Bubble Chamber: Status and Test

September 1, 2015

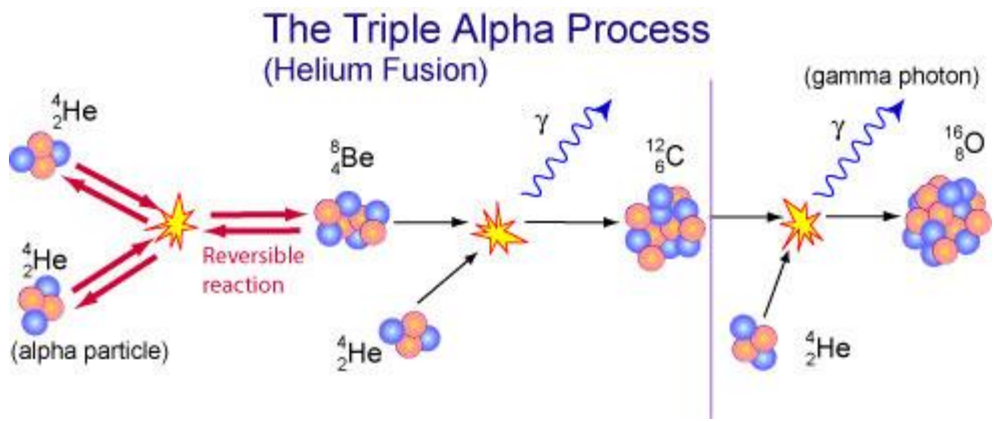
https://wiki.jlab.org/ciswiki/index.php/Bubble_Chamber

Outline

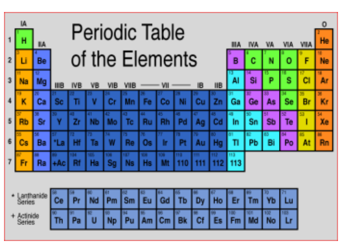
- Nucleosynthesis and $^{12}C(\alpha,\gamma)^{16}O$ Reaction
- Time Reversal Reaction: $^{16}O(\gamma,\alpha)^{12}C$
- Bubble Chamber
- Electron Beam Requirements
- Bremsstrahlung Beam
- Penfold-Leiss Cross Section Unfolding
- JLab Projected Results
- Bubble Chamber Test Plans

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

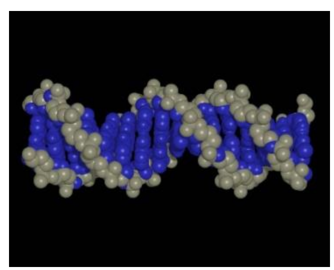
Stellar Helium burning



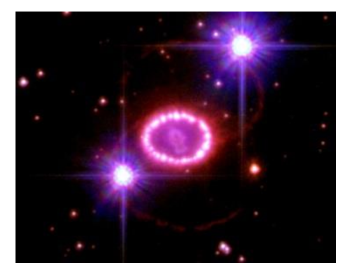
- The *holy grail* of nuclear astrophysics:



Affects synthesis of most of elements in periodic table



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



Determines minimum mass star requires to become supernova

HEROIC EFFORTS IN SEARCH OF $^{12}C(\alpha,\gamma)^{16}O$

- Previous cross section 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

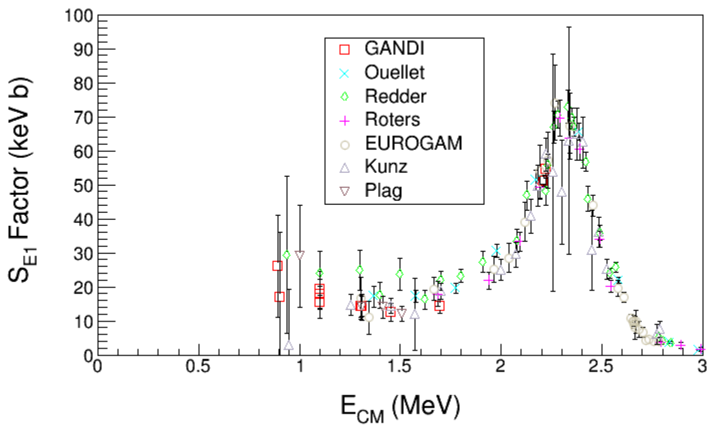
ASTROPHYSICAL S-FACTOR $^{12}C(\alpha,\gamma)^{16}O$

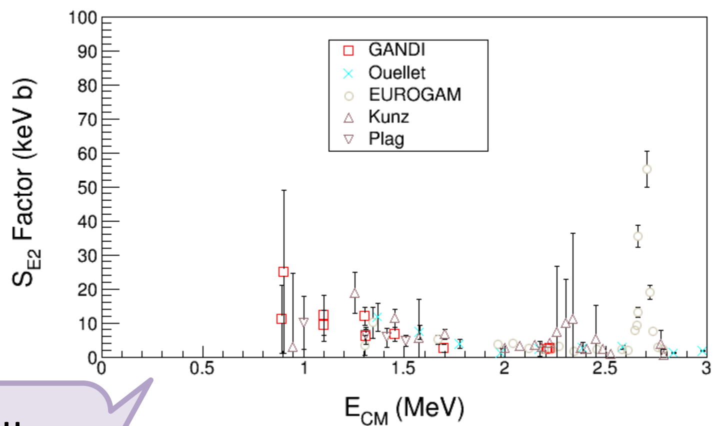
- Define *S-Factor* to remove both 1/E dependence of nuclear cross sections and Coulomb barrier transmission probability:

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

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

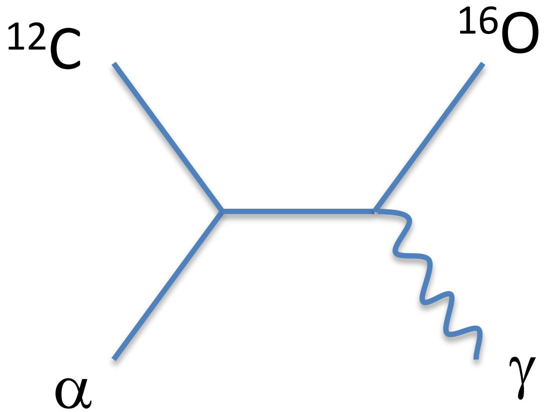
Author	$S_{tot}(300)$ (keV b)
Hammer (2005)	162±39
Kunz (2001)	165±50





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

Time Reversal Reaction

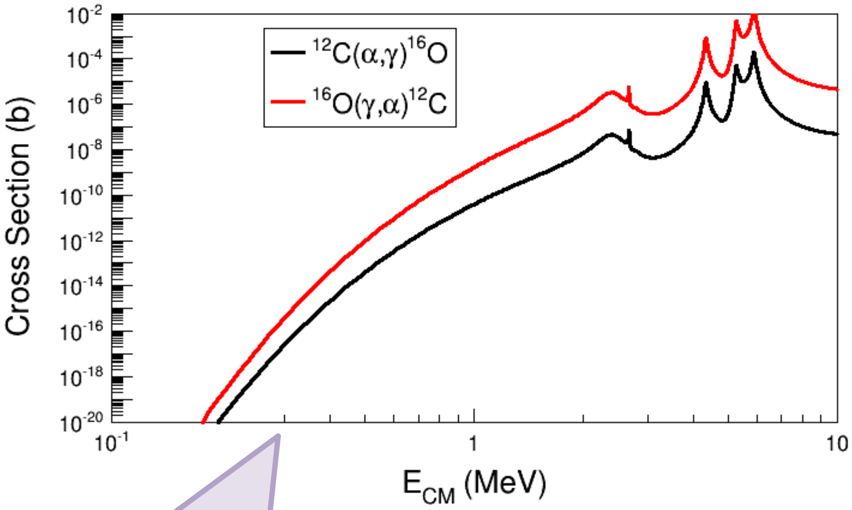


$$m_{^{12}C\alpha}c^2 = \frac{M(^{12}C)\cdot M(\alpha)}{M(^{12}C)+M(\alpha)} = 2796 \text{ MeV}$$

$$Q = +7.162 \text{ MeV}$$

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

$$\sigma_{(\gamma,\alpha)}(E_\gamma) = \frac{m_{^{12}C\alpha}c^2 E_{CM}}{E_\gamma^2}\sigma_{(\alpha,\gamma)}(E_{CM})$$



Stellar helium burning at E = 300 keV, T=200 10^6 K

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
- Bremsstrahlung at JLab $\sim 10^9\ \gamma$/s (top 250 keV)
- Target density up to 10^4 higher than conventional targets. Number of ^{16}O nuclei = $3.5 \times 10^{22}/cm^2$ (3.0 cm cell)
- Measures total cross section σ_{tot} (or $S_{tot}=S_{E1} + S_{E2}$)
- 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})

THE BUBBLE CHAMBER

1 Cell is cooled then filled with room temperature gas

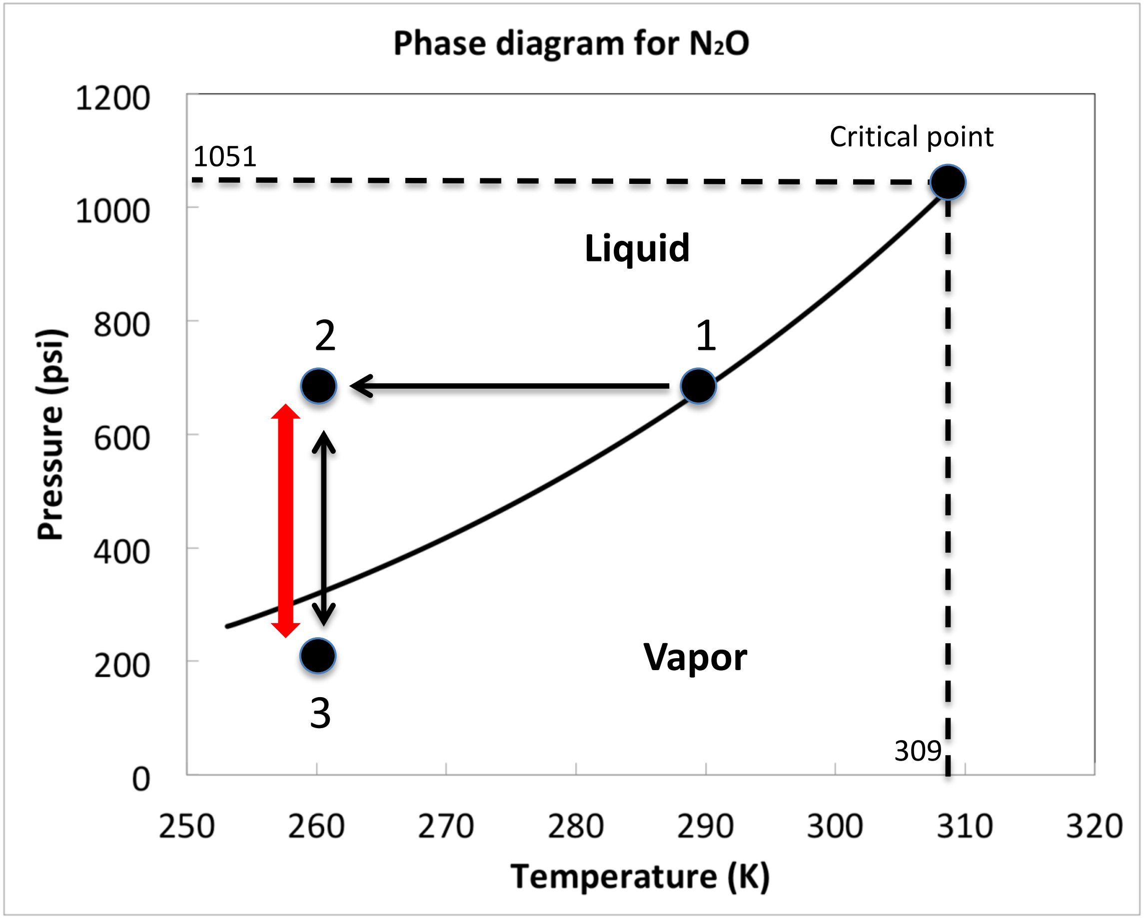
2 Gas is cooled and condenses into liquid

3 Once cell is completely filled with liquid, pressure is reduced creating a superheated liquid

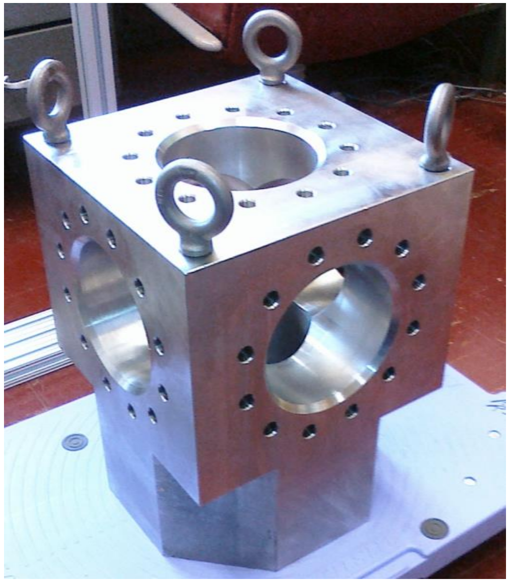
3 Nuclear reactions induce bubble nucleation

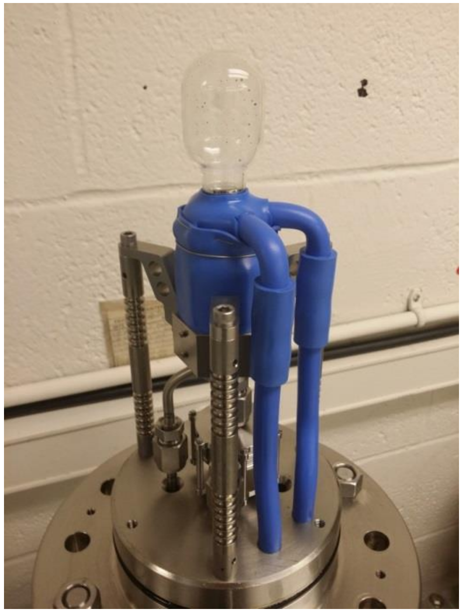
2 High speed camera detects bubble and repressurizes

3 System depressurizes and ready for another cycle



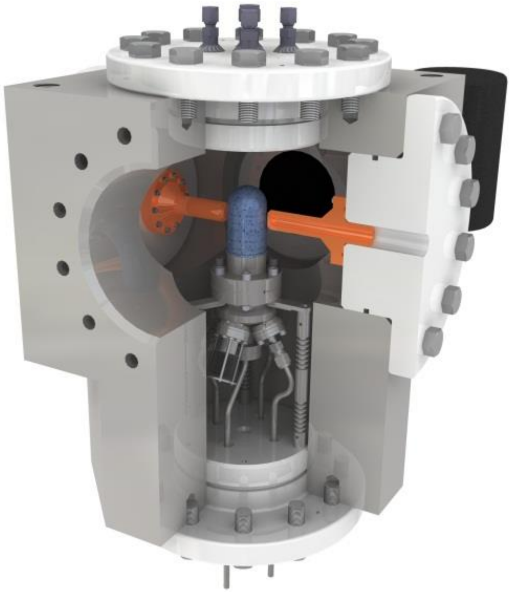
N_2O (Laughing Gas) Bubble Chamber

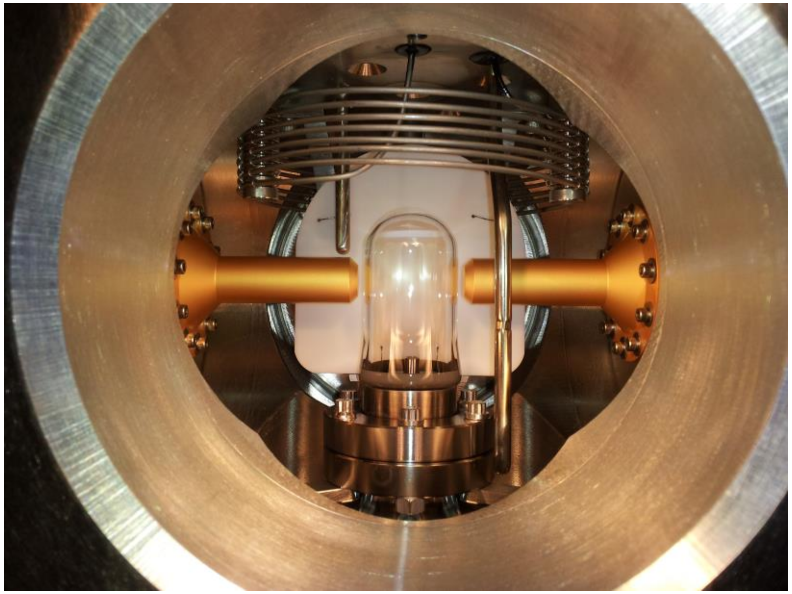




T = -10˚C

P = 50 atm





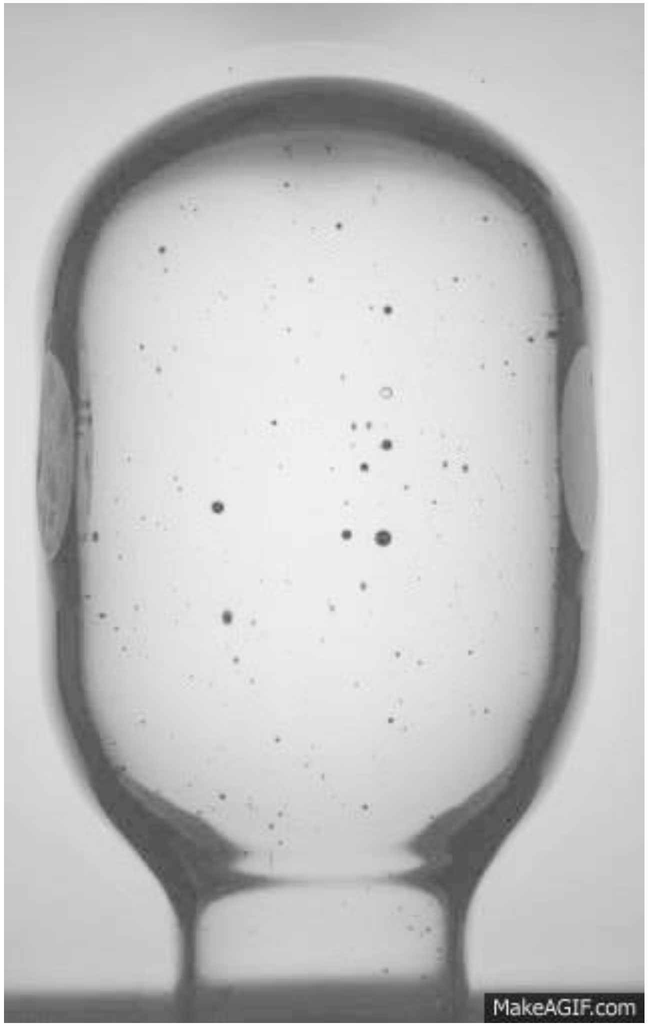
USER INTERFACE

Bubble Growth and Quenching

100 Hz Digital Camera
Δt = 10 ms

N_2O Chamber with PuC neutron source

3.0 cm



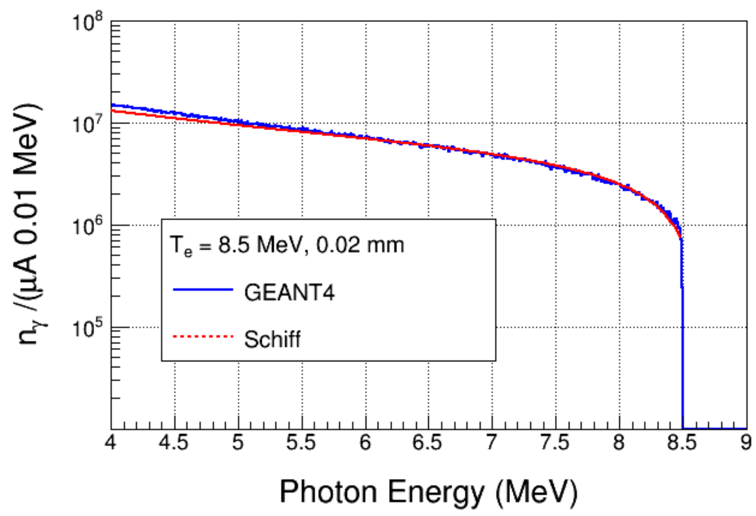
Electron Beam Requirements

I. Beam Properties at Radiator:

Beam Kinetic Energy, (MeV)	7.9 – 8.5
Beam Current (μA)	0.01 – 100
Absolute Beam Energy Uncertainty	<0.1%
Relative Beam Energy Uncertainty	<0.02%
Energy Resolution (Spread), σ_T /T	<0.06%
Beam Size, $\sigma_{x,y}$ (mm)	1
Polarization	None

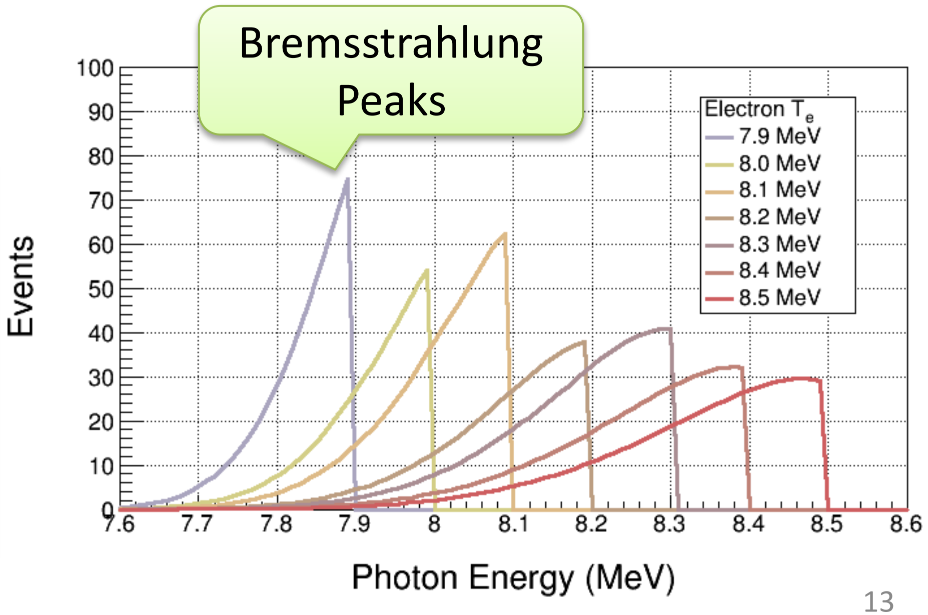
BREMSSTRAHLUNG BEAM

- 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 cross section; only photons near endpoint contribute to yield
II. No-structure (resonances)



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

- Solution can be written in two forms:

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

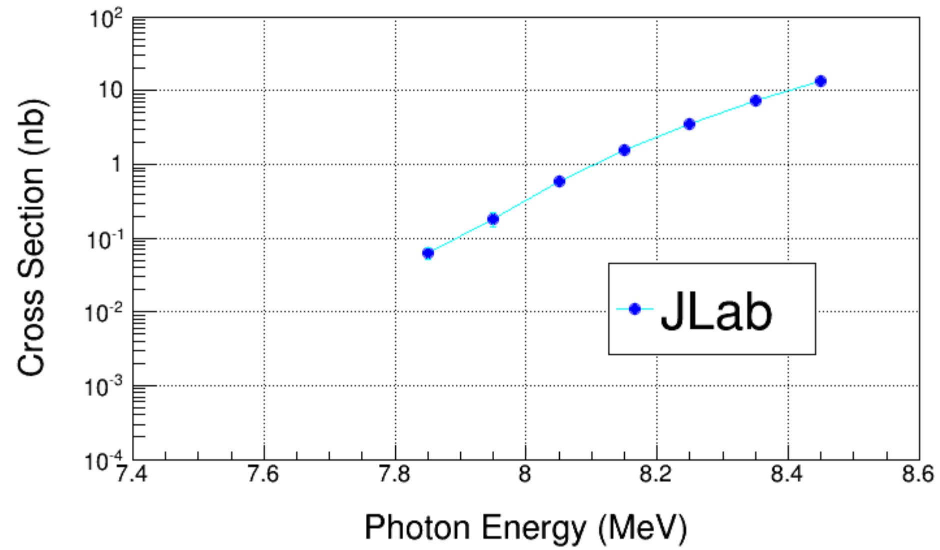
- Or, Matrix form:

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

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

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

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



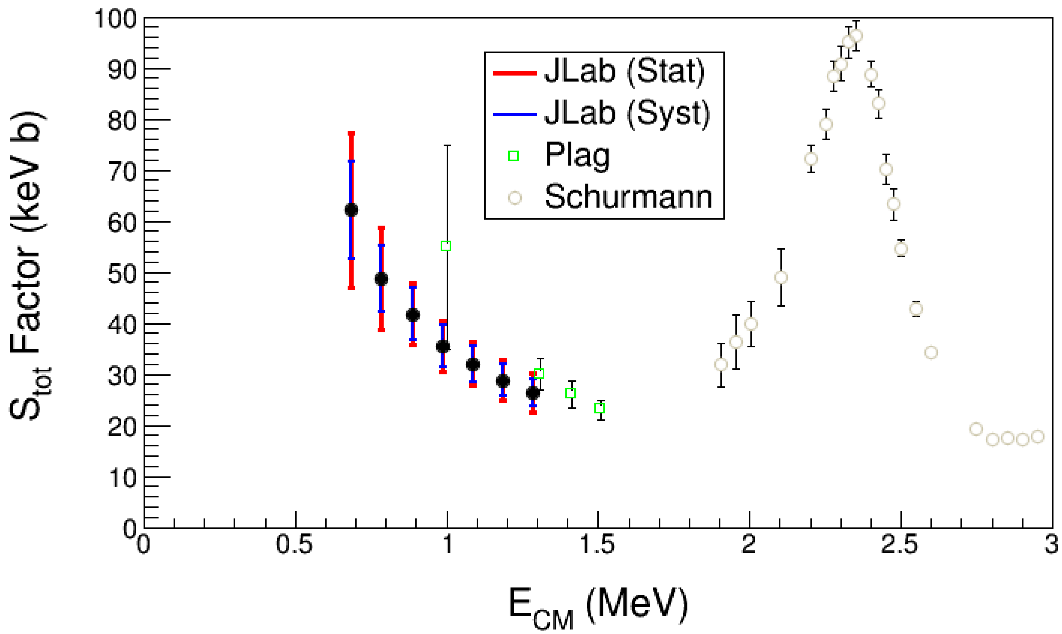
Absolute Beam Energy, δE	0.1%
Beam Current, $\delta I/I$	3%
Photon Flux, $\delta\varphi/\varphi$	5%
Radiator Thickness, $\delta R/R$	3%
Bubble Chamber Thickness, $\delta T/T$	3%
Bubble Chamber Efficiency, ε	5%

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

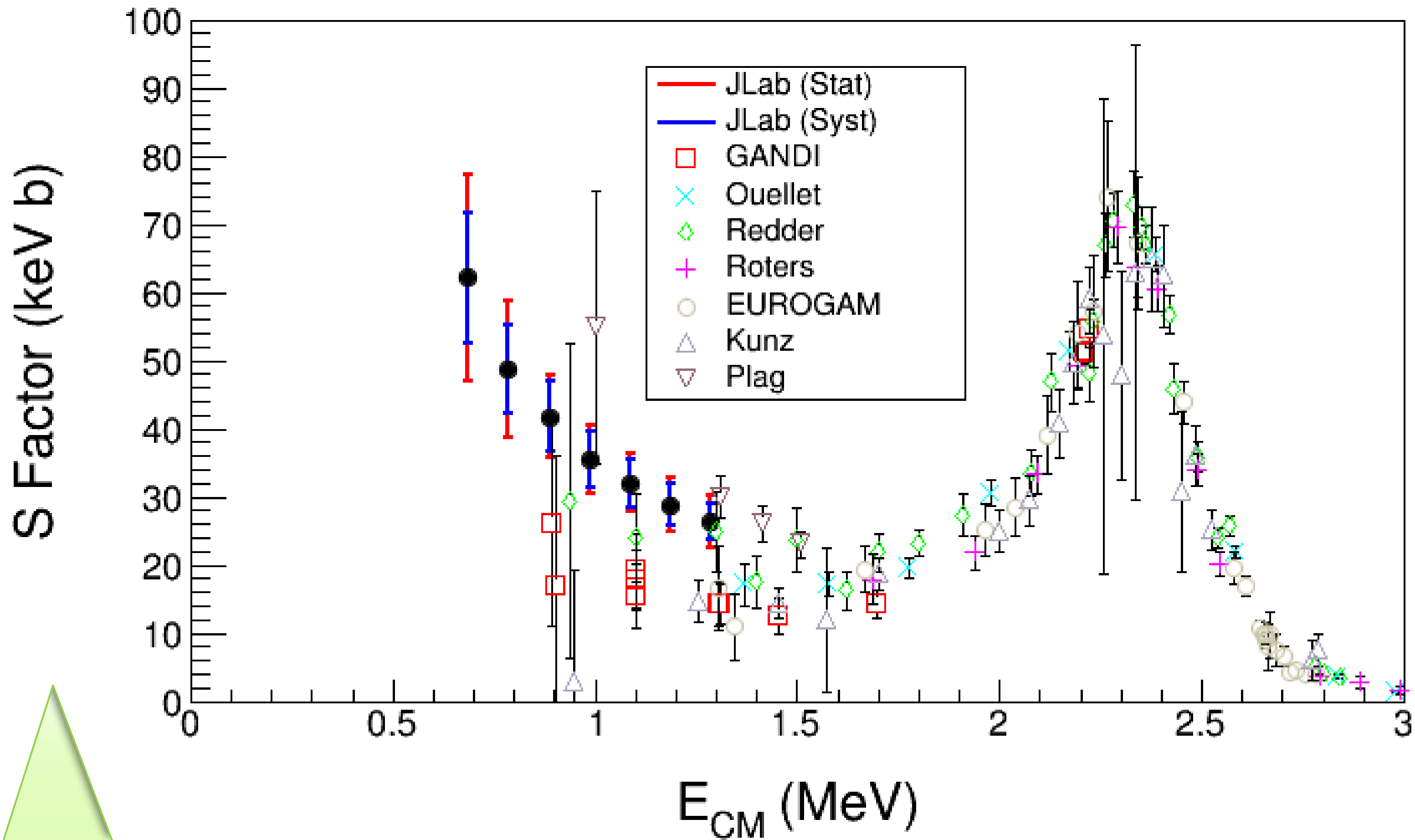
JLab Projected $^{12}C(\alpha,\gamma)^{16}O$ S-Factor

- 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

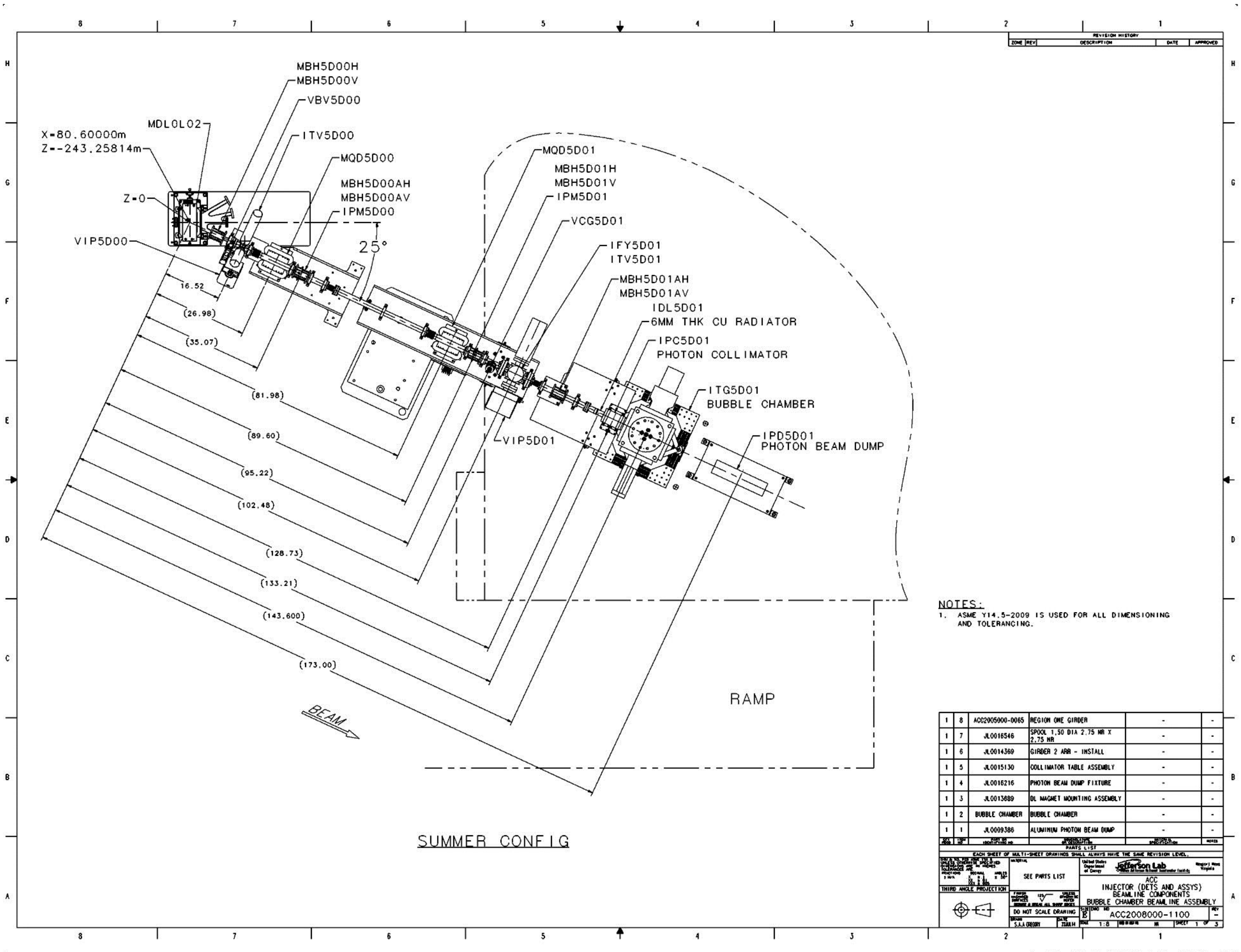


Bubble Chamber experiment measures total S-Factor, $S_{E1} + S_{E2}$



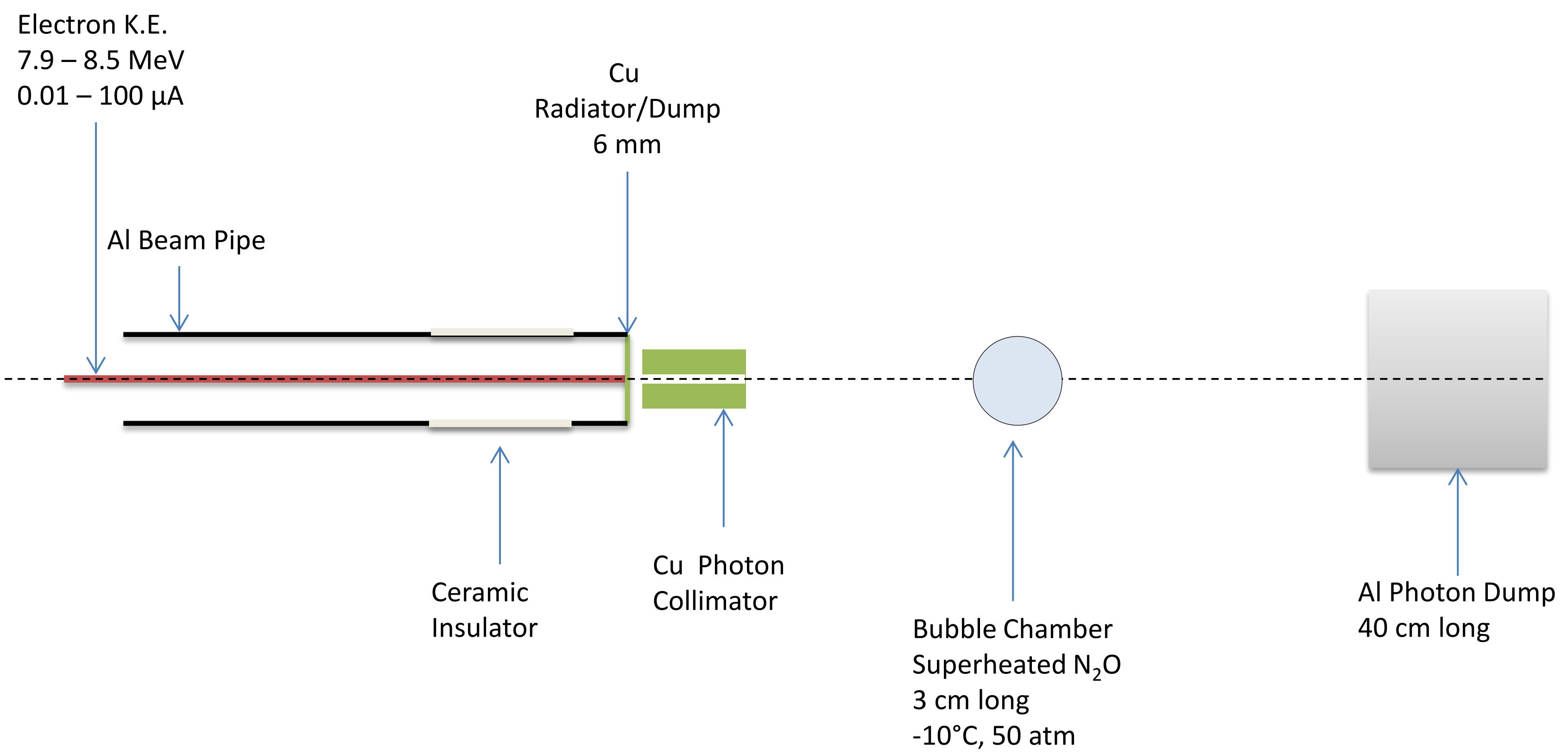
Total S-Factor ~ S_{E1}
(S_{E2} is small)

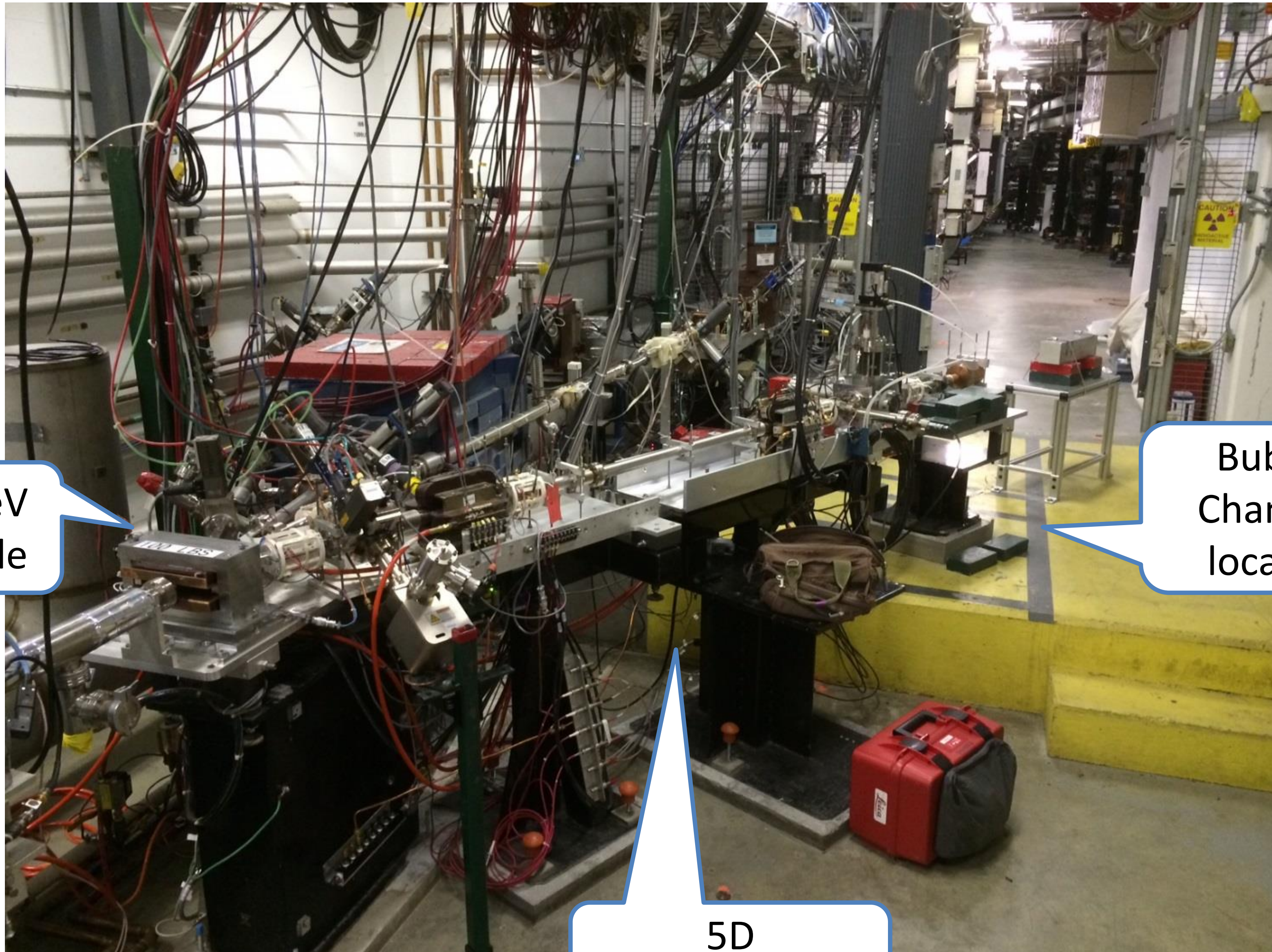
Test Beamline

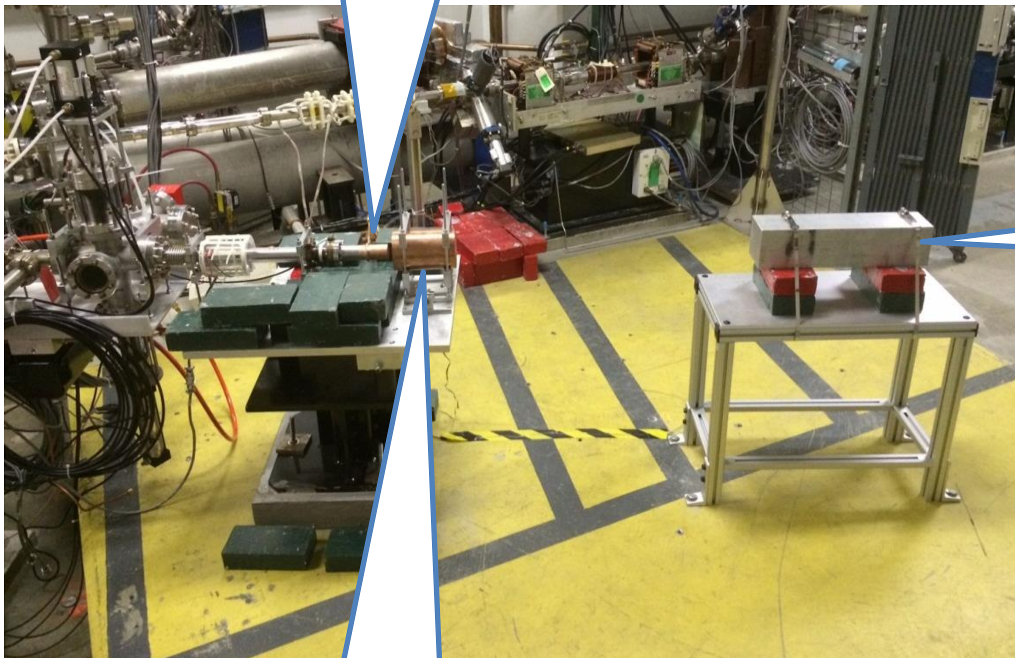


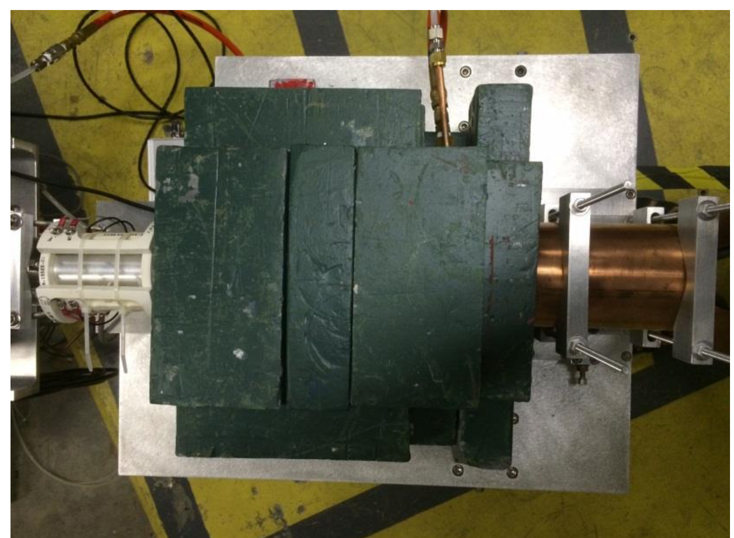
Schematics of Test Beamline

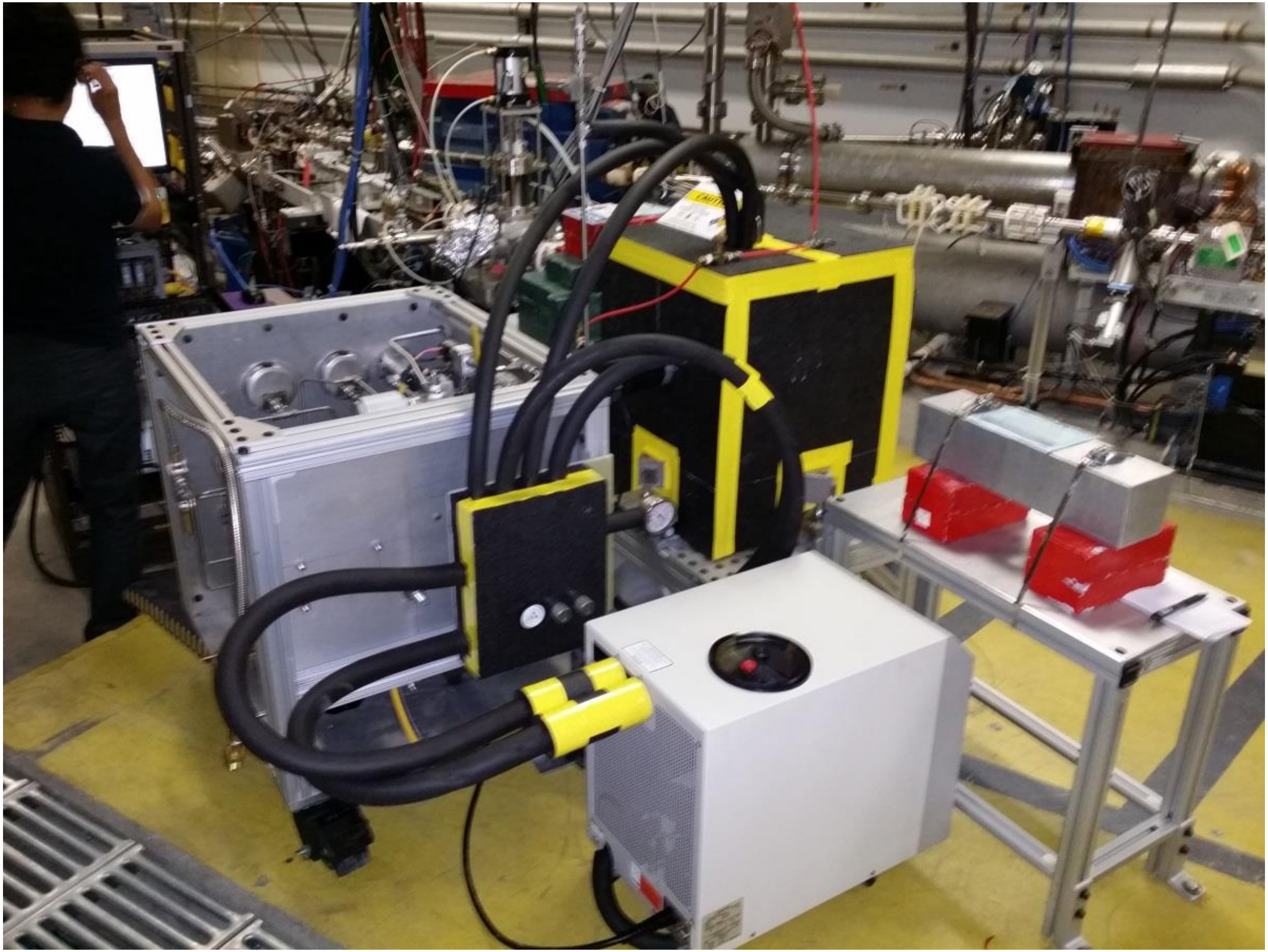
- Power deposited in radiator (100 μA and 8.5 MeV) :
  I. 6 mm: Energy loss = 8.5 MeV, P = 850 W
- Pure Copper and Aluminum (high neutron threshold):
  I. $^{63}C(\gamma,n)$ threshold = 10.86 MeV
  II. $^{27}Al(\gamma,n)$ threshold = 13.06 MeV



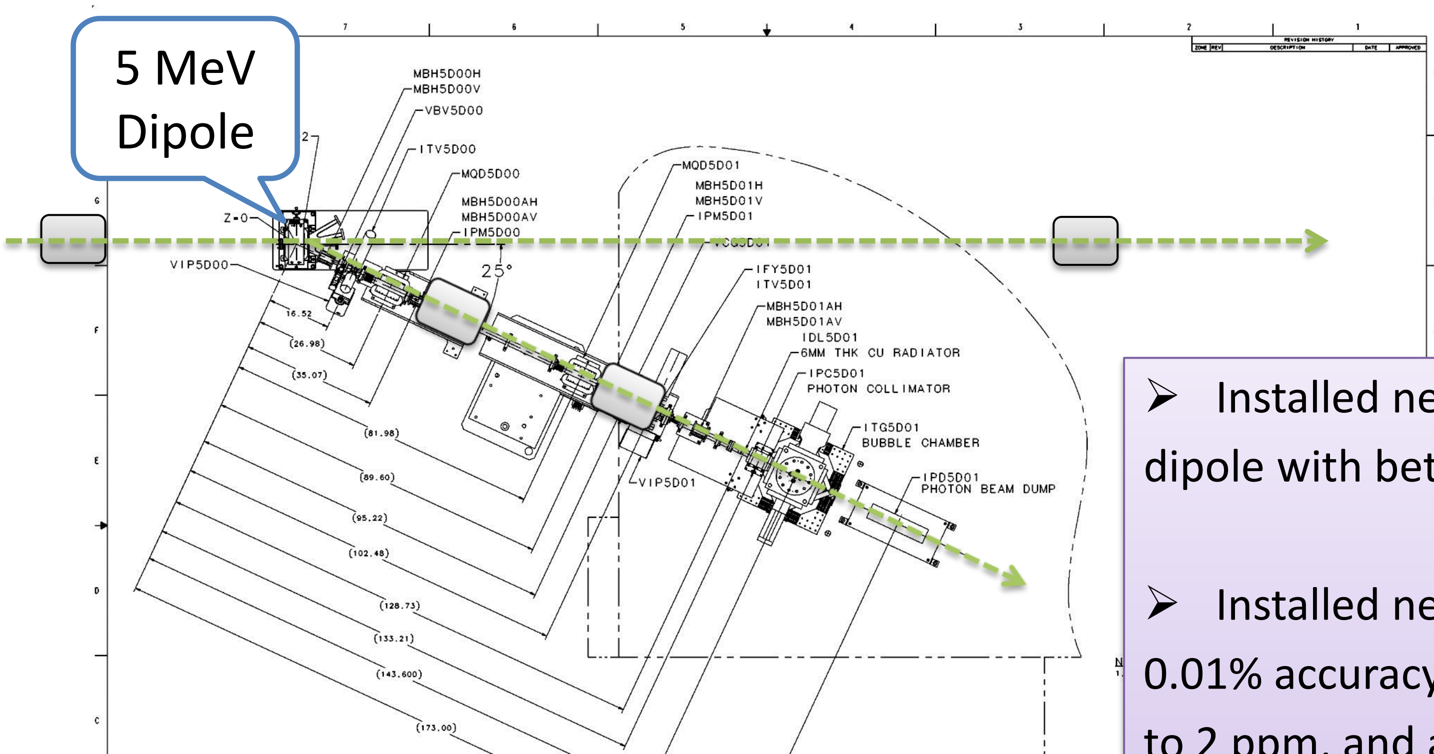

5 MeV
Dipole
Bubble
Chamber
location
5D
Spectrometer


Cu Electron Radiator/Dump
Al Photon Dump
Cu Photon Collimator





MEASURING ABSOLUTE BEAM ENERGY



- Installed new higher field dipole with better uniformity
- Installed new Hall probe: 0.01% accuracy, resolution to 2 ppm, and a temperature stability of 10 ppm/°C
- Still need to shield Earth's and other stray magnetic fields

Beam Position Monitor (BPM)

Electron Beam Momentum

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

TEST BEAMLINE COMMISSIONING

- Beamline was ready since Fall 2014
- Approved to run 10 μA CW and total energy of 10 MeV
- Completed hot checkout and beam checkout
- Beam Studies completed so far:
  I. Delivered 10.0 μA and 9.65 MeV (kinetic) for 5 hours in August 2015
  II. Measured beam momentum at different ¼ cryo-unit settings
  III. Measured beam charge at different beam currents
- Re-doing realistic thermal analysis to run at 100 μA

BUBBLE CHAMBER TEST PLANS

1. Fill with natural N_2O – test bubble chamber systems operation

2. With beam on bubble chamber radiator (Sept 8 – 18, 2015):

   I. How does CCD camera perform under beam-on conditions?
   II. Count rates on bubble chamber. Do we get single or multiple bubbles from Bremsstrahlung beam exposure?
   III. Measure gamma ray beam spatial profile as reflected by bubble distribution. Is collimator effective in defining the gamma-ray beam?

3. Background measurements:

   I. Measure beam off environmental background in chamber-injector area
   II. Measure beam on background by looking outside fiducial volume
   III. Measure background with beam to Faraday Cup in CEBAF beamline (about two meters from chamber)
   IV. Measure neutron events in chamber. Neutron radiation detectors in injector region will indicate if any neutrons are generated (especially at beam kinetic energies higher than 8.5 MeV).

4. Fill with C_2F_6 – test bubble chamber systems operation. This is planned later in September after first beam test.

5. With beam (planned in Oct 16 – 22, 2015)

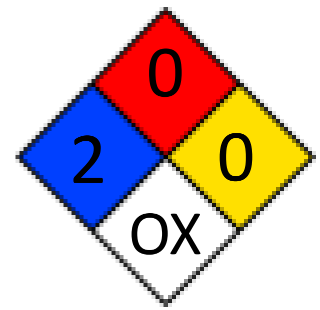
   I. Measure few data points of from $^{19}F(\gamma,\alpha)^{15}N$ (Q = +4.013 MeV) to perform a Penfold-Leiss unfolding
   II. Compare measured cross section to our HIGS data

➢ Fluorine is suitable for a first Penfold-Leiss unfolding:
   - Only one stable natural isotope (^{19}F)
   - Low electron beam kinetic energy (4.6 – 5.2 MeV) – below threshold of any background reaction

Can we measure a cross section below our limit at HIGS of 3 nb?

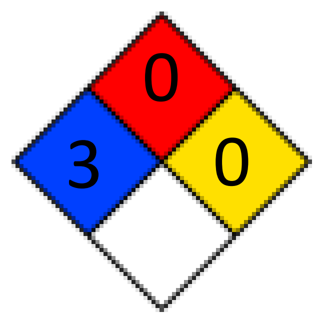
BUBBLE CHAMBER SAFETY REVIEWS

- Superheated liquid: N_2O, Nitrous oxide (laughing gas)
  I. Colorless, non-flammable gas, with slightly sweet odor and taste



- High pressure system:
  I. Design Authority: Dave Meekins
  II. T = -10˚C
  III. P = 50 atm

- Buffer liquid: Mercury
  I. Closed system
  II. Volume: 150 mL



- Bubble Chamber Safety Review was on Aug 18, 2015

- Temporary Operational Safety Procedures (**TOSP**) is approved

BACKUP SLIDES

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

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

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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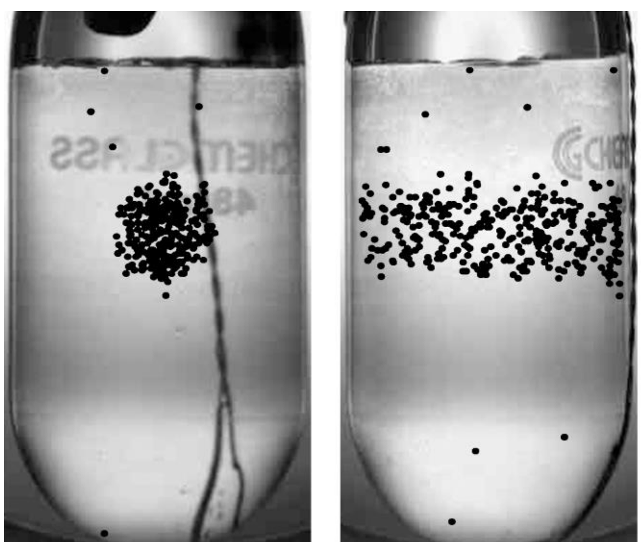
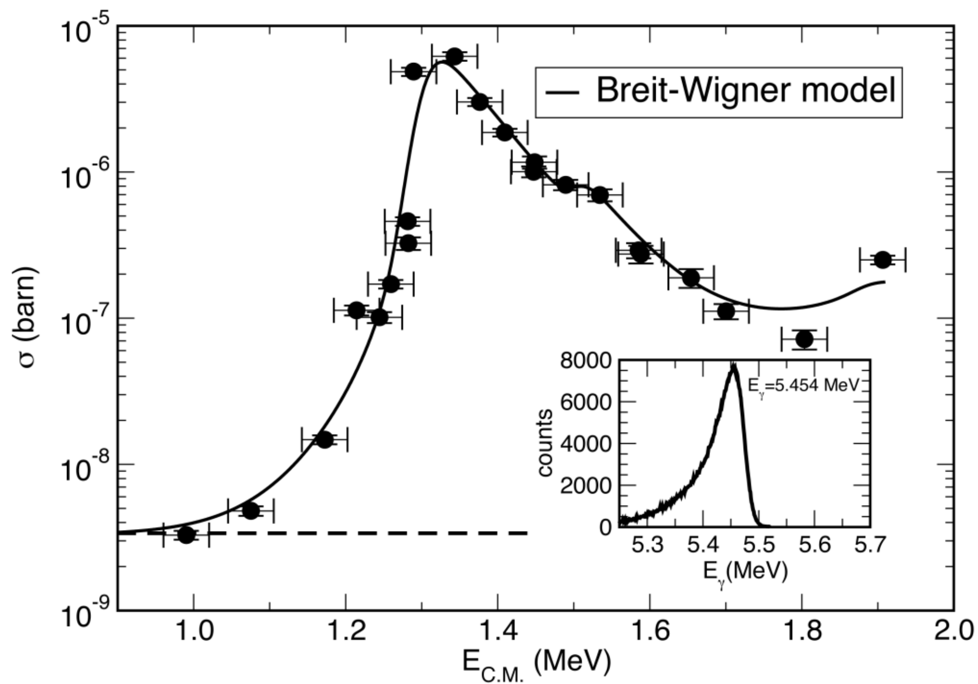
[f] Triangle Universities Nuclear Laboratory, Durham, NC 27708, USA

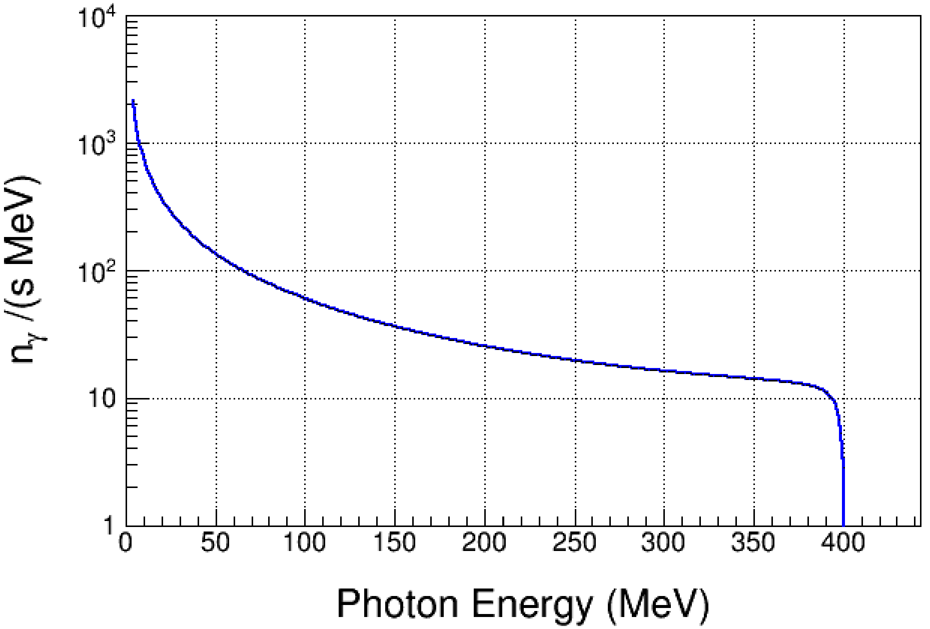




BREMSSTRAHLUNG BACKGROUND AT HIGS

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

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



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