Recent Progresses of/with the AMUR Code

Japan Atomic Energy Agency

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Contents

1. Status of the AMUR code
2. Simultaneous Analysis of the ^{17}O system
   $^{16}O(n,tot)$, $^{16}O(n,n)$, $^{13}C(\alpha,\alpha)$, $^{13}C(\alpha,n)$

⇨ (Presented in R-matrix workshop (Santa Fe) & ND2016)

3. Progress of AMUR (POL/ANA,DA)
4. Status of analysis for the ^{28}Si system

⇨ (Works done during the last 2-month)

AMUR (A MUlti-channel R-matrix Code)

Evaluation tool for the resonant cross-sections
(under development)

Theoretical calculation

Wigner-Eisenbud's form.

$\longrightarrow$ σ, $d\sigma(\theta)/d\Omega$, $Pol(\theta)/d\Omega$

--- Parameters ---

- *Boundary condition* (R_c, B_c)
- *Energy eigenvalue* (E_λ)
- *Reduced-width amp.* (γ_c)

Analysis of measurement

KALAM method (GLSQ)

$\longrightarrow$ Parameter & covariance

--- Parameters, e.g., ---

- *Renormalization*
- *Resolution, etc…*

Dynamic link (Object-oriented)

✓ All the parameter could have prior uncertainty

✓ Unitarity-constraint simultaneous analysis

Object-oriented (C++)

◆ Controlled by “ Macros.C ”, e.g.,

```
Particle n ( 0001 );
Particle t  ( 1003 );
```

```
Nucleus  Li6  ( 3006);
Nucleus  He4( 2004);
```

```
Channel c[2];
  c[0].Set( t,He4, 0.5, 1, 0.5 );  // ( partition, J, l, s )
  c[1].Set( n,Li6,  0.5, 1, 0.5 );
```

```
System x;
  x.Boundary::Rc( t,He4 )->SetValue( 3.0 )->Error( 1.0 );
  x.Boundary::Bc( ch[0]  )->SetValue( 4.0 )->Error( 1.0 );
```

◆ Can be operated on ROOT (CERN library)

◆ Multi-threads ◆ Easy access to EXFOR (C4/C5)

Efforts to Calculate Various Reactions

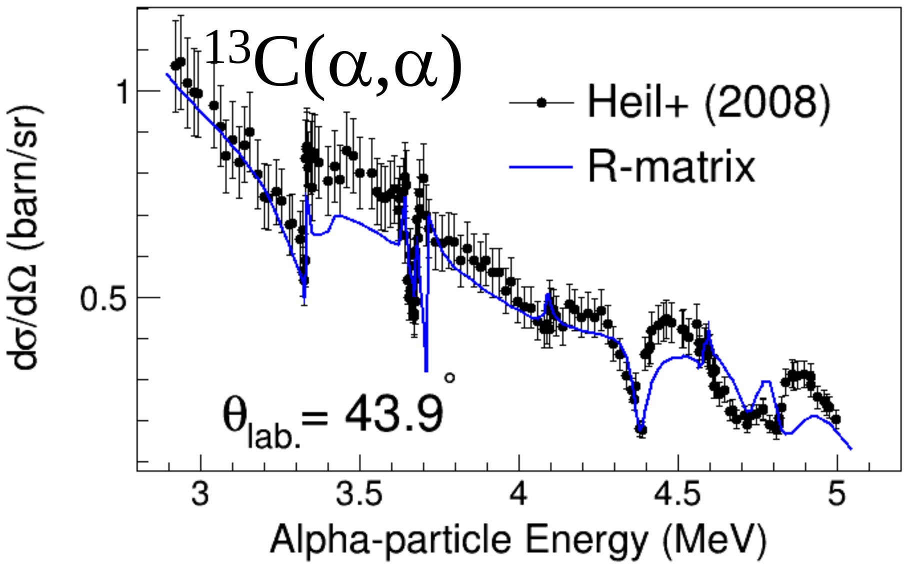
- Coulomb scattering amplitude was incorporated

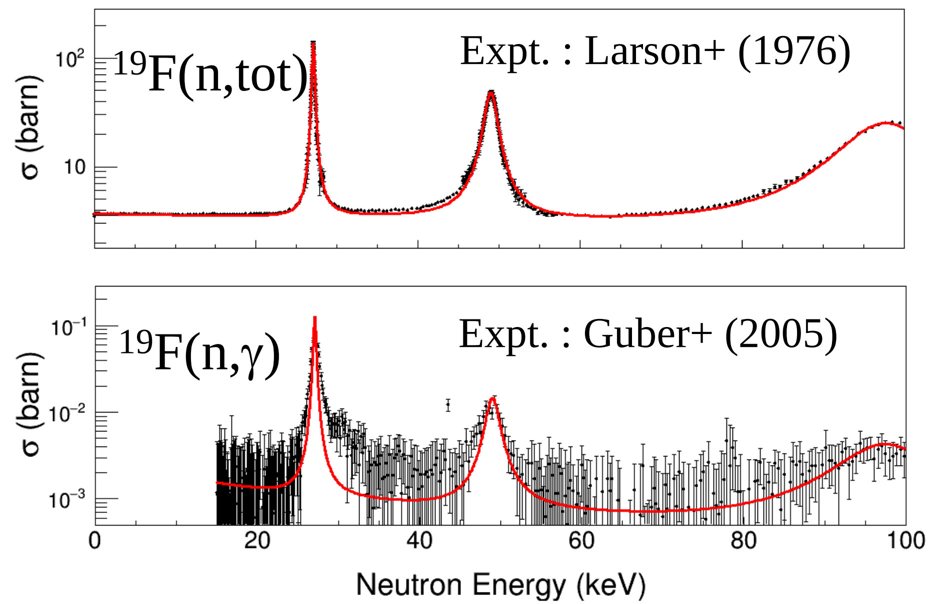
$$\left(\frac{d\sigma}{d\Omega}\right)_{el.} \sim \left|A_{coul} + A_{nucl}\right|^2$$

- Reich-Moore approximation was introduced

$$R_{cc'} = \sum_{\lambda} \frac{\gamma_{\lambda c}\gamma_{\lambda c'}}{E_\lambda - E - i\Gamma_{\lambda\gamma}/2}$$

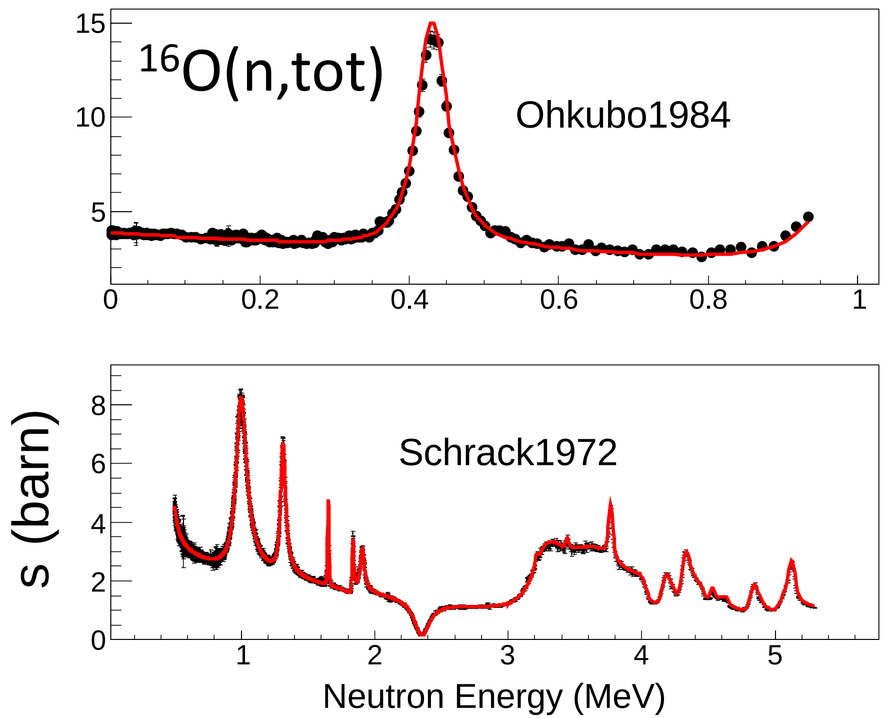
(optional)



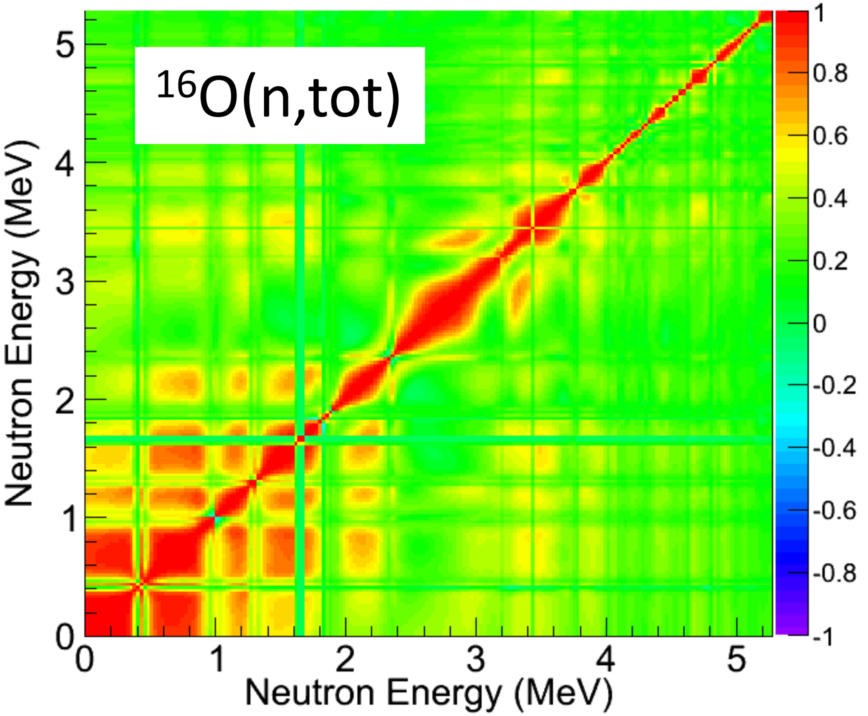


Analysis of ^{17}O System

Shape analysis (norm.-free)



Correlation matrix

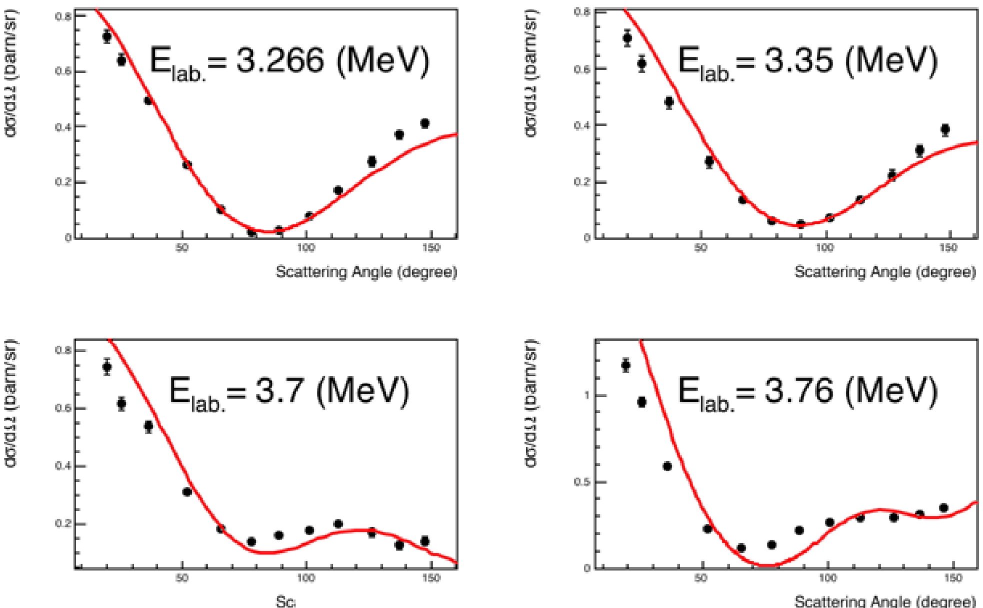


Re-normalization found to be **<u>~1.0 (uncertainty < 0.5%)</u>**

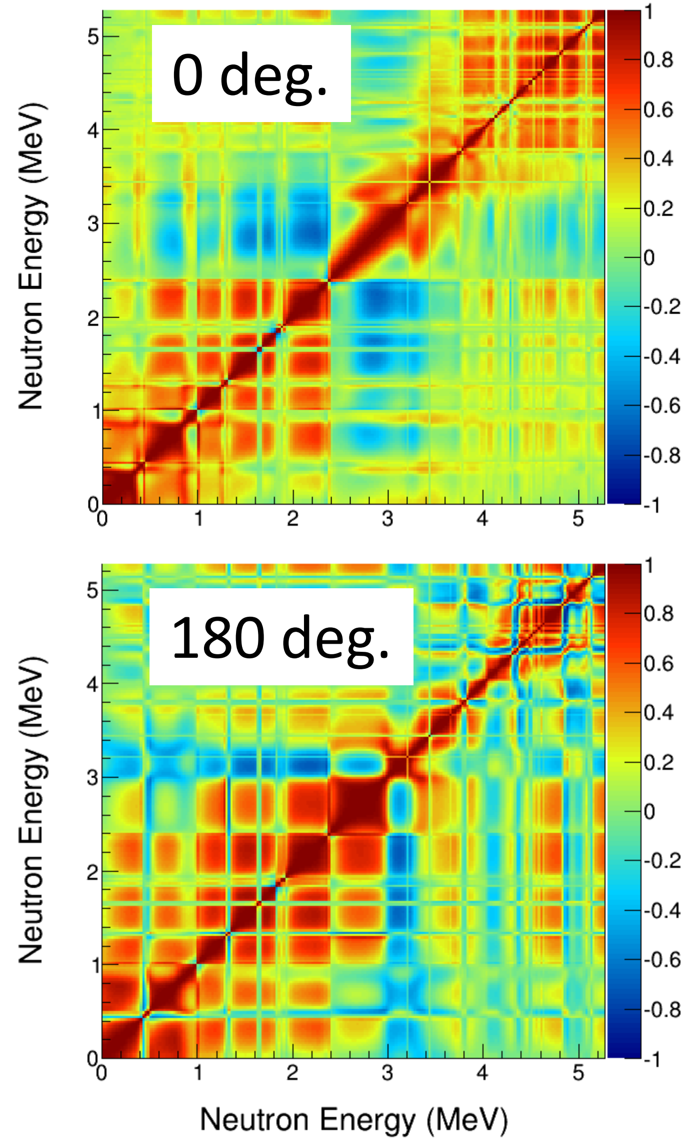
You can see traces of **<u>the (near) unitary limit</u>**

Analysis of ^{17}O System

^{16}O(n,el), $d\sigma(\theta)/d\Omega$

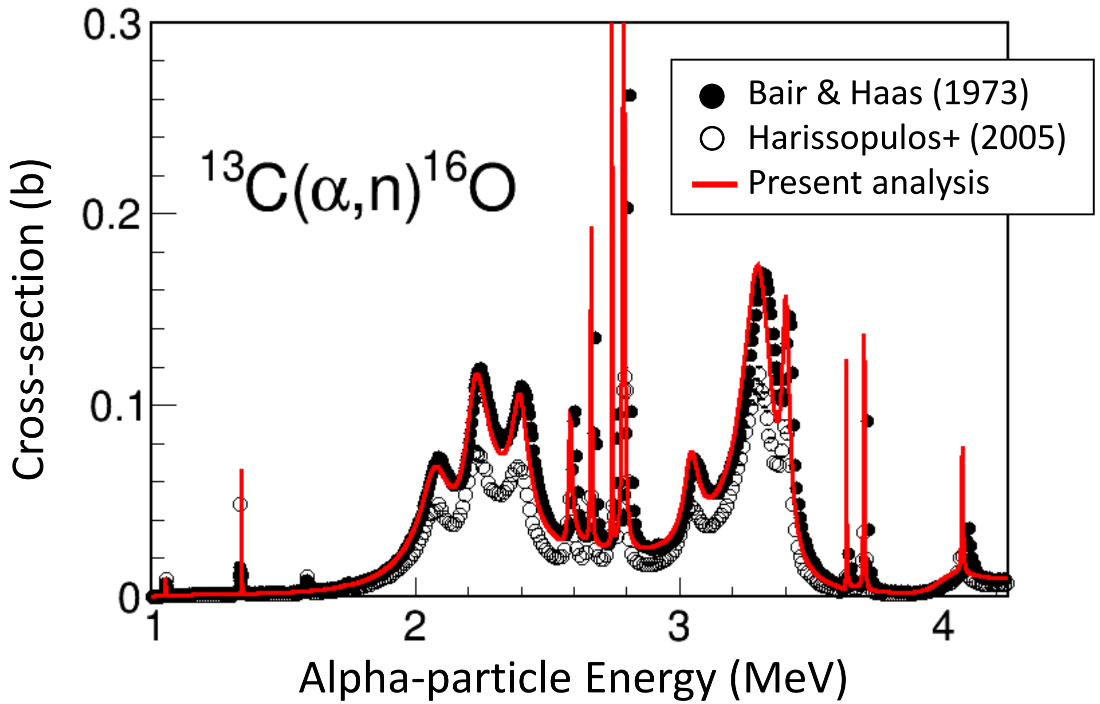


Scattering Angle (deg.)



<u>Much constraints</u> should be expected from corresponding measurements.

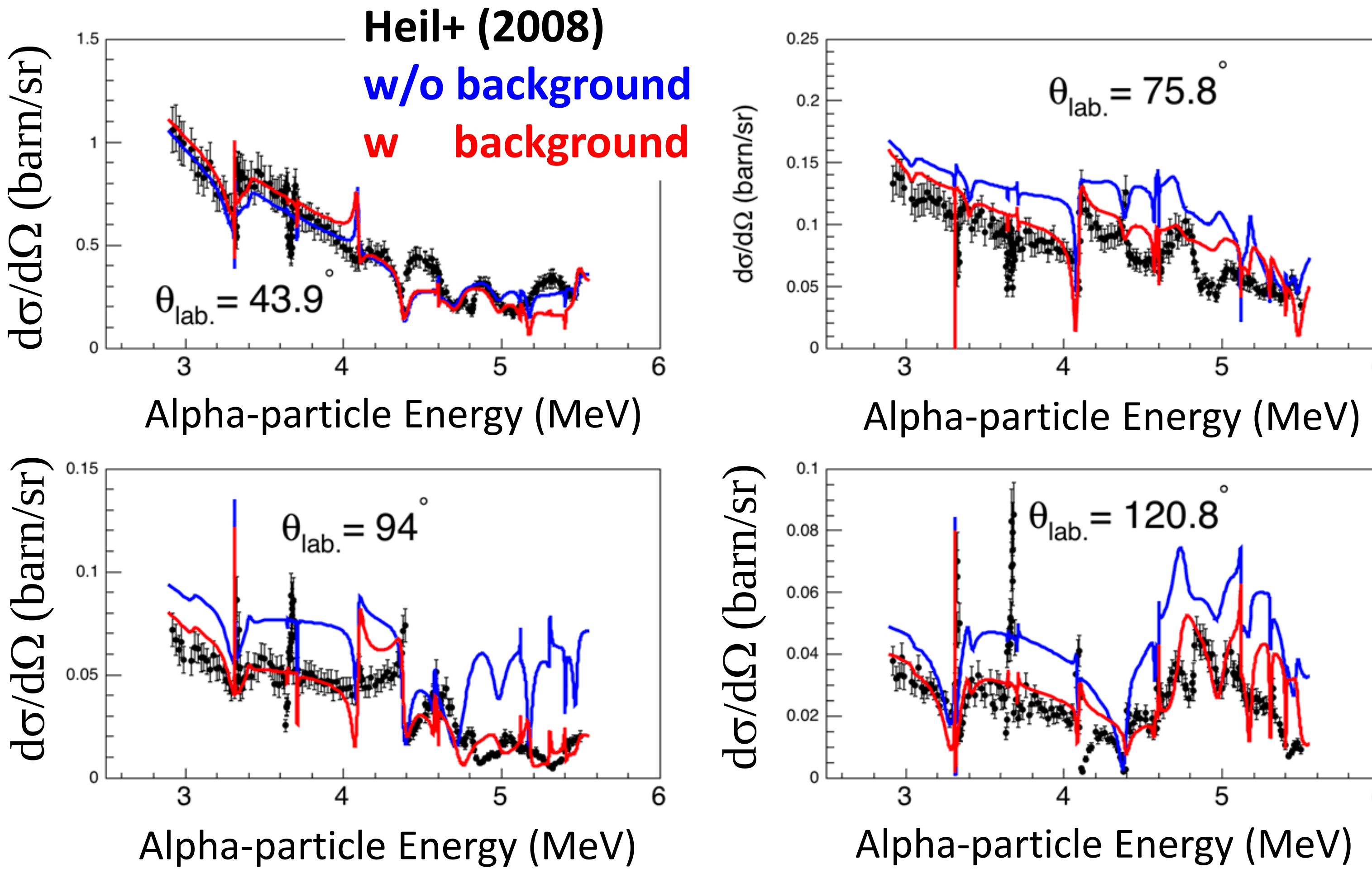
Analysis of ^{17}O System



- Simultaneous analysis with $^{16}O(n,tot)$
- Difference of measurements could be solved
- Consistent with preceding results by EDA (G.Hale & M.Paris, Los Alamos)

Issue in $^{13}C(\alpha,\alpha)$ Scattering

If **large backgrounds** are add **only to elastic channels**, situation becomes much better (thanks to deBoer).



How we should give Background ?

In **simultaneous** analysis : $^{16}O(n,x)$, $^{13}C(\alpha,x)$,

$$R_{cc'} = \sum_{\lambda} \frac{\gamma_{\lambda c}\gamma_{\lambda c'}}{E_\lambda - E - i\Gamma_{\lambda\gamma}/2} + R_\infty^{(dist.)} + R_\infty^{(n)} + R_\infty^{(\alpha)}$$

$R_\infty^{(n)}$: from only "neutron" channels

$R_\infty^{(\alpha)}$: from only "α-particle" channels

What is the sources ?

1. **Shape-elastic (correction to hard-sphere)**
2. **Compound states (from distant levels)**
3. Any others ? (e.g., direct reactions ?)

What is the "*Tricks*" ?

(1. Trick on theoretical backgrounds)

$$R_{cc'} = \sum_{\lambda} \frac{\gamma_{\lambda c}\gamma_{\lambda c'}}{E_\lambda - E - i\Gamma_{\lambda\gamma}/2} + R_\infty^{(dist.)} + R_\infty^{(n)} + R_\infty^{(\alpha)}$$

$R_\infty^{(n)}$: from only "neutron" channels

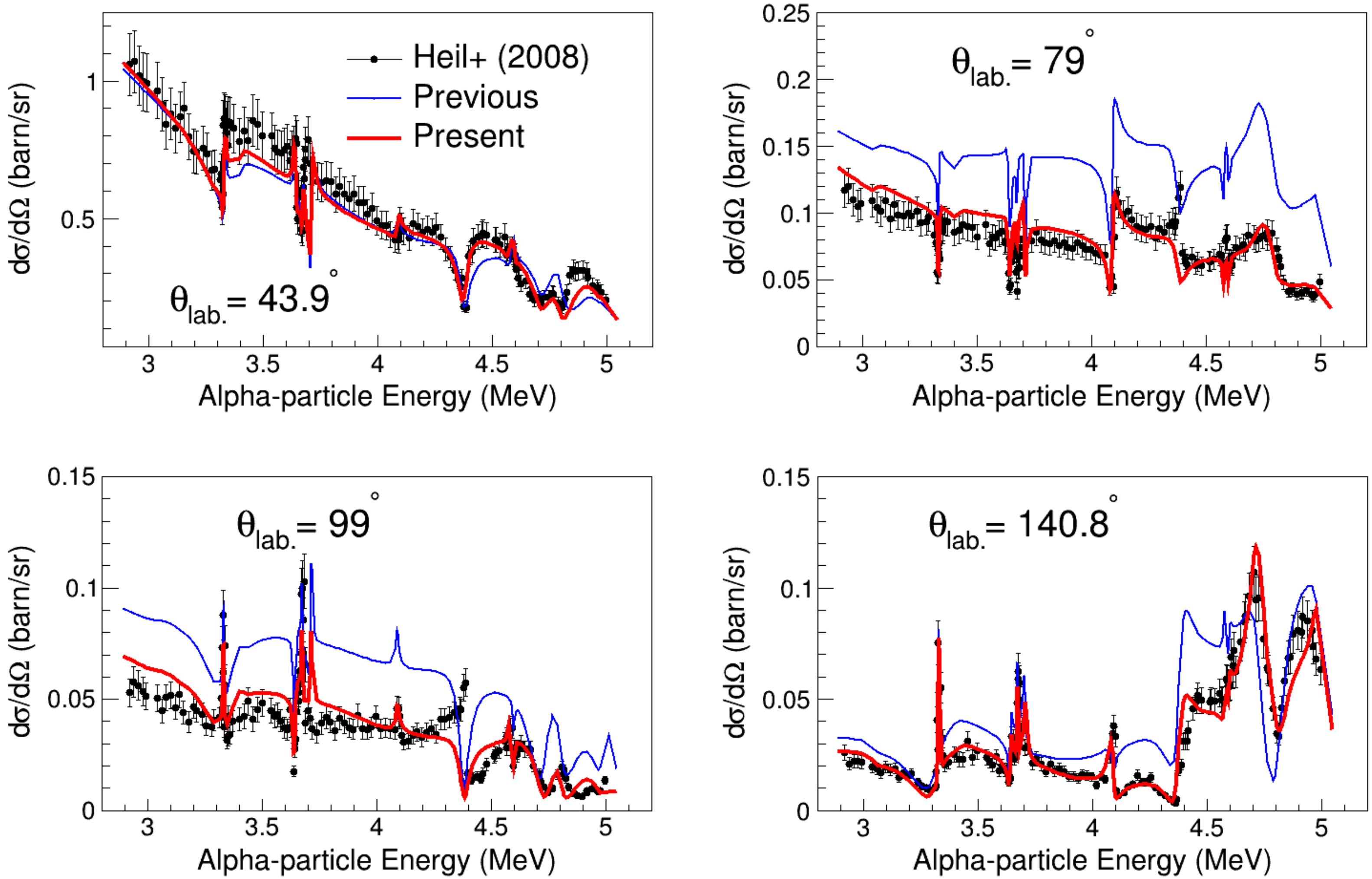
$R_\infty^{(\alpha)}$: from only "α-particle" channels

(2. Trick on radius values)

	Channel radius	Hard-sphere radius
n + ^{16}O	4.66 (fm)	4.34 (fm)
α + ^{13}C	6.90 (fm)	5.55 (fm)

Both tricks are necessary to obtain simultaneous fits

Problem could be "*Technically*" Solved



I did some simple "tricks" on the R-matrix

Recent Progress (POL/ANA,DA)

Now ready to analyze POL/ANA

Analytical formulae for ½ particle

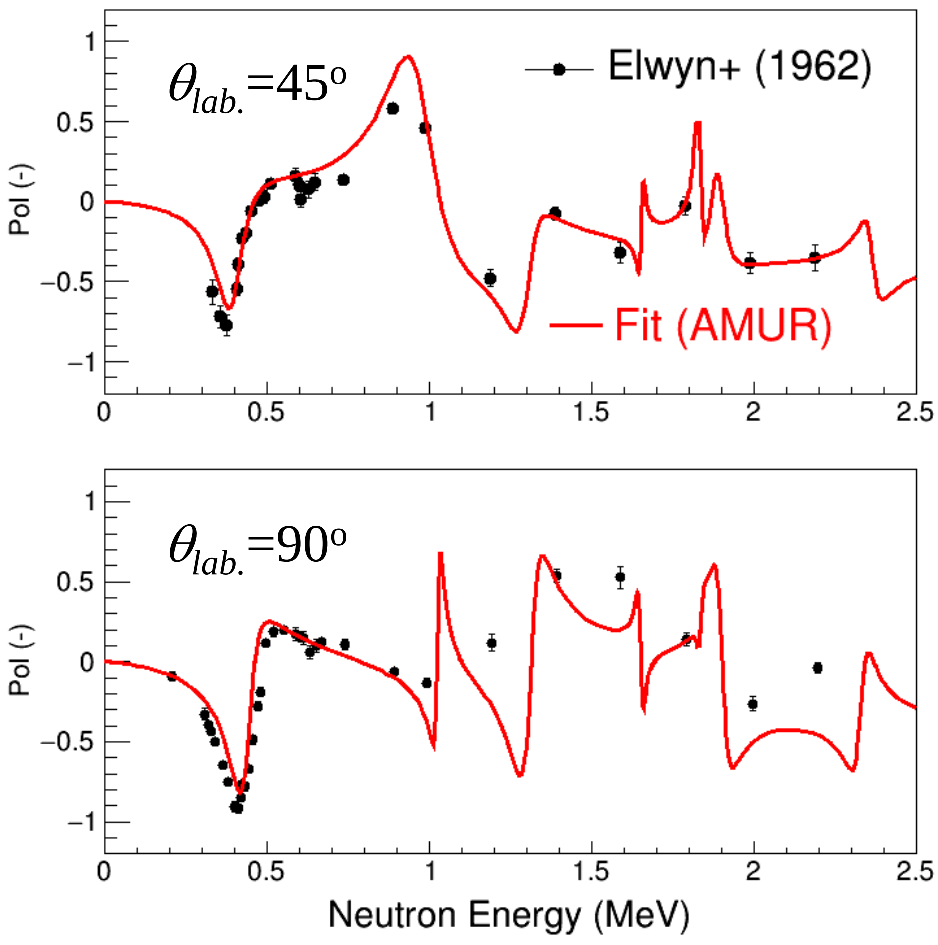
$$Pol(\theta) = \mathrm{Re}\left(\frac{A^* B + A B^*}{|A| + |B|} \right)$$

where,

$$A(\theta) = \frac{i}{2k} \sum_{s,l=0} \left[(l+1) T_{cc'}^{J=|l+s|} + l T_{cc'}^{J=|l-s|} \right] P_l(\theta)$$

$$B(\theta) = \frac{1}{2k} \sum_{s,l=1} \left[T_{cc'}^{J=|l+s|} - T_{cc'}^{J=|l-s|} \right] P_l^1(\theta)$$

$^{16}O(n,n_0)$, POL, DA

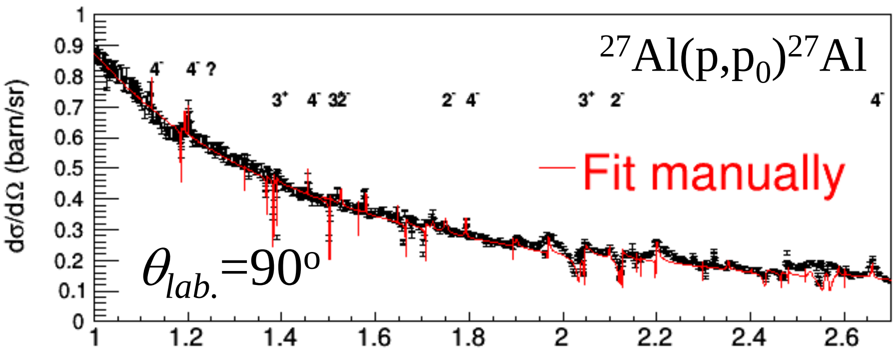


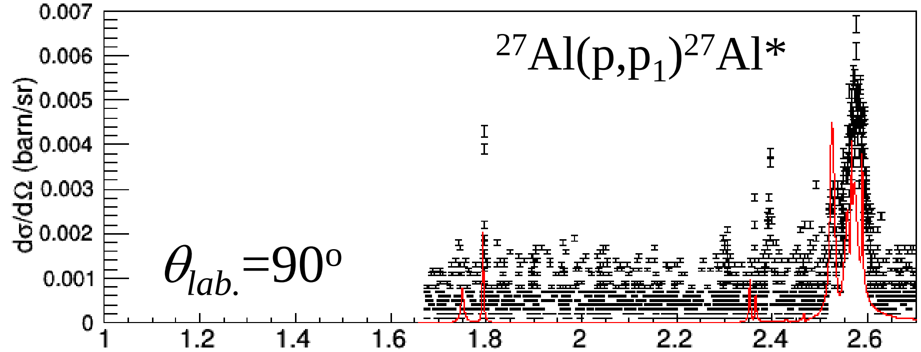
Analysis for ^{28}Si System

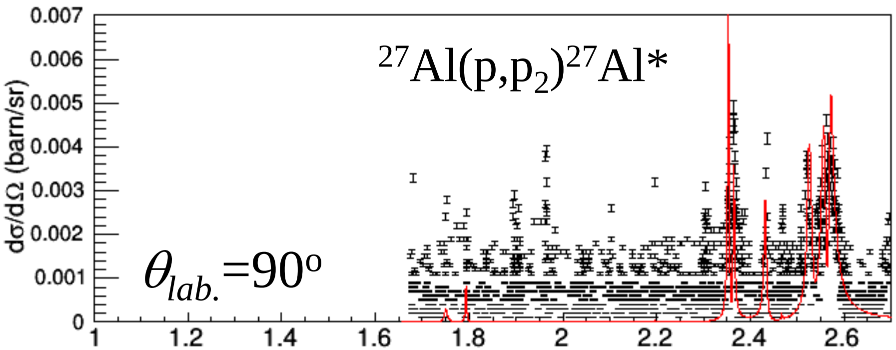
Q. How we obtain the initial parameters ???

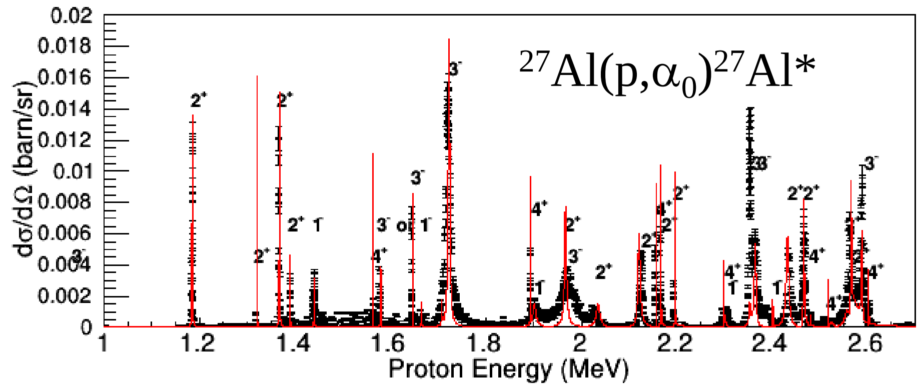
- Experimental data -> Nelson1984 (Ep<3MeV)
- Reactions -> $^{27}Al(p,p_0)$, (p,p_1), (p,p_2), (p,α_0), (p,α_1)
- ^{28}Si levels -> ENSDF (0^+, 2^-, 2^+, 3^-, 3^+, 4^-, 4^+)

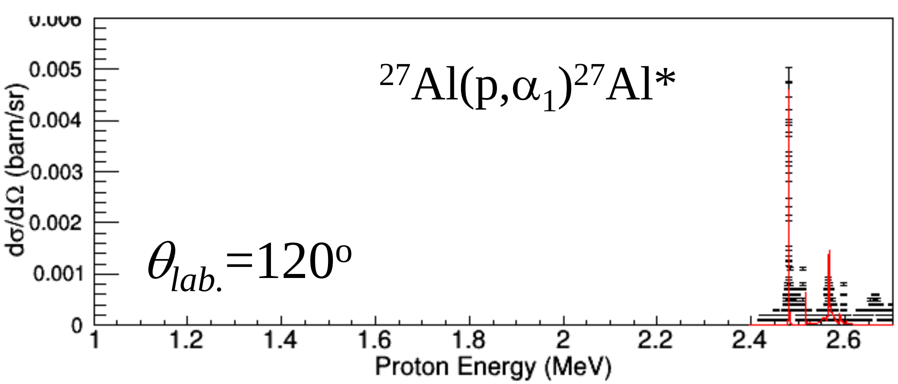
Analysis for ^{28}Si System











- E_λ values were “fixed” to ENSDF.
- R_c, B_c, γ_c were given manually.

→ Reasonable “initial guess”

Analysis for ^{28}Si System

Good points

- Exploit the knowledge from structure measurements (ENSDF).
- "Physically accountable" resonance parameters (?)

Bad points (?)

- Can not employ "FILE-2" in ENDF-6 format (use FILE-3&6).

(E_R values are required for the "reconstruction")