Error Analysis I

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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:

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

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

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

Statistical Error

Statistical Error Propagation (1)

- 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:

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

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

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

Statistical Error Propagation (2)

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

Although,

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

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

For mono-chromatic beam

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

Statistical Error Propagation (Wrong)

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

- Then:

Wrong

$$[d\sigma^2] = [N^2]^{-1} \bullet [dY^2]$$

- This is equivalent to:

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

Wrong

Systematic Error

Systematic Error Propagation (1)

- For absolute beam energy uncertainty of δE (= 0.1%):

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

E_i (MeV)	dy_i/y_i (%)	$d\sigma_i/\sigma_i$ (%)
7.9	17.4	12.6
8.0	12.3	10.5
8.1	10.0	9.1
8.2	8.6	7.1
8.3	7.6	6.3
8.4	6.8	5.8
8.5	6.1	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:

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

$$
\left[dY^2\right] = \begin{bmatrix} (dy_1)^2 & 0 & \cdots & 0 \\ 0 & (dy_2)^2 & \cdots & \vdots \\ \ddots & \ddots & \ddots & \vdots \\ 0 & \cdots & \cdots & (dy_n)^2 \end{bmatrix}
\qquad
\left[\sigma^2\right] = \begin{bmatrix} \sigma_1^2 & 0 & \cdots & 0 \\ 0 & \sigma_2^2 & \cdots & \vdots \\ \ddots & \ddots & \ddots & \vdots \\ 0 & \cdots & \cdots & \sigma_n^2 \end{bmatrix}
$$

Systematic Error Propagation (2)

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

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:

$$(dy_i)^2 = (dy_i(\delta E))^2 + \left[\left(\frac{\delta I}{I}\right)^2 + \left(\frac{\delta R}{R}\right) + \left(\frac{\delta T}{T}\right)^2 + \varepsilon^2\right] y_i^2$$

$$(dN_{ij})^2 = \left(\frac{\delta\phi}{\phi}\right)^2 N_{ij}^2$$

Results

I. Radiator Thickness = 0.02 mm
II. Bubble Chamber Thickness = 3.0 cm
III. Number of ^{16}O nuclei = 3.474e22 /cm^2
IV. Background subtraction of $^{18}O(\gamma,\alpha)^{14}C$
V. $^{17}O(\gamma,n)^{16}O$: Still to do

Electron Beam K. E.	Beam Current (μA)	Time (hour)	y_i	dy_i (no bg)	dy_i (with bg)
7.9	100	100	545	23	134
8.0	100	20	581	24	77
8.1	80	10	852	29	60
8.2	20	10	634	25	40
8.3	10	10	812	28	39
8.4	4	10	746	27	36
8.5	2	10	763	28	32

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

Electron Beam K. E.	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

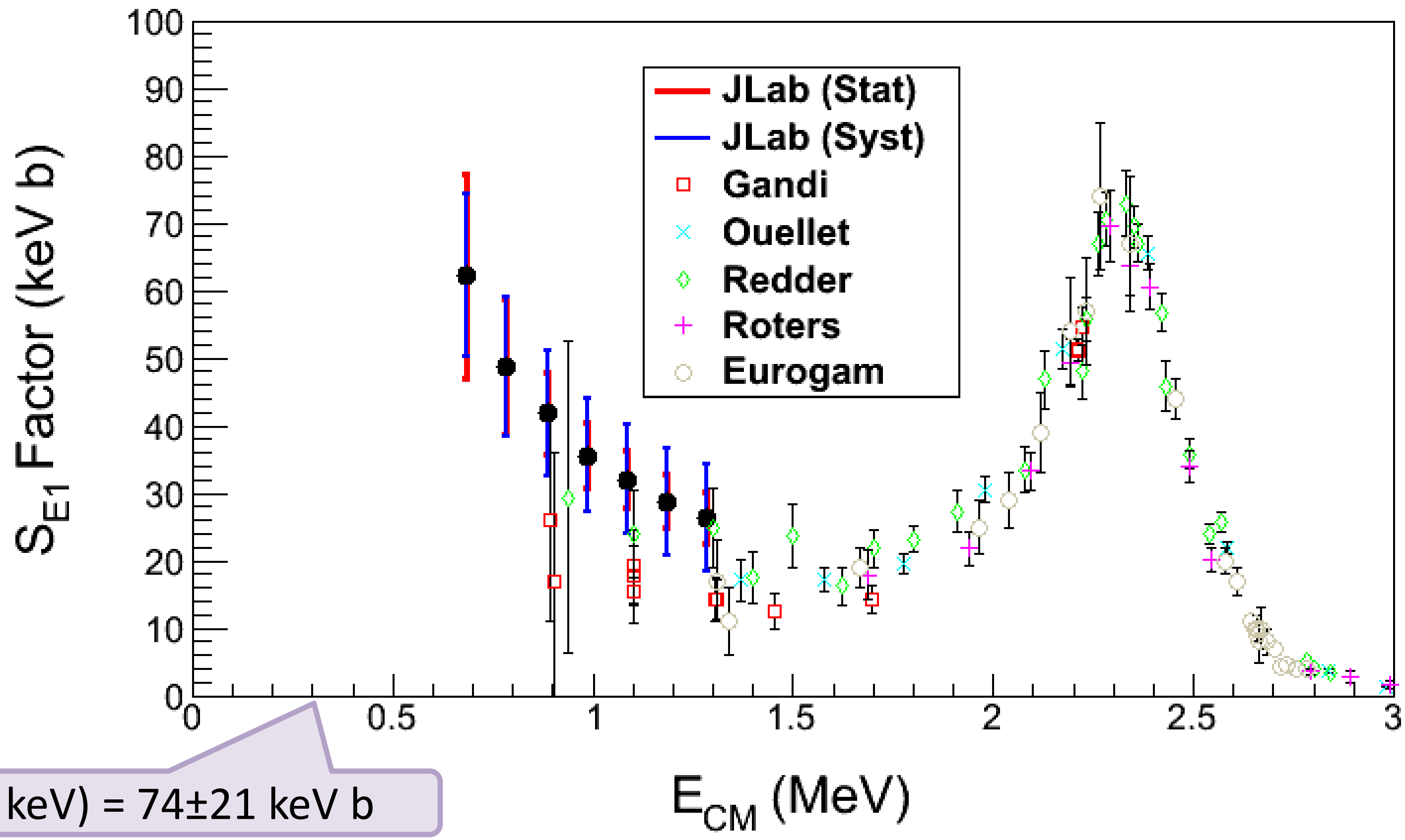
Electron Beam K. E.	Cross Section (nb)	Sys Error (Energy, %)	Sys Error (Total, %)
7.9	0.046	17.4	19.5
8.0	0.185	18.1	21.1
8.1	0.58	18.4	22.1
8.2	1.53	18.9	23.6
8.3	3.49	19.7	25.4
8.4	7.2	20.6	27.7
8.5	13.6	21.6	30.1

Electron Beam K. E.	Gamma Energy (MeV)	E_{CM} (MeV)	Cross Section (nb)	S_{E1} Factor (keV b)	Stat Error (%)	Sys Error (%)
7.9	7.85	0.69	0.046	62.2	24.5	19.5
8.0	7.95	0.79	0.185	48.7	20.7	21.1
8.1	8.05	0.89	0.58	41.8	14.7	22.1
8.2	8.15	0.99	1.53	35.5	13.8	23.6
8.3	8.25	1.09	3.49	32.0	13.3	25.4
8.4	8.35	1.19	7.2	28.8	13.8	27.7
8.5	8.45	1.29	13.6	26.3	14.8	30.1

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

- Statistical Error: dominated by background subtraction from $^{18}O(\gamma,\alpha)^{14}C$ (depletion = 5,000)

- Systematic Error: dominated by absolute beam energy (δE = 0.1%)



S_{E1}(300 keV) = 74±21 keV b