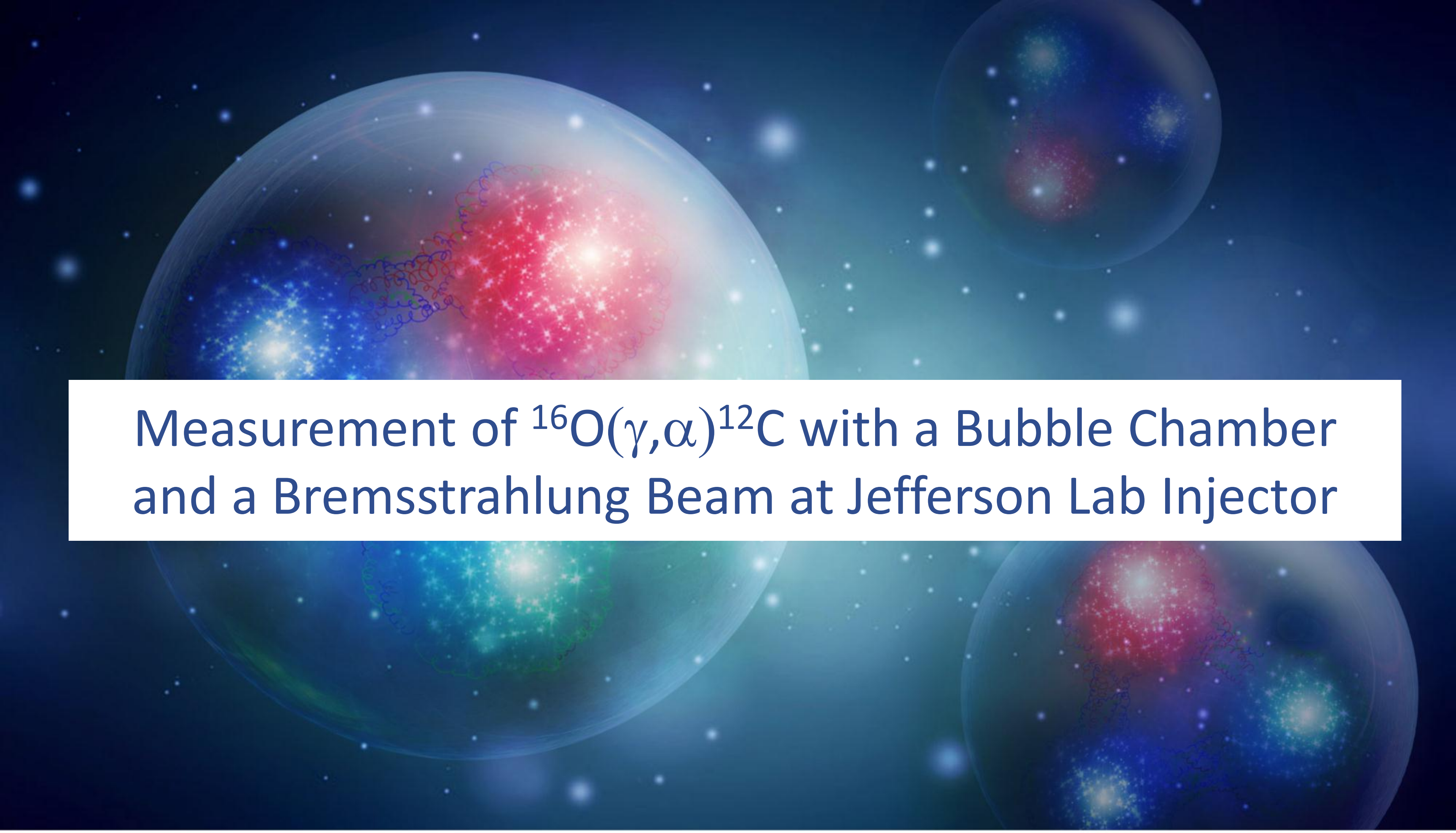

Measurement of $^{16}\mathrm{O}(\gamma,\alpha)^{12}\mathrm{C}$ with a Bubble Chamber and a Bremsstrahlung Beam at Jefferson Lab Injector

Riad Suleiman

January 9, 2014

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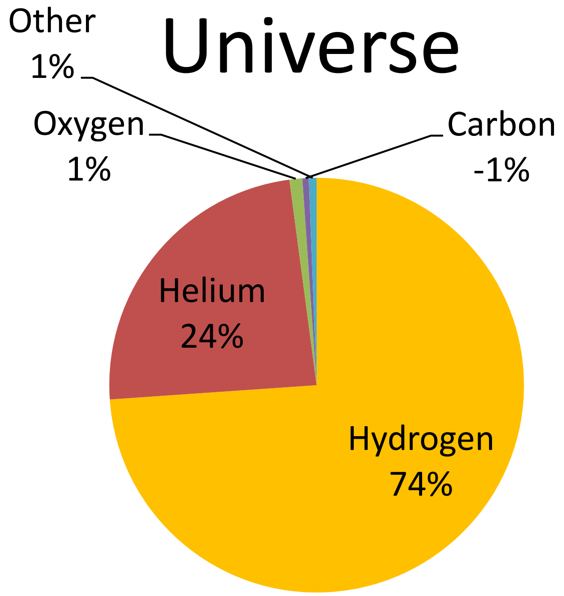
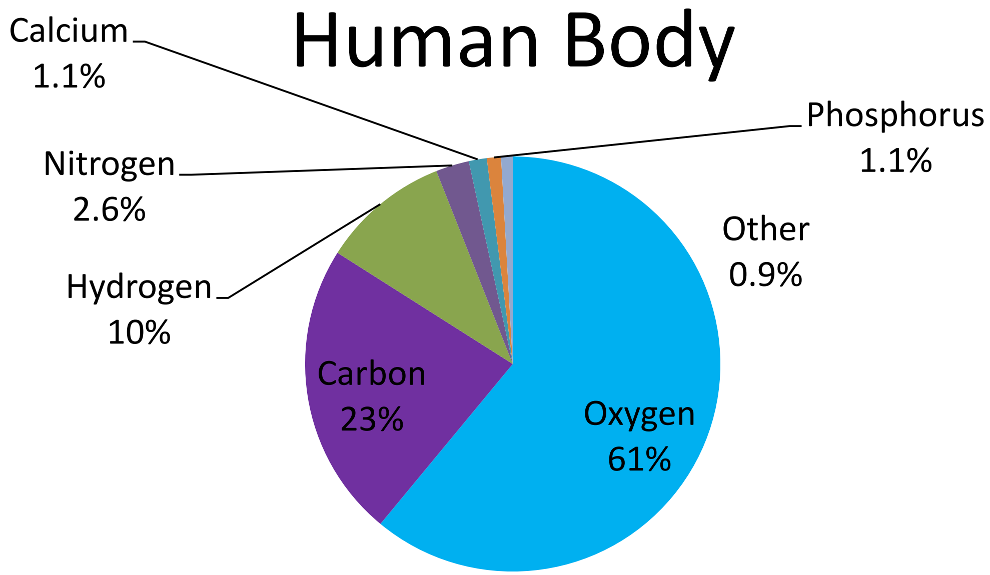
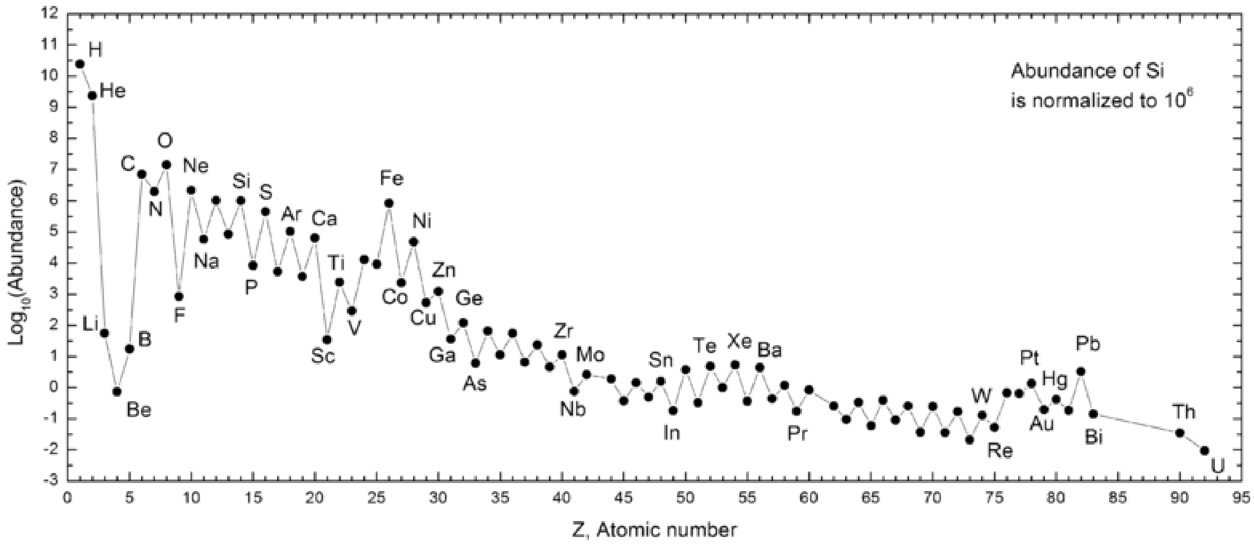
OUTLINE

- 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

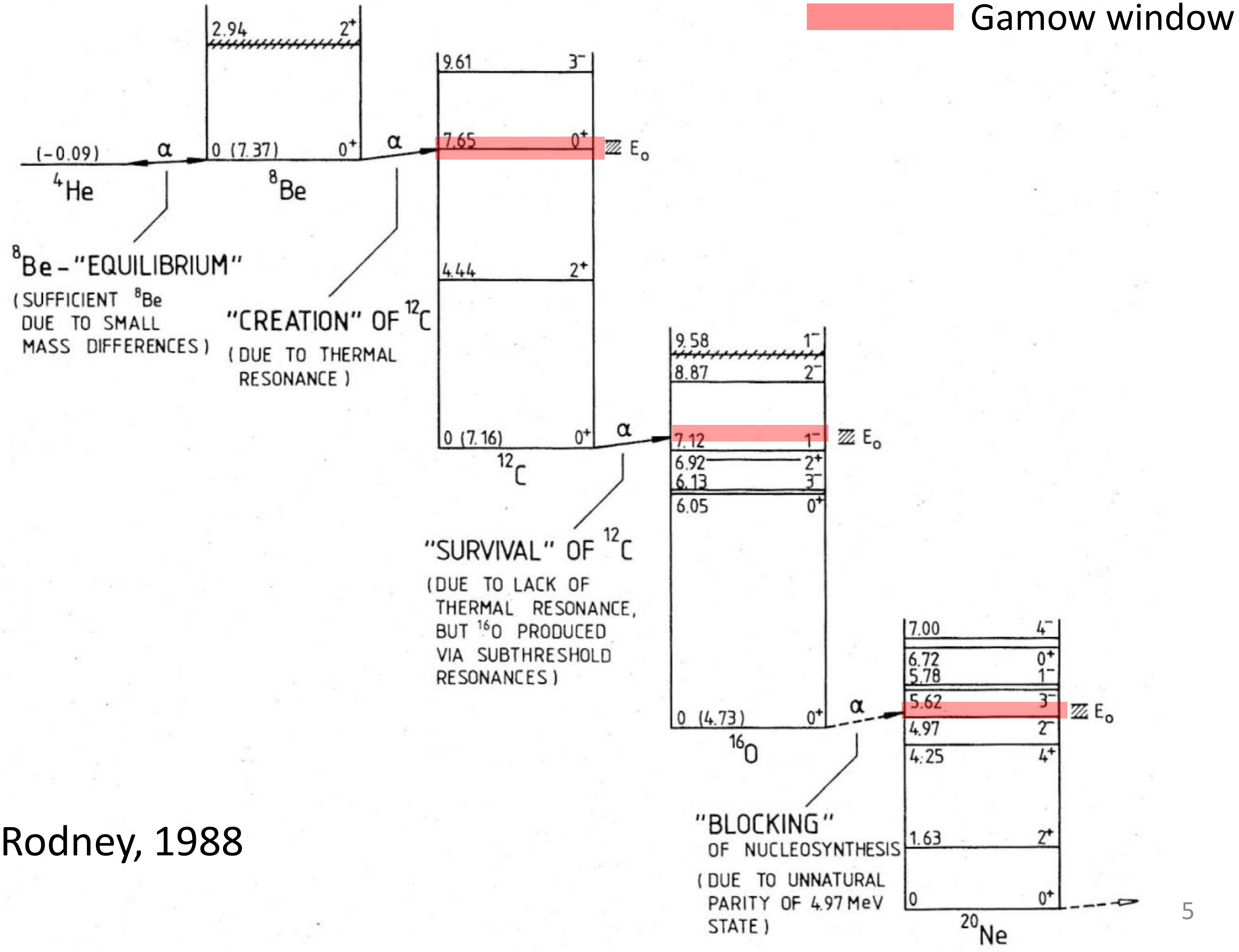
RELATIVE ABUNDANCE OF ELEMENTS BY WEIGHT


Universe


Human Body



STELLAR HELIUM BURNING



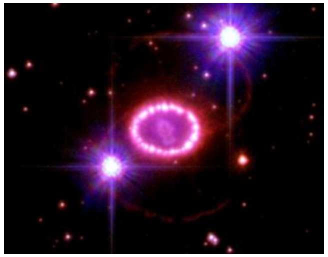
Rolfs and Rodney, 1988

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

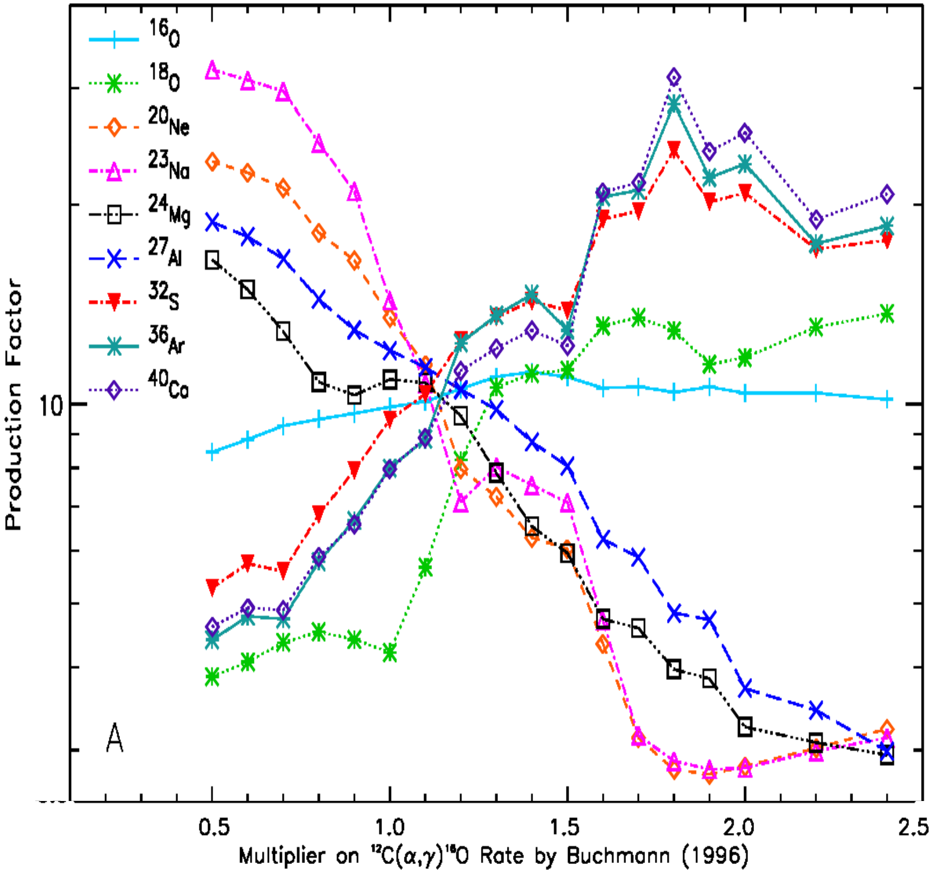
- The “holy grail” of nuclear astrophysics

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

Sets the C to O ratio in the universe



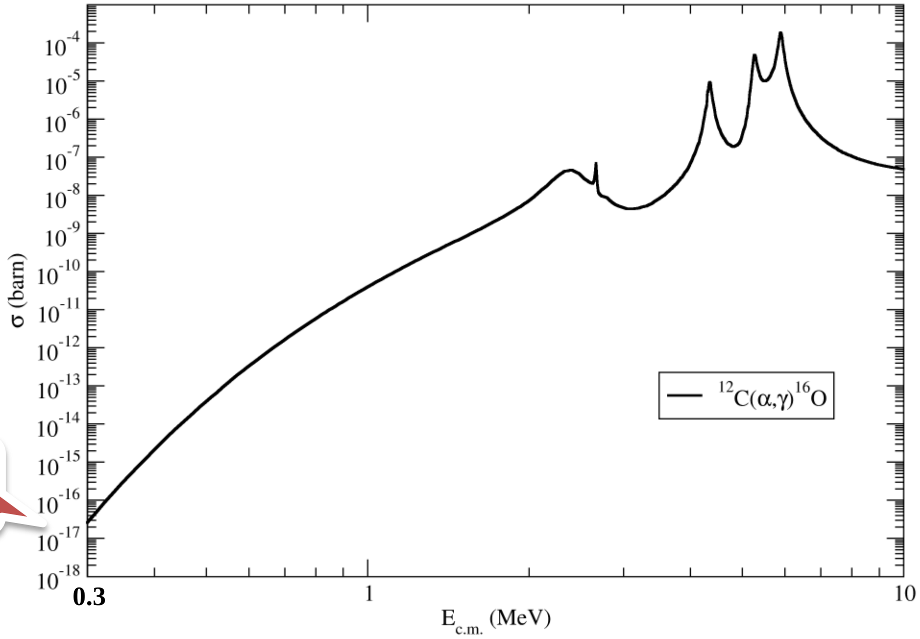
Determines the minimum mass a star requires to become a supernova



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

STELLAR CARBON BURNING

- Helium burning stage of stellar evolution occurs at $T=10^9$ K
- Most effective stellar energy, $E_{CM} = 0.3$ MeV
- He burning at cross section $\sigma \sim 10^{-17}$ barn



Stellar Energy

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

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

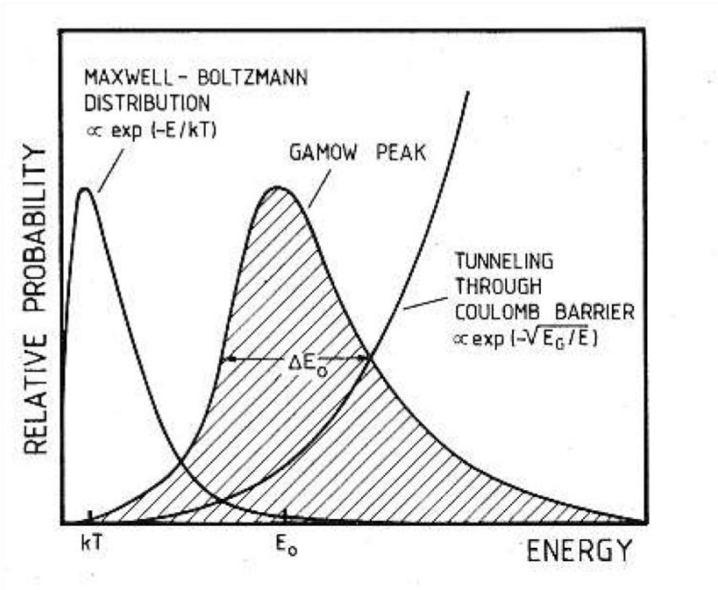
$$<\sigma v> = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} S(E_0) \int_0^\infty \exp\left(-\frac{E}{kT} - \frac{b}{E^{1/2}}\right) dE \qquad b = \left(\frac{2\mu}{\hbar^2}\right)^{1/2} \pi Z_1 Z_2 e^2$$

Gamow peak

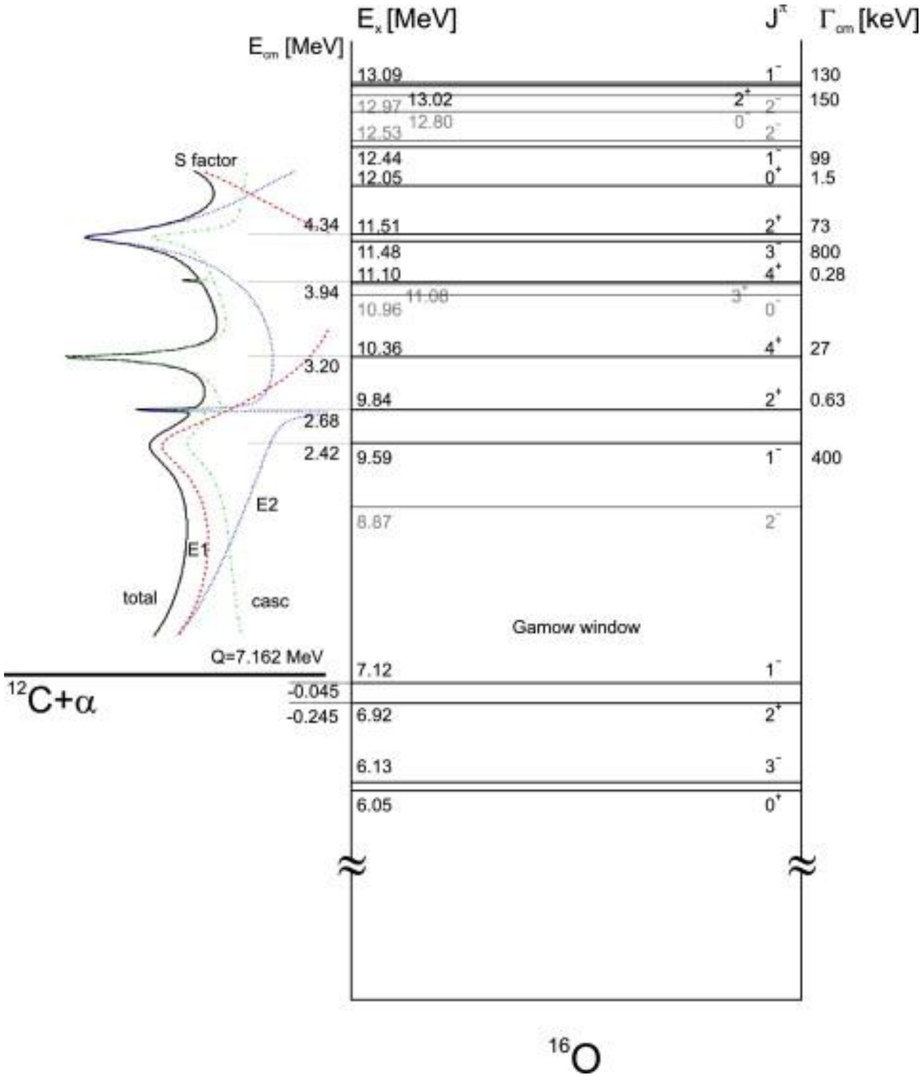
* The rate has a peak shape product of two negative exponentials: Maxwell-Boltzmann distribution at low energy and tunneling through the Coulomb barrier for higher E.

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

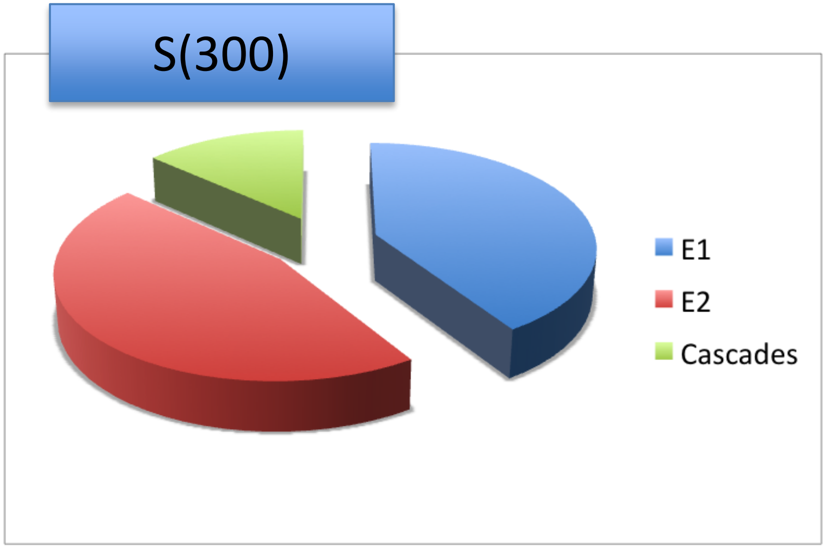
* The concept can be extended to a general S(E)



ENERGY LEVEL-DIAGRAM OF 16O



No Resonances but interferences



Kunz 2001, Matei 2006

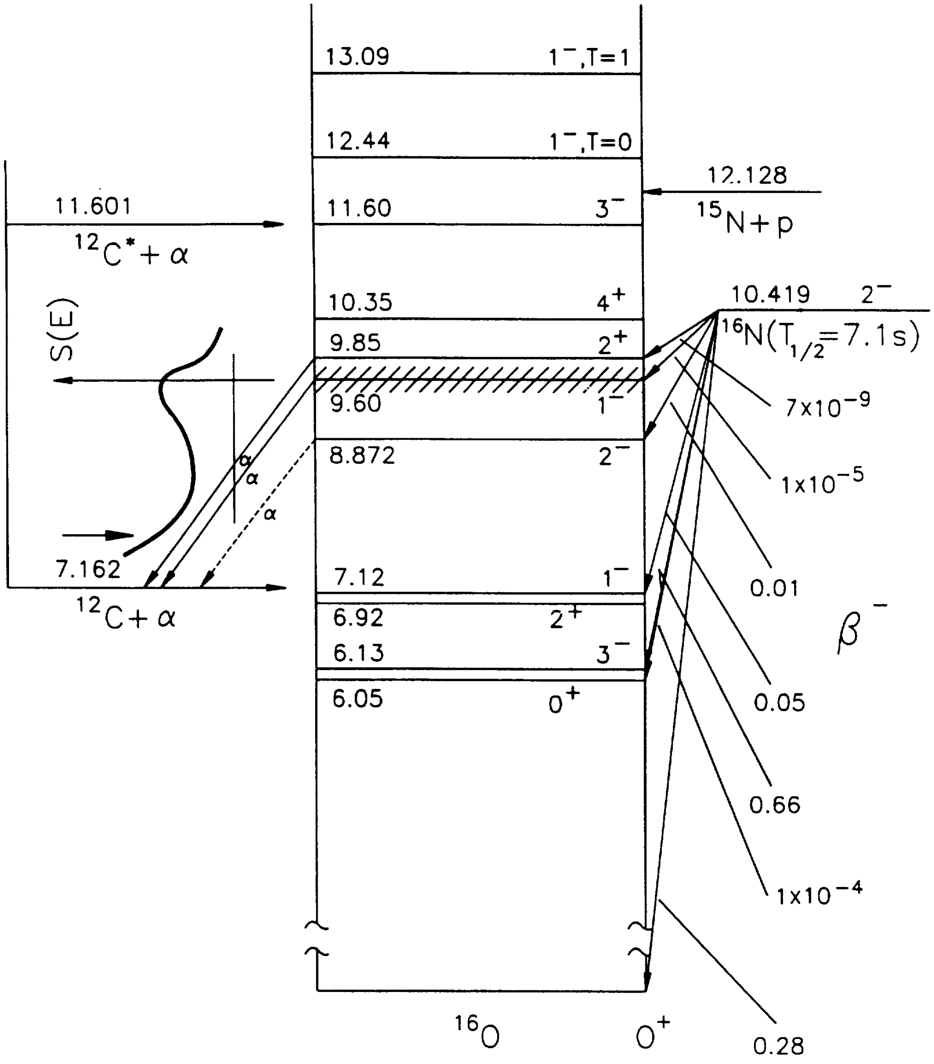


FIG. 1. Partial energy-level diagram for ^{16}O (adapted from [4]).

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

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

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

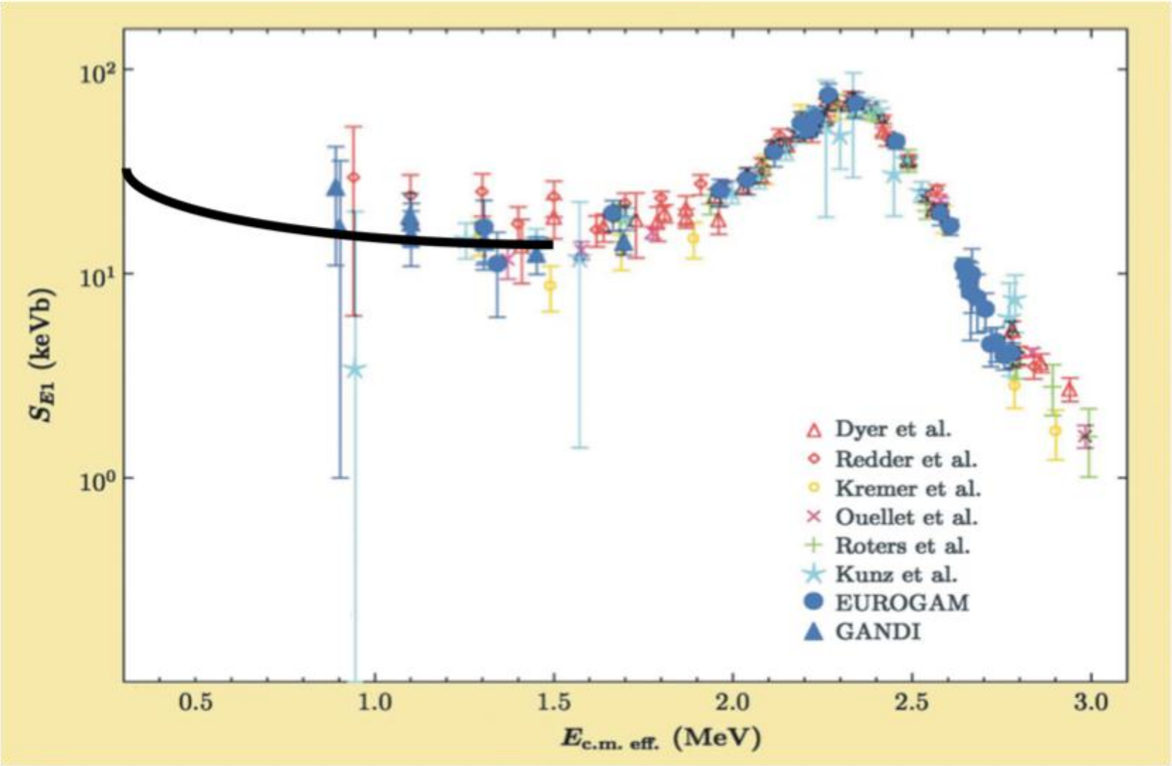
$^{12}C(\alpha,\gamma)^{16}O$

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

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

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

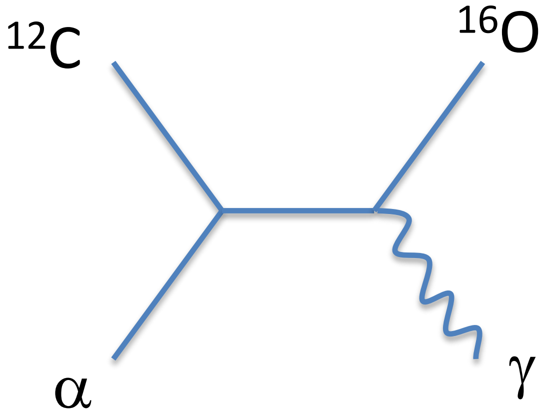
$$\eta = \frac{1}{137} Z_{\alpha} Z_{^{12}C}\sqrt{\frac{m_{^{12}C\alpha}}{2E_{CM}}}$$

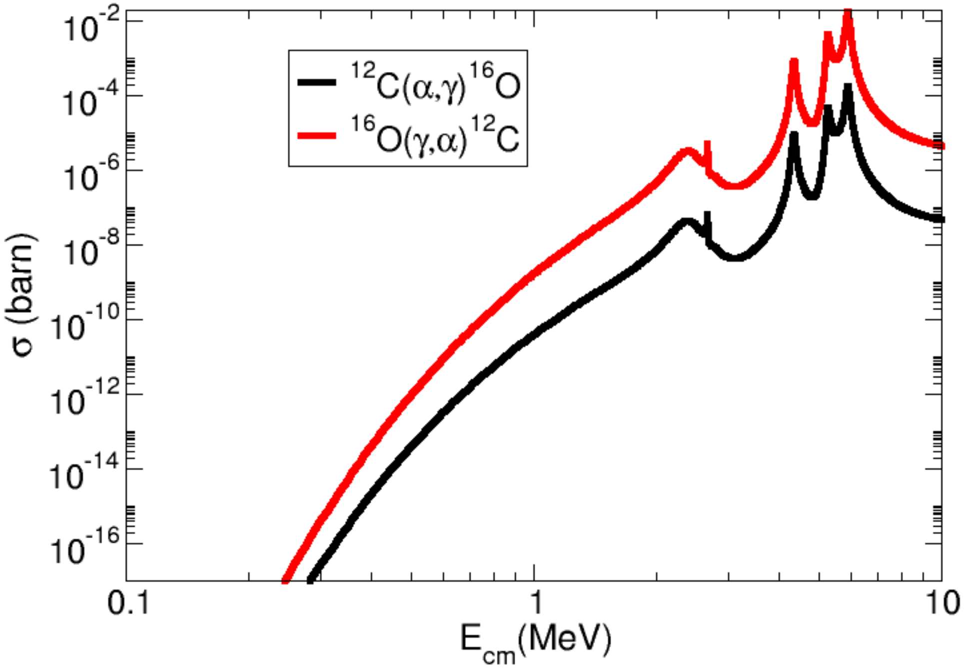


Stellar helium burning at E=300 keV

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:

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

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

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

$$E_{A\alpha}=E_{CM}=\frac{M(^{12}C)}{M(^{12}C)+M(\alpha)}E_\alpha$$

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

This image cannot currently be displayed.

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

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

NEW APPROACH: INVERSE REACTION + BUBBLE CHAMBER

beam target signal

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

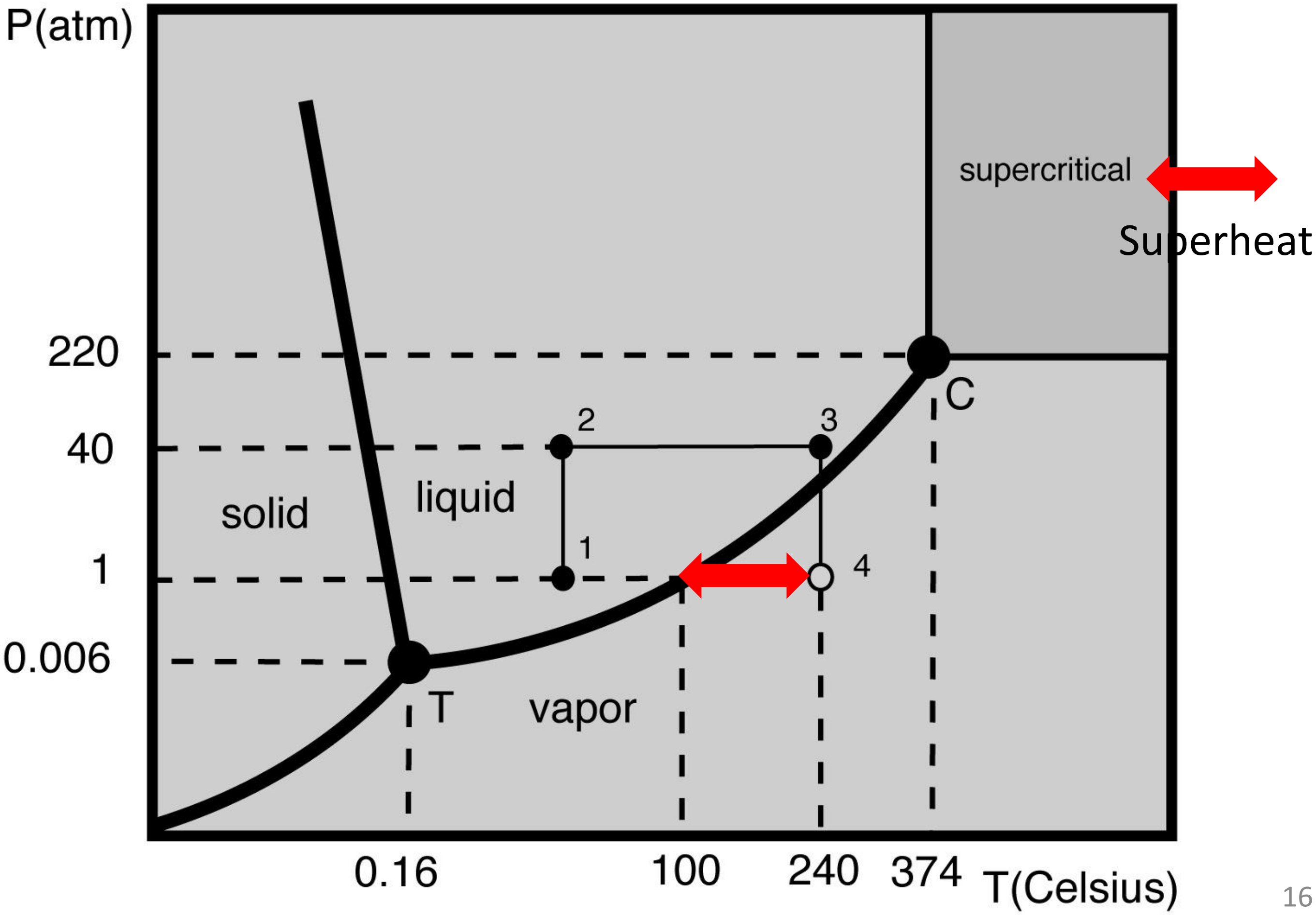
Monochromatic γ beam at HIγS
~ $10^{7\text{-}8}$ γ/s

Bremsstrahlung at JLab
~ $4\mathrm{x}10^{9}$ γ/s (top 250 keV)

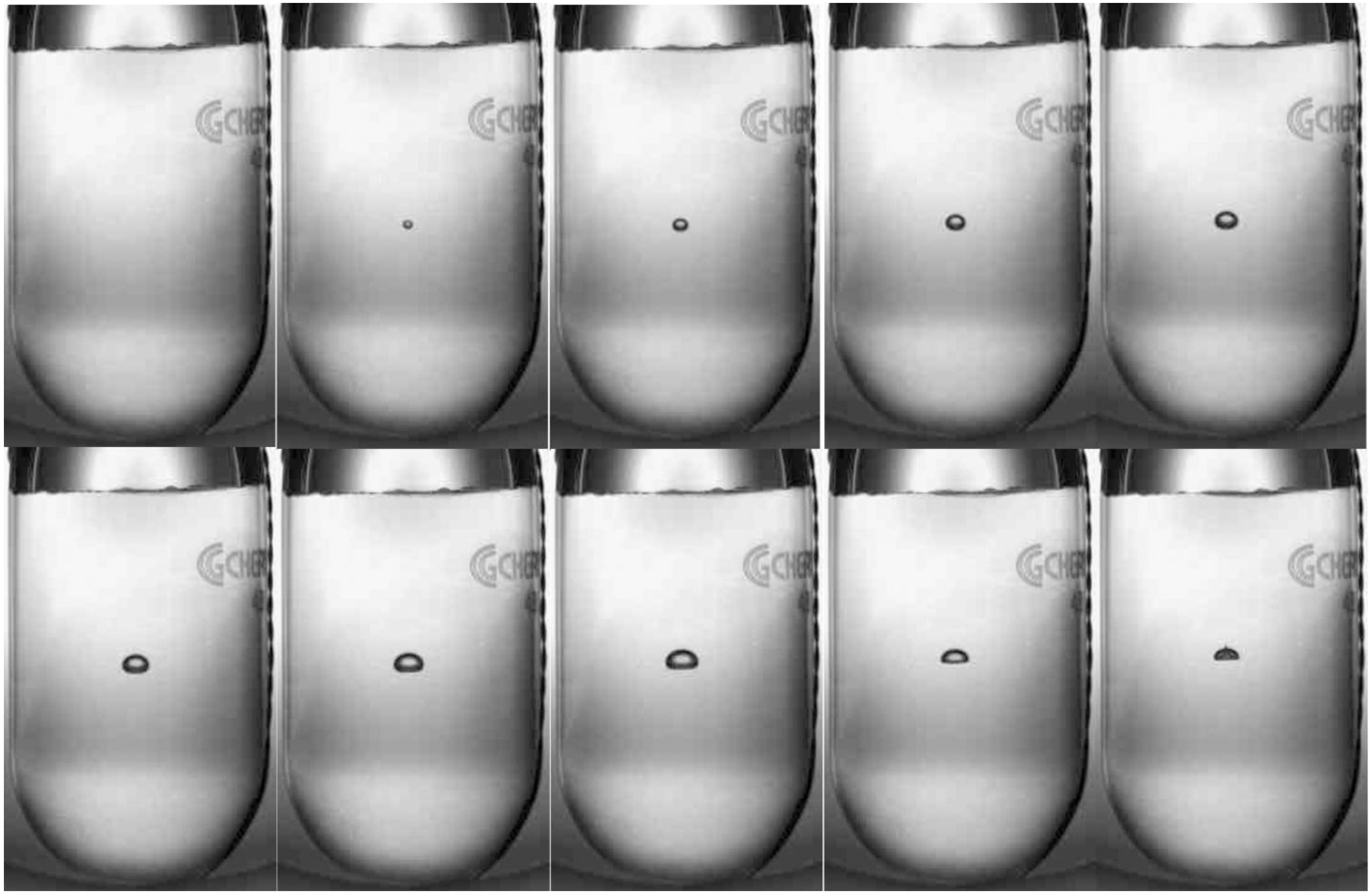
- Extra gain (x100) by measuring time inverse reaction
- Target density up to $\mathrm{x}10^{6}$ higher than conventional targets
- Superheated liquid will nucleate from α and ^{12}C recoils
- Electromagnetic debris (degraded electrons and gammas, or positrons) that escape the collimator/electron beam 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



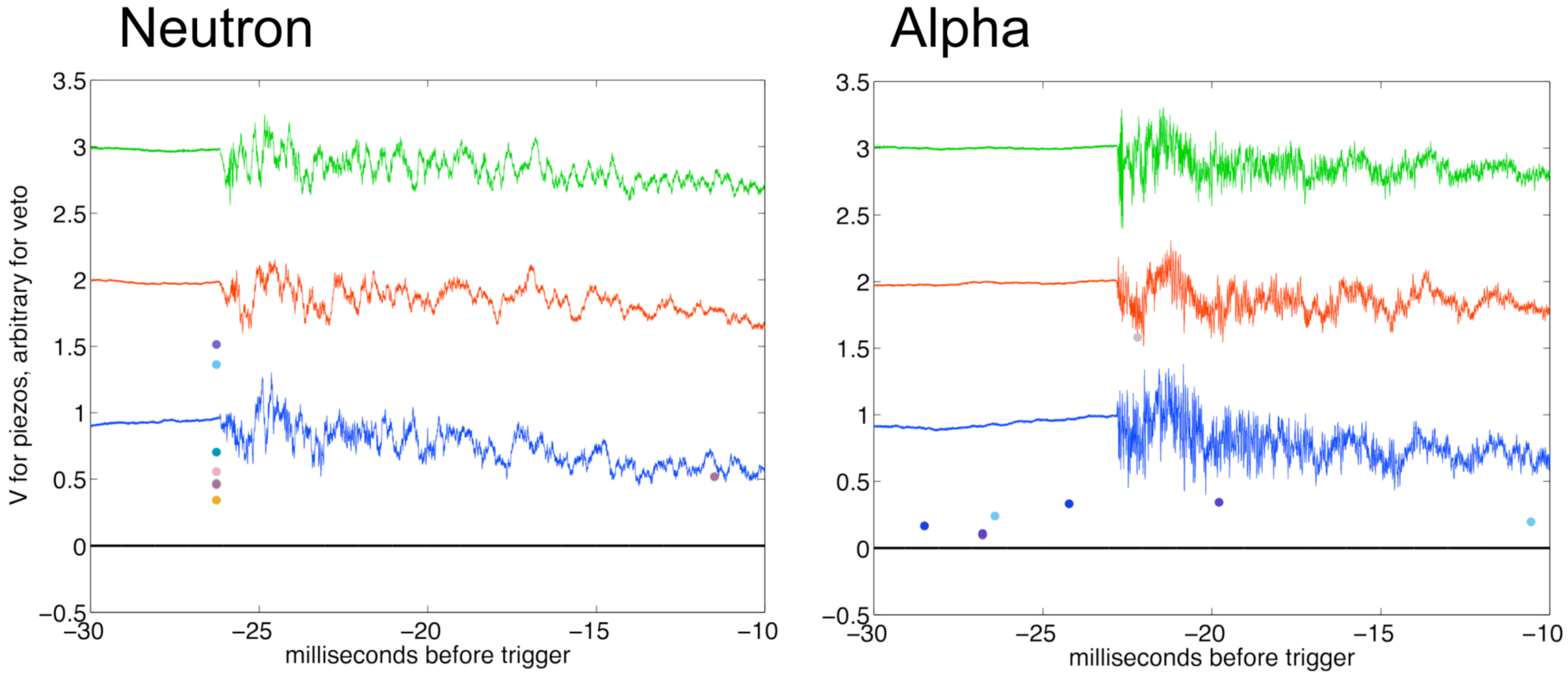
$^{19}F(\gamma,\alpha)^{15}N$ in R134a

$\Delta t = 10$ ms

ACOUSTIC SIGNAL: PARTICLE ID

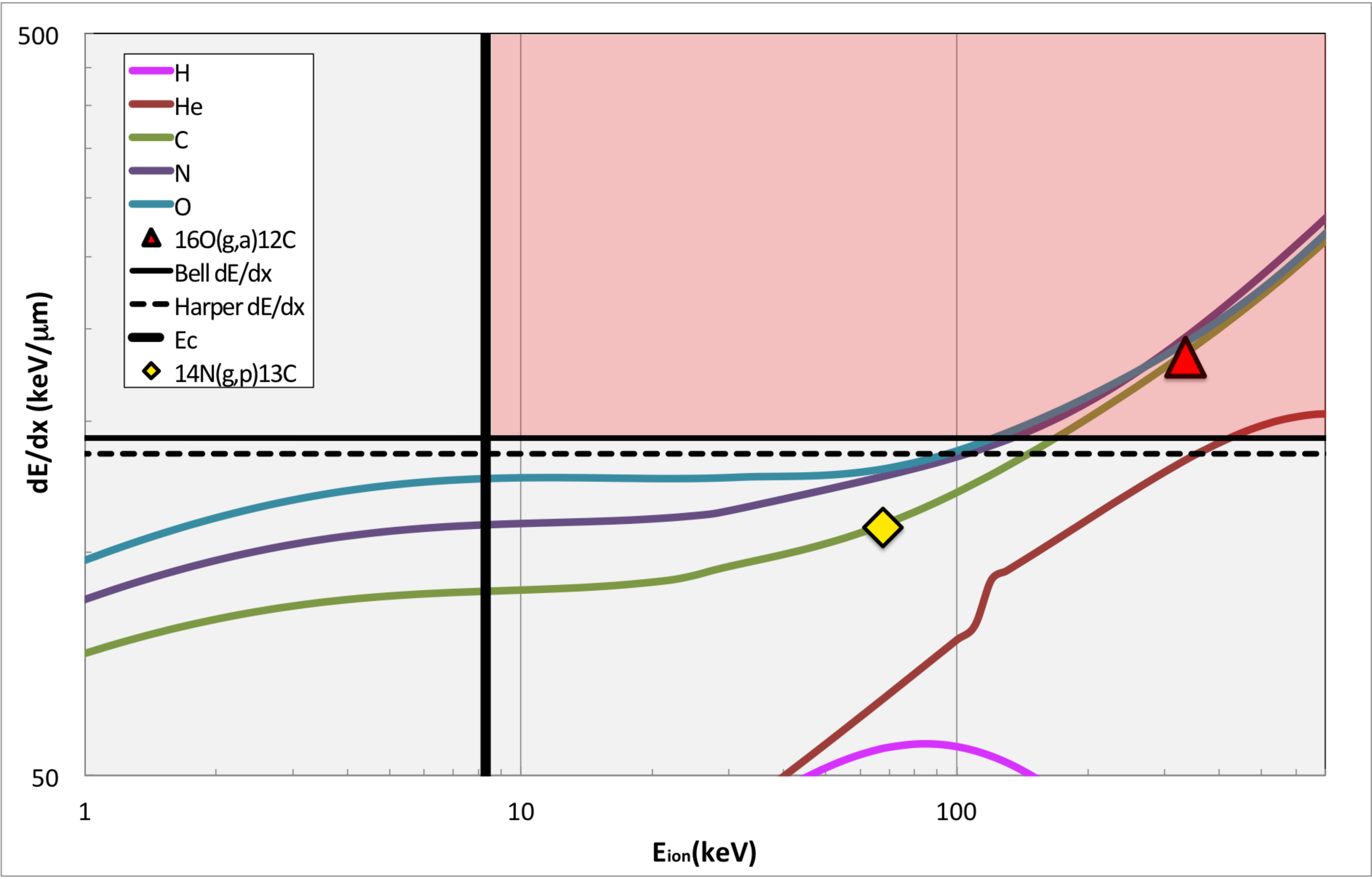
Acoustic Signatures, time domain

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

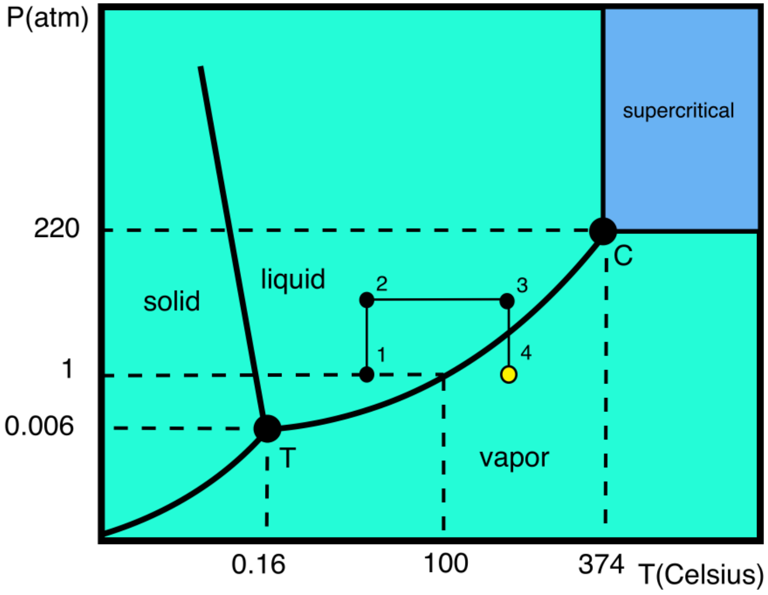


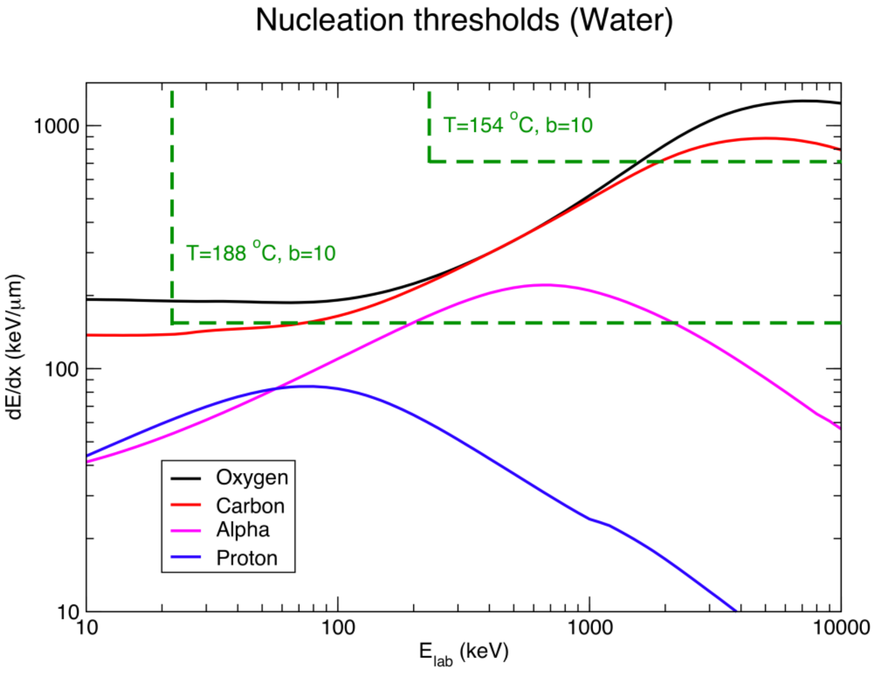
COUPP, FNAL, courtesy of A. Sonnenschein

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

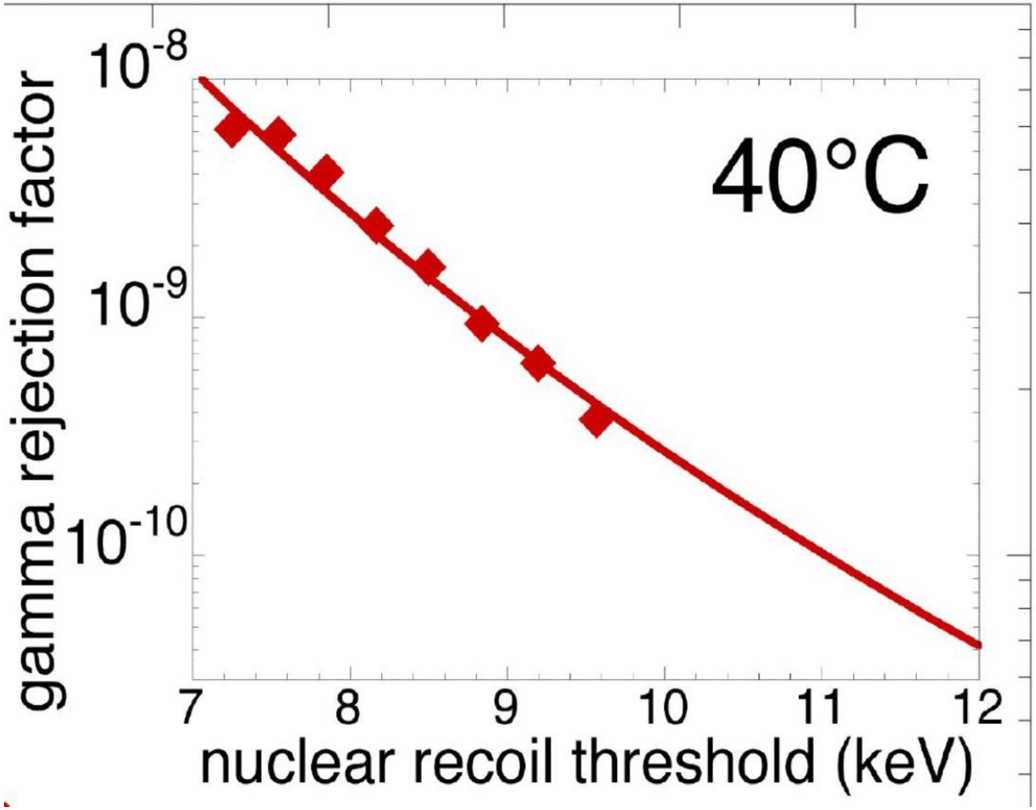


Bubble chamber basics



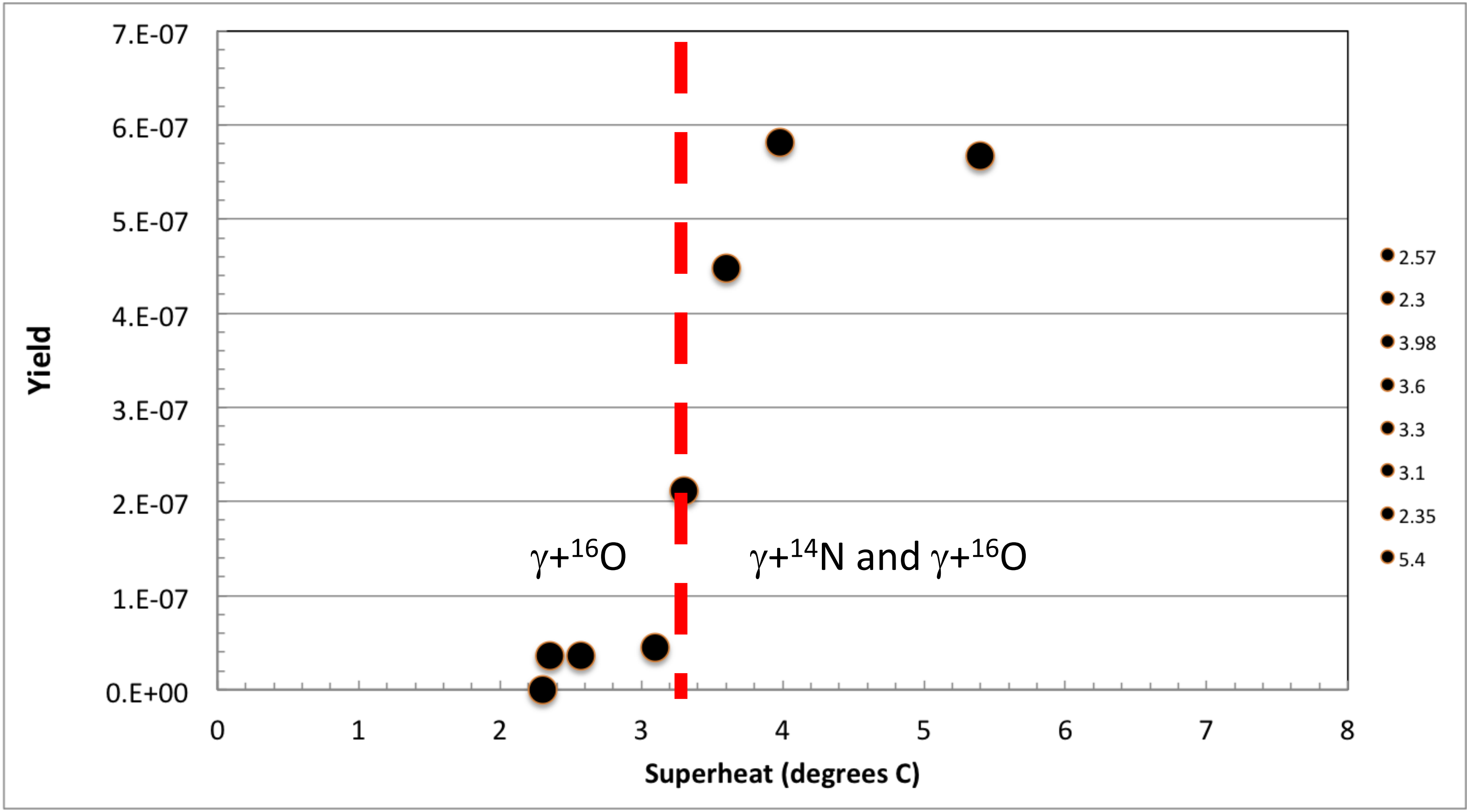


Gamma suppression



COUPP exp. FNAL

EFFICIENCY CURVE

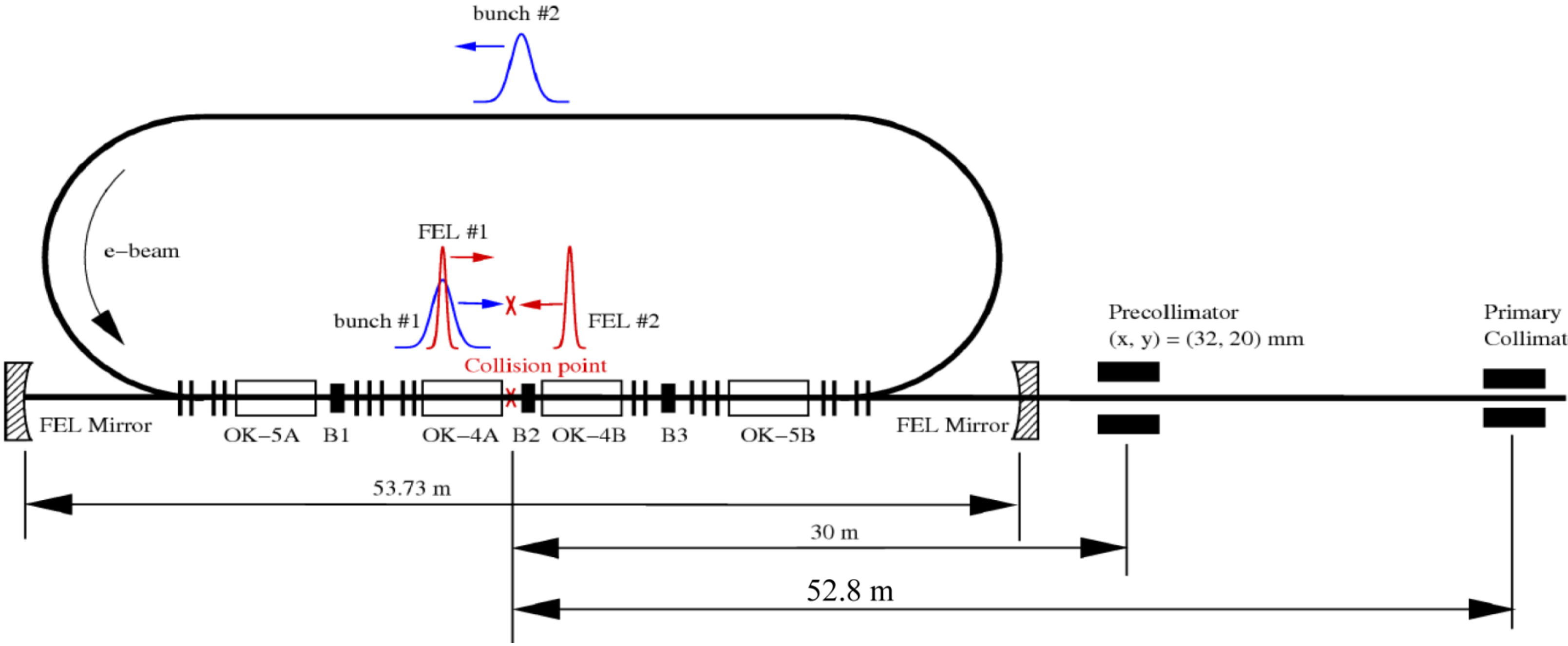


N_2O efficiency curve, HIGS April 2013. E_γ = 9.7 MeV

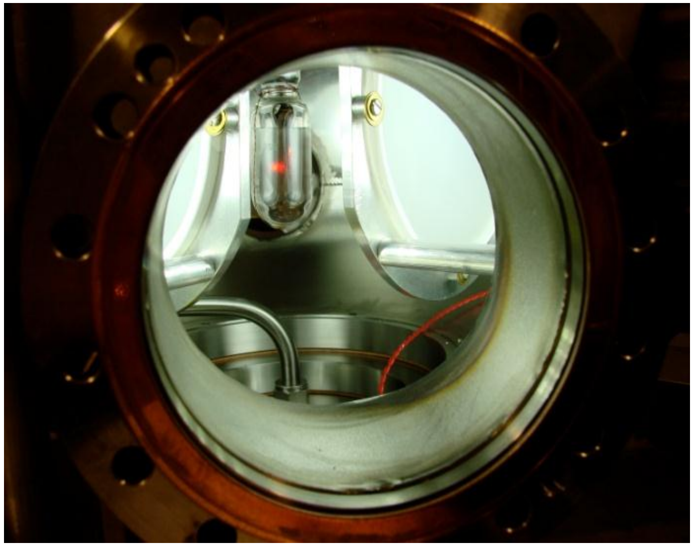
Bubble Chamber at HIGS

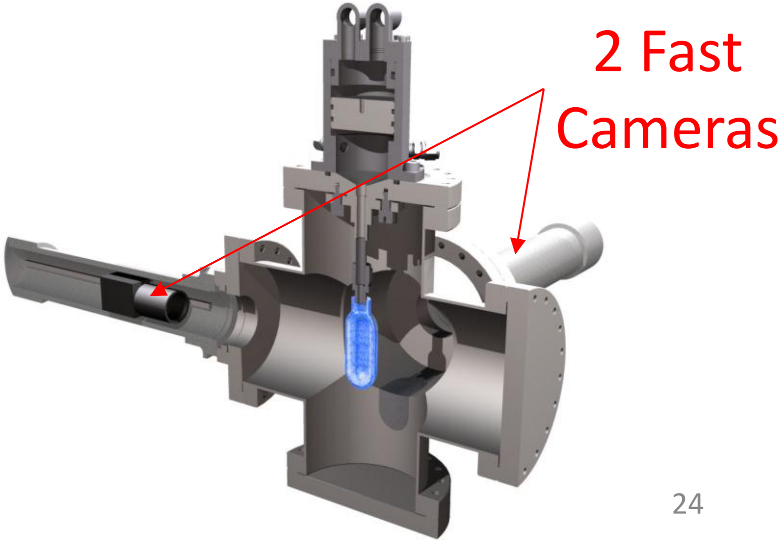
I. High Intensity Gamma Source (HIGS) at Duke University

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



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





2 Fast Cameras

C_4F_{10} Bubble Chamber

T = 310 K

P = 160 kPa – 900 kPa

Physics Letters B 719 (2013) 74–77

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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

C. Ugalde[a,*], B. DiGiovine[b], D. Henderson[b], R.J. Holt[b], K.E. Rehm[b], A. Sonnenschein[c], A. Robinson[d], R. Raut[e,f,1], G. Rusev[e,f,2], A.P. Tonchev[e,f,3]

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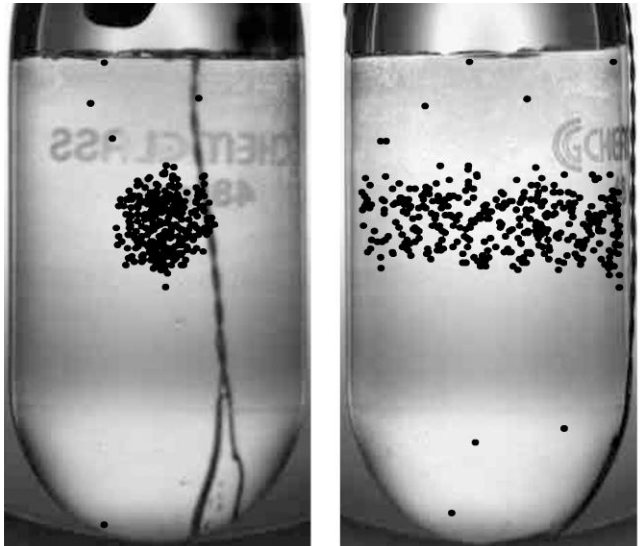
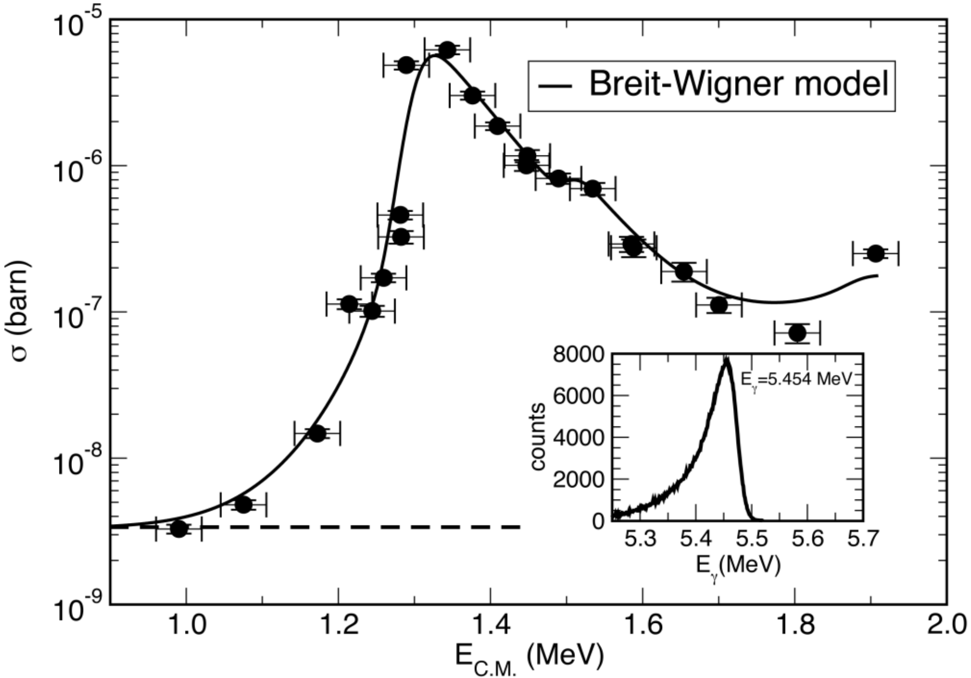
[e] *Department of Physics, Duke University, Durham, NC 27708, USA*
[f] *Triangle Universities Nuclear Laboratory, Durham, NC 27708, USA*





Bremsstrahlung Background at HIGS

Vacuum: 2×10^{-10} Torr

Residual Gas: $Z = 10$

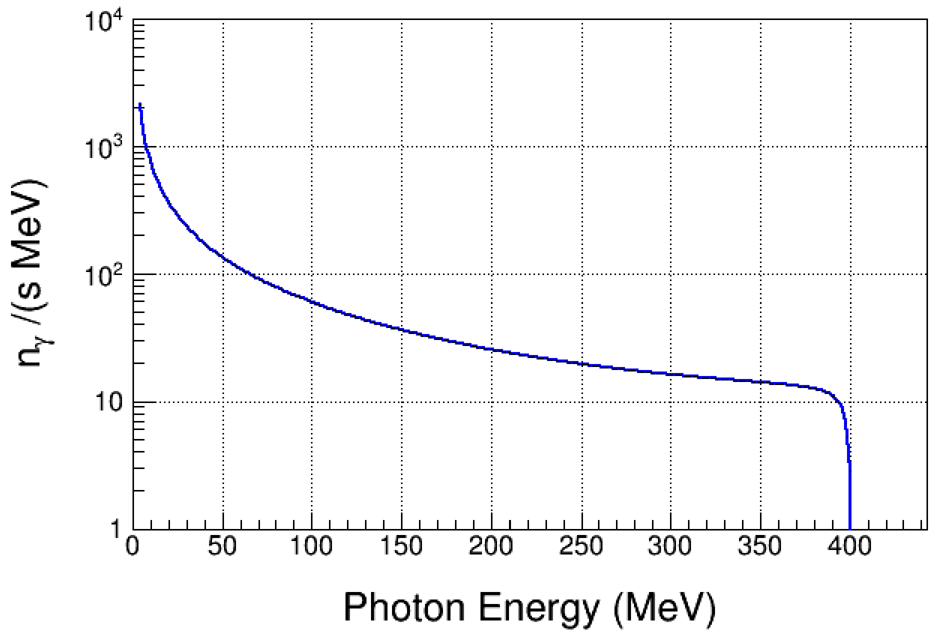
Electron Beam Energy: 400 MeV

Electron Beam Current: 41 mA

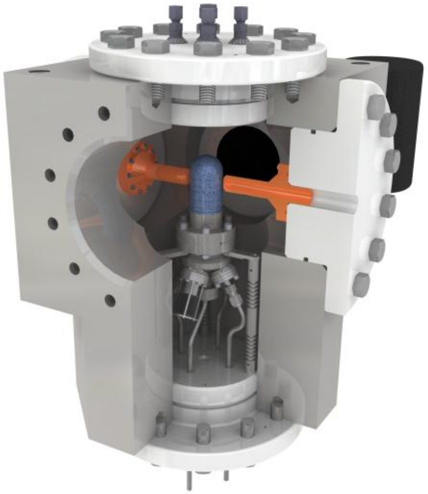
Interaction Length: 35 m

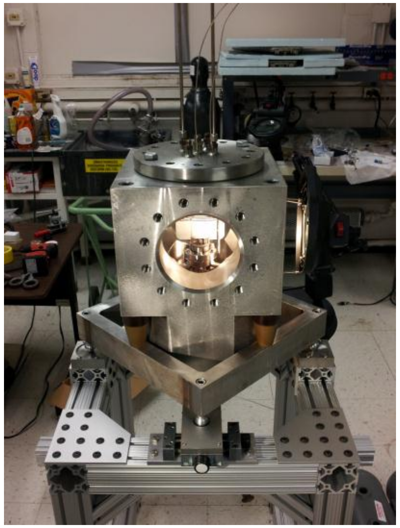
→

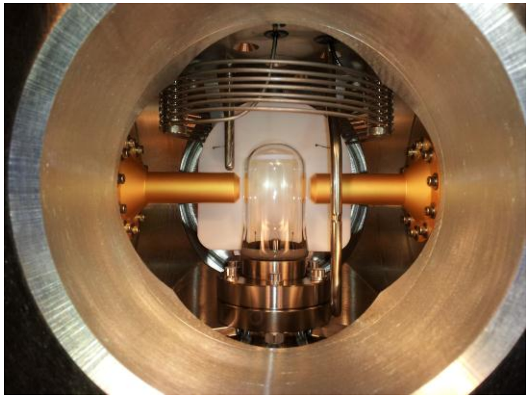
Strong Bremsstrahlung Background



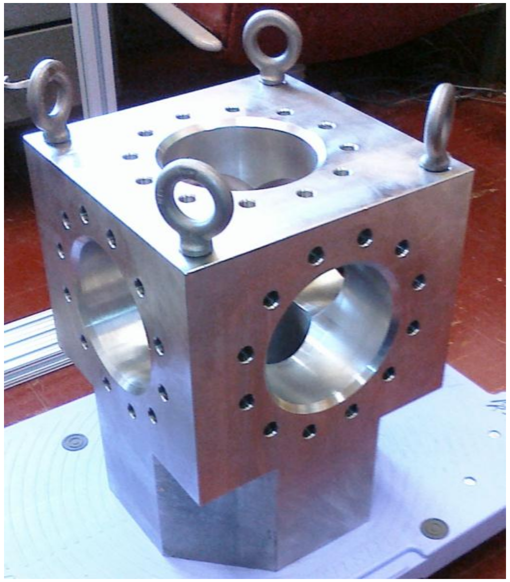
RECENT WORK

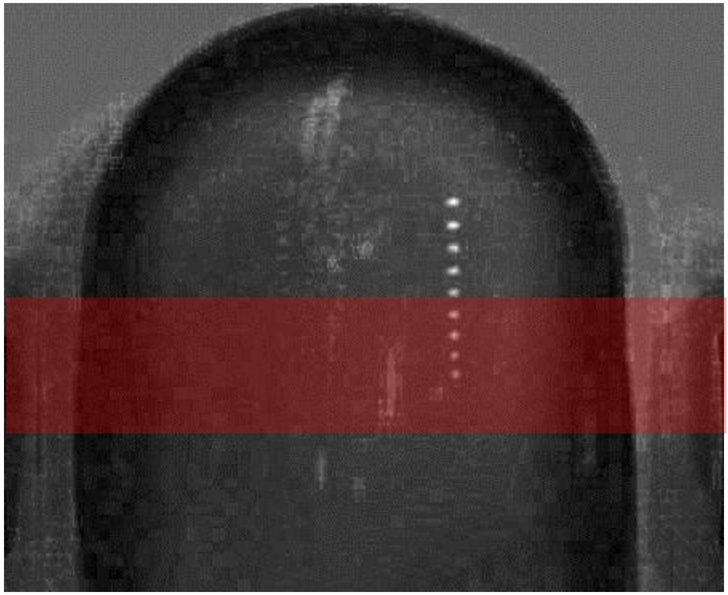






N_2O Bubble Chamber
First $\gamma+O \rightarrow \alpha+C$ bubble
April 2013





SUPERHEATED TARGETS

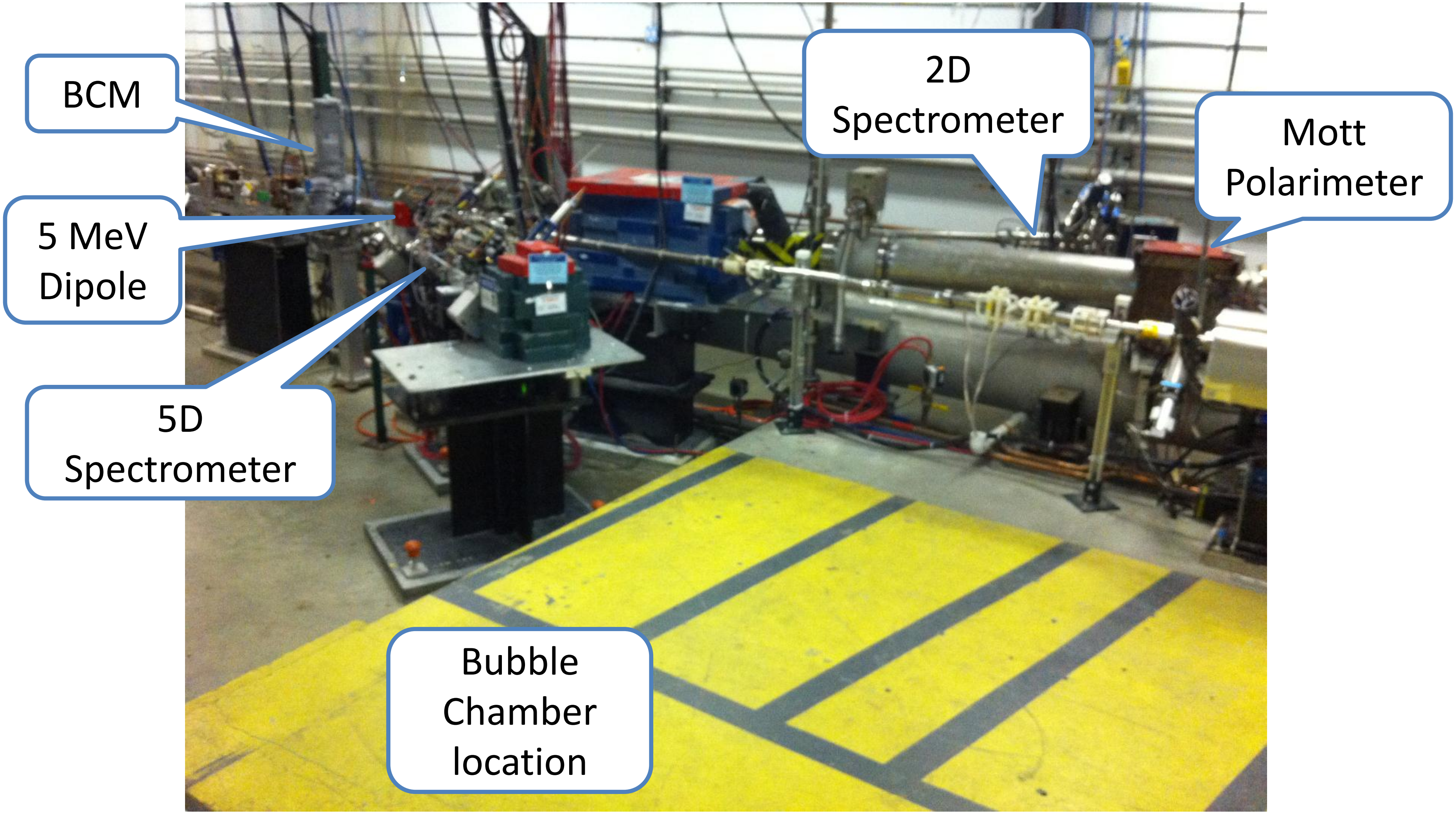
I. List of superheated liquids to be used in the experiment:

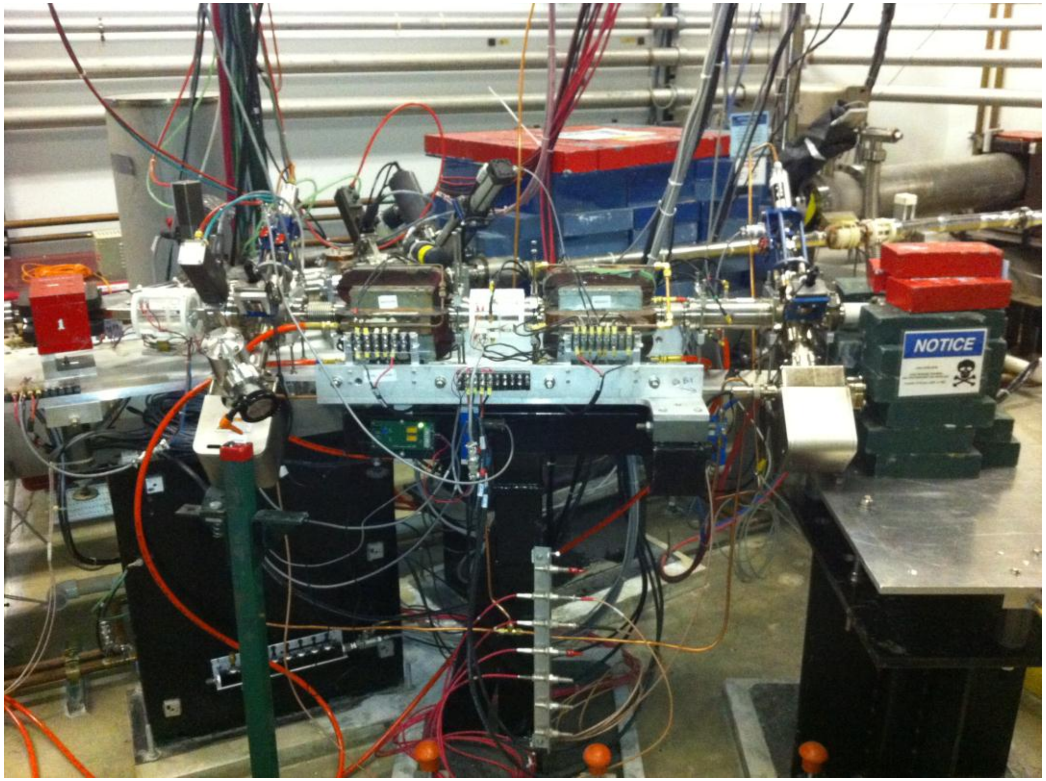
N_2O Targets	^{16}O	^{17}O	^{18}O
Natural Target	99.757%	0.038%	0.205%
^{16}O Target		Depleted > 5,000	Depleted > 5,000
^{17}O Target		Enriched > 80%	<1.0%
^{18}O Target		<1.0%	Enriched > 80%

II. Readout:

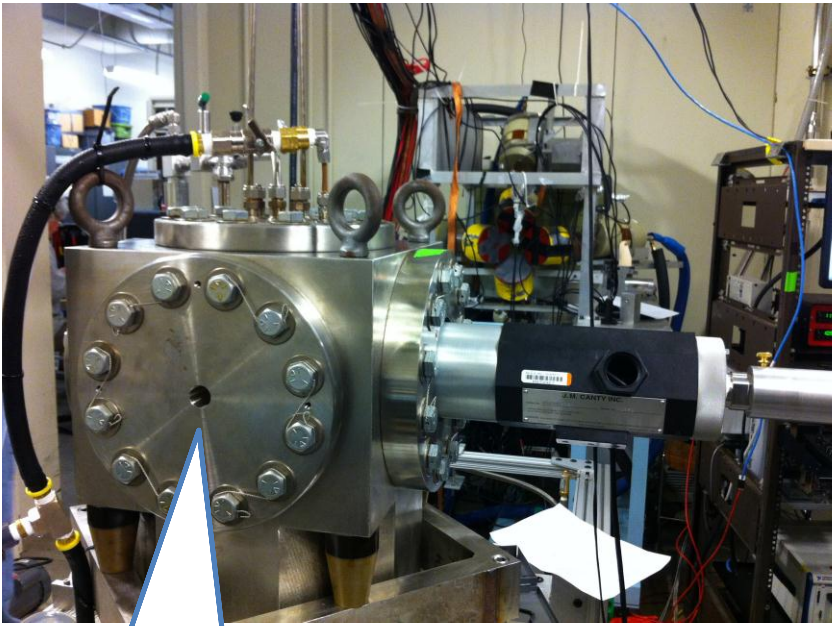
  I. Optical Camera
  II. Acoustic Signal to discriminate between (γ,α) and (γ,n) events

EXPERIMENTAL SETUP





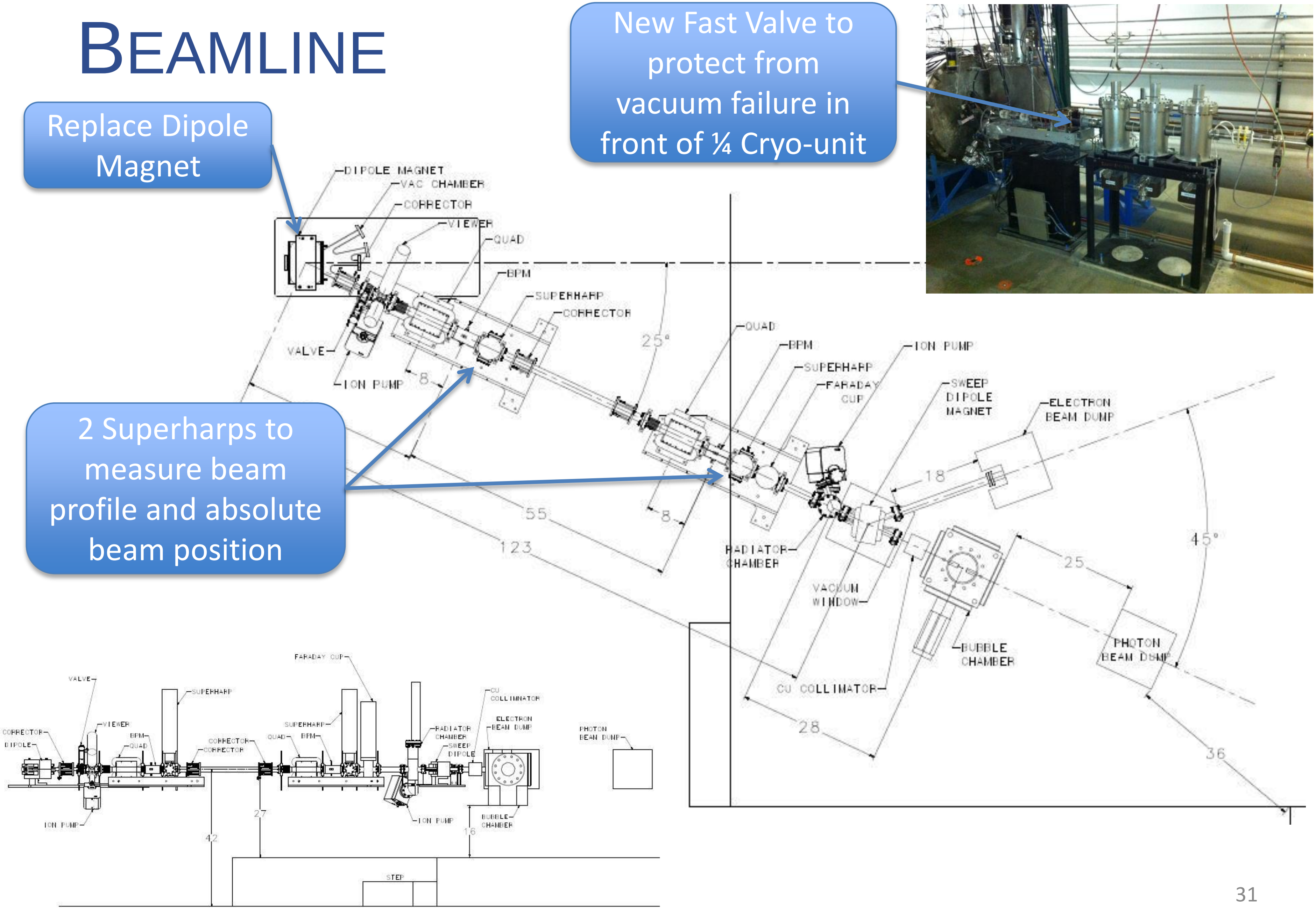
5D Spectrometer



Bubble Chamber at HIGS

Photon Beam Entrance

BEAMLINE



Replace Dipole Magnet

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

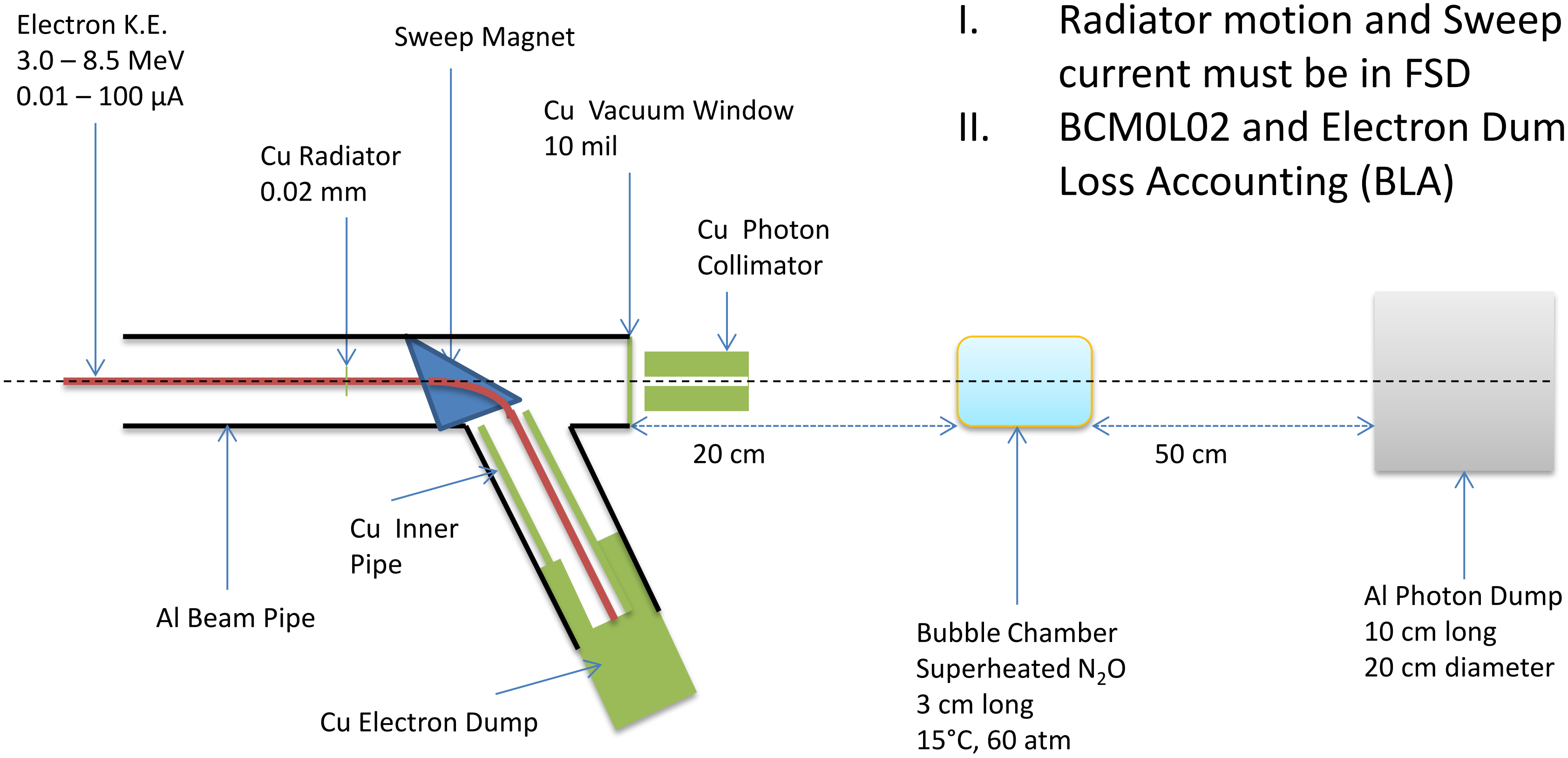
2 Superharps to measure beam profile and absolute beam position

SCHEMATICS

- Power deposited in radiator (100 μA and 8.5 MeV) :
  - I. 0.02 mm: Energy loss = 21 keV, P = 2.1 W
  - II. 0.10 mm: Energy loss = 112 keV, P = 11 W
- Pure Copper and Aluminum (high neutron threshold):
  - I. $^{63}\mathrm{C}(\gamma,n)$ threshold = 10.86 MeV
  - II. $^{27}\mathrm{Al}(\gamma,n)$ threshold = 13.06 MeV

I. Radiator motion and Sweep Dipole current must be in FSD

II. BCM0L02 and Electron Dump in Beam Loss Accounting (BLA)



BEAM REQUIREMENTS

I. Beam Properties at Radiator:

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

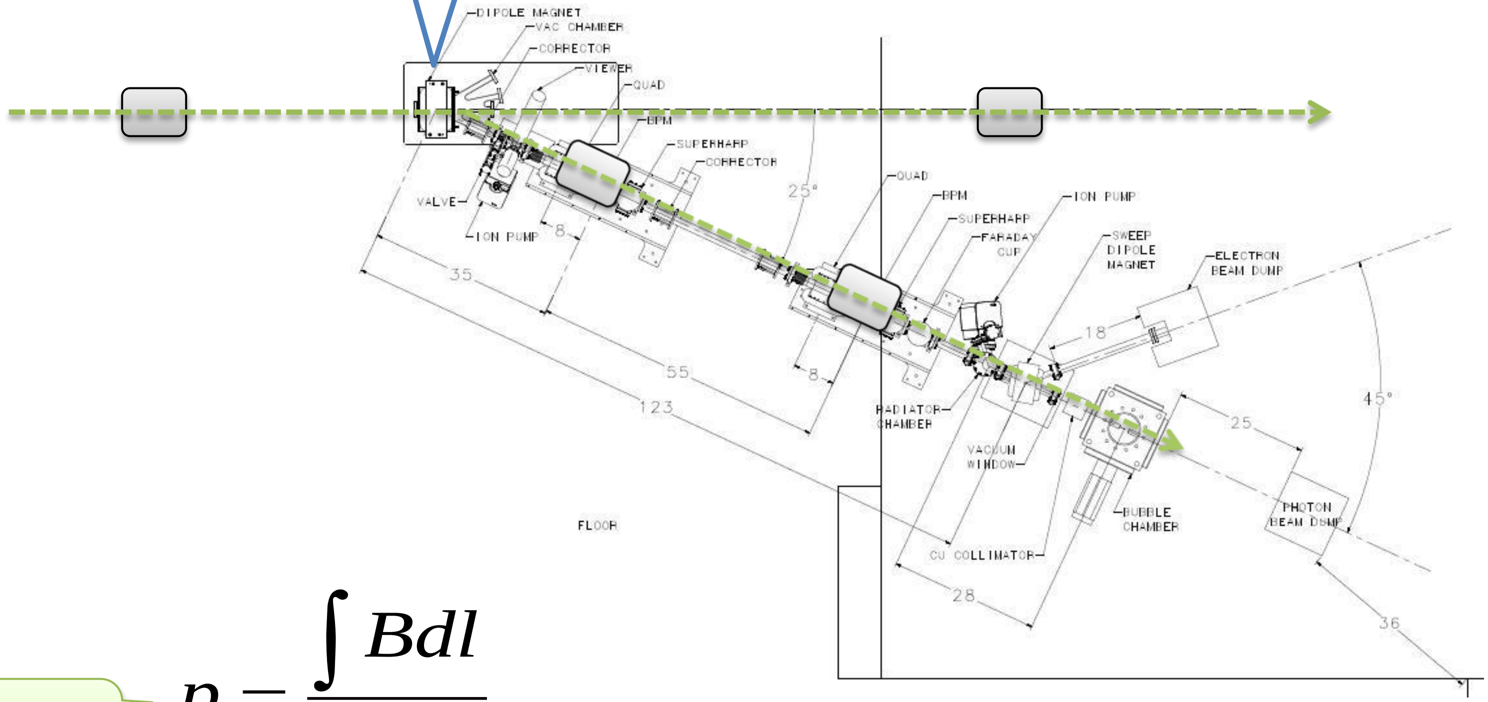
II. PEPPo achieved p=8.25 MeV/c or K.E.=7.75 MeV. Maximum stable ¼- cryounit cavity gradients achieved: 8.4 MV/m and 6.1 MV/m (7.25 MV/m average). Vacuum in the beam line indicates that field emission and desorbed gas are the most problematic, but improve with processing.

III. Helium process the ¼-cryounit

ABSOLUTE BEAM ENERGY

▢ BPM

5 MeV
Dipole



Electron Beam Momentum

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

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

Goal:

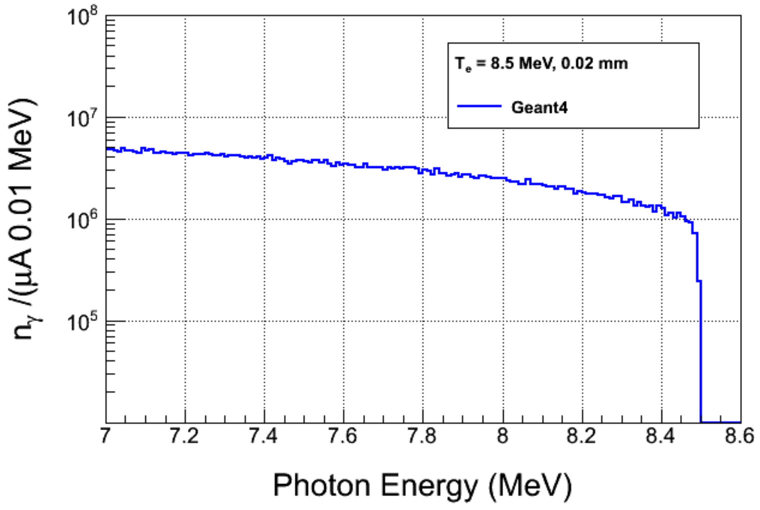
I. Jay Benesch designed and now fabricating higher quality dipole (more uniformity, higher field)

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

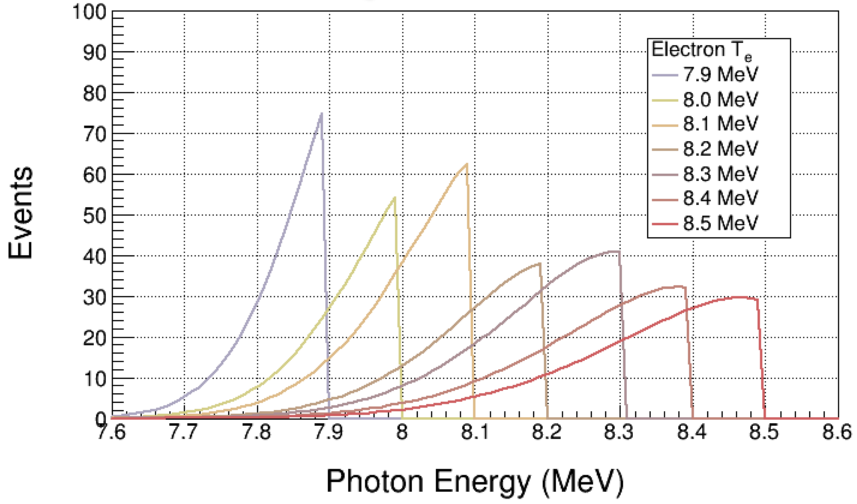
III. Relative beam energy error: <0.02%

BREMSSTRAHLUNG BEAM

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



Bremsstrahlung Peaks



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

I. Very steep; only photons near endpoint contribute to yield
II. No-structure (resonances)

GEANT4 SIMULATION

- ➢ Both GEANT4 and FLUKA use models that calculate wrong photo–nuclear cross sections. Both do not allow for user's cross sections.
  - I. Use GEANT4 and FLUKA to produce the photon spectrum impinging on the super heated liquid.
  - II. Fold the above photon spectrum with our cross sections in stand-alone codes.

- Use GEANT4 to design Radiator/Collimator/Dump
- Geometry in GEANT4:

PENFOLD-LEISS CROSS SECTION UNFOLDING

- Measure Yields at: $E = E_1, E_2, \ldots, E_n$ where,

$$E_i - E_{i-1} = \Delta, i = 2, n$$

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

- The solution can be written in two forms:

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

- Or, Matrix form:

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

$$[\sigma] = [N]^{-1} \bullet [Y]$$

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} = \begin{bmatrix} N_{\gamma,11} & 0 & \cdots & 0 \\ N_{\gamma,21} & N_{\gamma,22} & \cdots & 0 \\ \vdots & \ddots & \ddots & 0 \\ N_{\gamma,n1} & N_{\gamma,n2} & \cdots & N_{\gamma,nn} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \vdots \\ \sigma_n \end{bmatrix}$$

STATISTICAL ERROR PROPAGATION

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

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

In case of background Subtraction

- With:

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

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

- Then:

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

- Where:

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

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

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

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

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

For mono-chromatic beam

$$\left(\frac{d\sigma_i}{\sigma_i}\right)^2 = \left(\frac{dy_i}{y_i}\right)^2 = \frac{1}{y_i}$$

RESULTS

I. Radiator Thickness = 0.02 mm

II. Bubble Chamber Thickness = 3.0 cm. Number of ^{16}O nuclei = 3.474e22 /cm^2

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

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

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

No point-to-point systematic

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

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

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

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

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

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

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

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

OTHER SYSTEMATIC ERRORS

Beam Current, *δI/I*	3%
Photon Flux, *δφ/φ*	5%
Radiator Thickness, *δR/R*	3%
Bubble Chamber Thickness, *δT/T*	3%
Bubble Chamber Efficiency, *ε*	5%

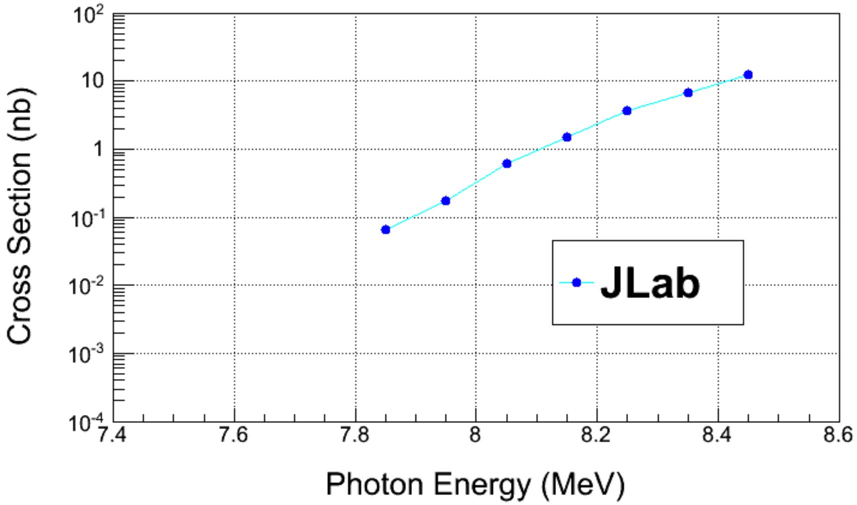
Simulation

- 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



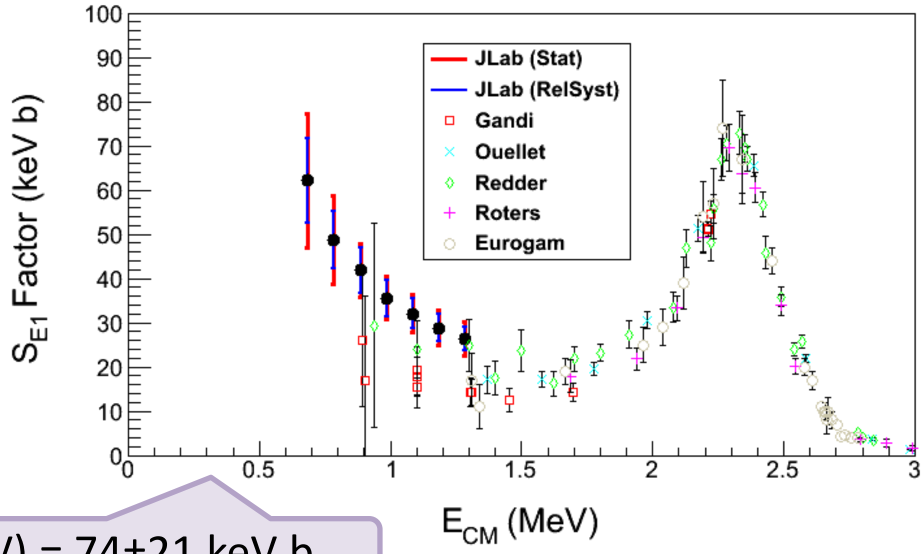
Electron Beam K. E.	Cross Section (nb)	Sys Error (Energy, %)	Sys Error (Total, %)
7.9	0.046	12.5	15.3
8.0	0.185	10.2	13.5
8.1	0.58	8.3	12.2
8.2	1.53	7.0	11.4
8.3	3.49	6.0	10.7
8.4	7.2	5.3	10.5
8.5	13.6	4.7	10.1

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

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

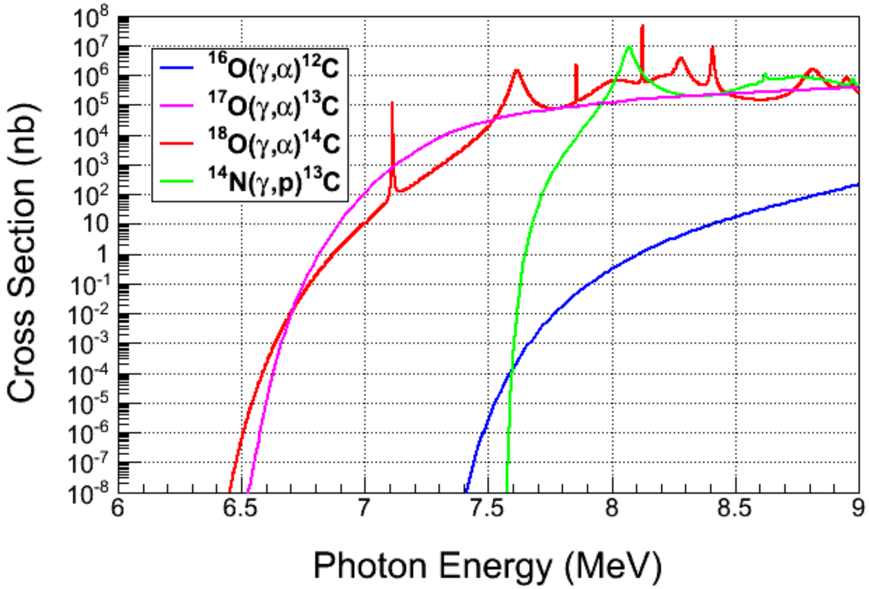
II. ^{18}O: 0.205%

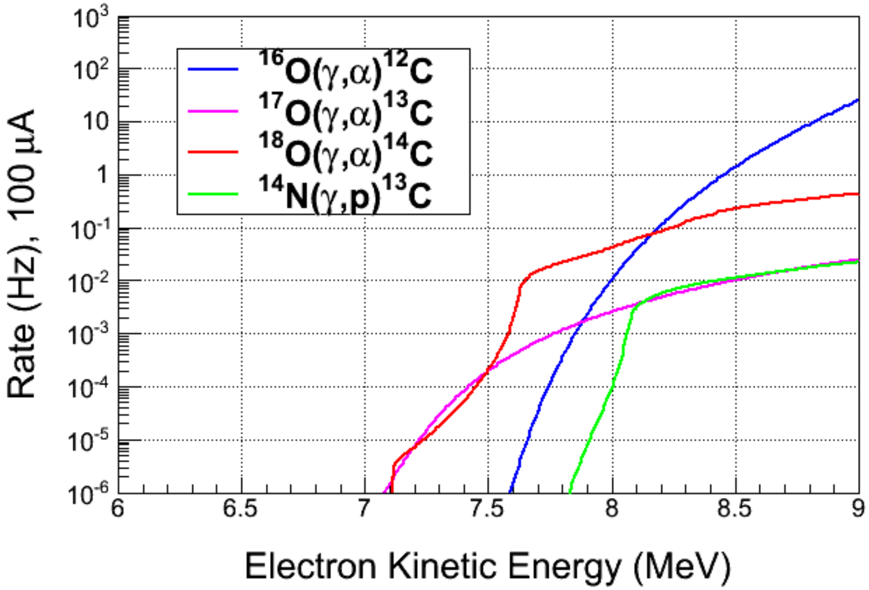
➢ Expected Rates:

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

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

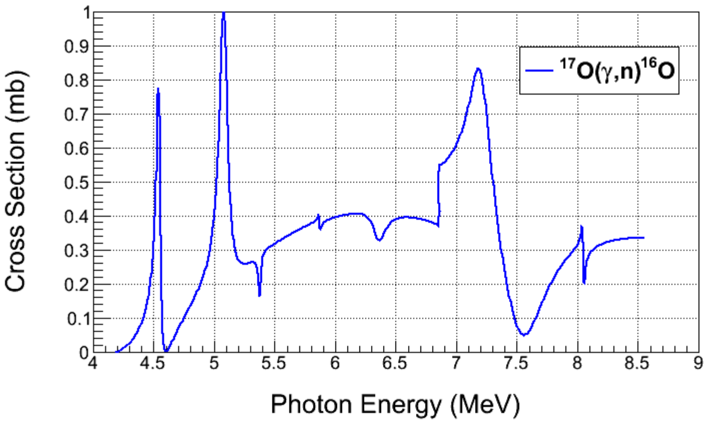
III. $^{14}N(\gamma,p)^{13}C$, detection eff.= 10^{-8}





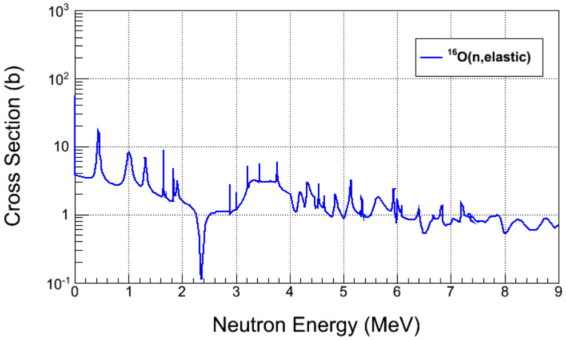
II. Background from:

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

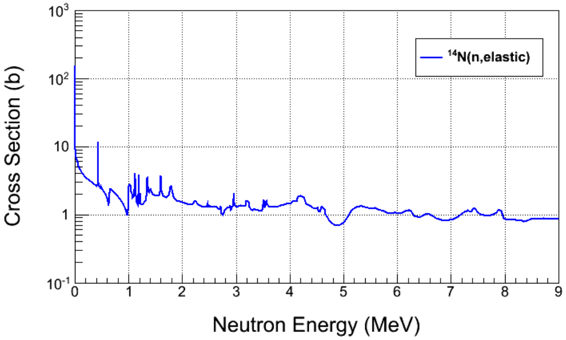


III. Cosmic–ray background:

- μ±–nuclear
- neutron–nuclear elastic scattering



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



ION ENERGY DISTRIBUTIONS

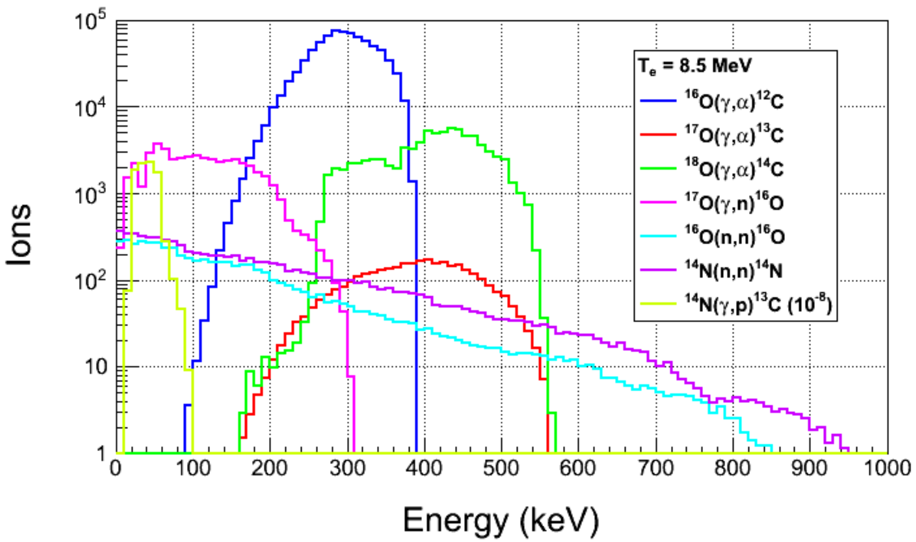
- ➢ Suppress background

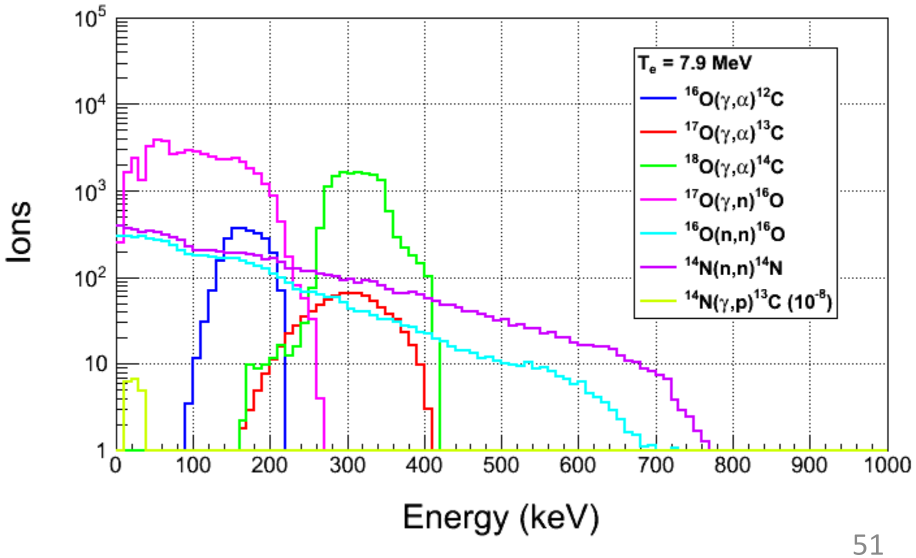
with Bubble Chamber threshold

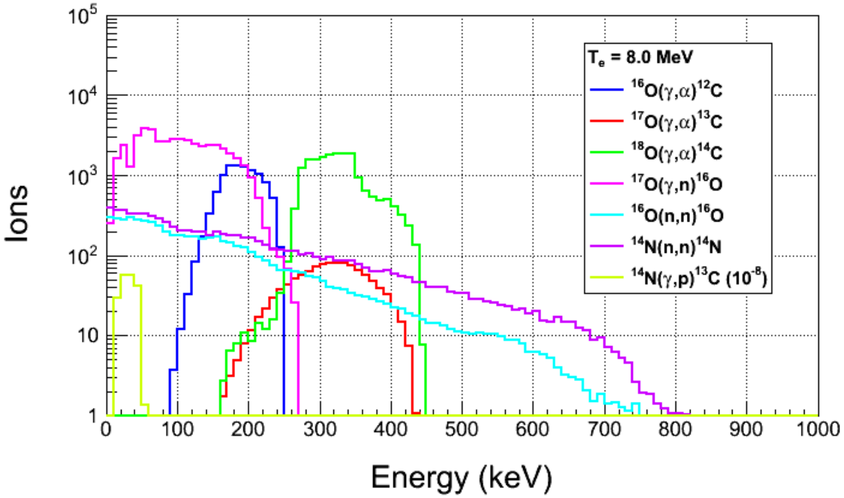
- ➢ Calculated with Depletion:
  - I. ^{17}O depletion = 5,000
  - II. ^{18}O depletion = 5,000

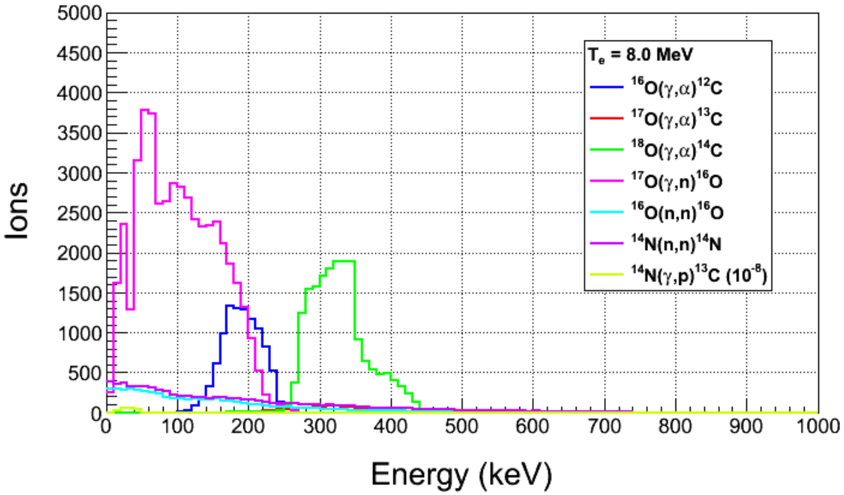
- ➢ Threshold Efficiency (function of superheat):

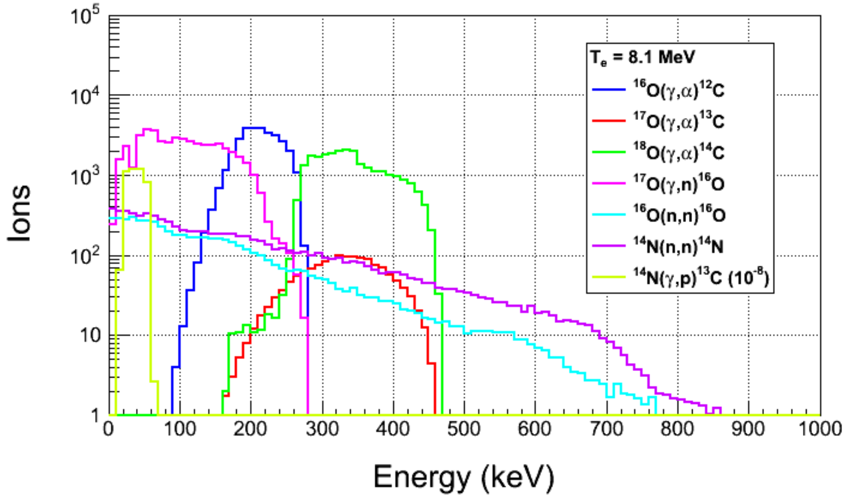
Particle	Efficiency
$e^{\pm}$	$<10^{-11}$
γ	$<10^{-11}$
(γ,n)	2×10^{-3}






Ions
Energy (keV)
T_e = 8.0 MeV
^{16}O(γ,α)^{12}C
^{17}O(γ,α)^{13}C
^{18}O(γ,α)^{14}C
^{17}O(γ,n)^{16}O
^{16}O(n,n)^{16}O
^{14}N(n,n)^{14}N
^{14}N(γ,p)^{13}C (10^{-8})
1
10
10^2
10^3
10^4
10^5
0
100
200
300
400
500
600
700
800
900
1000


Ions
Energy (keV)
T_e = 8.0 MeV
^{16}O(γ,α)^{12}C
^{17}O(γ,α)^{13}C
^{18}O(γ,α)^{14}C
^{17}O(γ,n)^{16}O
^{16}O(n,n)^{16}O
^{14}N(n,n)^{14}N
^{14}N(γ,p)^{13}C (10^{-8})
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0
100
200
300
400
500
600
700
800
900
1000


Ions
Energy (keV)
T_e = 8.1 MeV
^{16}O(γ,α)^{12}C
^{17}O(γ,α)^{13}C
^{18}O(γ,α)^{14}C
^{17}O(γ,n)^{16}O
^{16}O(n,n)^{16}O
^{14}N(n,n)^{14}N
^{14}N(γ,p)^{13}C (10^{-8})
1
10
10^2
10^3
10^4
10^5
0
100
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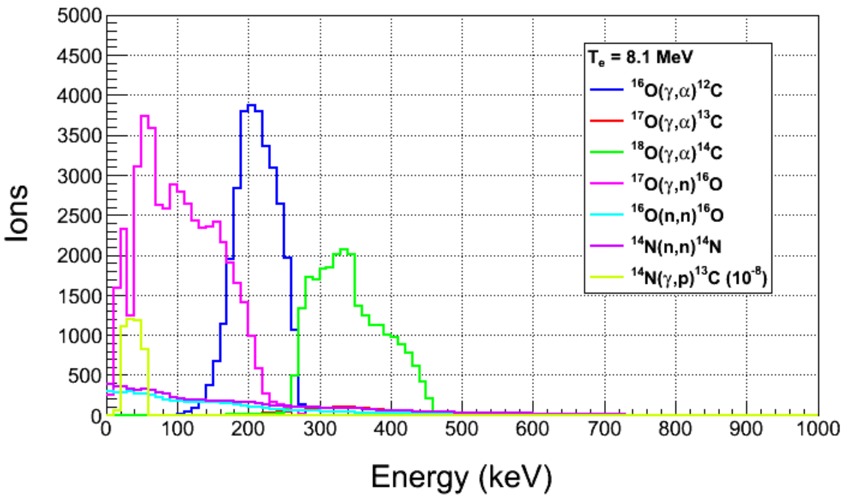
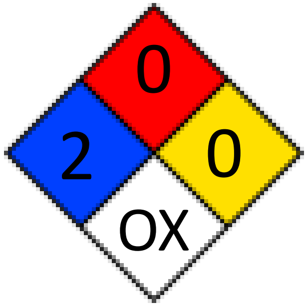

Ions
Energy (keV)
T_e = 8.1 MeV
^{16}O(γ,α)^{12}C
^{17}O(γ,α)^{13}C
^{18}O(γ,α)^{14}C
^{17}O(γ,n)^{16}O
^{16}O(n,n)^{16}O
^{14}N(n,n)^{14}N
^{14}N(γ,p)^{13}C (10^{-8})
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0
100
200
300
400
500
600
700
800
900
1000

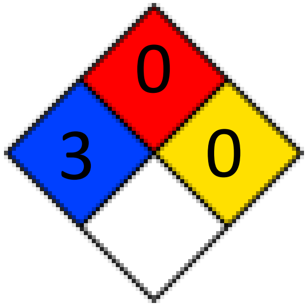
SAFETY

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



- High pressure system:
  1. Design Authority: Dave Meekins
  2. T =
  3. P =

- Buffer liquid: Mercury
  1. Closed system
  2. Volume: 135 mL



SUMMARY AND OUTLOOK

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

- Bubble Chamber issues:
  - Piezo–electric acoustical signal
  - Deadtime study (now $\tau \pm d\tau = 10.0 \pm 0.9$ s)
  - Measure O-isotope depletion

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

BACKUP SLIDES

COST ESTIMATE

I. New beamline components:
   I. New Dipole Magnet and Hall Probe
   II. 2 Super Harps
   III. Fast Valve

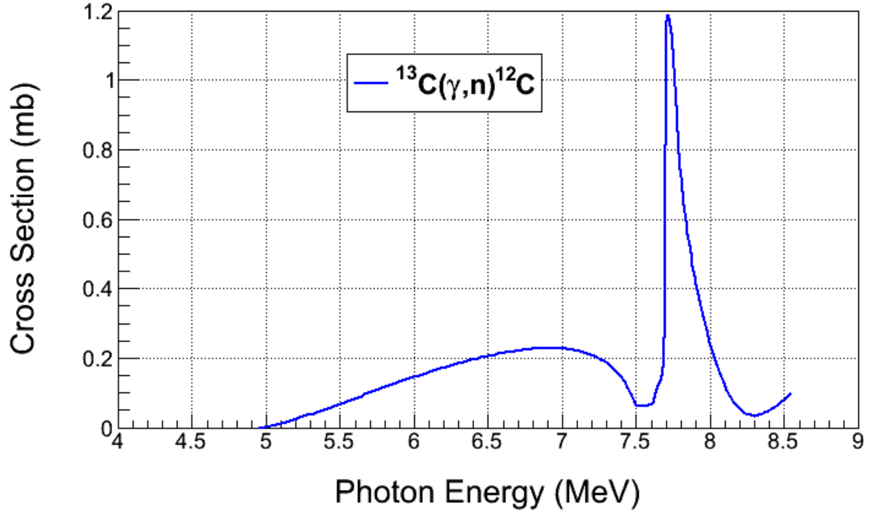
II. Summary of labor cost by group:

Group	Labor
Survey & Alignment	3 wks x 2
Magnet Test	1 wk x 2
Engineering Design	16 wks
Software	3 wks x 2
EES	6 wk x 2
EH&Q	4 wks

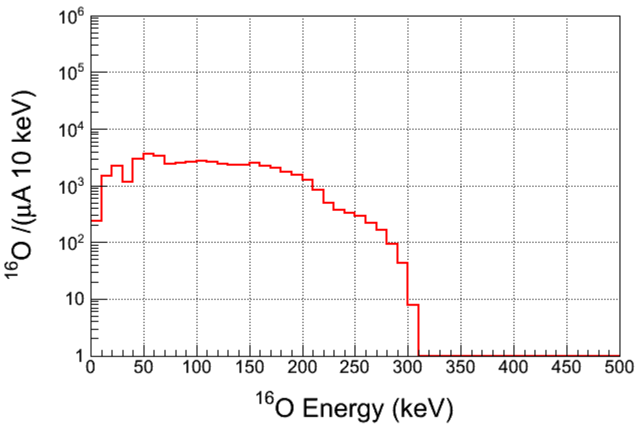
Item	Material Procurement	Shop	Labor
New Dipole Magnet	Dipole Magnet ($8,000) Hall Probe System ($10,000)		Design (2 week) Mapping (1 week) EESDC (1 week) Alignment (2 days)
New Beamline	2 Super Harps (20,000) Fast Valve ($23,000)	Pipes + Pedestals ($20,000)	Design (6 weeks) Alignment (1 week) Software (6 weeks) EES (6 weeks)
Radiator (cooled ladder, FSD)	0.02 and 0.10 mm Cu foils ($2,000)	$4,000	Design (2 week) Alignment (2 days)
Sweep Dipole			
Electron Dump	Pure Cu ($5,000)	Dump + Pipes ($15,000)	Design (4 weeks) Alignment (1 day)
Cu Collimator	Pure Cu ($5,000)	Collimator + Stand ($5,000)	Design (1 week) Alignment (1 day)
Photon Dump & Stand	Pure Al ($3,000)	$4,000	Design (1 week) Alignment (1 day)
Safety Review			4 weeks
Install			6 weeks
Bubble Chamber			Alignment (1 week)
Total	$76,000	$48,000	$80,000
Indirect G&A (55.65%)	$42,300	$26,400	$42,500
Indirect Stat & Fringe (57.15%)			$45,700
Total	**$118,300**	**$74,400**	**$168,200**

CO_2 SUPERHEATED LIQUID?

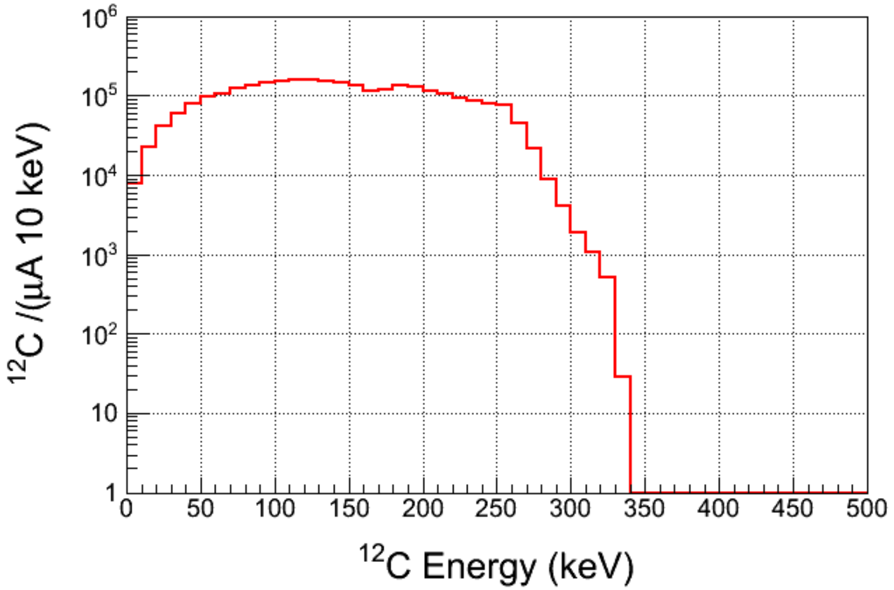
- Natural Abundance: ^{13}C: 1.07%
- Depletion: ^{13}C depletion=1,000
- $^{13}C(\gamma,n)^{12}C$ Background



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

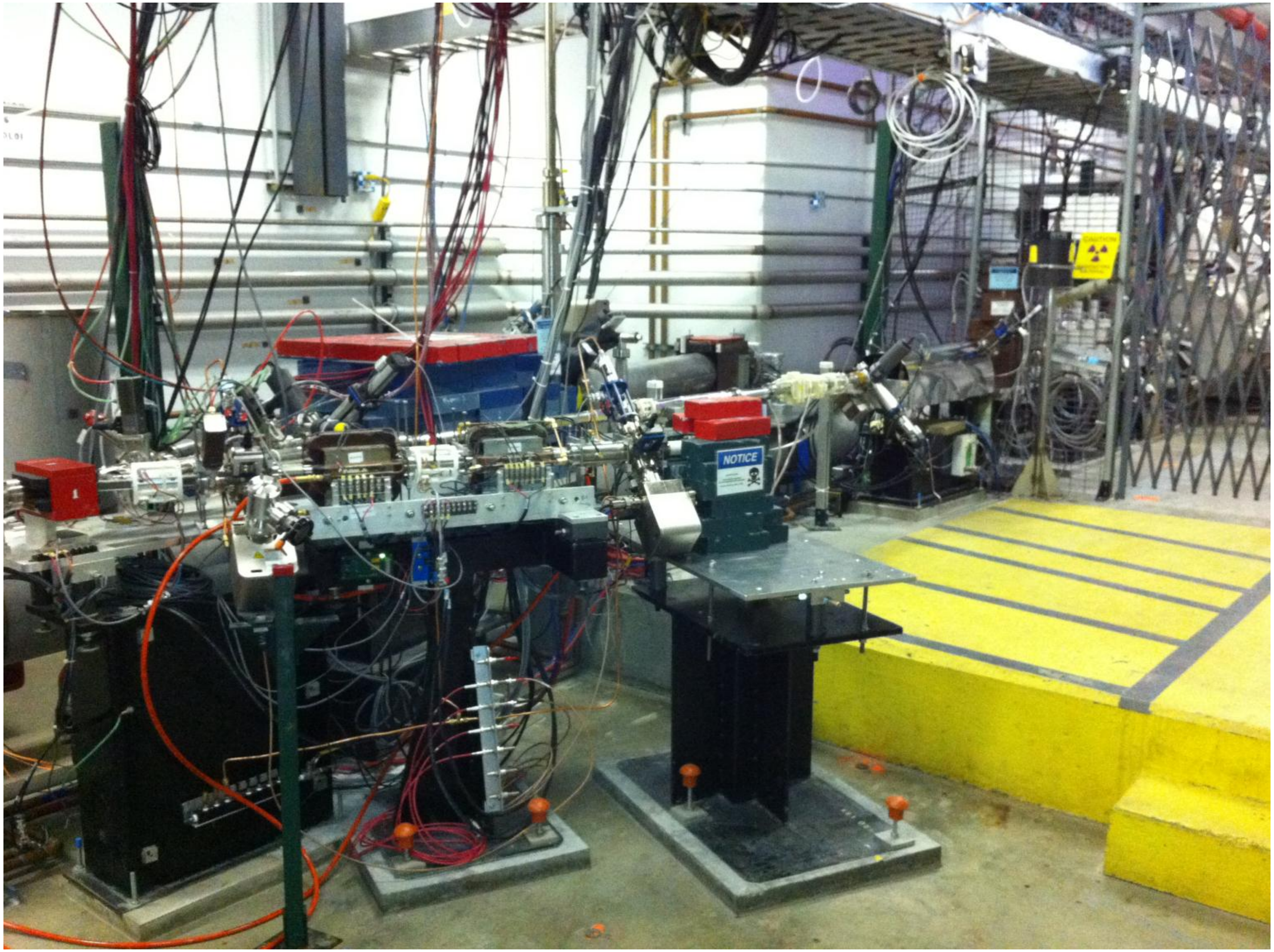


- $^{12}C(\gamma,2\alpha)\alpha$ Background



WATER SUPERHEATED LIQUID?

- Etching of glass vessel by superheated H_2O
- T = 250˚C
- P =



NOTICE