IAEA Technical meeting on (a,n) …, Nov. 8-12 (2021)

A correction to *non*-resonant process for elastic channels in R-matrix analysis

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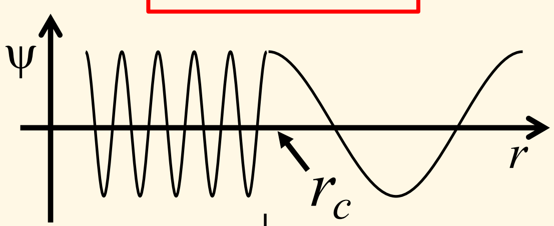
Contents

What is R-matrix ?

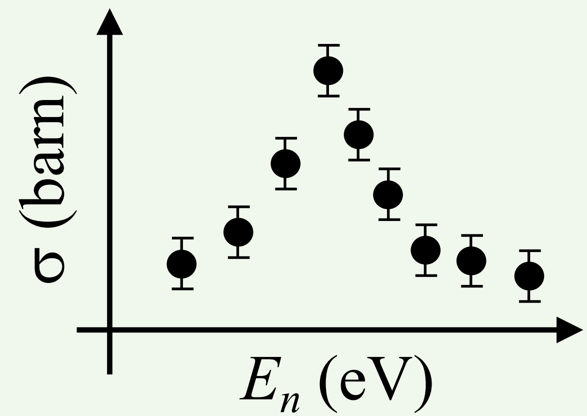
R-matrix — *fitting* → Experimental C.S.



Internal (X) ↔ External (φ)

Reduced-width amplitude $\gamma_c \sim \int \varphi_c^* X_c dS$

+



⇨ S-matrix ⇨ Cross-section evaluation

- ✓ Strictly based on the quantum mechanics
  (under the boundary condition : *R_c , B_c~l, and hard-sphere*)
- ✓ Good collabo. between the experiment and theory

AMUR (A MUlti-channel R-matrix Code)

Evaluation tool for the resonant cross-sections

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

KALMAN method (GLSQ)

$\longrightarrow$ Parameter & covariance

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

- *Renormalization*
- *Resolution, etc…*

Dynamic link (Object-oriented)

- ◆ C++ classes (operated on, e.g., ROOT/CLING)
- ◆ Multi-threads
- ◆ Easy access to EXFOR (C4/C5)

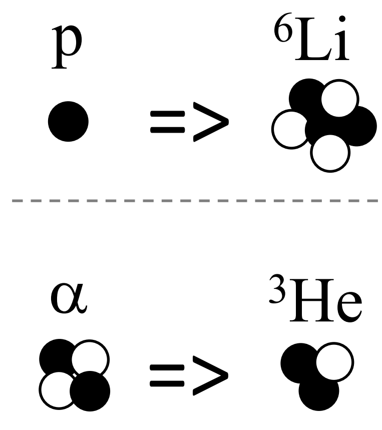
Test case @IAEA (Objective-1) 2017

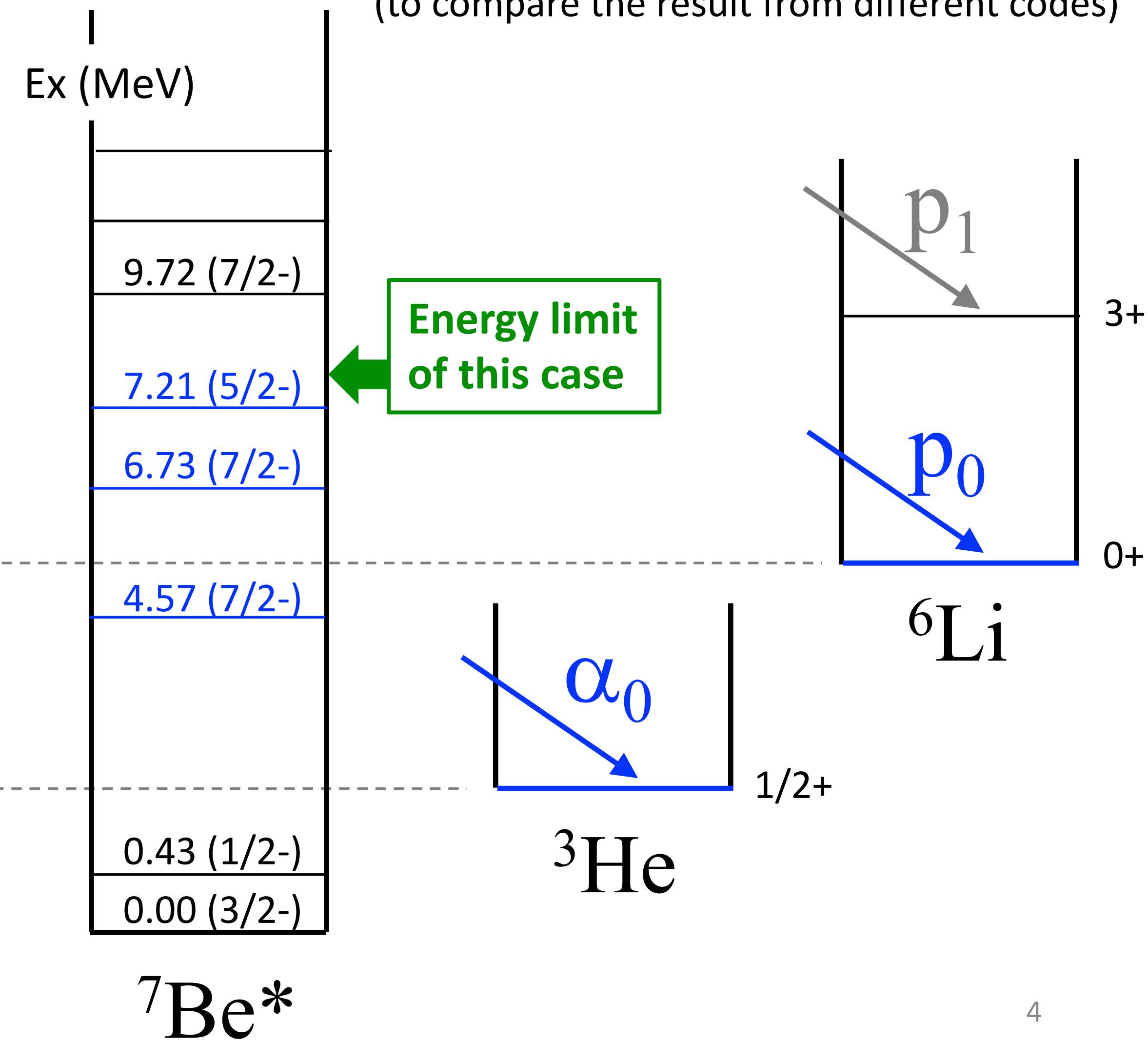
Objective : Simultaneous fit of experimental data for

^{6}Li(p,α_0), (p,p$_0$)

^{3}He(α,p$_0$), (α,α_0)

(to compare the result from different codes)





Very simple problem !

Test case @IAEA (Objective-1) 2017

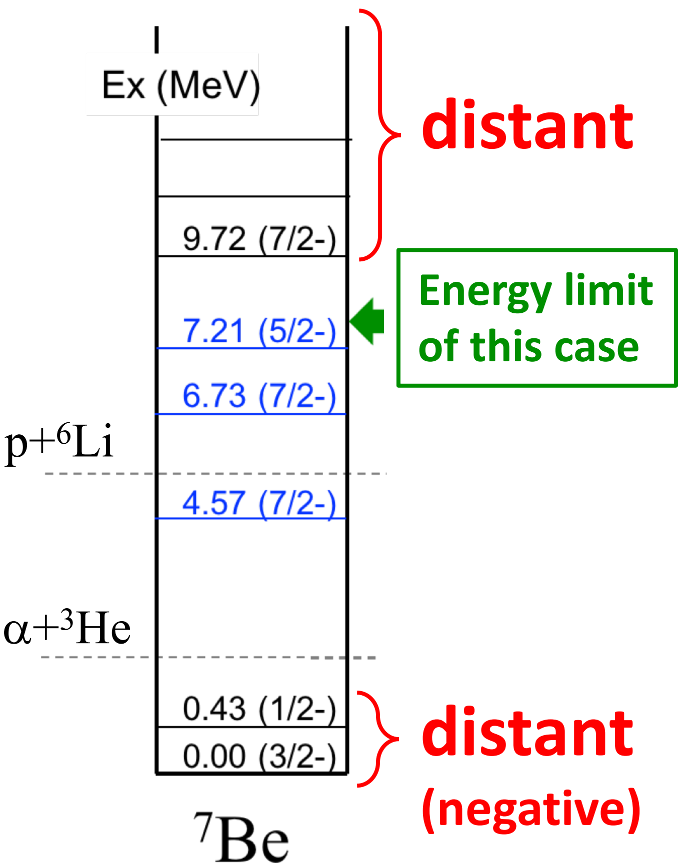
Experimental data to be fitted

Ref.	data type	% syst. unc.	file name	source
[1]	$^3He(\alpha,\alpha)^3He$, $\frac{d\sigma}{d\Omega}$	5	Barnard_aa.dat	EXFOR (A1269002)
[8]	$^3He(\alpha,\alpha)^3He$, $\frac{d\sigma}{d\Omega}$	?	Mohr_aa.dat	EXFOR (D0147002)
[10]	$^3He(\alpha,\alpha)^3He$, $\frac{d\sigma}{d\Omega}$	5	Tombrello_aa.dat	EXFOR (A1039002, A1039003)
[9]	$^3He(\alpha,\alpha)^3He$, $\frac{d\sigma}{d\Omega}$	1.5	Spiger_aa.dat	EXFOR (A1094006)
[9]	$^3He(\alpha,p_0)^6Li$, $\frac{d\sigma}{d\Omega}$	1.5	Spiger_ap0.dat	EXFOR (A1094008)
[7]	$^6Li(p,p)^6Li$, $\frac{d\sigma}{d\Omega}$	5	McCray_pp.dat	EXFOR (A1410002)
[4]	$^6Li(p,p)^6Li$, $\frac{d\sigma}{d\Omega}$	-	Fasoli_pp.dat	EXFOR (D0135002, D0135003)
[6]	$^6Li(p,p)^6Li$, $\frac{d\sigma}{d\Omega}$	-	Harrison_pp.dat	EXFOR (F0018002)
[3]	$^6Li(p,\alpha)^3He$, $\frac{d\sigma}{d\Omega}$	9	Elwyn_pa.dat	EXFOR (F0012002), (F0012003)
[2]	$^6Li(p,\alpha)^3He$, $\frac{d\sigma}{d\Omega}$	10	Lin_pa.dat	EXFOR (A1539002)
[5]	$^6Li(p,p_1)^6Li$, $4\pi a_0$	-	Harrison_pp1.dat	EXFOR (A1397003)
[5]	$^6Li(p,p_1)^6Li$, $\frac{d\sigma}{d\Omega}$	-	Harrison_pp1_ang_dists.dat	EXFOR (A1397002)
[9]	$^3He(\alpha,p_1)^6Li$, $\frac{d\sigma}{d\Omega}$	1.5	Spiger_ap1.dat	EXFOR (A1094009)

Prepared by J. deBoer

Standard(?) Approach

$$R_{cc'} = R_{cc'}^{levels} + R_{cc'}^{dist.}$$



AMUR:

Experimental data

^{6}Li(p,α_0), ^{6}Li(p,p_0), ^{3}He(α,p_0)

Fitting was successful

Experimental data

^{6}Li(p,α_0), ^{3}He(α,p_0), ^{3}He(α,α_0)

Fitting was successful

Experimental data

^{6}Li(p,α_0), ^{6}Li($\underline{p,p_0}$), ^{3}He(α,p_0), ^{3}He($\underline{\alpha,\alpha_0}$)

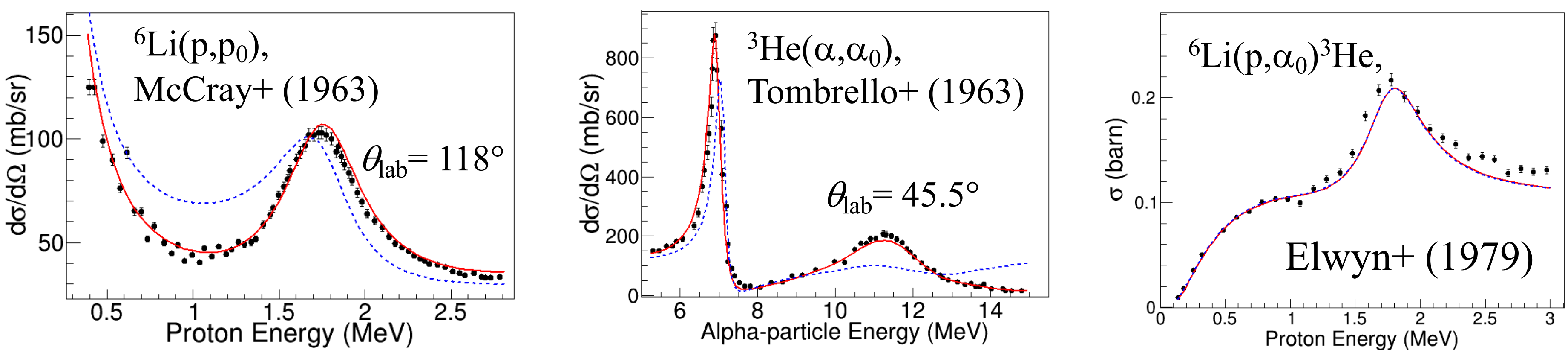
Fitting was NOT Successful !

A Correction to *Non*-resonant Process

Distant poles (pseudo/distant levels) were added <u>independently</u> for incident particles : p and α

$$R_{cc'} = R_{cc'}^{levels} + R_{cc'}^{dist.} + R_{cc}^{ind.}$$

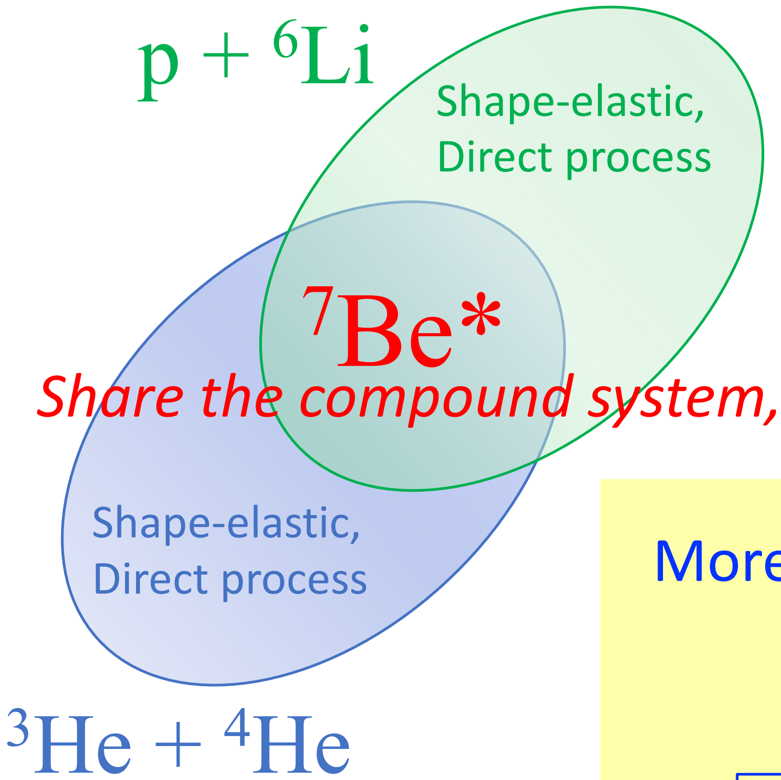
Example results



— With $R_{cc}^{ind.}$ .... $R_{cc}^{ind.}$ is switched off

Effect of $R_{cc}^{ind.}$ is clearly observed here …

Independent theoretical-backgrounds ?



..., However,
shape-elastic (direct process)
should be independent among the
different projectiles

More general R-matrix formalism *could be* :

$$R_{cc'} = R_{cc'} + R^{dist.}_{cc'} + R^{\infty}_{c}$$

Distant poles independent of
the incident particles, only to elastic
(correction to the hard-sphere ?)

Heil's Paper on $^{13}C(\alpha,n)$

PHYSICAL REVIEW C **78**, 025803 (2008)

The $^{13}C(\alpha, n)$ reaction and its role as a neutron source for the *s* process

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The $^{13}C(\alpha, n)^{16}O$ reaction constitutes the dominant neutron source for the main *s* process, which operates at a thermal energy of $kT = 8$ keV. Since the cross section at stellar energies is very small, the reaction rate cannot be directly determined and has to be extrapolated from cross section results obtained at higher energies. To remove various discrepancies in the normalization of previous data sets and to subsequently improve the reliability of the extrapolation, we performed measurements of the $^{13}C(\alpha, n)^{16}O$ reaction in the energy range $E_{c.m.} = 320$–700 keV. In addition, the double differential scattering cross section $^{13}C(\alpha, \alpha)^{13}C$ was measured in the energy range $E_{lab} = 2.6$–6.2 MeV for 28 angles. These data were used to constrain possible contributions from background resonances for a reliable extrapolation with the multichannel *R*-matrix code SAMMY. As a result, the uncertainties were significantly reduced, and a reaction rate of $(4.6 \pm 1.0) \times 10^{-14}$ cm^3/moles at $kT = 8$ keV ($T = 0.1 \times 10^9$ K) was determined.

I think that was very excellent work.

- Experimental work for 13C(a,n)16O and 13C(a,a)13C
- R-matrix analysis for 16O(n,tot), 16O(n,n)16O, …

Heil's Paper on $^{13}C(\alpha,n)$

However, in page 7

The large amount of new experimental low-energy α capture and scattering data necessitates a new, comprehensive R-matrix study. To increase the reliability of the extrapolation toward low energies, a multichannel R-matrix analysis was carried out using the code SAMMY [36] including all open reaction channels for the $^{13}C+\alpha$ and the $^{16}O+n$ system. In this approach, we have fitted simultaneously all available experimental data on $^{13}C+\alpha$ and $^{16}O+n$ reaction and scattering channels including the full set of bound states in ^{17}O and unbound resonance states up to 10 MeV excitation energy. Since the entrance channel configurations $^{16}O+n$ and $^{13}C+\alpha$ cannot be fitted simultaneously with the R-matrix code SAMMY, both configurations were treated separately, and the

→ **The same situation, as my analysis for $^{7}Be^{*}$**

Summary/Conclusion(?)

It was very difficult (impossible?) to fit experimental data of (p,p) and (a,a) simultaneously with the normal approach on the R-matrix fit.

Additional distant poles are probably needed for the elastic scatt. process (independent distant poles for the incident particle)

The same situation is found in study of Heil et al.

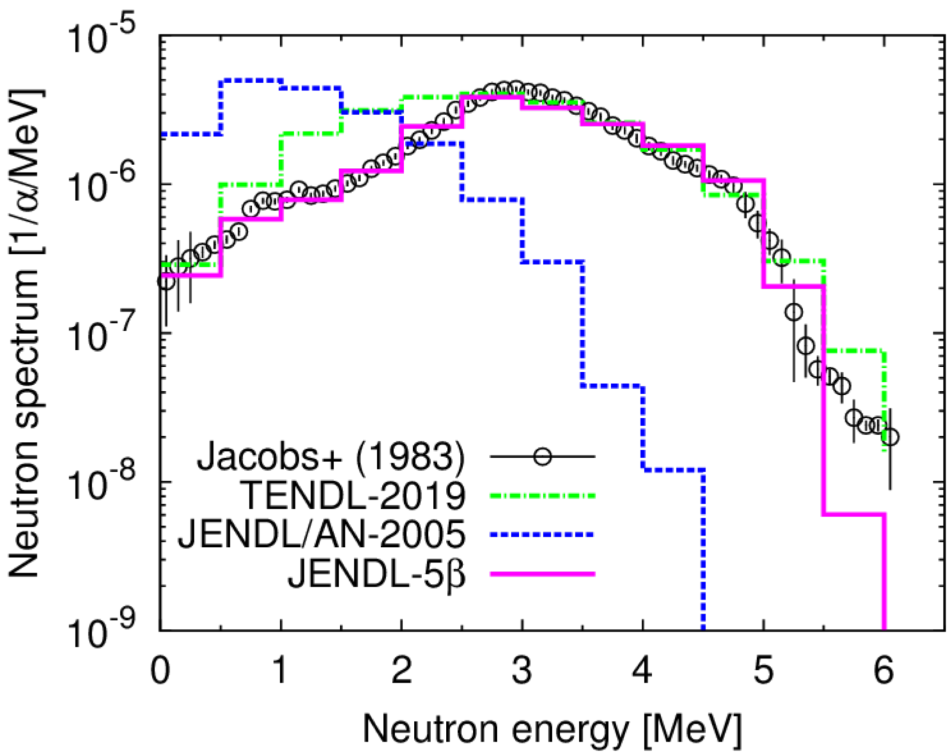
Appendix: α sub-library of JENDL-5

- In JENDL/AN-2005, neutron emission data of the (α,xn) reactions up to 15 MeV were evaluated **on the 17 light nuclei (Li – Si).**

→ They were validated by experimental thick target neutron yields.

- Following the work by NNL, energy and angular distribution are modified (thanks to J.-C. Sublet and S. Okumura (IAEA)).

D.P. Griesheimer et al., Nucl. Eng. Technol. **49**, 1199 (2017).



Neutron spectrum from thick BN + α-particles (5.5MeV)

Objective 1

particle pair 1		
light particle:	^{4}He	
	J =	0
	π =	+
	M =	4.0026
	Z =	2
heavy particle:	^{3}He	
	J =	0.5
	π =	+
	M =	3.01603
	Z =	2
Excitation Energy =	0	
Separation Energy =	1.587	
particle pair 2		
light particle:	^{1}H	
	J =	0.5
	π =	+
	M =	1.0078
	Z =	1
heavy particle:	^{6}Li	
	J =	1
	π =	+
	M =	6.0151
	Z =	3
Excitation Energy =	0	
Separation Energy =	5.6068	

Level 1		
	E_x =	0
	J^π =	$3/2^-$
	$(\mathrm{ANC},\gamma)_\alpha^{1/2,1}$ =	5.0,1.8
Level 2		
	E_x =	0.429
	J^π =	$1/2^-$
	$(\mathrm{ANC},\gamma)_\alpha^{1/2,1}$ =	5.0,3.0
Level 3		
	E_x =	4.56
	J^π =	$7/2^-$
	$\Gamma_\alpha^{1/2,3}$ =	0.157
Level 4		
	E_x =	6.75
	J^π =	$5/2^-$
	$\Gamma_\alpha^{1/2,3}$ =	1.345
	$\Gamma_{p_0}^{3/2,1}$ =	0.003
Level 5		
	E_x =	7.23
	J^π =	$5/2^-$
	$\Gamma_\alpha^{1/2,3}$ =	0.293
	$\Gamma_{p_0}^{3/2,1}$ =	0.508

Boundary parameters are fixed to B=-l, R=1.4($A_1^{1/3}+A_2^{1/3}$) fm

Include Levels 1-5 together with distant poles at E_λ=20 MeV

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