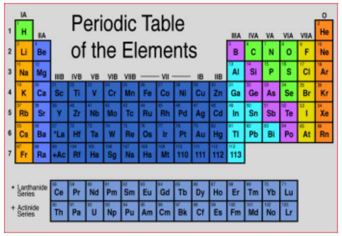




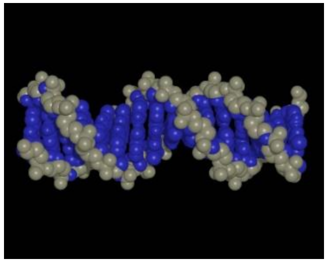


THE $^{12}C(\alpha,\gamma)^{16}O$ Reaction

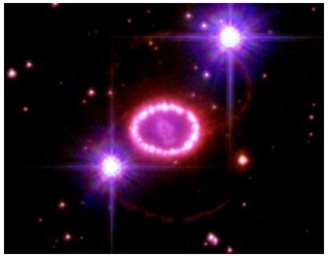
- The "holy grail" of nuclear astrophysics



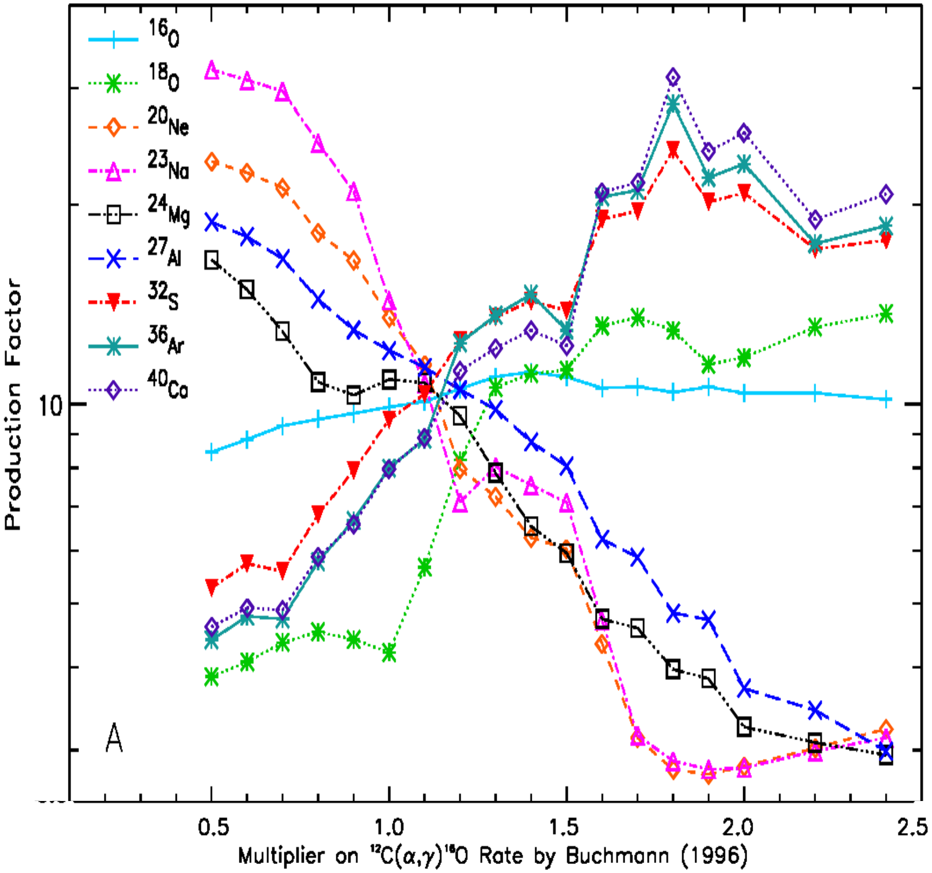
Affects the synthesis of most of the elements of the periodic table



Sets the C to O ratio in the universe

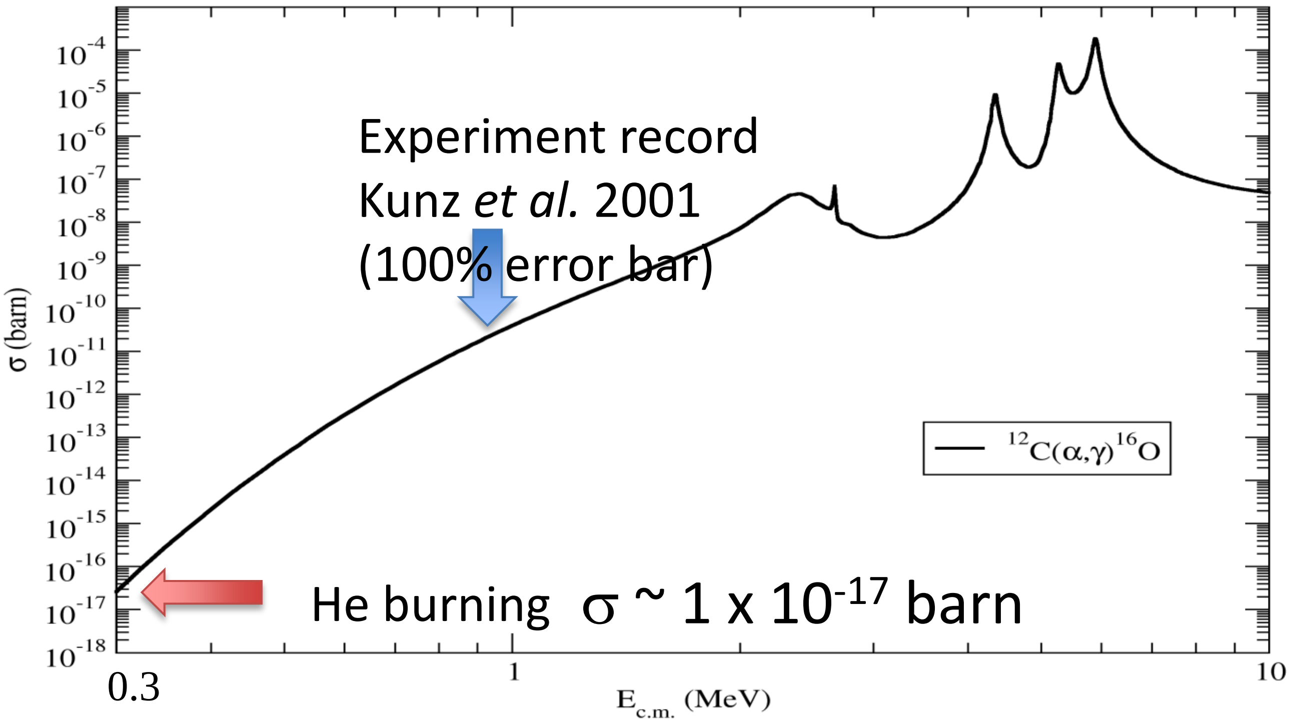


Determines the minimum mass a star requires to become a supernova



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

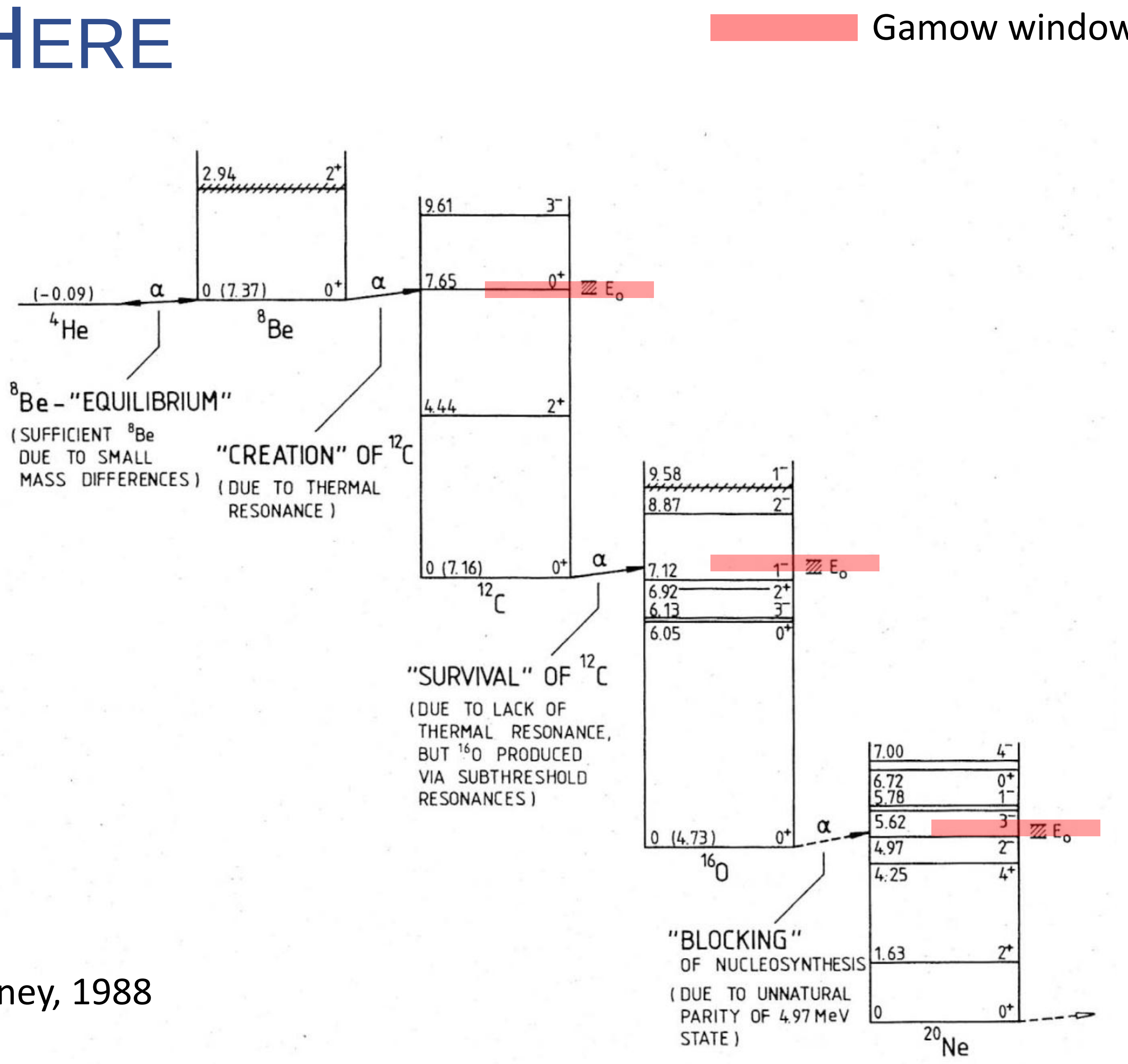
THERMO-NUCLEAR HELIUM BURNING



$$N_A\langle\sigma v\rangle = N_A\sqrt{\frac{8}{\pi\mu(kT)^3}}\int_0^\infty \sigma(E)E\exp\left(-\frac{E}{kT}\right)dE$$

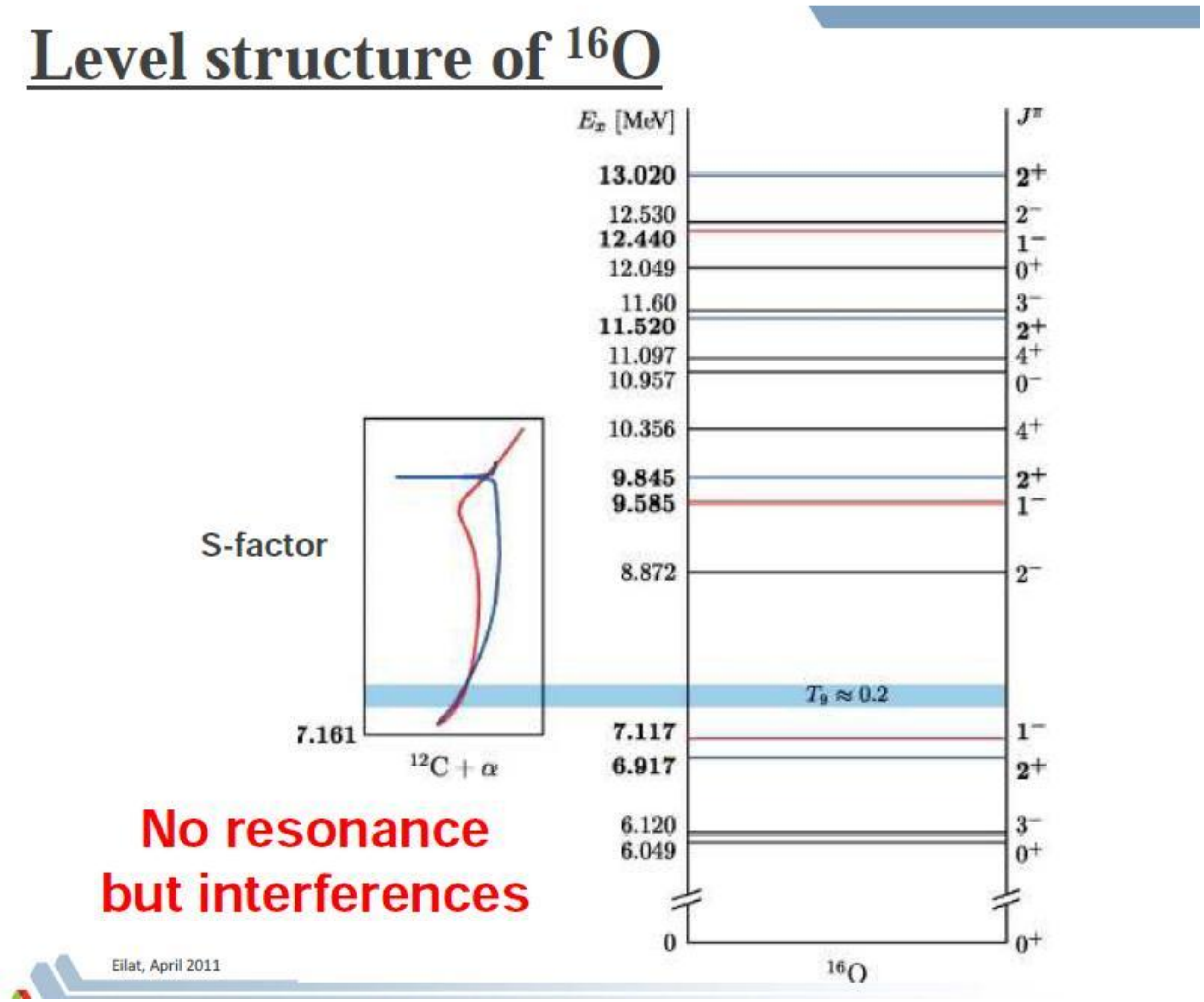
Title Here

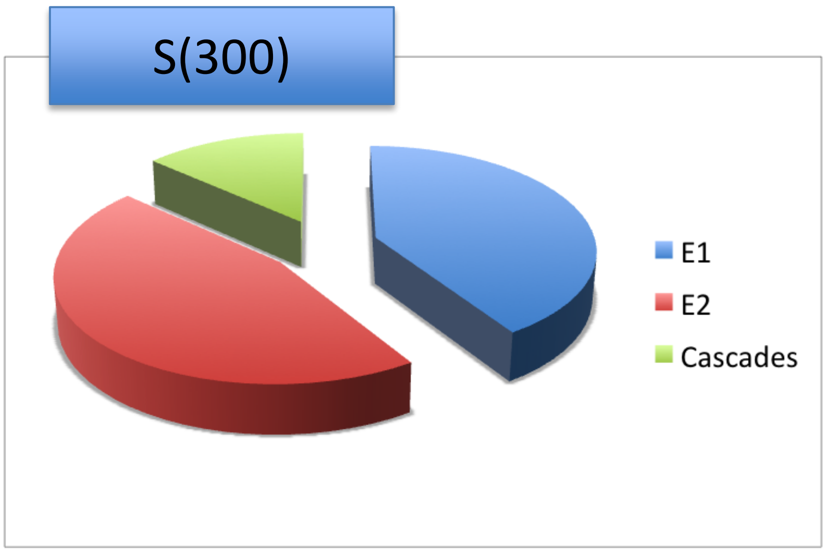
- Text go



Rolfs and Rodney, 1988

TIME REVERSAL





Kunz 2001, Matei 2006

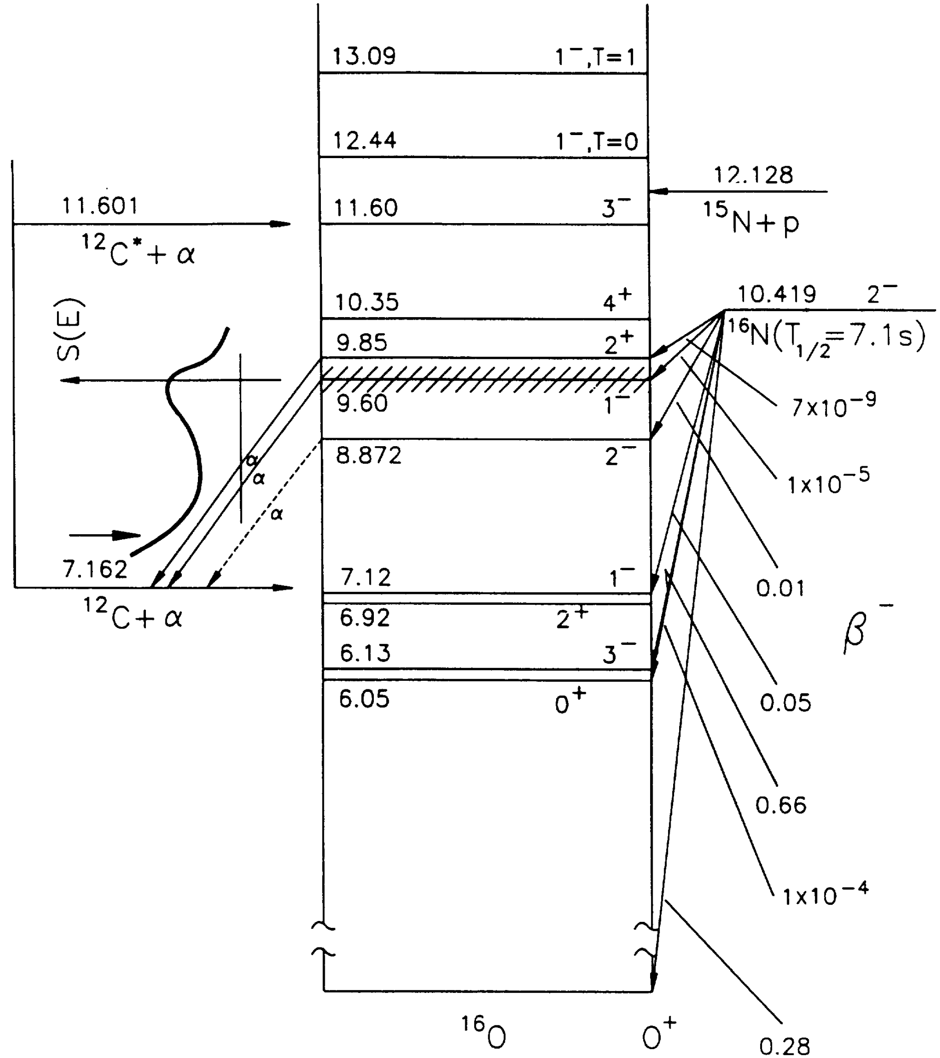


FIG. 1. Partial energy-level diagram for ^{16}O (adapted from [4]).

Heroic efforts in search of the holy grail of astrophysics: $^{12}C(\alpha,\gamma)^{16}O$

Luminosity ~ 1E34 $cm^{-2}s^{-1}$

Efficiency ~ 1E-3

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

Lum(HIγS) ~ 4E30 $cm^{-2}s^{-1}$

Lum(JLab) ~ 8E31 $cm^{-2}s^{-1}$

10 μA , top 100 keV

$\lambda_\gamma^2/\lambda_\alpha^2$ ~ 60

Bubble chamber: solid angle x efficiency = 100%

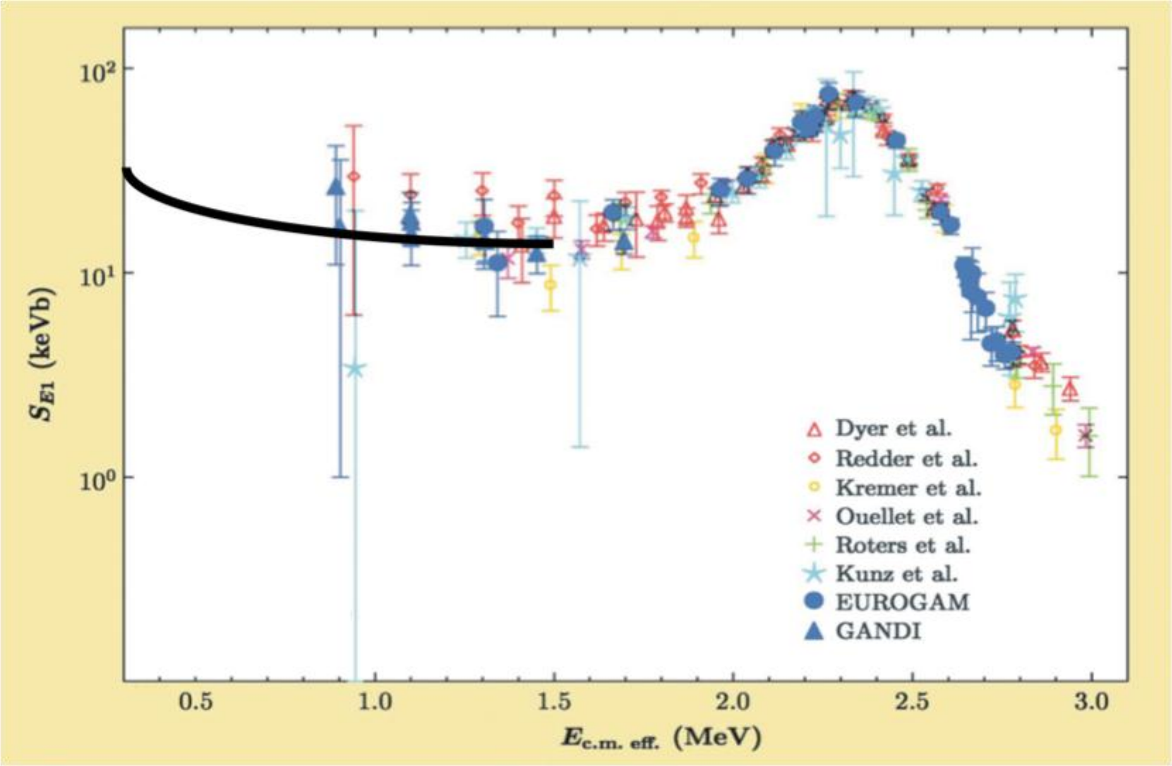
Expt	Beam current (mA)	Detector Effic. (%)	Target	Meas. Time (h)
Redder	0.7	Ge, 35	12C, ~3E18	900
Ouellet	0.03	Ge, 30	12C, 5E18	1950
Roters	0.02	BGO, 270	4He, 1E19	5000
Kunz	0.45	Ge, 100	12C, 3E18	700
EUROGAM	0.34	Ge, 70	1E19	2100

$^{12}C(\alpha,\gamma)^{16}O$ **$^{4}He(^{12}C,{}^{16}O)\gamma$**

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

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

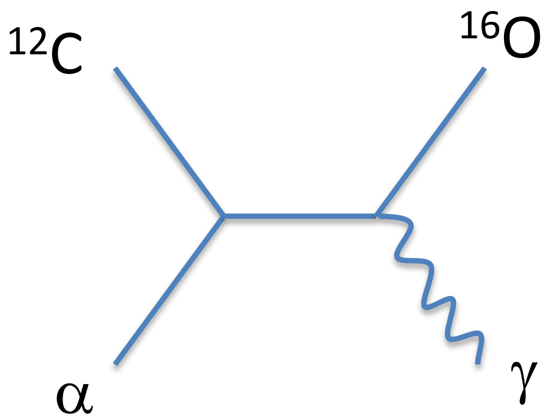
$$\eta = \frac{1}{137} Z_\alpha Z_{^{12}C} \sqrt{\frac{m_{^{12}C\alpha}}{2E_{CM}}}$$

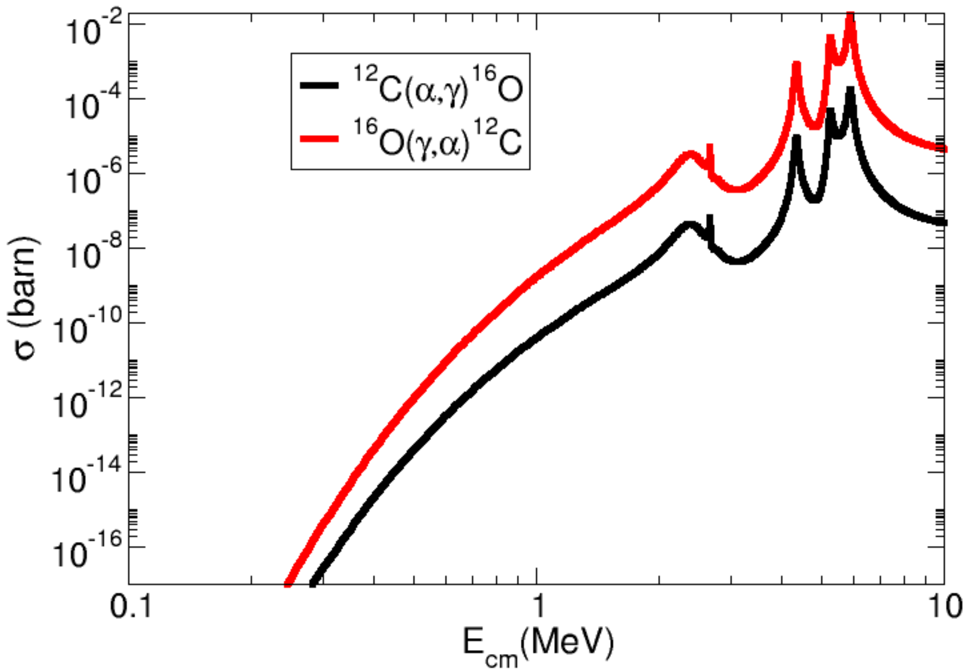


Stellar helium burning at E=300 keV

Author	S(300keV) (keV-b)
Buchmann (2005)	102-198
Caughlan and Fowler (1988)	120-220
Hammer (2005)	162+-39

Time Reversal Reaction





$$\omega_A \frac{\sigma_A(X,\gamma)}{\lambda_\alpha^2} = \omega_B \frac{\sigma_B(\gamma,X)}{\lambda_\beta^2}$$

(γ,α) and (α,γ) – Reciprocity Relation

- A(α, γ)B:

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

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

$$J_i = 0, J_j = 0, J_\alpha = 0 \qquad E_{A\alpha} = E_{CM} = \frac{M(^{12}C)}{M(^{12}C)+M(\alpha)}E_\alpha$$

$$E_{CM} = \sqrt{m_B^2 + 2E_\gamma m_B} - m_B - Q \qquad Q = m_A + m_\alpha - m_B = 7.162MeV$$

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

- σ(γ,α) is over two orders of magnitude larger than σ(α, γ)

New Approach: Inverse Reaction + Bubble Chamber

beam | target | signal

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

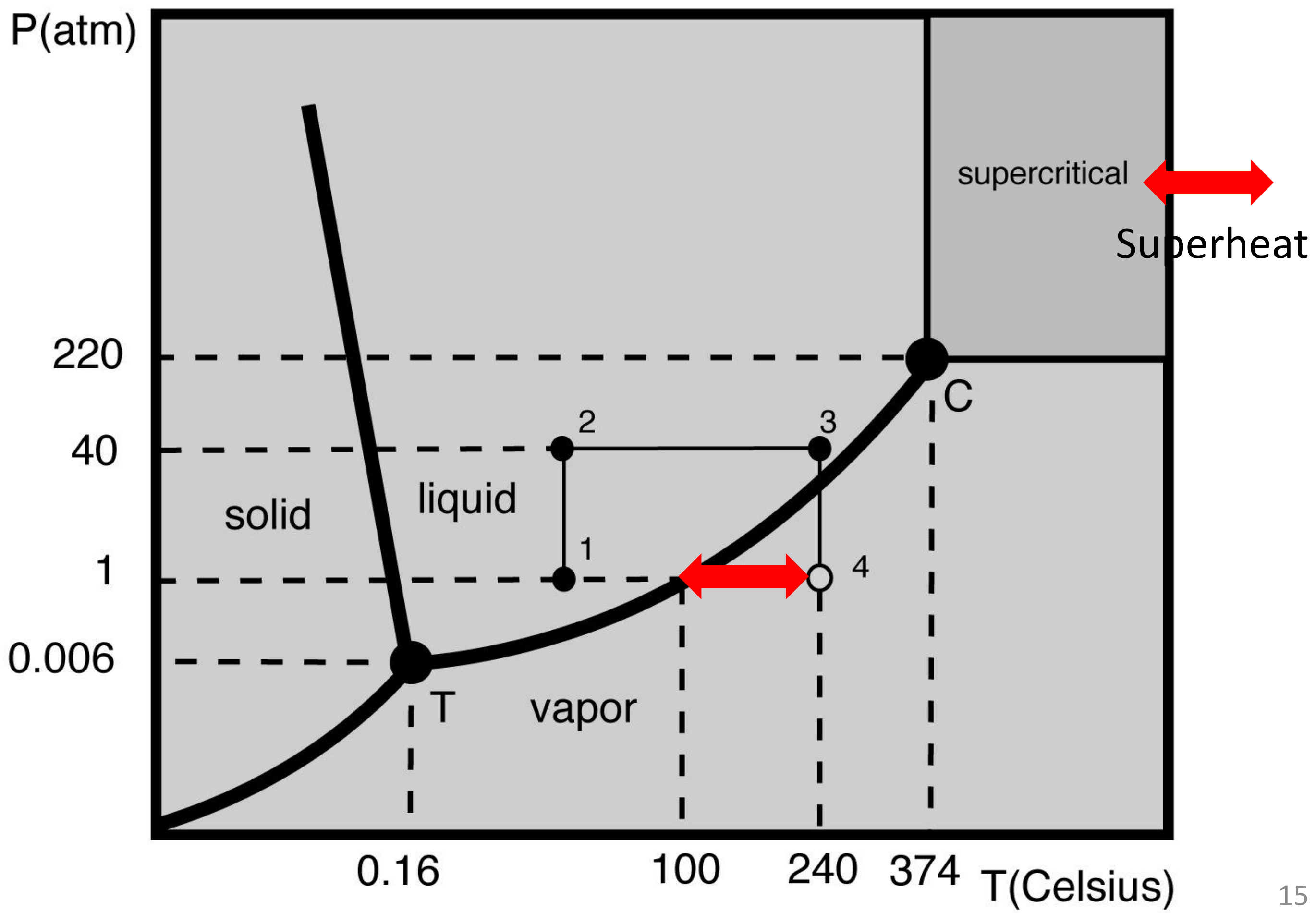
Monochromatic γ beam at HIγS
~ 10^{7-8} γ/s

Bremsstrahlung at JLab
~ 4×10^{9} γ/s (top 250 keV)

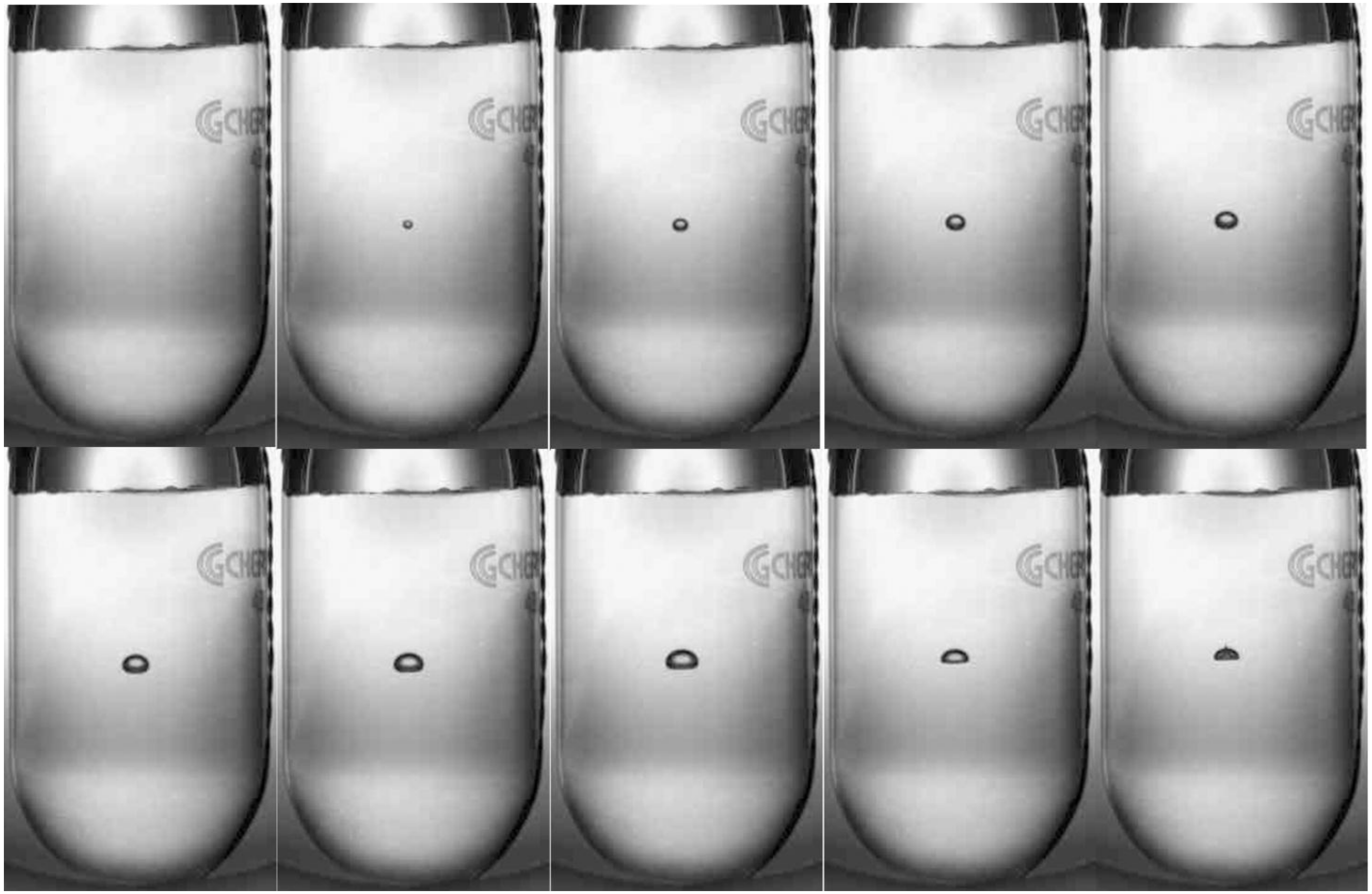
- Extra gain (x100) by measuring time inverse reaction
- Target density up to $\times 10^{6}$ higher than conventional targets
- Superheated liquid will nucleate from α and ^{12}C recoils
- Electromagnetic debris (degraded electrons and gammas, or positrons) that escape the collimator/electron beam do NOT trigger nucleation (detector is insensitive to γ-rays by at least 1 part in 10^{11}).

BUBBLE CHAMBER THEORY AND DESIGN

- Donald Glaser, 86, won Nobel for inventing chamber to detect subatomi
- Dark Mat
- COUPP F
- PICASSO
- SIMPLE P



BUBBLE GROWTH AND QUENCHING



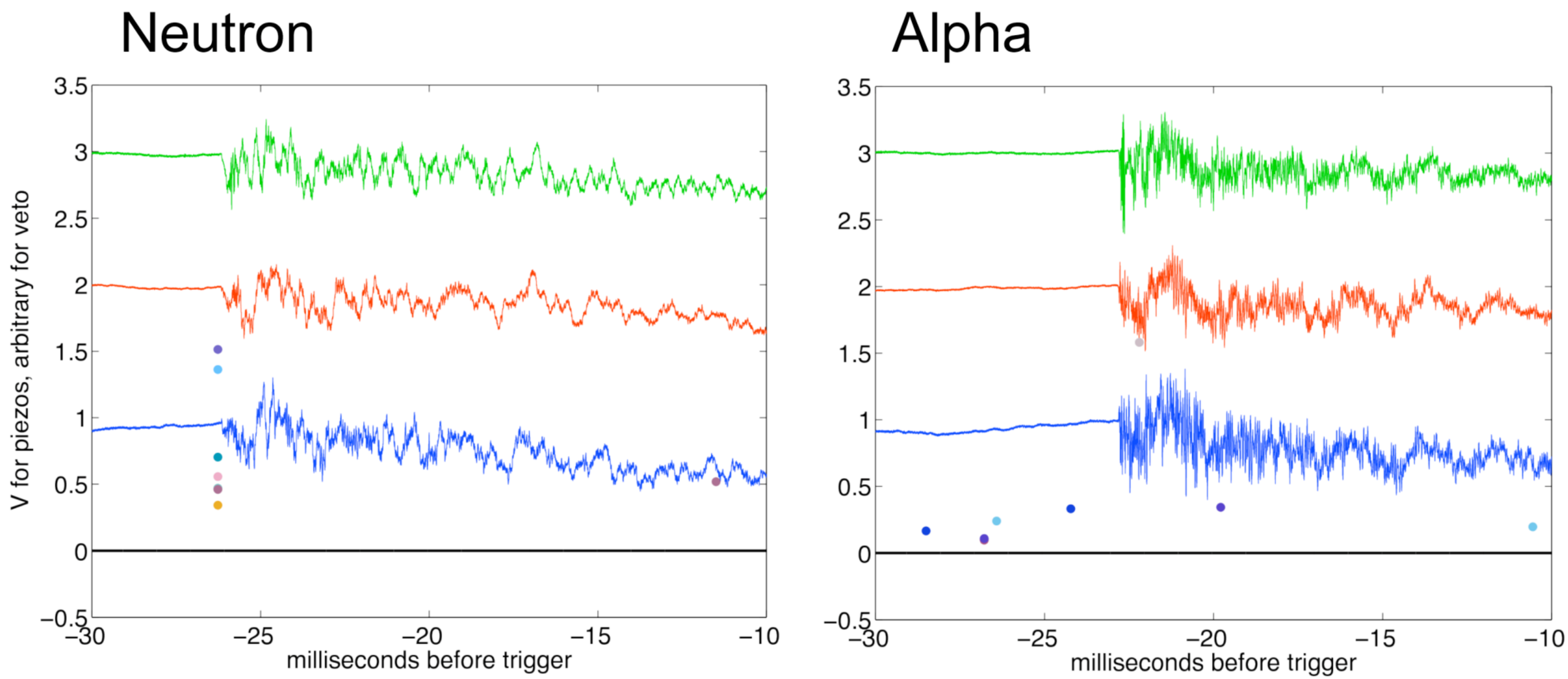
$^{19}F(\gamma,\alpha)^{15}N$ in R134a

$\Delta t = 10$ ms

Acoustic Signal: Particle ID

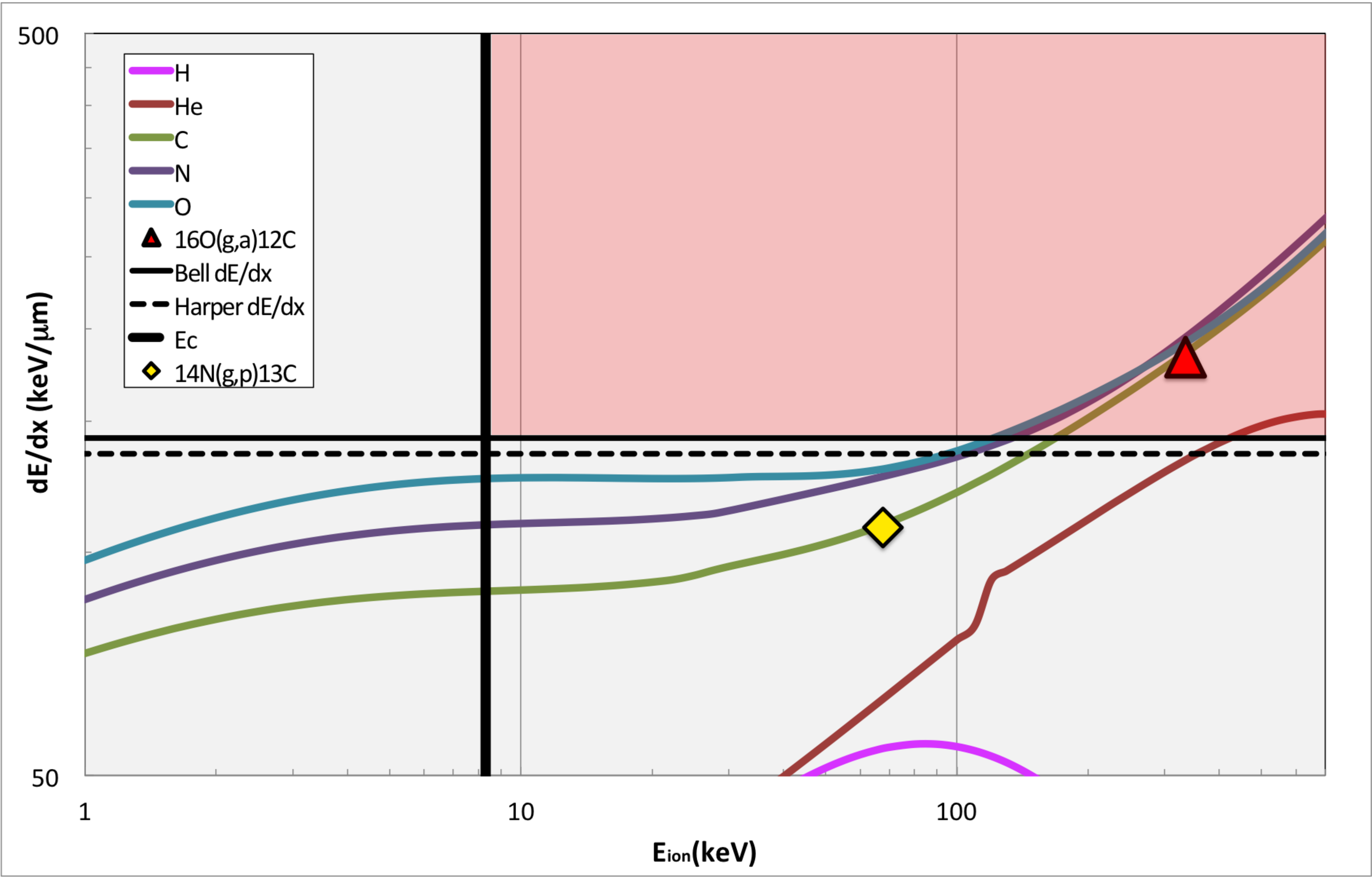
Acoustic Signatures, time domain

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

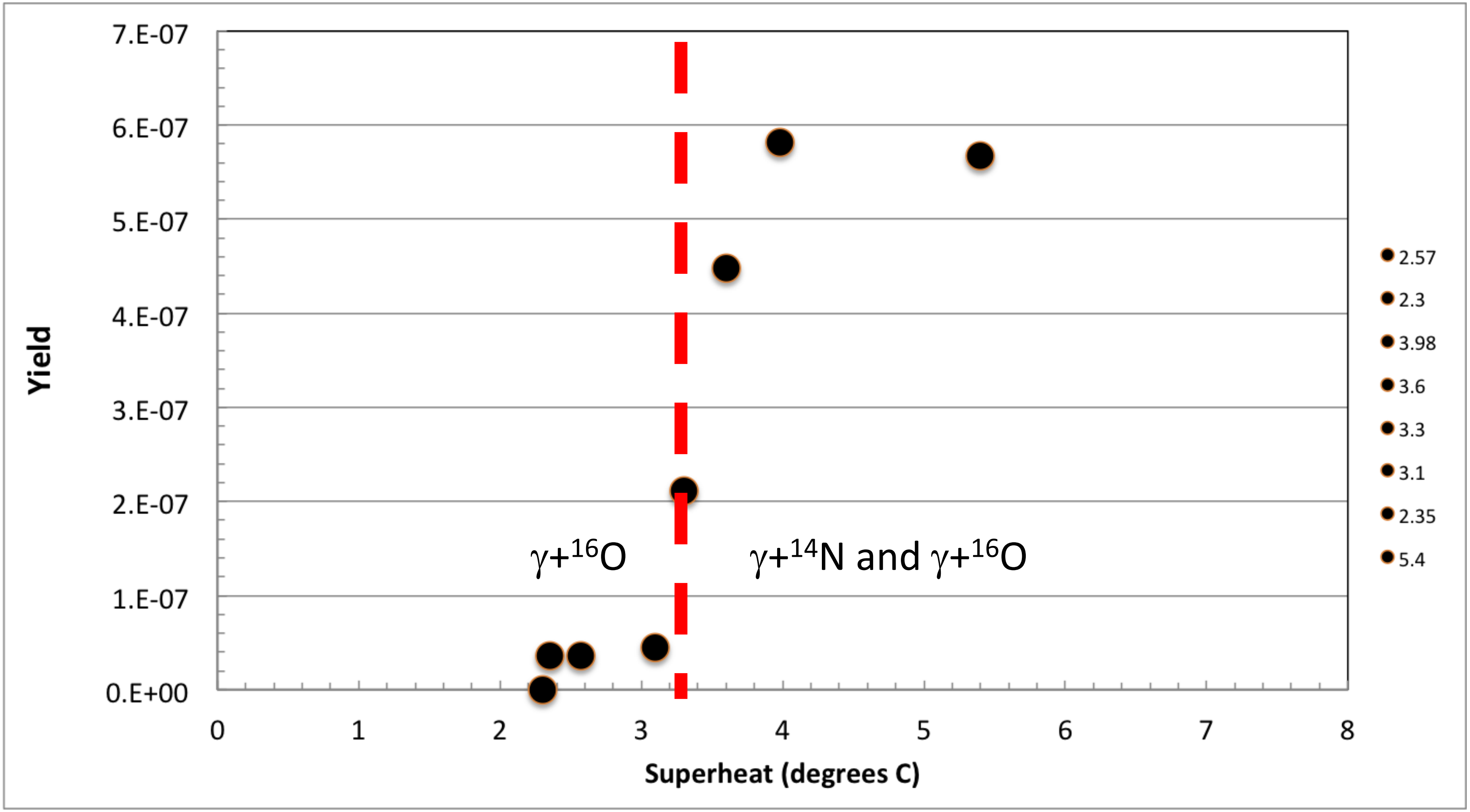


COUPP, FNAL, courtesy of A. Sonnenschein

N_2O thresholds, Superheat = 3.3 ^{O}C, Eγ=8.5 MeV

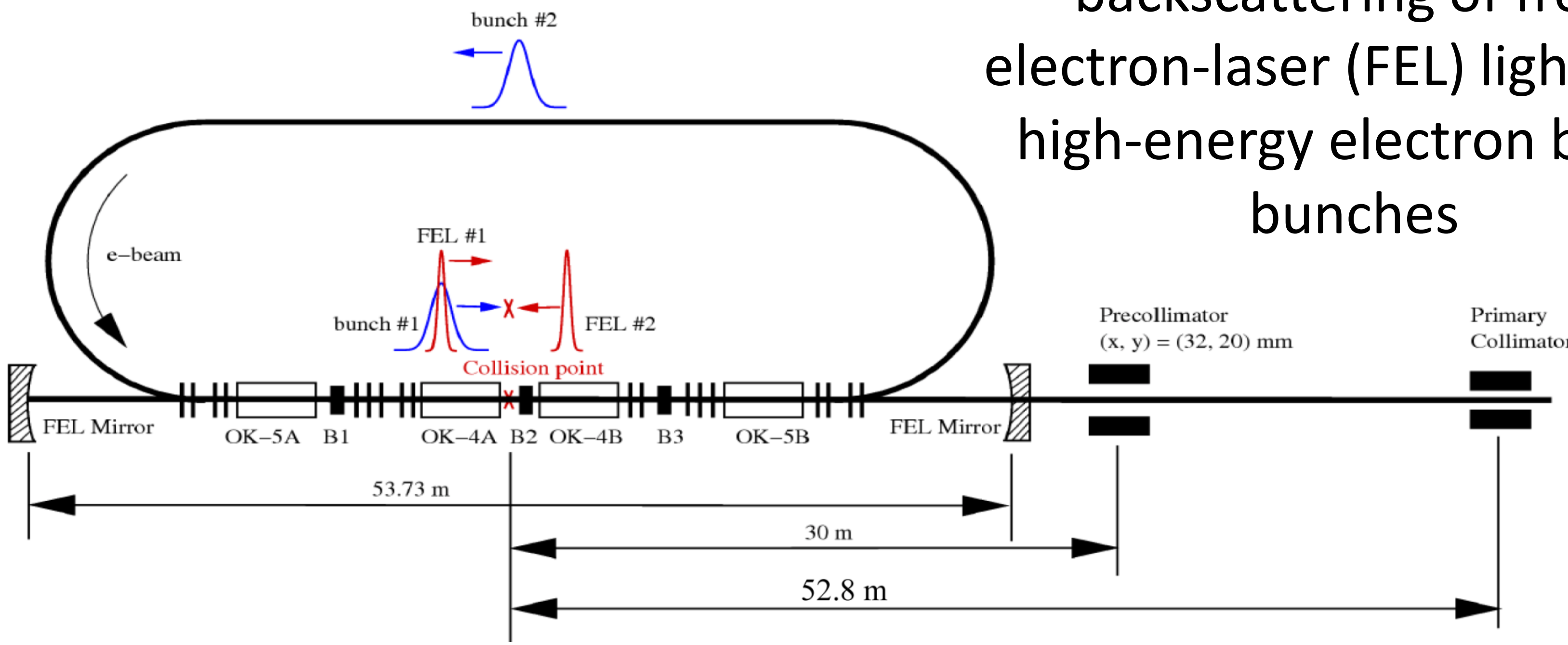


EFFICIENCY CURVE



N_2O efficiency curve, HIGS April 2013. $E_\gamma = 9.7$ MeV

BUBBLE CHAMBER AT HIGS

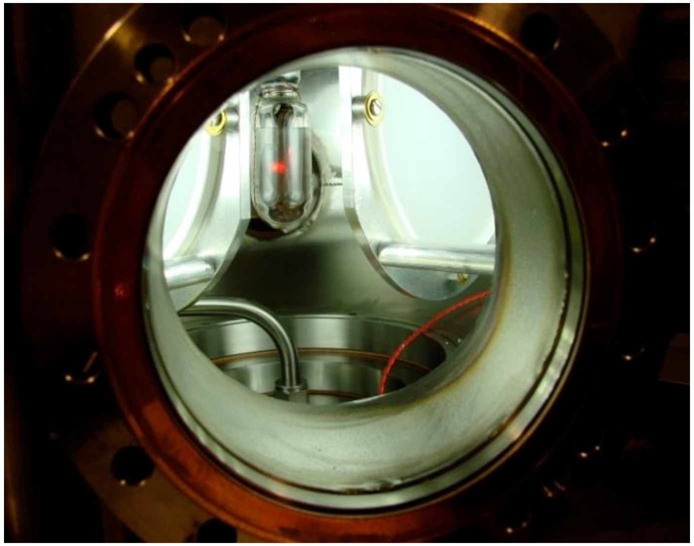


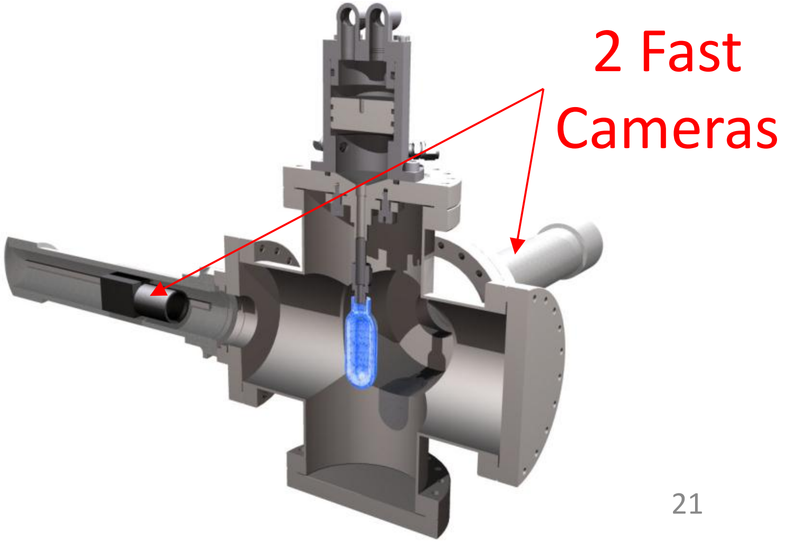
γ-rays generated by Compton backscattering of free-electron-laser (FEL) light from high-energy electron beam bunches

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

Strong Bremsstrahlung Background

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





C_4F_{10} Bubble Chamber

T=310 K

P= 160 kPa – 900 kPa

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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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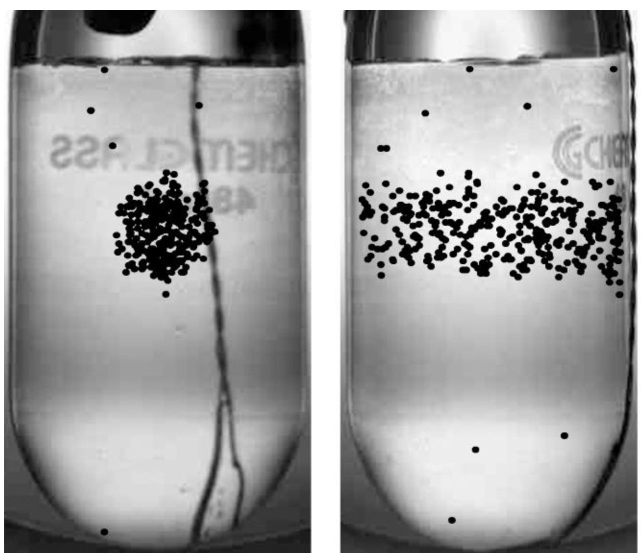
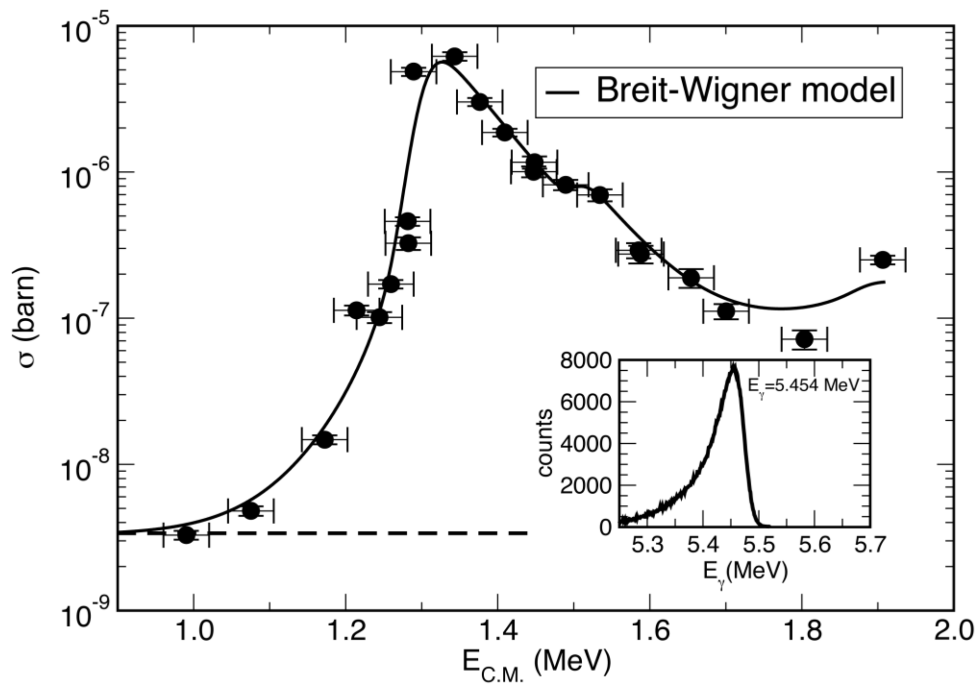
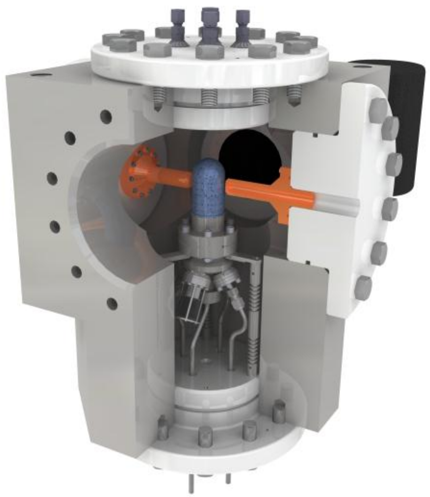
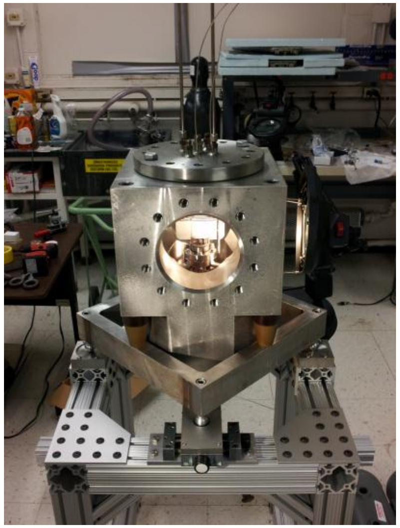
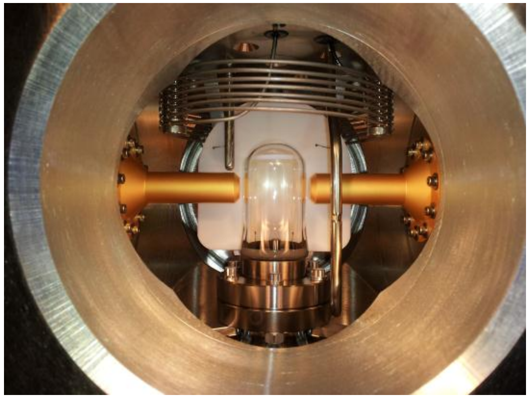




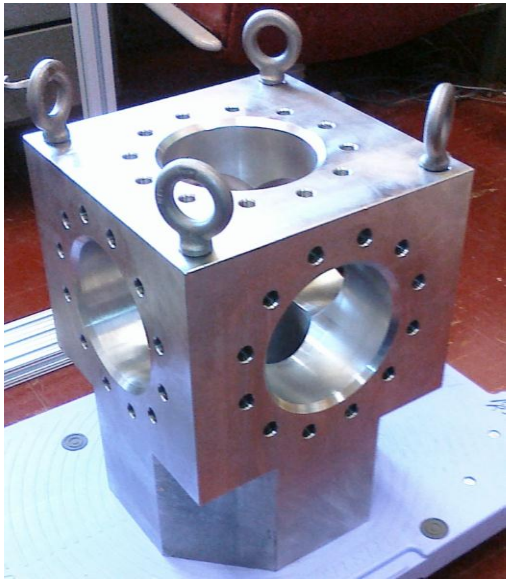
Recent Work

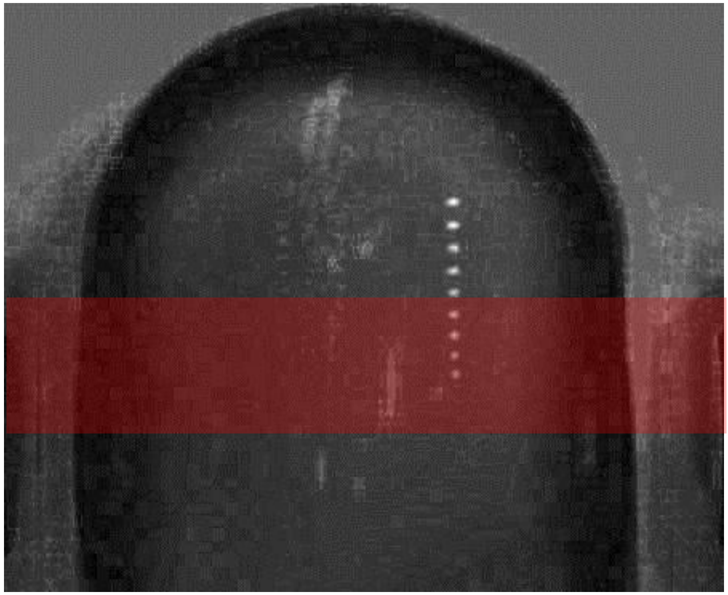






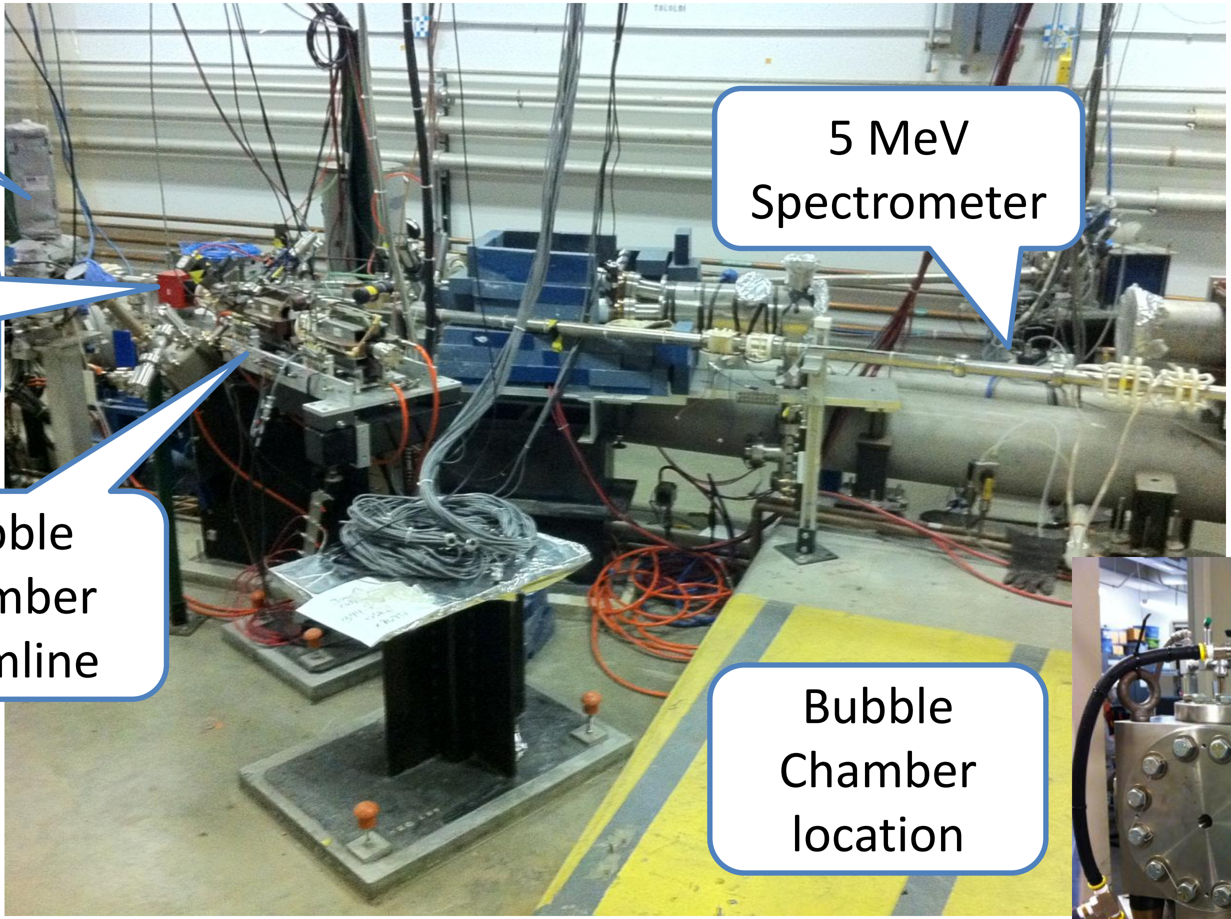
N_2O Bubble Chamber
First γ+O→α+C bubble
April 2013

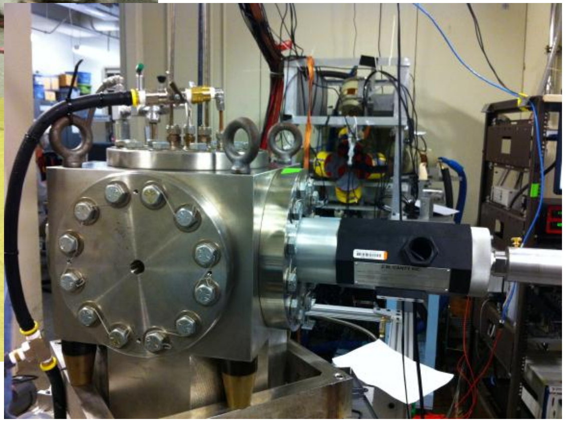




EXAMPLE

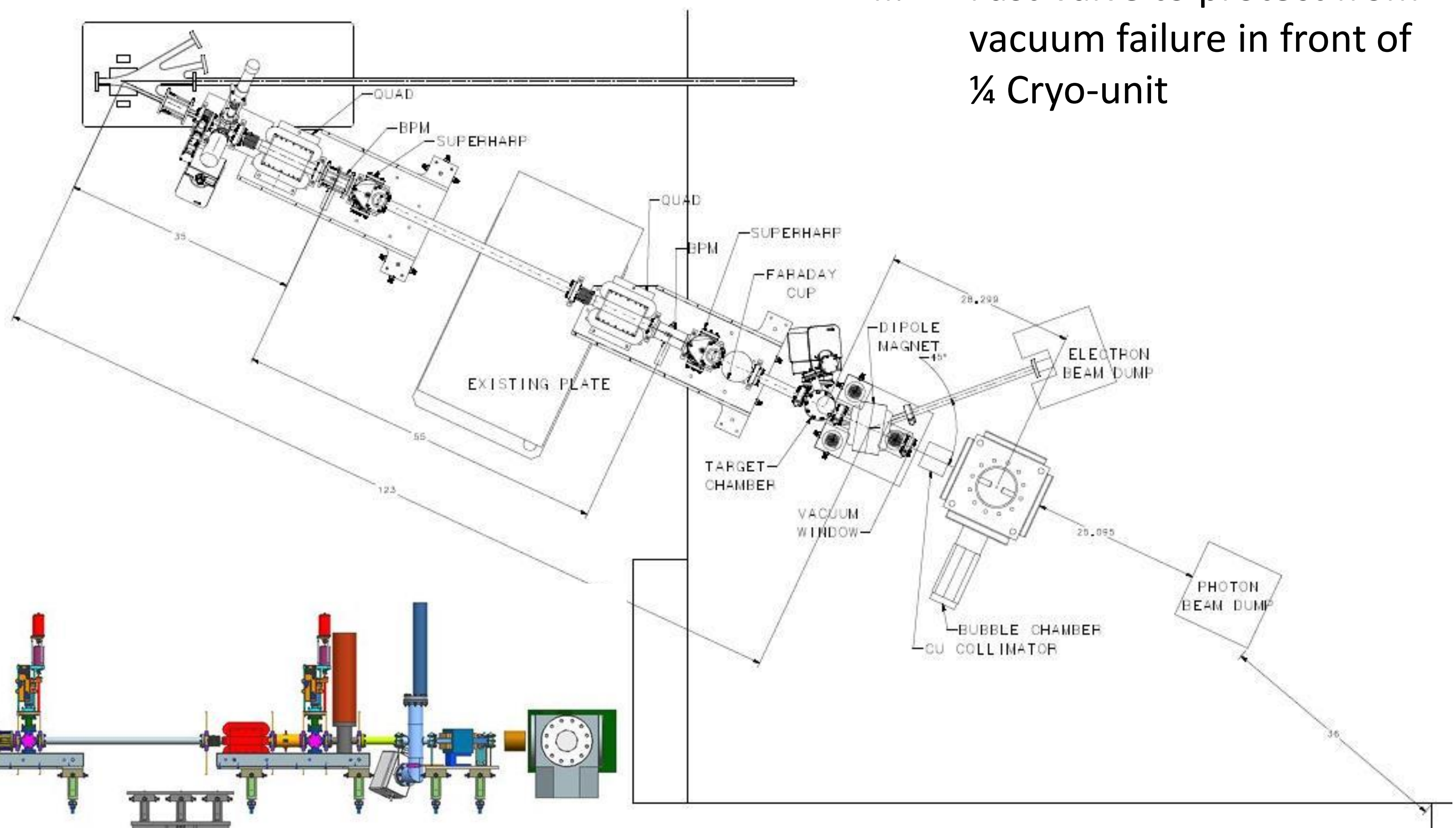
Experimental Setup

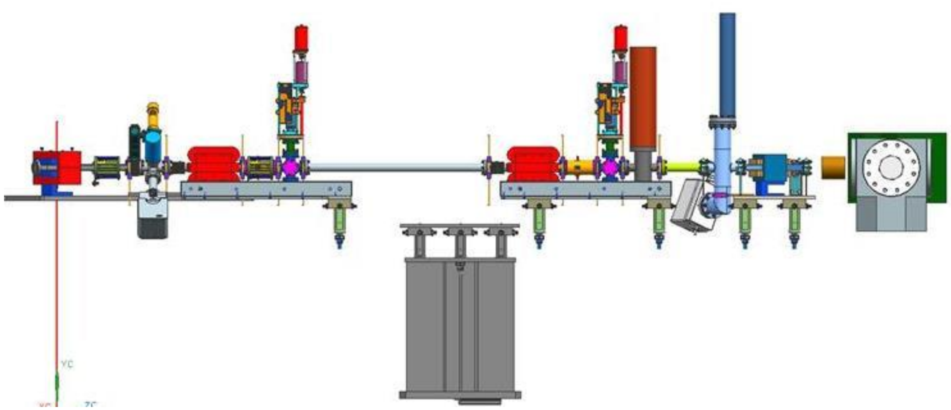




BEAMLINE

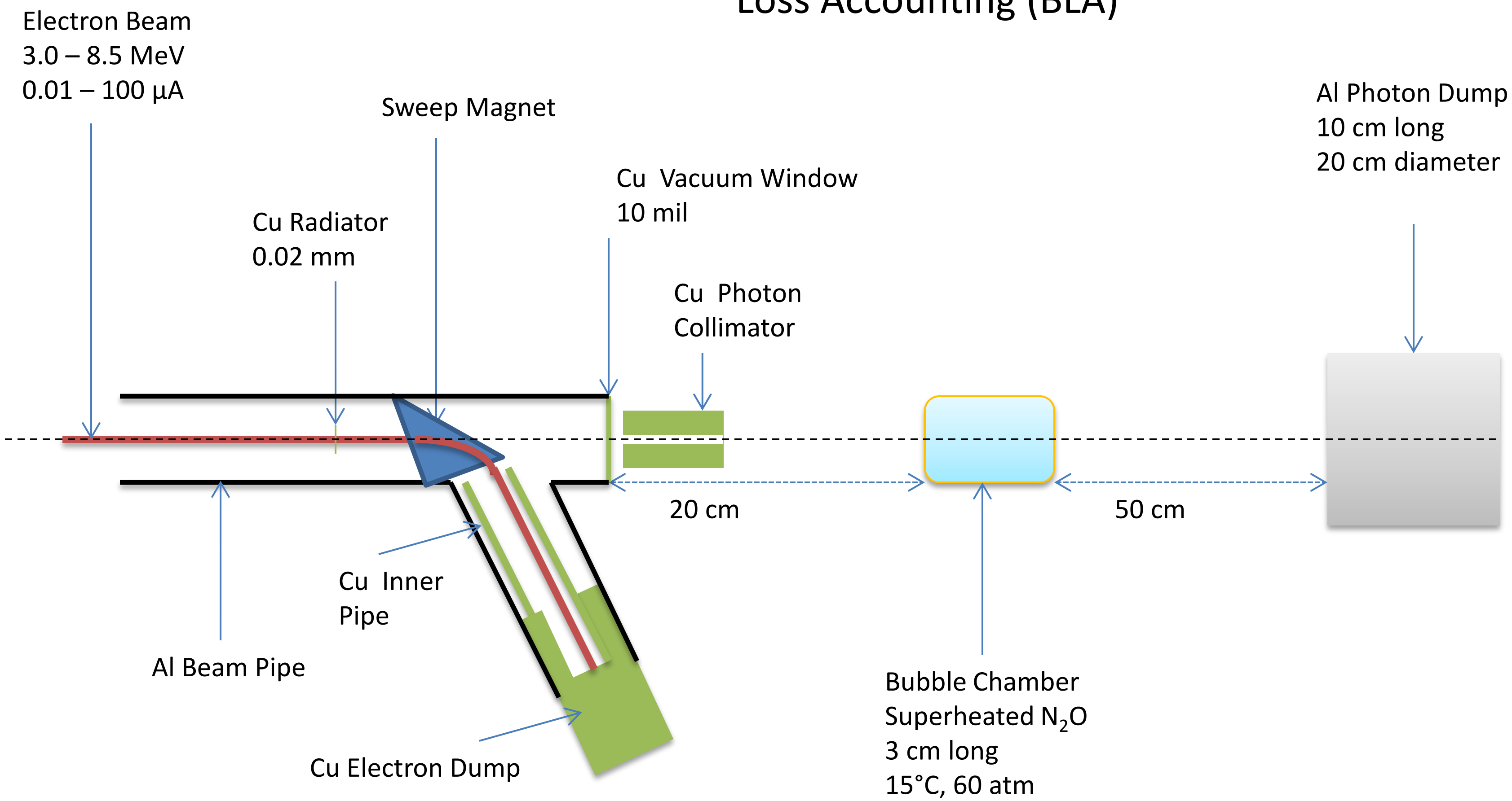
I. 2 Super Harps to measure beam profile and absolute beam position
II. Fast Valve to protect from vacuum failure in front of ¼ Cryo-unit





SCHEMATICS

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)	3.0 – 8.5
Beam Current (μA)	0.01 – 100
Absolute Beam Energy	0.1%
Relative Beam Energy	0.05%?
Energy Resolution (Spread), σ_T /T	0.06%
Beam Size, $\sigma_{x,y}$ (mm)	1 – 2

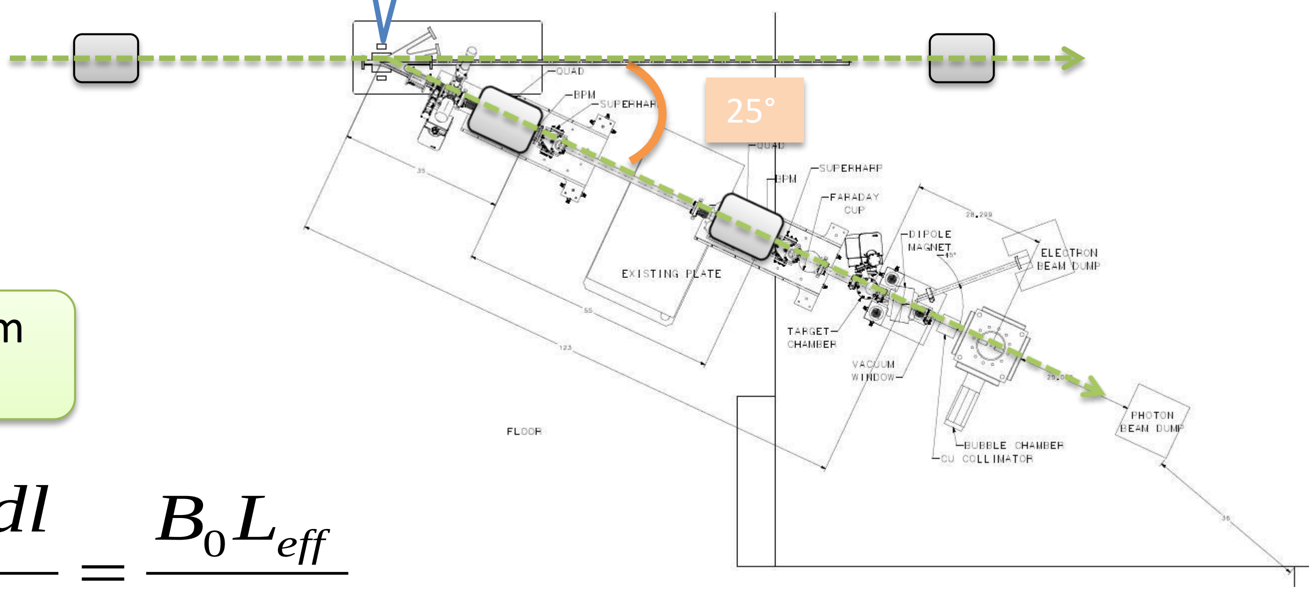
II. PEPPo achieved p=8.25 MeV/c or K.E.=7.75 MeV. Maximum stable ¼- cryounit cavity gradients achieved: 8.4 MV/m and 6.1 MV/m (7.25 MV/m average). Vacuum in the beam line indicates that field emission and desorbed gas are the most problematic, but improve with processing.

III. Helium process the ¼-cryounit

ABSOLUTE BEAM ENERGY

BPM

5 MeV Dipole



Electron Beam Momentum

$$p = \frac{\int Bdl}{\theta} = \frac{B_0 L_{eff}}{\theta}$$

- Absolute beam energy is now known to 1%:

  New larger dipole magnet with better field uniformity
  - New and very accurate field map
  - Build a detailed TOSCA model
  - Add a Hall probe or NMR magnetometer for field monitoring
  - Accurate and more stable power supply
  - Add mu metal on all beam pipes to shield Earth field

- For 8.5 MeV/c: dipole current = 3.3 A, B_0 = 1120 G
- Error Budget:
  - Bending angle:

    ($\Delta\theta/\theta$) ~ BPM Resolution / distance between BPMs on PEPPo line = 0.5%
  - Field uniformity (variation in B across aperture): $\Delta B/B_0$ = 0.5%
  - Effective Length: $\Delta L_{eff}/L_{eff}$ = 0.13%
  - Power supply: $\Delta I/I$ = 2 mA / 3.3 A = 0.06%
  - Earth field: 0.5 G/ 1116 G = 0.04%

Non-resonant charged particle reactions
(The Gamow peak)

Let's write the cross section as $\sigma(E) = \frac{1}{E}\exp(-2\pi\eta)S(E)$

and substitute in $<\sigma v> = \left(\frac{8}{\pi\mu}\right)^{1/2}\frac{1}{(kT)^{3/2}}\int_0^\infty \sigma(E)E\exp\left(-\frac{E}{kT}\right)dE$

If no resonances are present S(E) = S(Eo) = constant, so

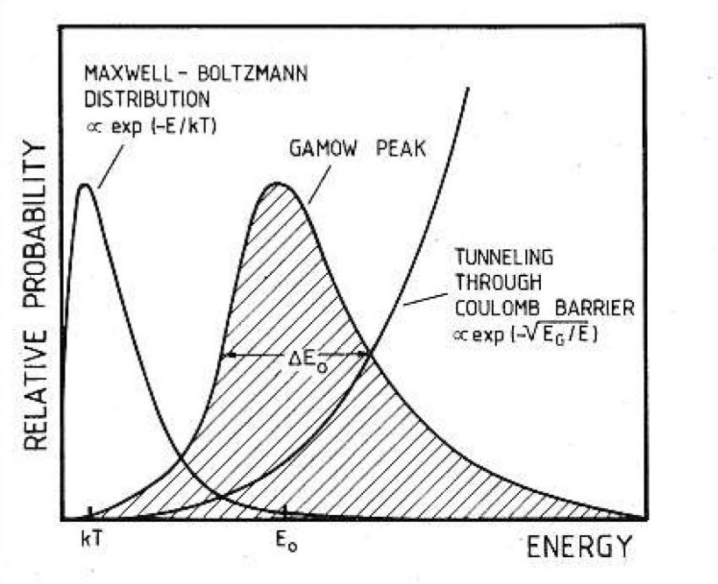
$$<\sigma v> = \left(\frac{8}{\pi\mu}\right)^{1/2}\frac{1}{(kT)^{3/2}}S(E_0)\int_0^\infty \exp\left(-\frac{E}{kT}-\frac{b}{E^{1/2}}\right)dE \qquad b = \left(\frac{2\mu}{\hbar^2}\right)^{1/2}\pi Z_1 Z_2 e^2$$

Gamow peak

* The rate has a peak shape product of two negative exponentials: Maxwell-Boltzmann distribution at low energy and tunneling through the Coulomb barrier for higher E.

* It represents the region in energy where reactions are more likely to occur.

* The concept can be extended to a general S(E)



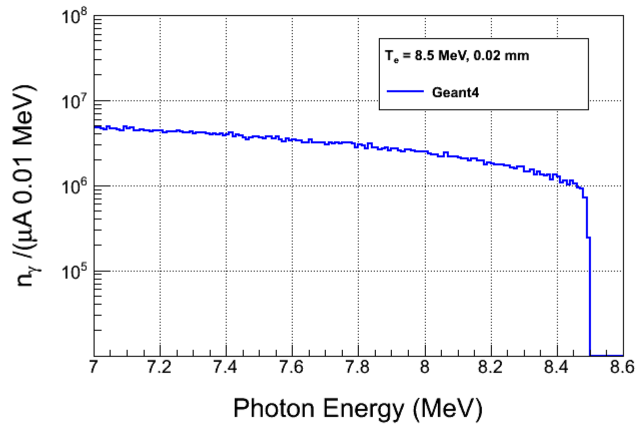
Superheated Liquids

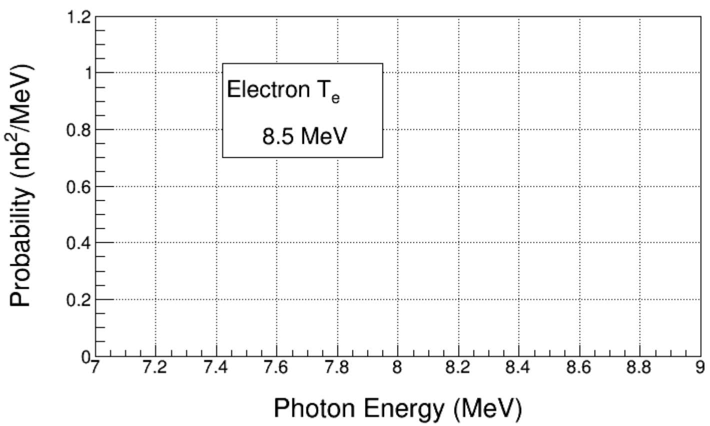
I. List of superheated liquids to be used in the experiment:

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

BREMSSTRAHLUNG BEAM





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:

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

- Where:

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

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

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

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

Although,

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

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

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

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:

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

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

$$E_0 = 7.8 + \delta E$$

$$E_i = E_0 + i\Delta$$

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

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

No point-to-point systematic

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

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

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

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

Other Relative 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%

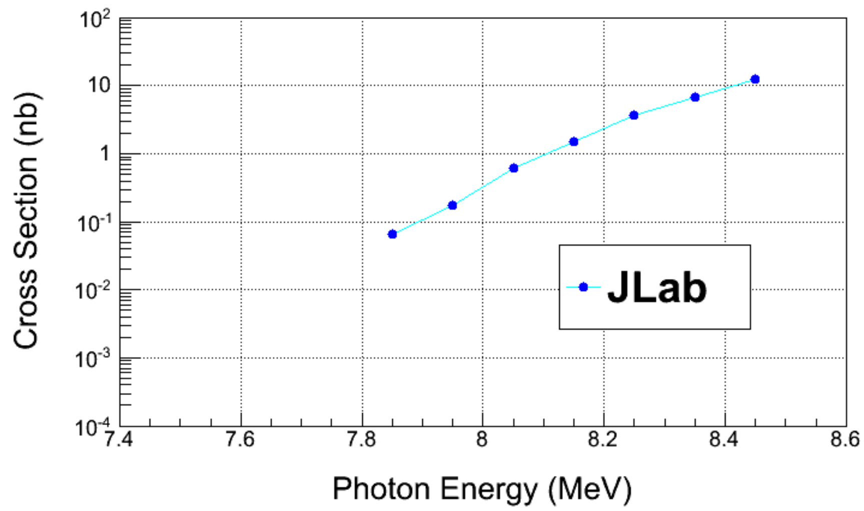
Simulation

- 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



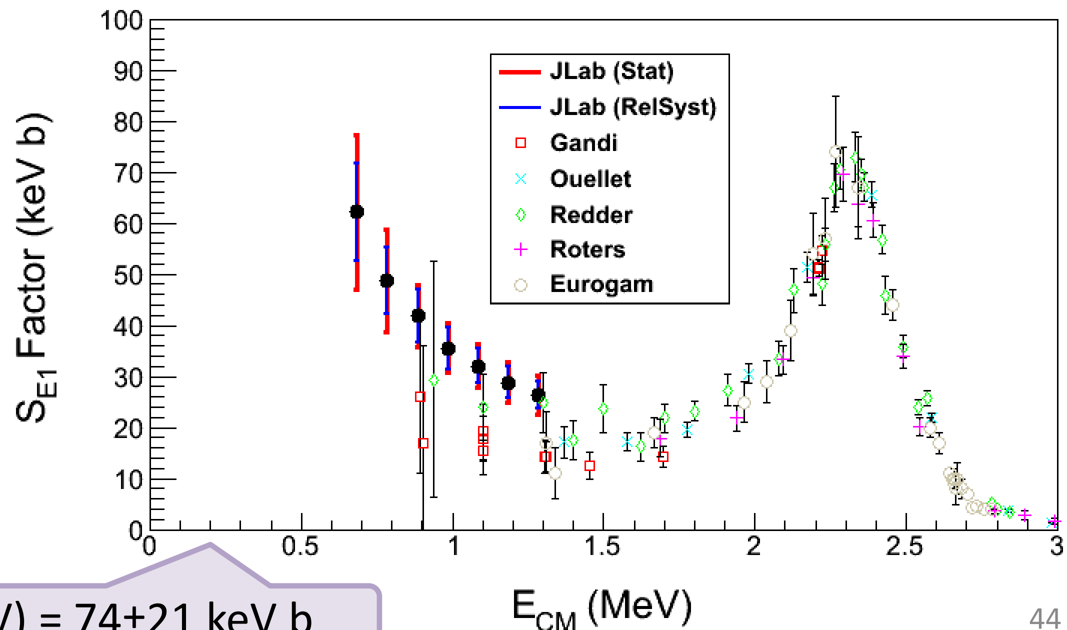
Electron Beam K. E.	Cross Section (nb)	Sys Error (Energy, %)	Sys Error (Total, %)
7.9	0.046	12.5	15.3
8.0	0.185	10.2	13.5
8.1	0.58	8.3	12.2
8.2	1.53	7.0	11.4
8.3	3.49	6.0	10.7
8.4	7.2	5.3	10.5
8.5	13.6	4.7	10.1

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

$^{12}C(\alpha, \gamma)^{16}O$ 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_{E1} 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



S_{E1}(300 keV) = 74±21 keV b

BACKGROUNDS

I. Background from oxygen isotopes and nitrogen in N_2O:

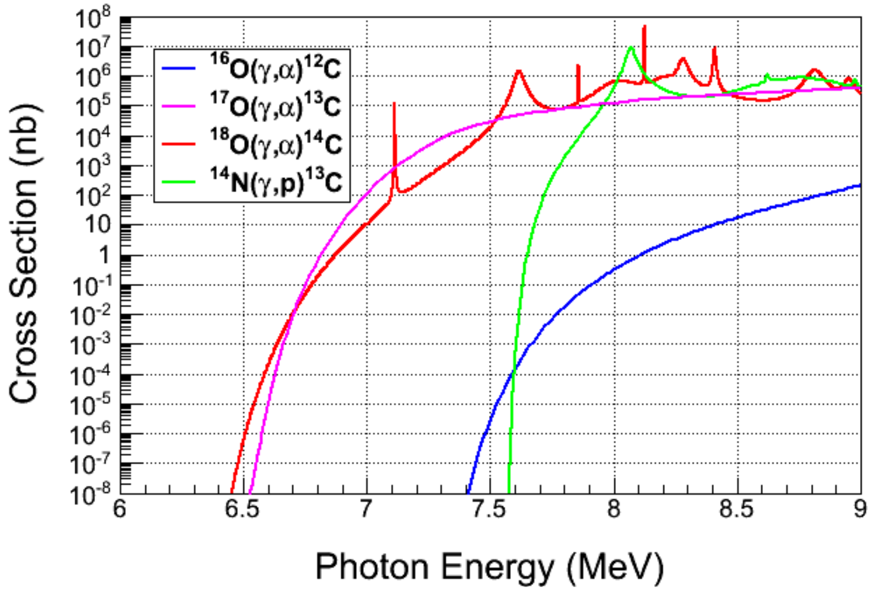
– $^{18}O(\gamma,\alpha)^{14}C$
– $^{17}O(\gamma,\alpha)^{13}C$
– $^{14}N(\gamma,p)^{13}C$

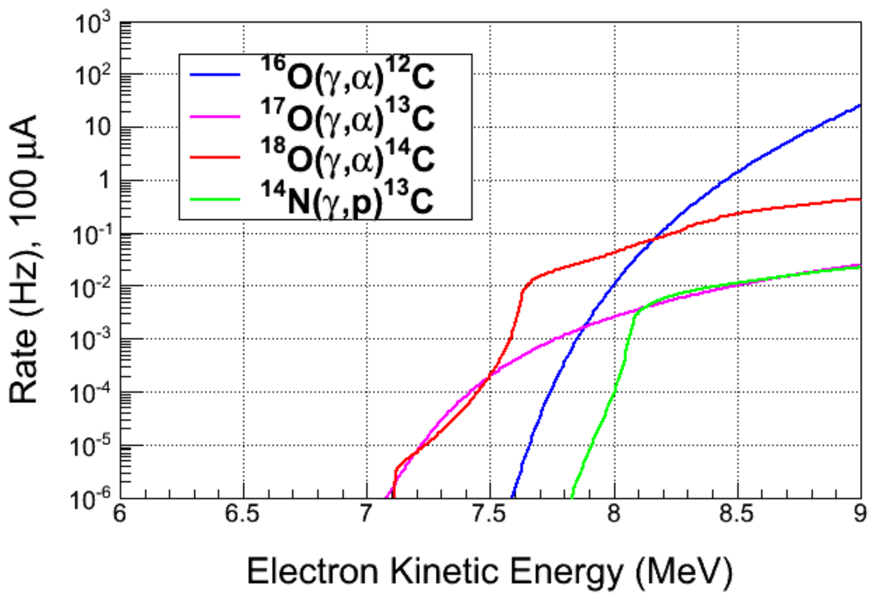
➢ Natural Abundance:

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}





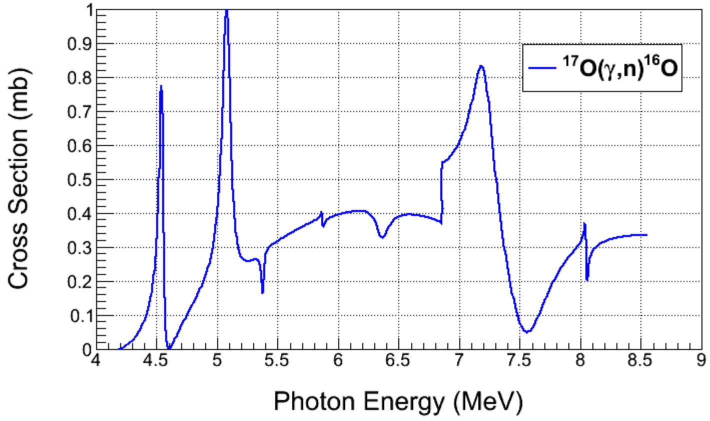
II. Background from:

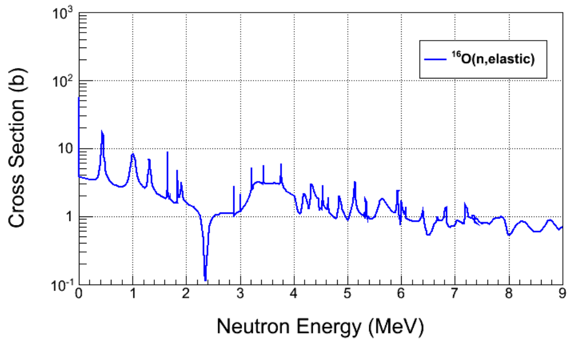
- $^{17}O(\gamma,n)^{16}O$

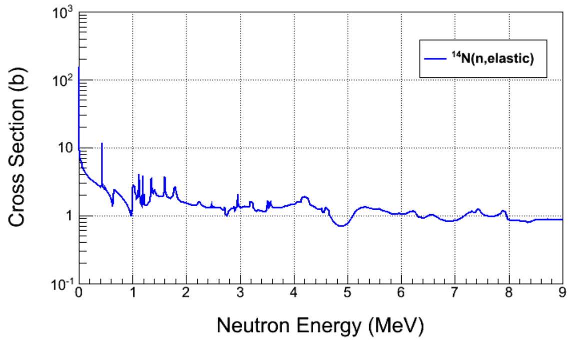
III. Cosmic-ray background:

- $\mu_{\pm}$-nuclear
- Secondary neutron-nuclear

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







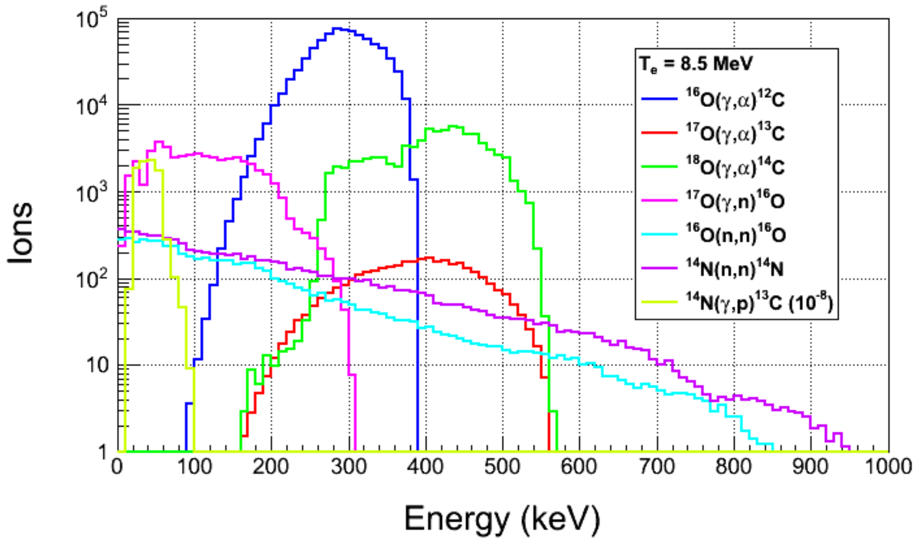
Ion Energy Distributions

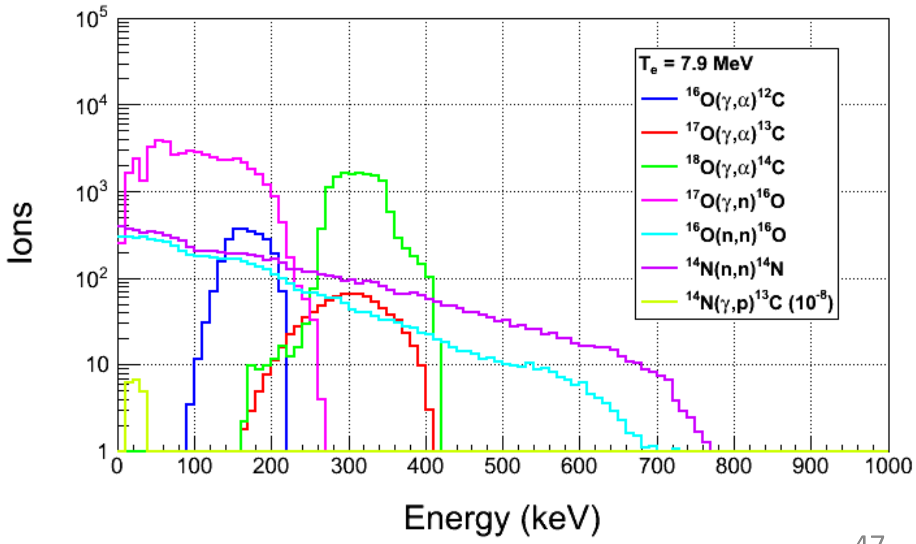
- Suppress background with Bubble Chamber threshold

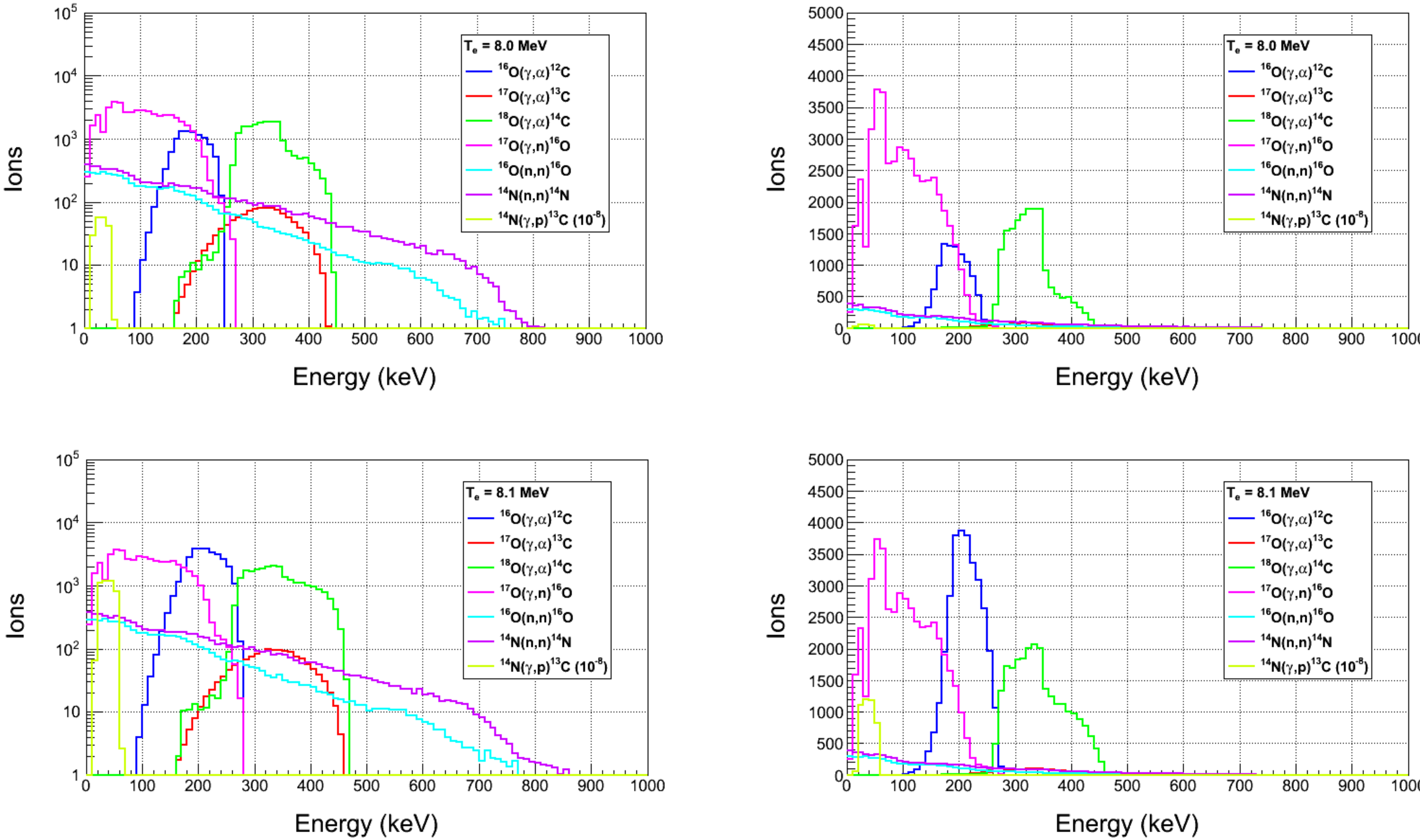
- Calculated with Depletion:
  - I. ^{17}O depletion=5,000
  - II. ^{18}O depletion=5,000

- Threshold Efficiency (function of superheat):

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

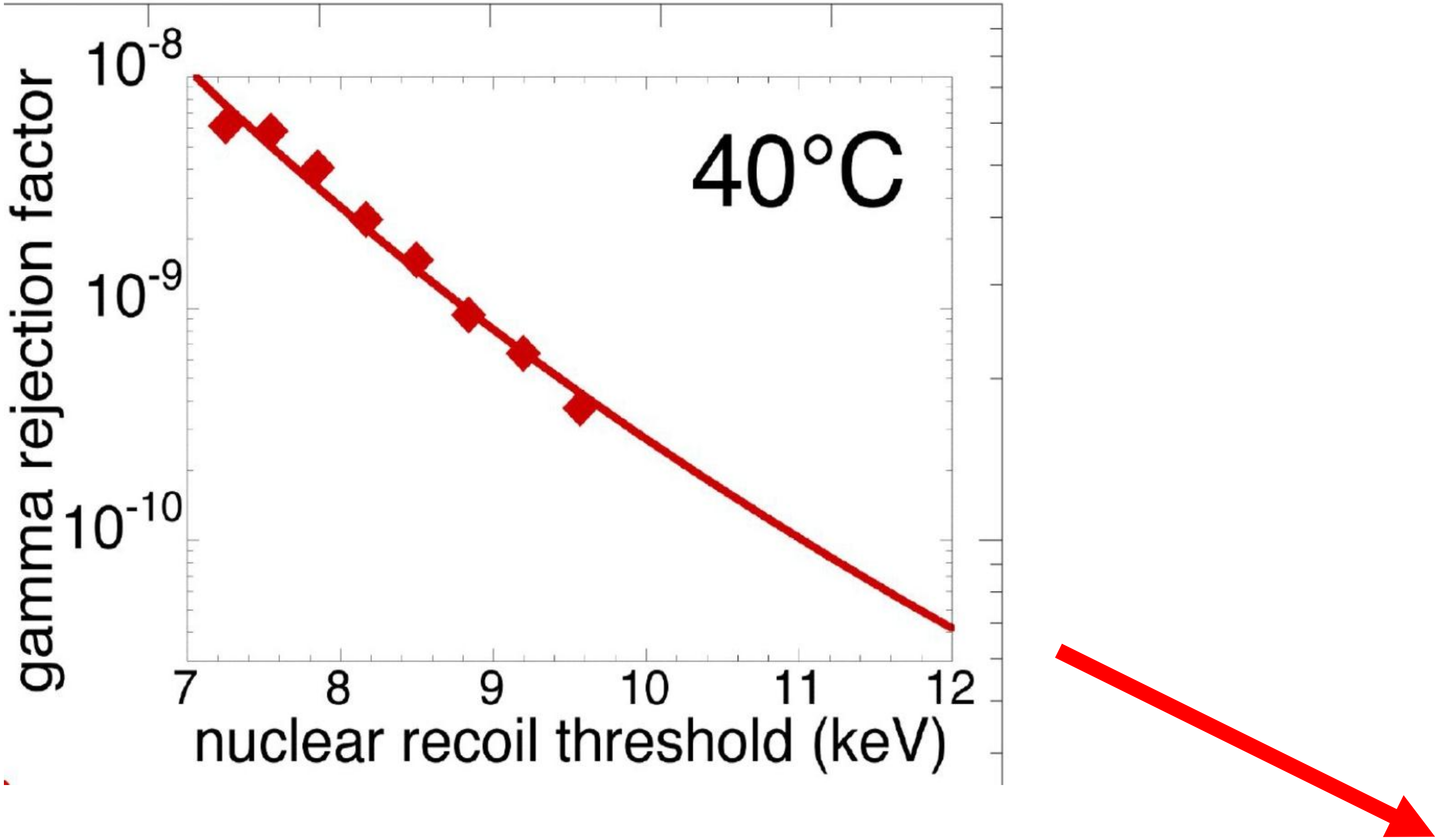






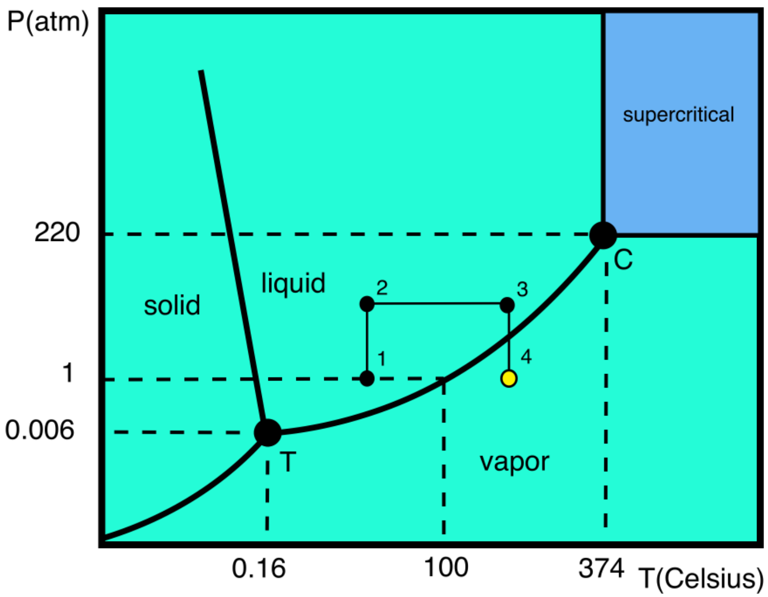
Ions
Energy (keV)
T_e = 8.0 MeV
$^{16}O(\gamma,\alpha)^{12}C$
$^{17}O(\gamma,\alpha)^{13}C$
$^{18}O(\gamma,\alpha)^{14}C$
$^{17}O(\gamma,n)^{16}O$
$^{16}O(n,n)^{16}O$
$^{14}N(n,n)^{14}N$
$^{14}N(\gamma,p)^{13}C$ (10^{-8})
Ions
Energy (keV)
T_e = 8.0 MeV
$^{16}O(\gamma,\alpha)^{12}C$
$^{17}O(\gamma,\alpha)^{13}C$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

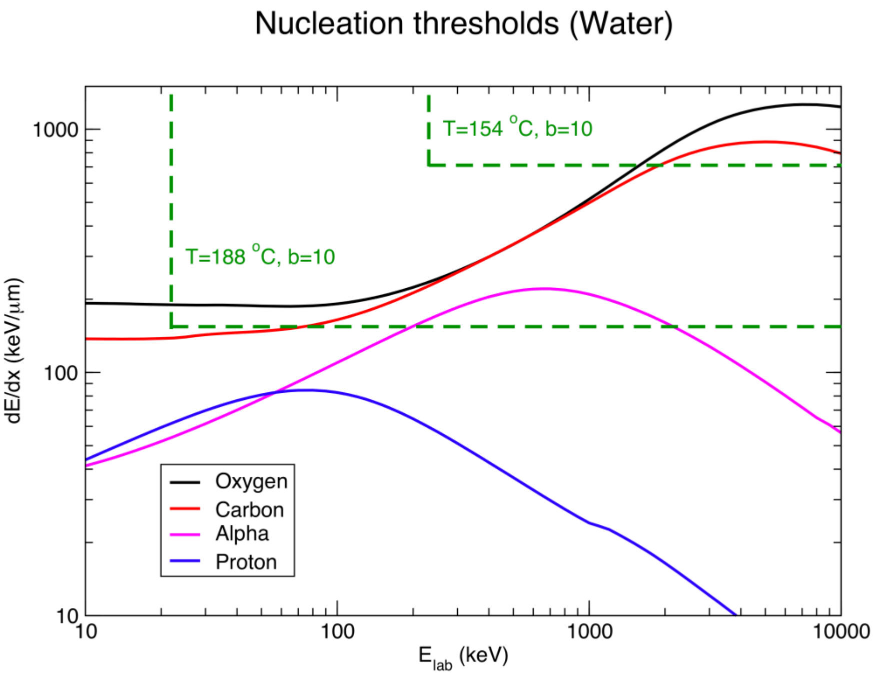
Gamma suppression

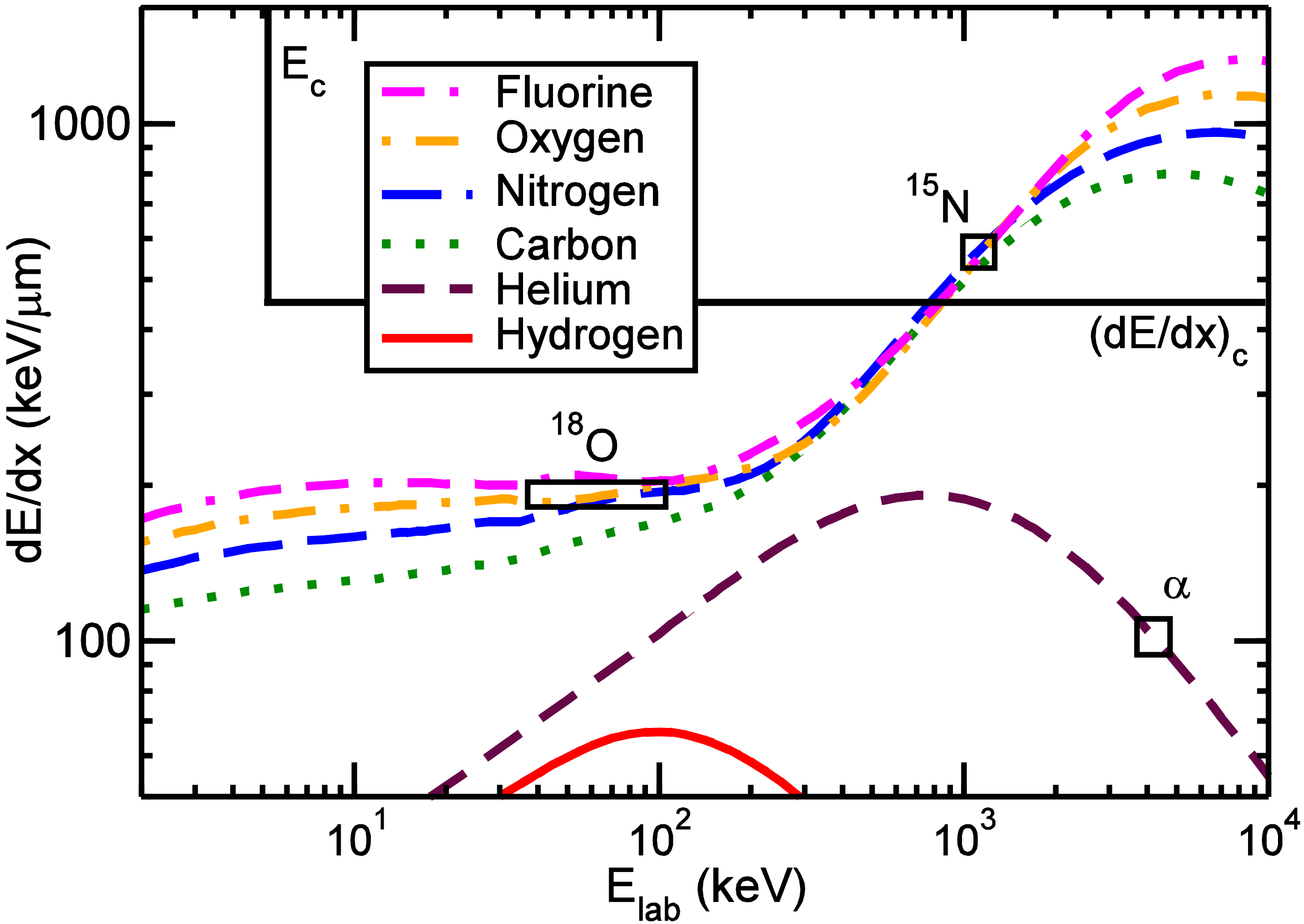


COUPP exp. FNAL

Bubble chamber basics

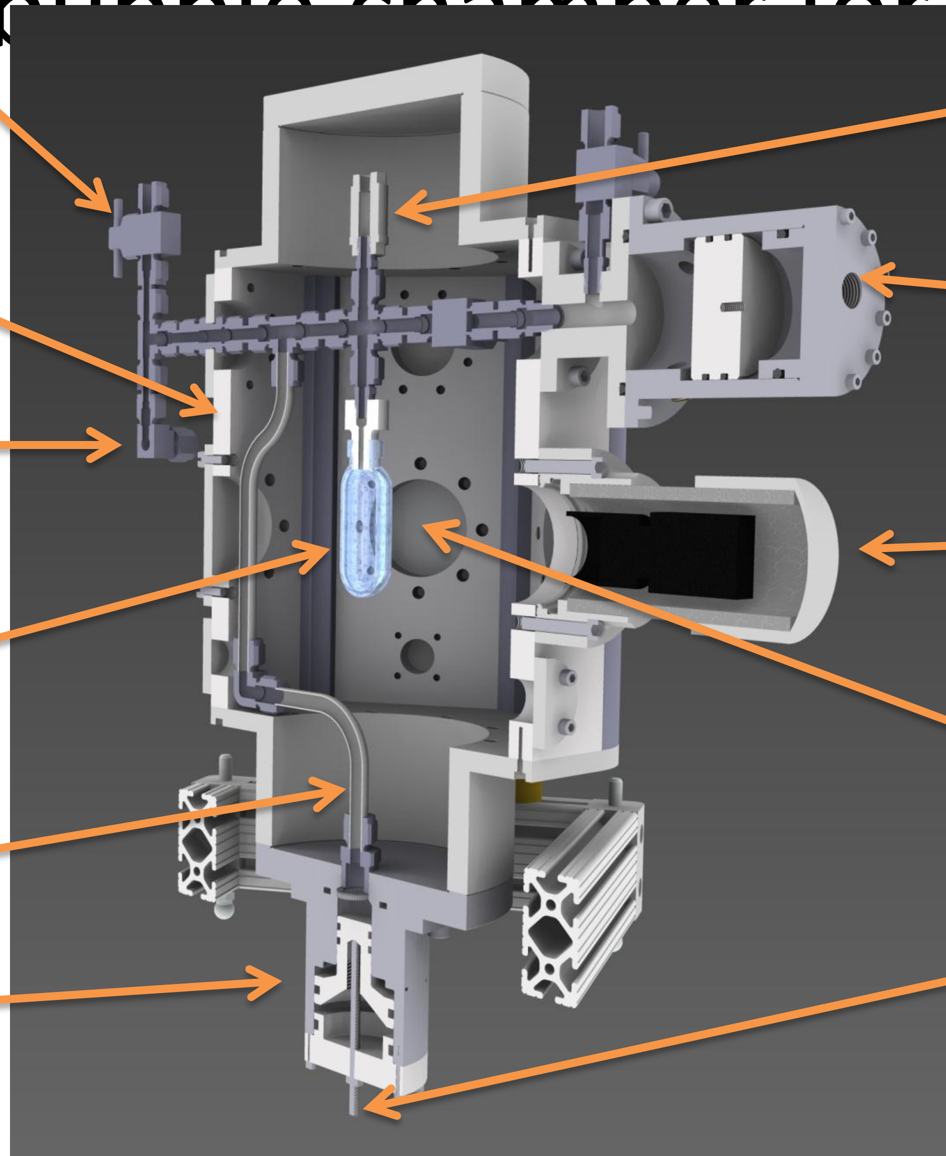






E_c
Fluorine
Oxygen
Nitrogen
Carbon
Helium
Hydrogen
15N
18O
α
(dE/dx)_c
1000
100
dE/dx (keV/μm)
10^1
10^2
10^3
10^4
E_lab (keV)

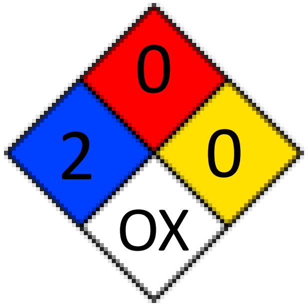
C_4F_{10} bubble chamber for JLab



Courtesy of B. DiGiovine

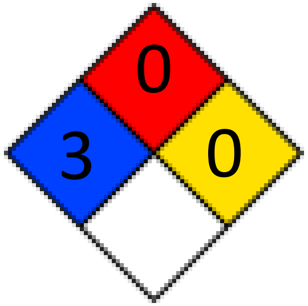
SAFETY

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



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

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



SUMMARY AND OUTLOOK

- Test N_2O Bubble Chamber at HIγS (February 2014)
- Perform $^{18}O(\gamma,\alpha)^{14}C$ and $^{17}O(\gamma,\alpha)^{13}C$ experiments at HIγS (Summer 2014)
- Test Bubble Chamber at JLab with Bremsstrahlung beam (October 2014)
- If successful, run depleted N_2O bubble chamber at JLab $^{16}O(\gamma,\alpha)^{12}C$

- Bubble Chamber issues:
  - Piezo-electric acoustical signal
  - 10 sec deadtime -> 2 sec deadtime

- Background tests:
  - Measure cosmic-ray background
  - Study chamber efficiency vs. superheat

BACKUP SLIDES

Cost Estimate

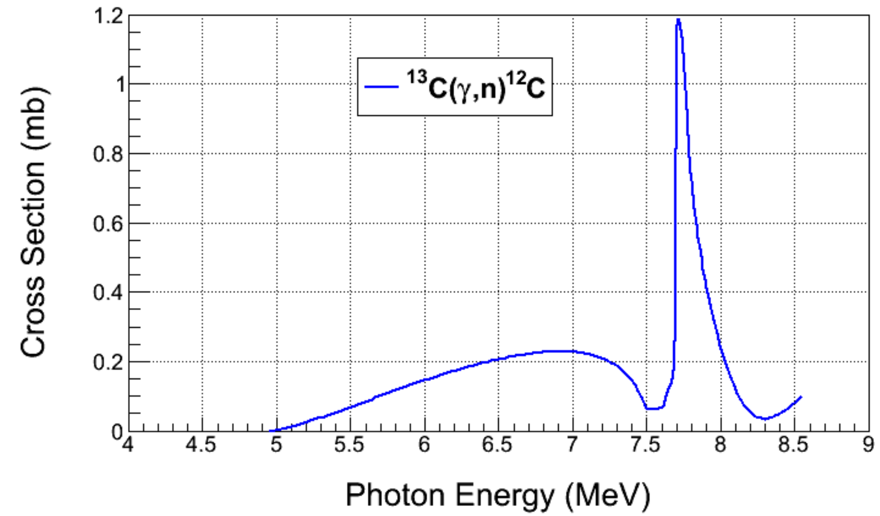
I. New beamline components:
   I. New Dipole Magnet and Hall Probe
   II. 2 Super Harps
   III. Fast Valve
II. Summary of labor cost by group:

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

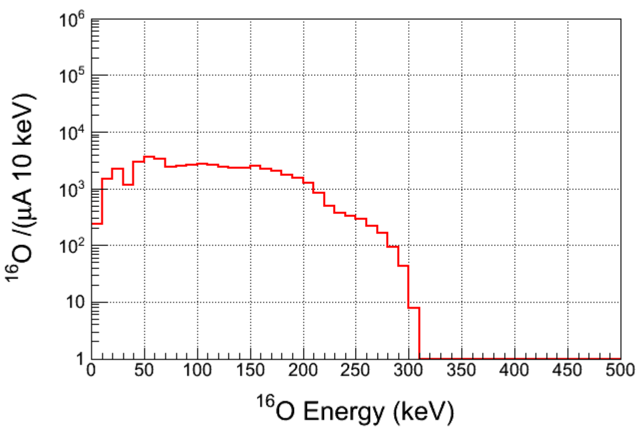
Item	Material Procurement	Shop	Labor
New Dipole Magnet	Dipole Magnet ($8,000) Hall Probe System ($10,000)		Design (2 week) Mapping (1 week) EESDC (1 week) Alignment (2 days)
New Beamline	2 Super Harps (20,000) Fast Valve ($23,000)	Pipes + Pedestals ($20,000)	Design (6 weeks) Alignment (1 week) Software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

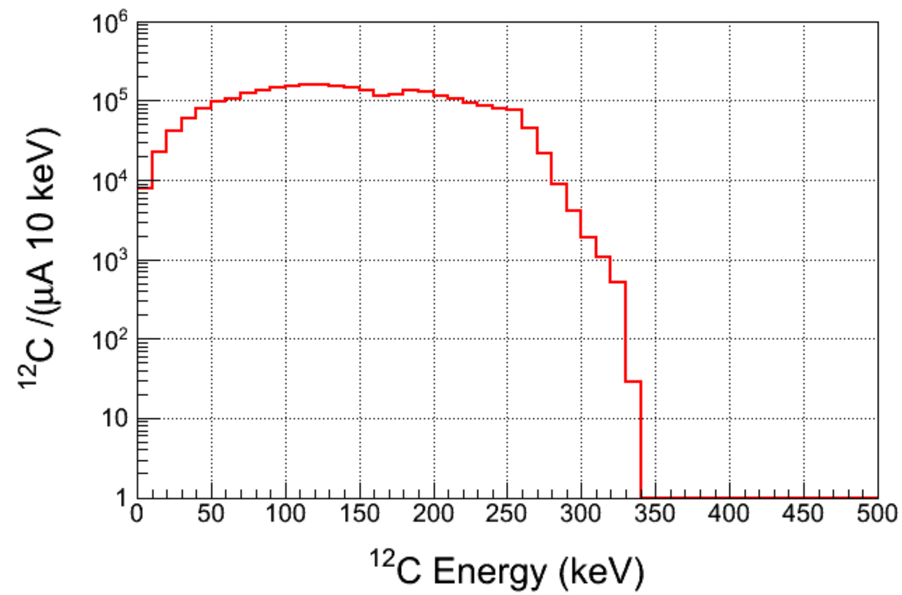
CO_2 SUPERHEATED LIQUID?

- 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 due to HF.