R-matrix Analysis of ^{8}Be System

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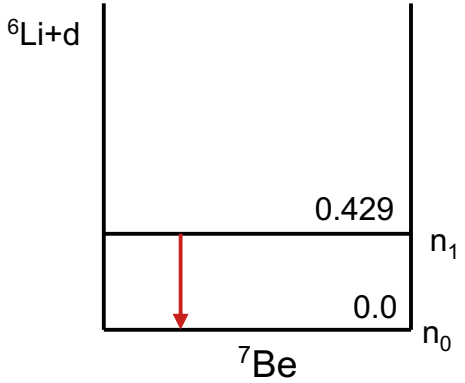
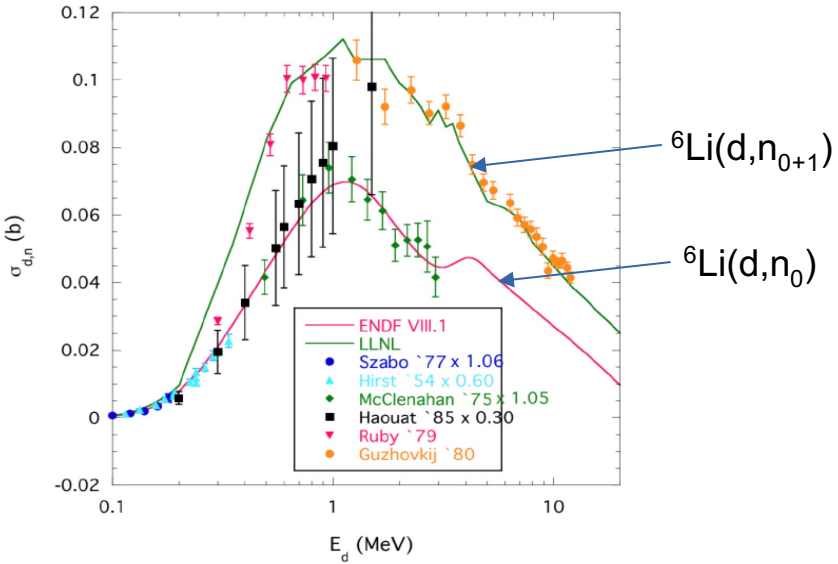
Outline

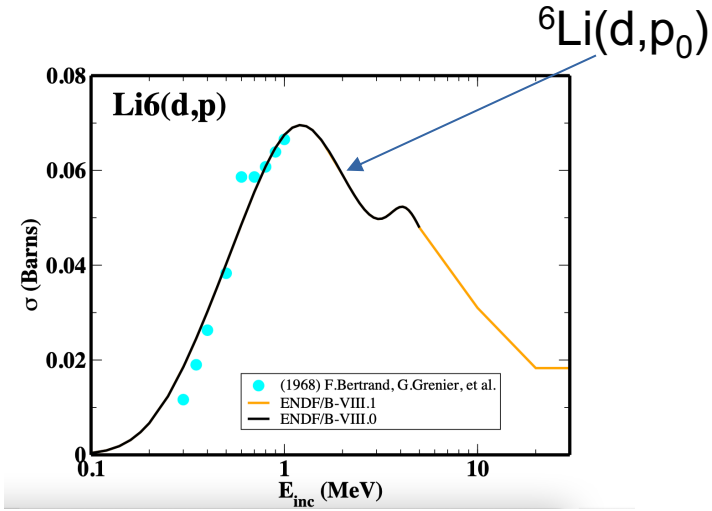
- Motivation
- New Measurement of deuterium induced reactions on ^{6}Li
  - Experimental details
  - Preliminary results
- *R*-matrix analysis of ^{8}Be
  - Preliminary results
  - Comparisons with Energy Dependent Analysis (EDA) code from LANL

Motivation

- Deuterium induced reactions on ^{6}Li are important for nuclear structure and nuclear astrophysics.
- ENDF/LANL includes only (d,n_0) and (d,p_0) partial cross sections. LLNL-2010 is consistent describing ^{6}Li(d,n_{0+1}) but their ^{6}Li(d,p) calculation seems to be only ^{6}Li(d,p_0).
- The inconsistencies in the *R*-matrix evaluations from literature demands new measurements and new *R*-matrix evaluation of ^{8}Be system including more channels.



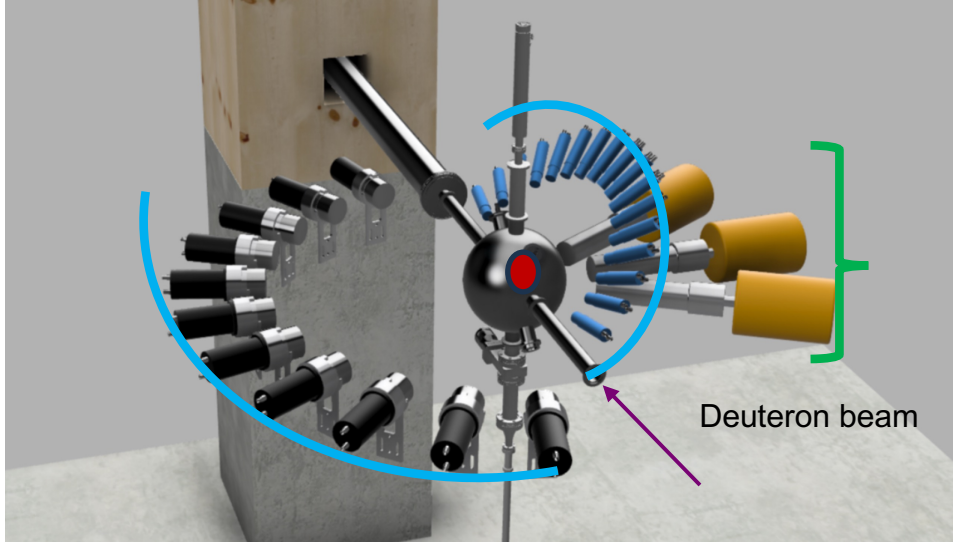


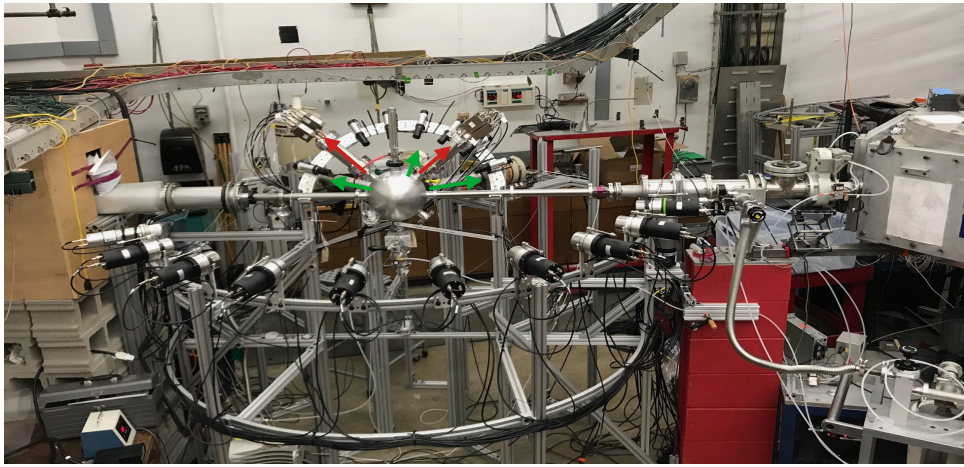


2010 LLNL vs 2004 LANL (from CSEWG talk by Ian Thompson c.a. 2017)

Experimental Details

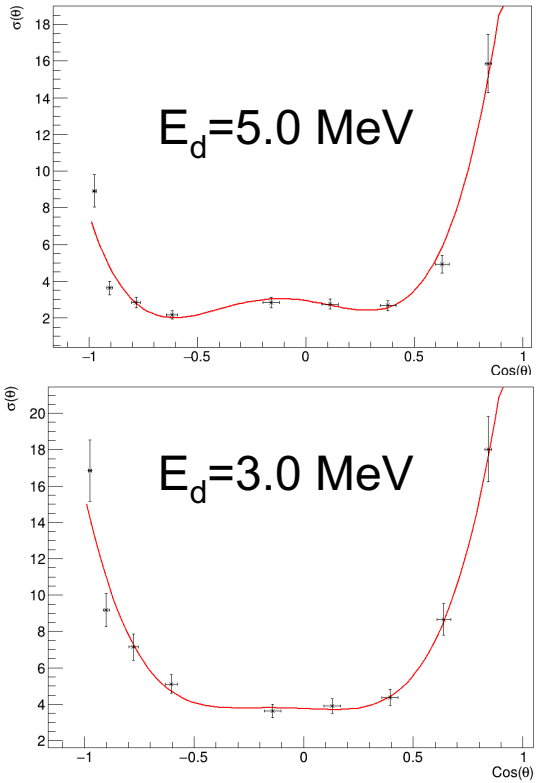
- Performed at University of Notre Dame using FN Tandem in collaboration with ORNL and LANL.
- Thin target: 200 ug/cm^2 metallic ^{6}Li on 20ugm/cm^2 C backing.
- E_d=1.8-15.0 MeV
- Neutrons: detected by Deuterated Liquid Scintillator Array (ODeSA)
  - Angular coverage 10 – 170 degrees
  - TOF spectra
- Charged Particles: detected by Silicon detectors placed at 45^o and 135^o.
  - Set up as E-dE1-dE2 array.
- Gammas: detected by 3 detectors
  - (HpGe+ GEANIE) at 45^o, 90^o and 135^o degrees.
- Also had 20 stilbene neutron detectors
- Activation measurement was also performed. (Results included in *R*-matrix fit)



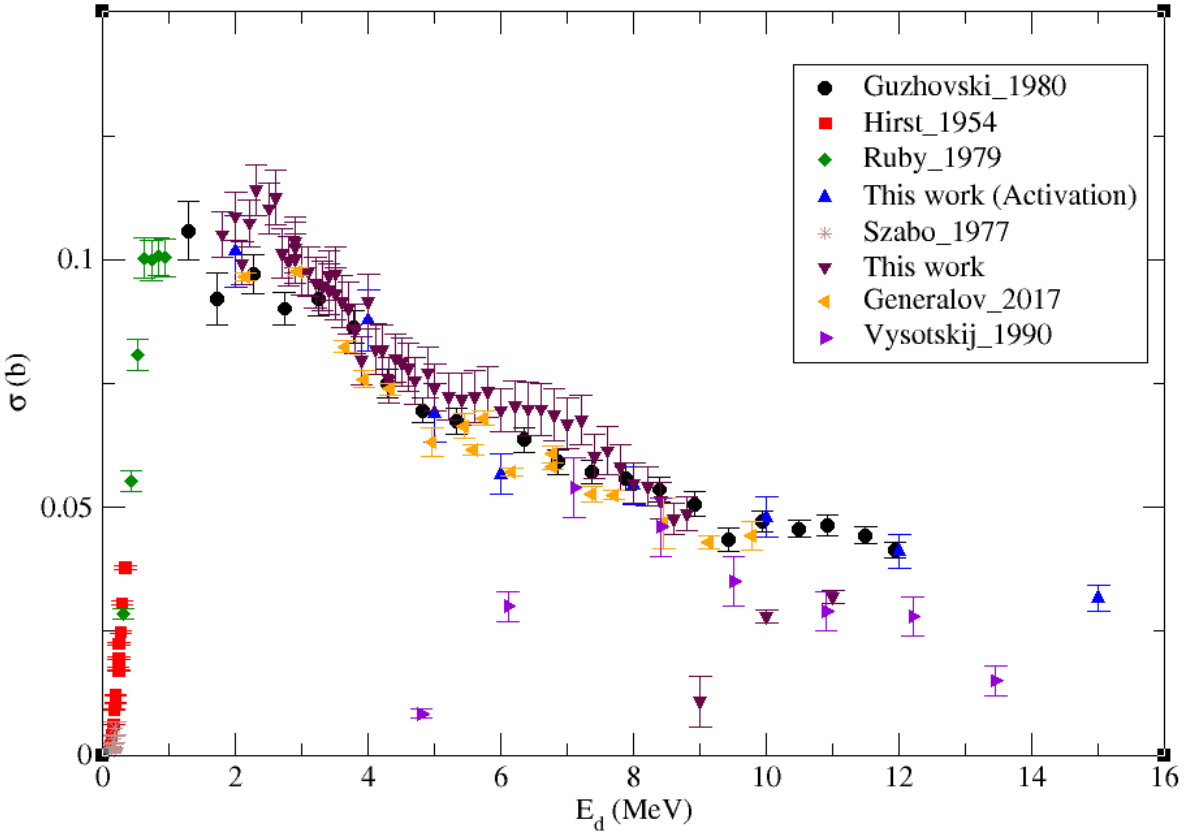


$^{6}Li(d,n_{0+1})^{7}Be$ Analysis

Angular distributions



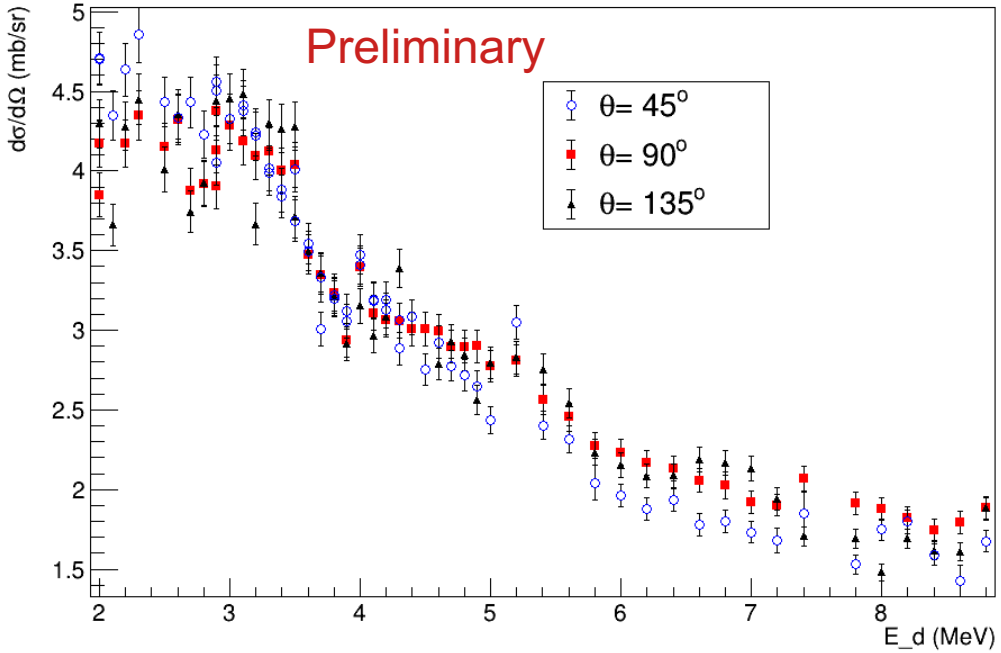
Integrated Cross Sections



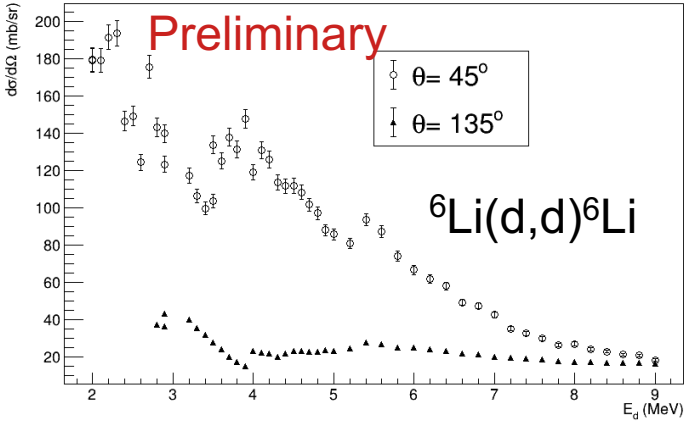
Results: statistical error bar only

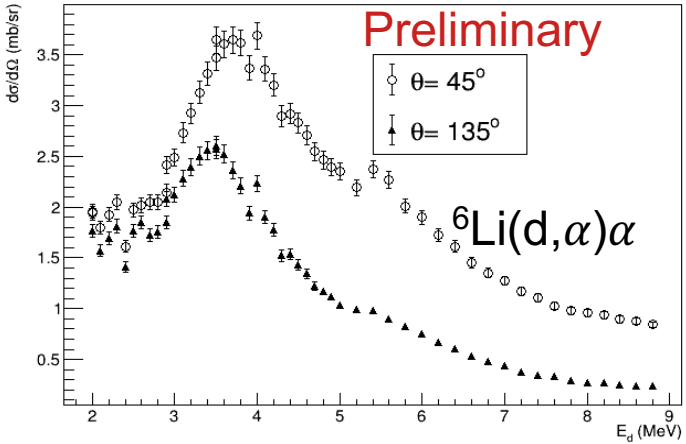
Gamma Angular distributions from $^{6}Li(d,n_1)^{7}Be$

- $^{6}Li(d,n_1)^{7}Be$ produces 429-keV gammas, detected by three gamma detectors.
- The integrated cross section would provide the $^{6}Li(d,n_1)^{7}Be$ component which in could be subtracted from $^{6}Li(d,n_{0+1})^{7}Be$ to determine $^{6}Li(d,n_0)^{7}Be$ cross sections.

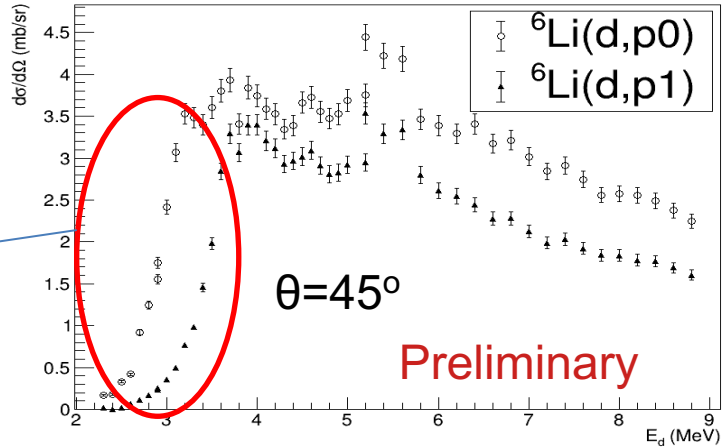


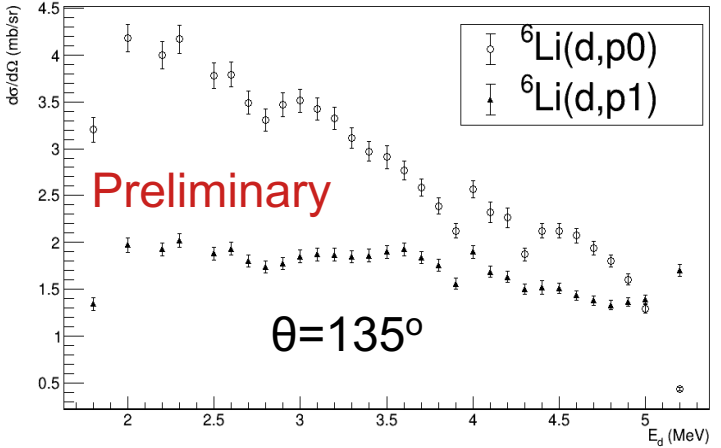
Charged Particle Channels





Threshold effects in Si detector





These results will be included in the *R*-matrix analysis of ^{8}Be system.

R-matrix Analysis of ^{8}Be System with AZURE2

- Goal: Multichannel *R*-matrix analysis to describe the ^{8}Be system.
- Ongoing Work: Simultaneous fitting of data for ^{8}Be compound nucleus including various channels.
- The data included so far are for these reaction channels:

^{6}Li(d,d)^{6}Li	^{7}Li(p,p)^{7}Li*
^{6}Li(d,α)α	^{7}Li(p,n_0)^{7}Be
α(α,α)α	^{7}Li(p,n_1)^{7}Be
^{6}Li(d,n_0)^{7}Be	^{7}Li(p,α)α
^{6}Li(d,n_1)^{7}Be	α(α,p)^{7}Li
^{6}Li(d,p_1)^{7}Li	α(α,p)^{7}Li*
^{6}Li(d,p_1)^{7}Li	^{7}Be(n,p)^{7}Li
^{7}Li(p,p)^{7}Li	^{7}Be(n,γ)^{8}Be

Channel	Channel Radius (fm)
^{6}Li+d	6.4639
α+α	4.0
^{7}Be+n_0	4.15
^{7}Be+n_1	5.0
^{7}Li+p_0	4.15
^{7}Li+p_1	5.0

- Channel radius values for different channels taken from EDA calculations.
- Sensitivity to channel radius needs to be studied.
- The absolute normalizations of data are fixed at 1.

^{8}Be Levels Information

- Taken from NNDC
- The levels highlighted in red have not been included so far.
- The 22.63 MeV level was introduced with 1^+ spin, parity assignment.
- The 22.98 MeV level was introduced with 2^+ spin, parity assignment.
- The 21.5 MeV state used have negative parity.
- Max orbital angular momentum, l=4

Background Levels
0^+ at 32 MeV
2^+ at 32 MeV
4^+ at 32 MeV

Data Sources:
- EXFOR
- ^{6}Li(d,n)^{7}Be activation data from University of Notre Dame, 2022.
- Total data points: 1837

E(level) (keV)	XREF	Jπ(level)
0.0	ABCDE HIJKL PQRS UVW YZabcdef	0+
3030 *10*	ABCDE HIJKL PQRS UVW YZabcd f	2+
11.35E+3 *15*	CD JK P R UVW Z bcd	4+
16626 *3*	BCD HI KL PQR UVW YZabc	2+
16922 *3*	CD HI KL PQR UVW YZabc	2+
17640.0 *10*	E I L N PQ UVW Za c	1+
18150 *4*	I L N PQ UV Za	1+
18910	I LMN P T	2-
19069 *10*	I L N P UV	3+
19235 *10*	MN P TUVW Z e	3+

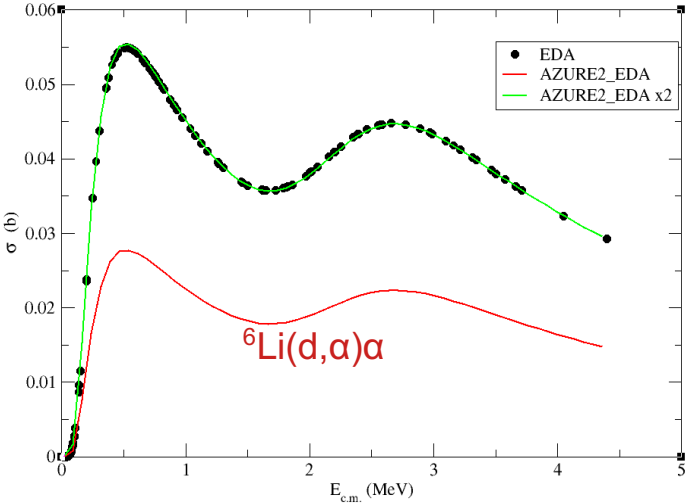
E(level) (keV)	XREF	Jπ(level)
19400	I MN U	1-
19860 *50*	D I K O RS VW Z	4+
20100	D MNOP S V Z	2+
20200	D M P Z	0+
20.9E+3	N	4-
21.5E+3	LM T Z	3(+)
22000	L	1-
22.05E+3 *10*	U W	2+
22.63E+3 *10*	K W	1+
22.98E+3 *10*	W	2+

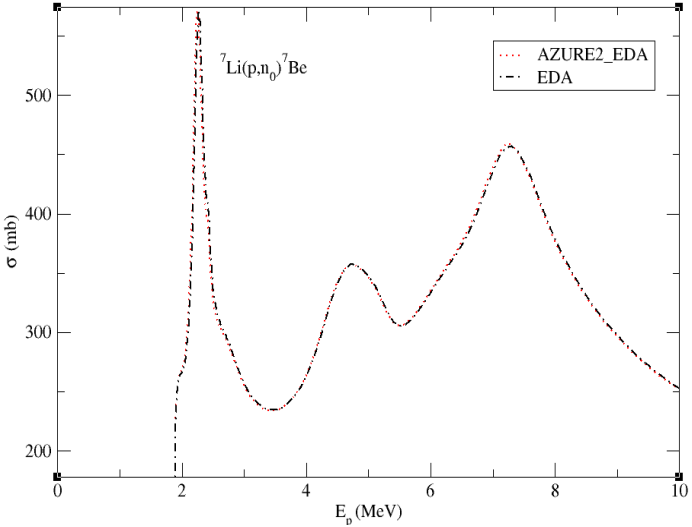
E(level) (keV)	XREF	Jπ(level)
24000	L O Z	(1,2)-
25200	D G O Z	2+
25500	D G	4+
27494.1 *18*	EFG X	0+
28600?	L	
32E3?	Z	
≈41E3?	G	

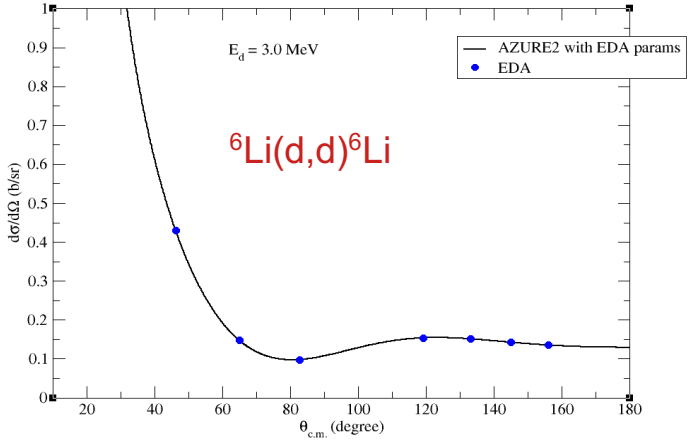
- States highlighted in red are not used so far.

Comparisons with EDA

- M.Paris provided the EDA parameters.
- These parameters were converted into AZURE2 parameters by C. Brune (Ohio University).
- Benchmarked the calculation for various channels.
- Identical particles in the exit channel: EDA calculates (or fits) the production data whereas AZURE uses the reaction cross section data. Data are scaled accordingly for these channels only!!!



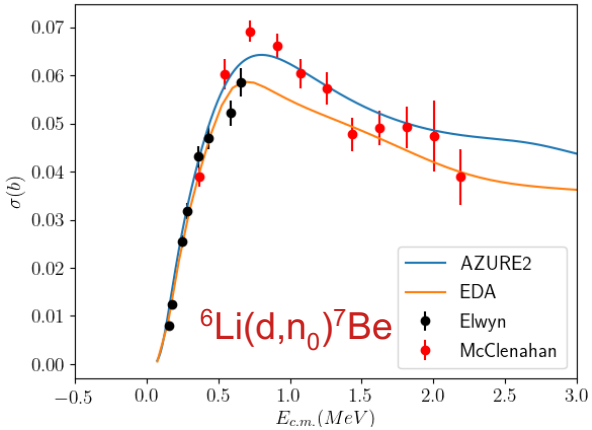


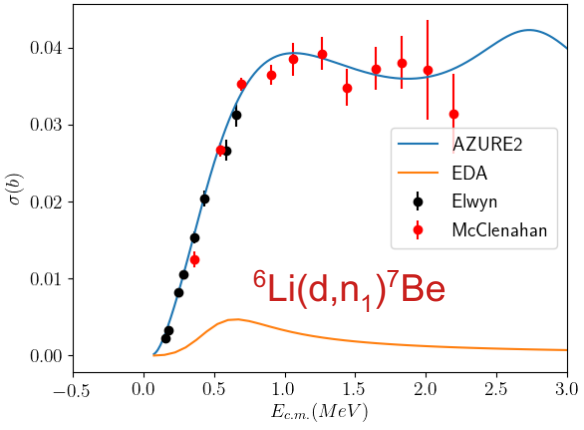


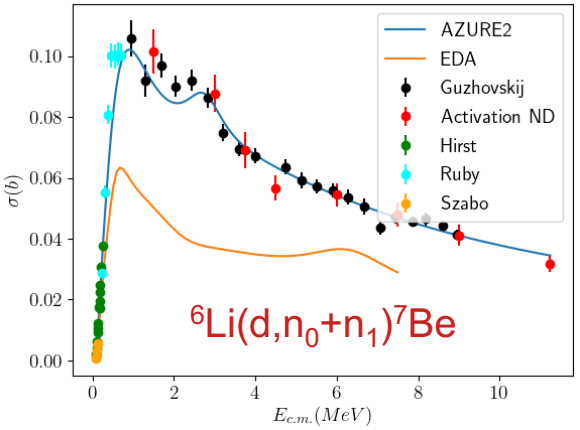
Results and comparisons with EDA

$^{6}Li(d,n_0)^{7}Be$ and $^{6}Li(d,n_1)^{7}Be$

- AZURE2 produces both $^{6}Li(d,n_0)^{7}Be$ and $^{6}Li(d,n_1)^{7}Be$ quite well and even the 7Be production data.
- EDA reproduced the $^{6}Li(d,n_0)^{7}Be$ data quite well but not $^{6}Li(d,n_1)^{7}Be$.

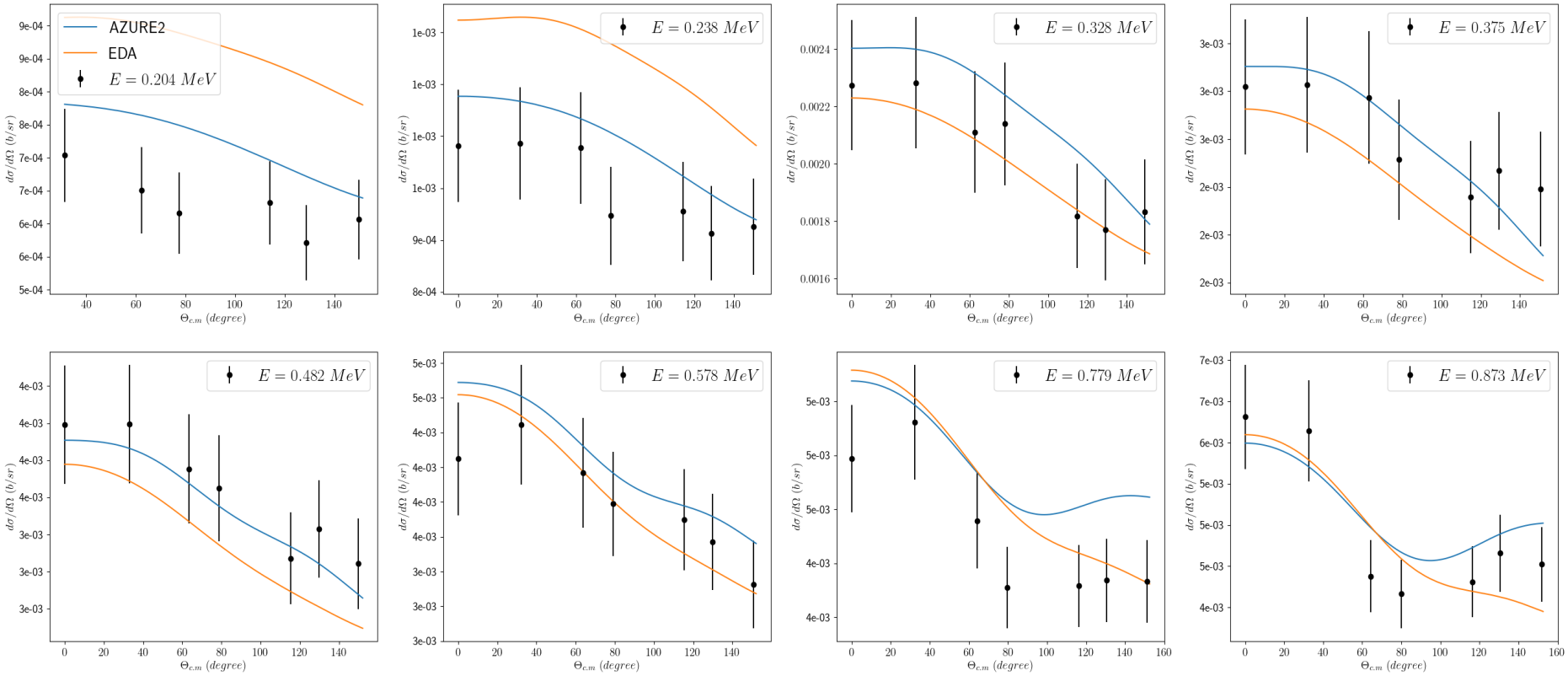






Data Used: $^{6}Li(d,n_{0,1})^{7}Be$: Elwyn *et. al.* (Phys. Rev. C, 16, 1977)
McClenahan *et. al.* (Nucl. Phys, 11, 1975)
$^{6}Li(d,n_{0+1})^{7}Be$: Hirst *et. al.* (Philosophical Magazine, Vol.45, Issue.366,1954)
Ruby *et. al.* (Nuclear Science and Engineering, Vol.71, 1979)
Szabo *et. al.* (Nuclear Physics, Section A, Vol.289, 1977)
Guzhovskij *et. al.* (Izv. Rossiiskoi Akademii Nauk, Ser.Fiz., Vol.44 (1980))

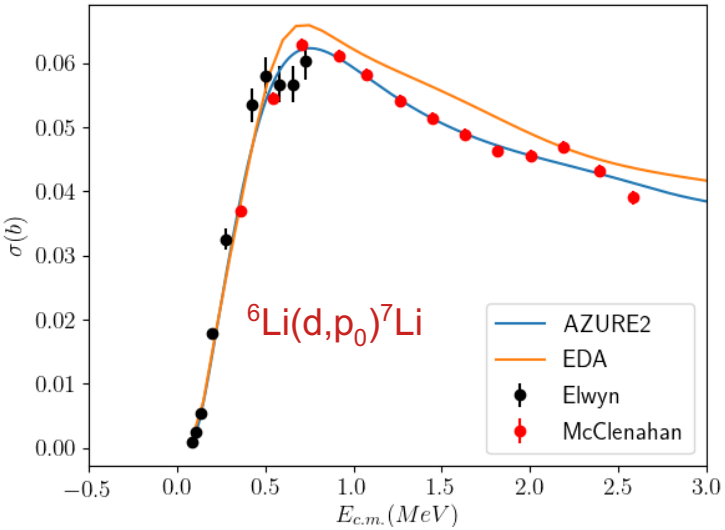
$^{6}Li(d,n_0)^{7}Be$

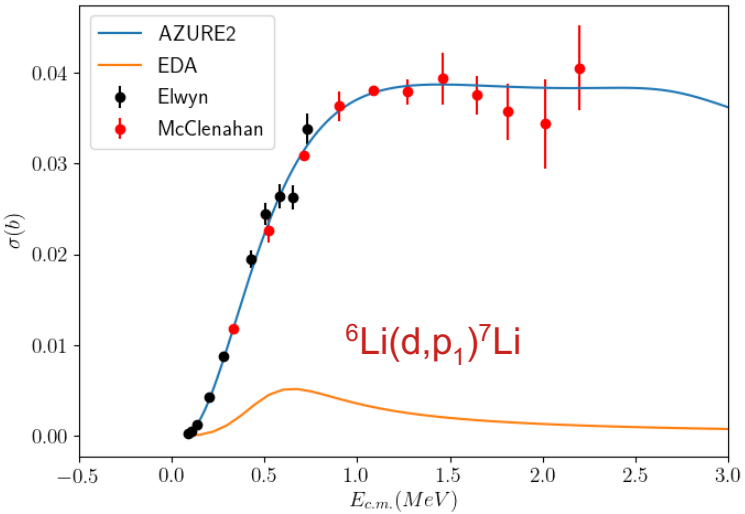


Data Used: $^{6}Li(d,n_{0,1})^{7}Be$: Elwyn *et. al.* (Phys. Rev. C, 16, 1977)

$^6Li(d,p_0)^7Li$ and $^6Li(d,p_1)^7Li$

- AZURE2 produces both $^6Li(d,p_0)^7Li$ and $^6Li(d,p_1)^7Li$ quite well.
- EDA reproduces the $^6Li(d,p_0)^7Li$ data but $^6Li(d,p_1)^7Li$ is not well constrained.



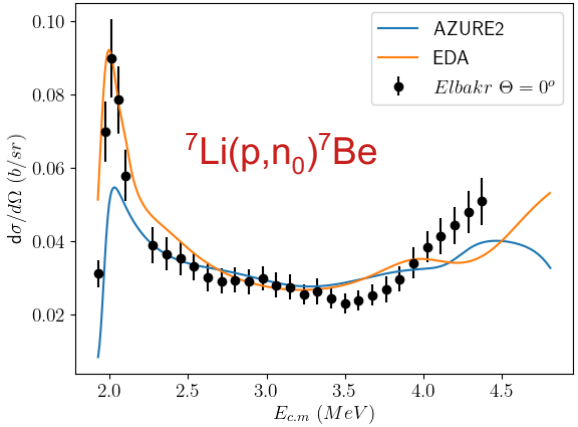


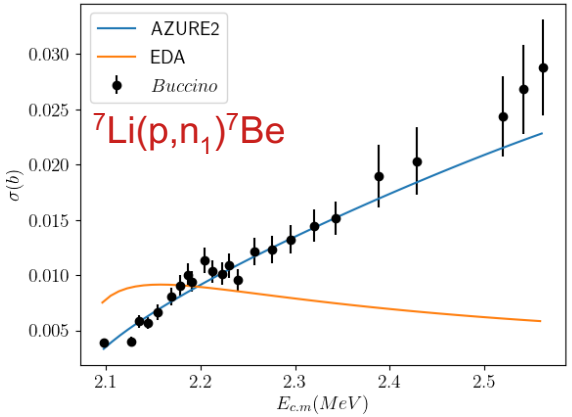
Data Used: $^6Li(d,p_{0,1})^7Li$: Elwyn *et. al.* (Phys. Rev. C, 16, 1977)

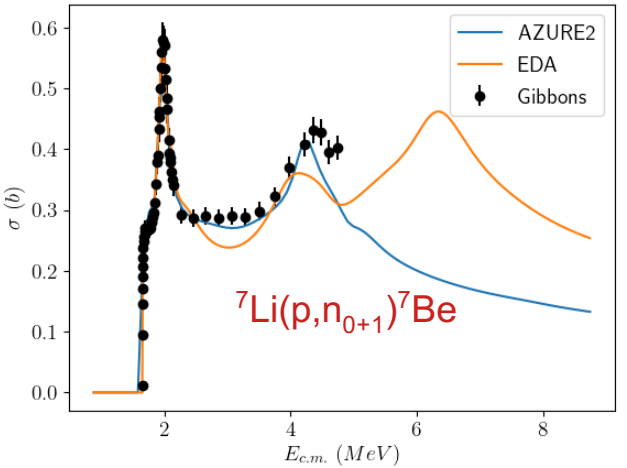
McClenahan *et. al.* (Nucl. Phys, 11, 1975)

$^{7}Li(p,n_0)^{7}Be$ and $^{7}Li(p,n_1)^{7}Be$

- AZURE2 produces both $^{7}Li(p,n_0)^{7}Be$ and $^{7}Li(p,n_1)^{7}Be$ quite well.
- EDA reproduces the $^{7}Li(p,n_0)^{7}Be$ data quite well $^{7}Li(p,n_1)^{7}Be$ data is not included.

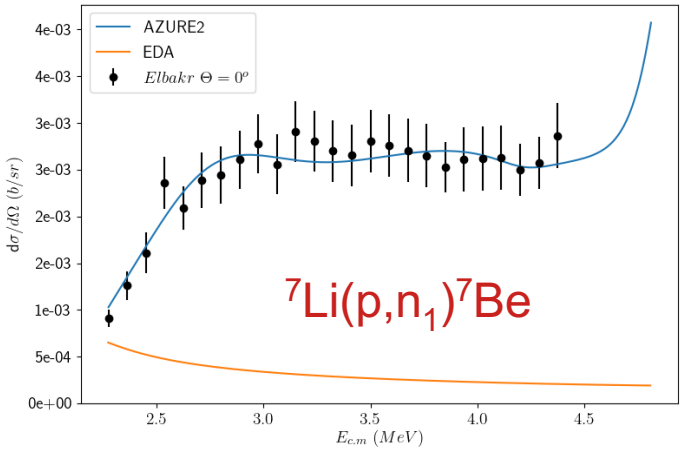


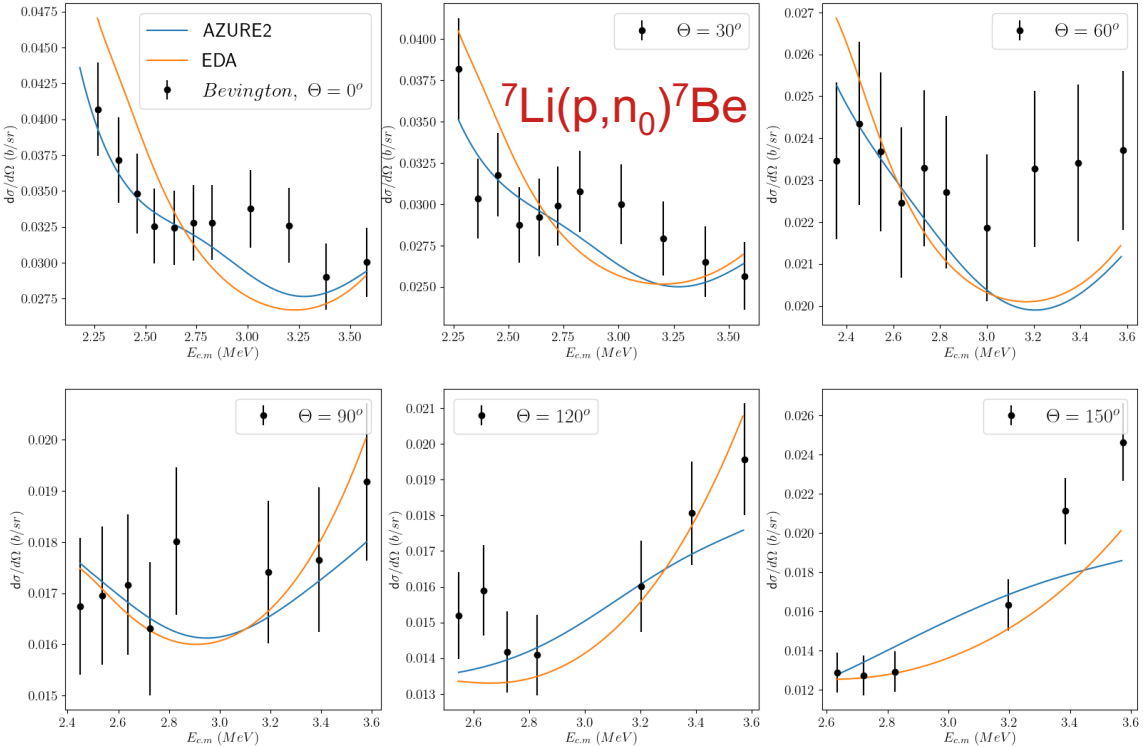




Data Used: $^{7}Li(p,n_0)^{7}Be$: Angular distribution: Elbakr *et. al.* (Nuclear Instrum.and Methods in Physics Res., Vol.105, p.519 (1972))
$^{7}Li(p,n_1)^{7}Be$:Integrated cross section: Buccino *et. al.* (Nuclear Physics, Vol.53, Issue.3, p.375 (1964))
$^{7}Li(p,n_{0+1})^{7}Be$:Integrated Cross section: Gibbons *et. al.* (Physical Review, Vol.114, p.571 (1959))

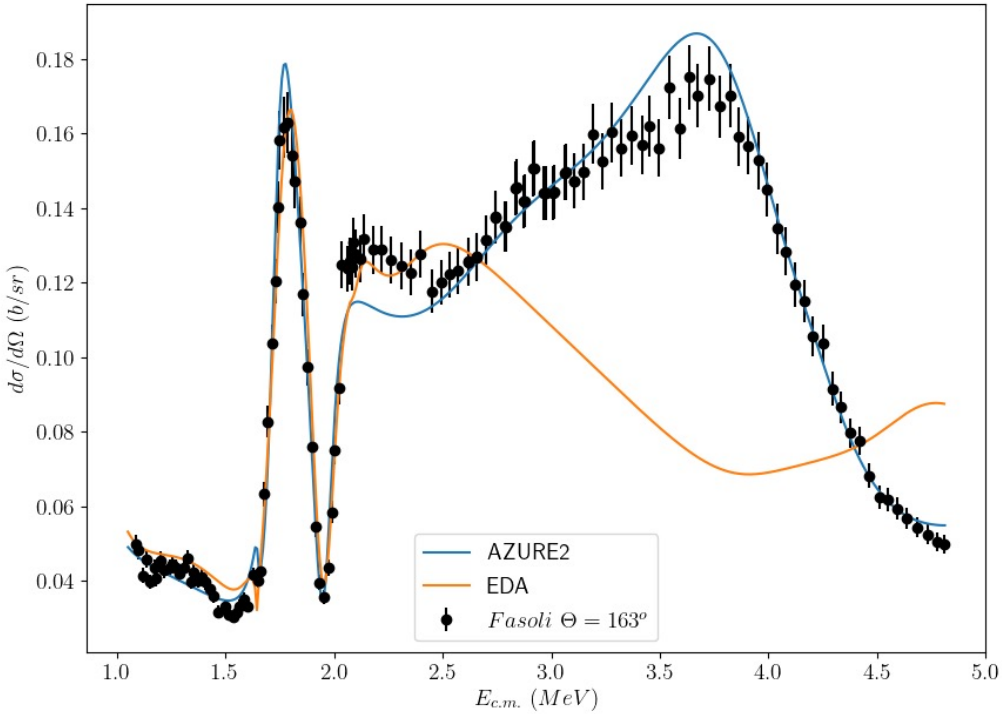
$^{7}Li(p,n_0)^{7}Be$ and $^{7}Li(p,n_1)^{7}Be$





Data Used: $^{7}Li(p,n_1)^{7}Be$: Angular distribution: Elbakr *et. al.* (Nuclear Instrum.and Methods in Physics Res., Vol.105, p.519 (1972))
:Angular distribution: Bevington *et. al.* (Physical Review, Vol.121, Issue.3, p.871 (1961))

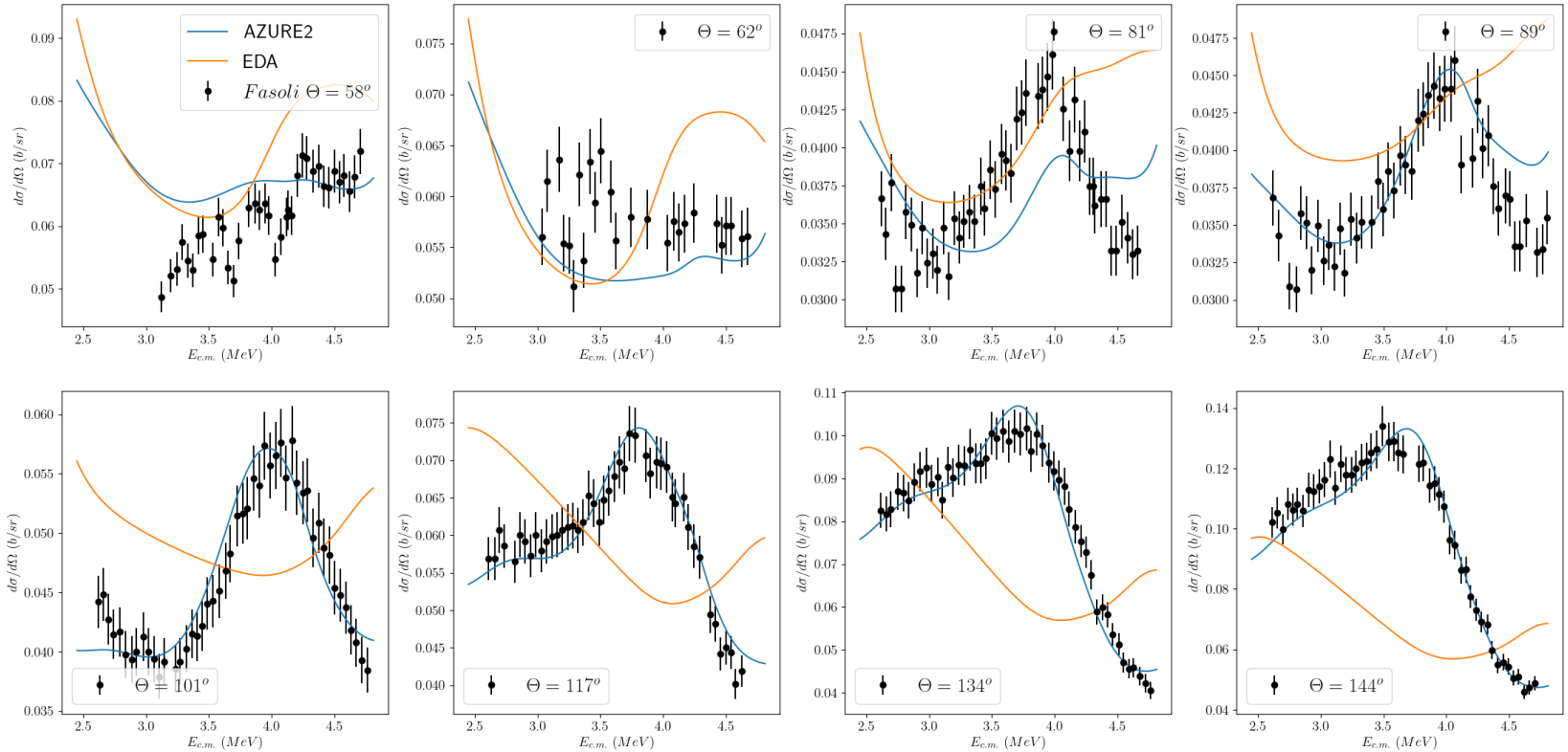
^{7}Li(p,p)^{7}Li



Data Used:^{7}Li(p,p)^{7}Li : Differential cross section: Fasoli *et. al.* (Nuovo Cimento, Vol.34, Issue.3, p.542 (1964))

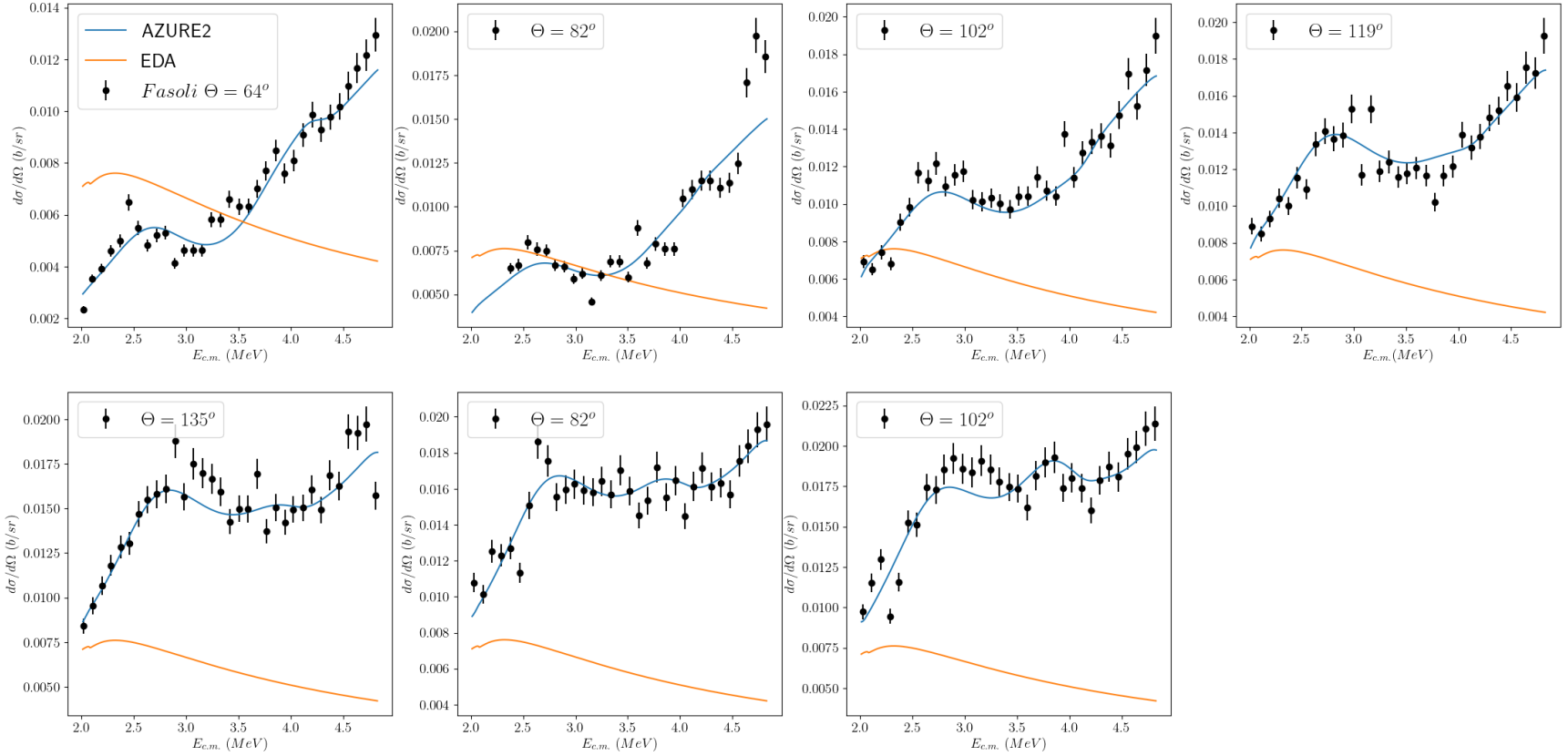
$^{7}Li(p,p)^{7}Li$

- Fitting at forward angles is not good.



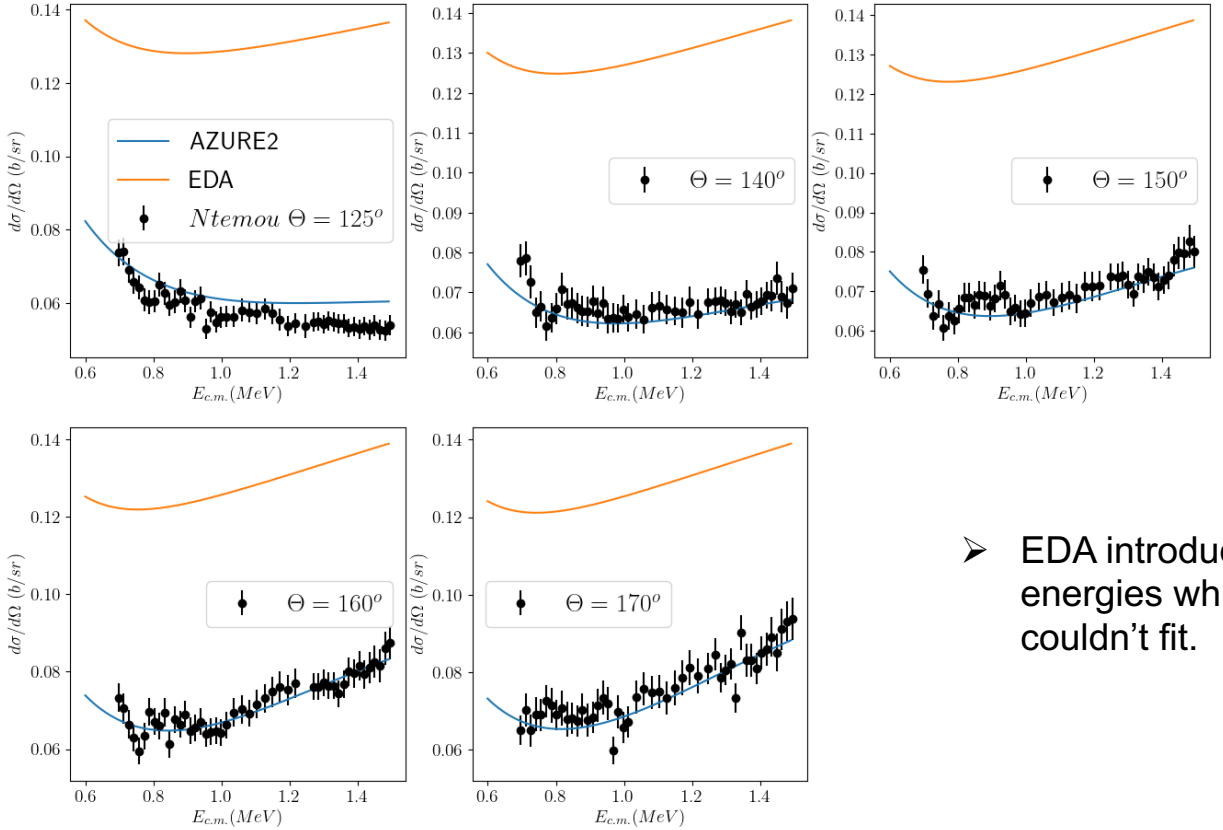
Data Used:$^{7}Li(p,p)^{7}Li$: Differential cross section: Fasoli *et. al.* (Nuovo Cimento, Vol.34, Issue.3, p.542 (1964))

^{7}Li(p,p')^{7}Li



Data Used:^{7}Li(p,p')^{7}Li : Differential cross section: Fasoli *et. al.* (Nuovo Cimento, Vol.34, Issue.3, p.542 (1964))

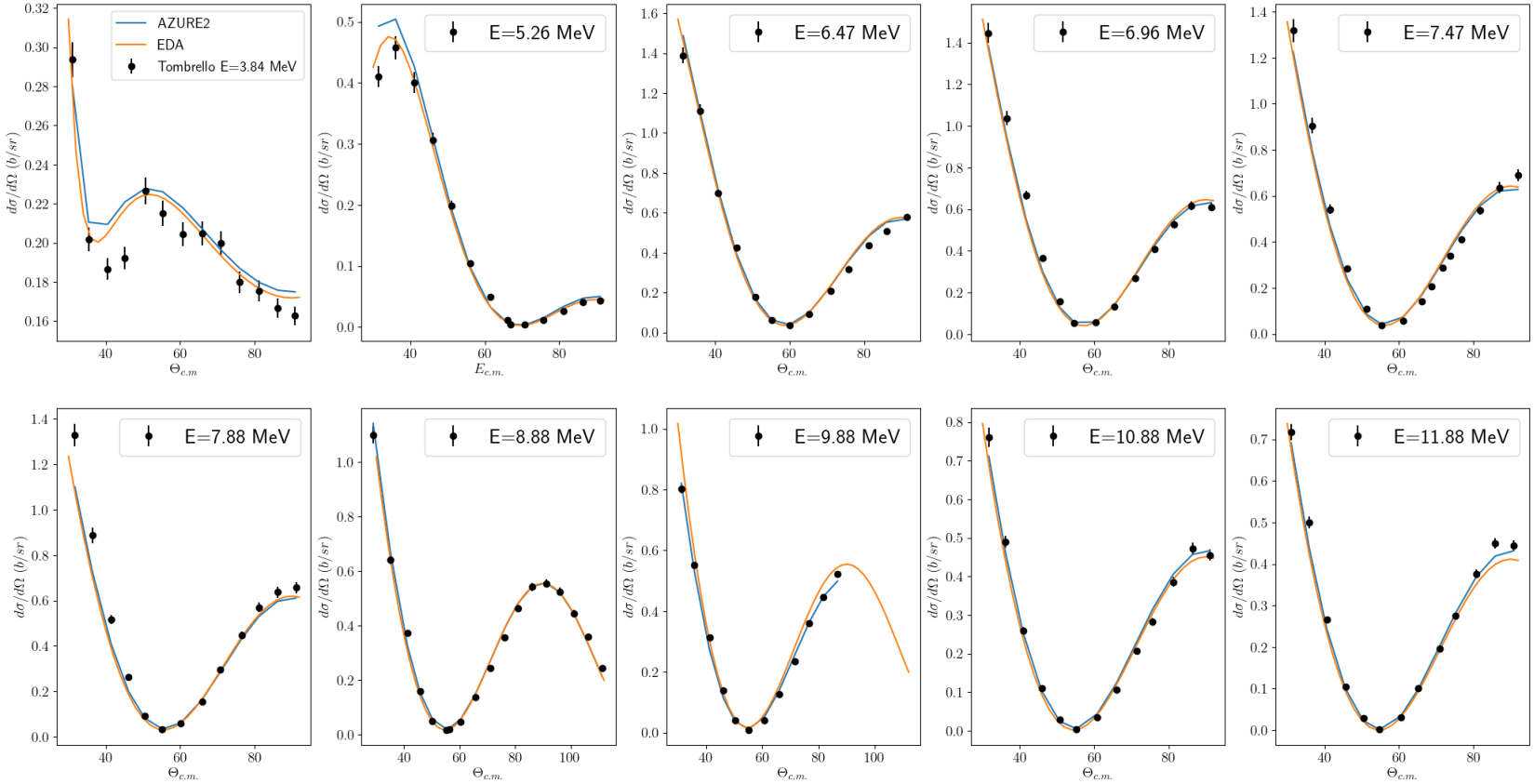
^{6}Li(d.d)^{6}Li



- EDA introduces data at high energies which AZURE2 couldn't fit.

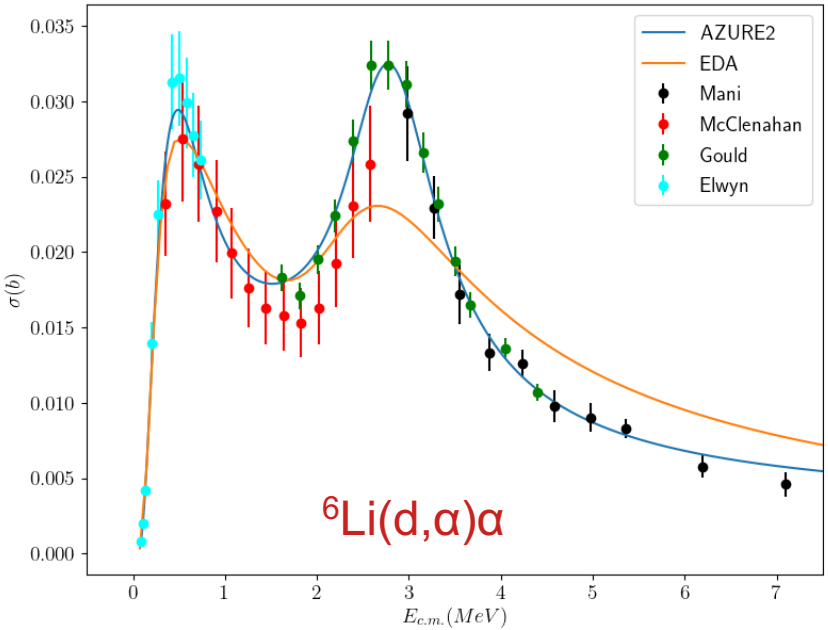
Data Used: ^{6}Li(d,d)^{6}Li : Angular distribution: Ntemou *et. al.* (Nucl. Instrum. Methods in Physics Res., Sect.B, Vol.407, p.34 (2017)

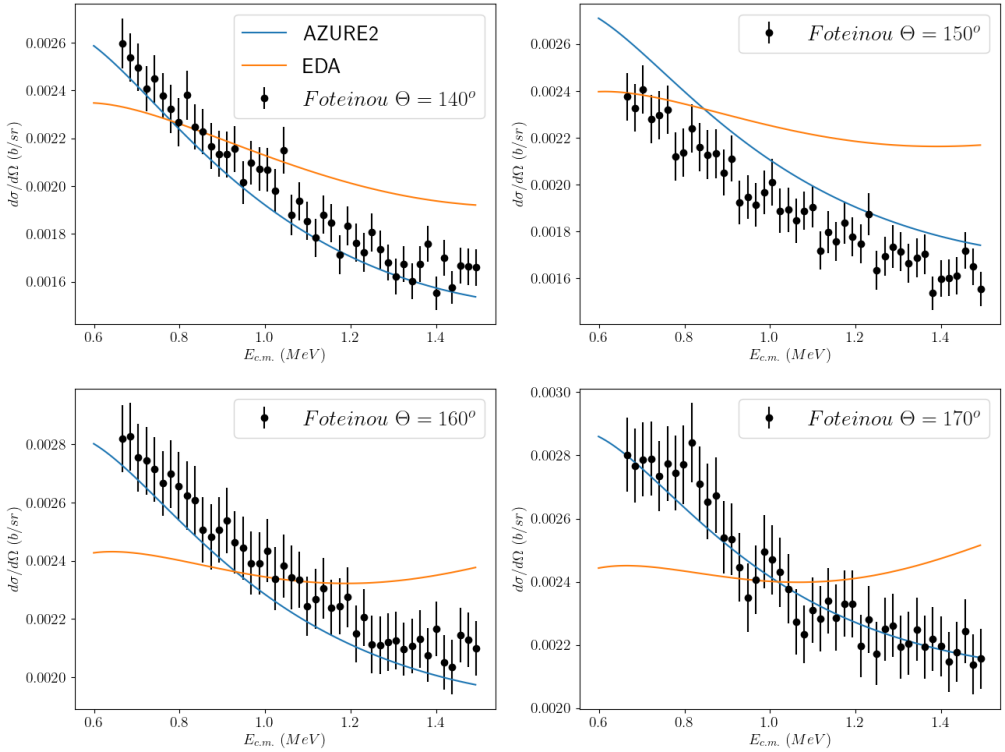
$\alpha(\alpha,\alpha)\alpha$



Data Used:α(α,α)α : Differential cross section: T.A. Tombrello et. al.. (Phys. Rev. 129,2252,1963)

^{6}Li(d,α)α

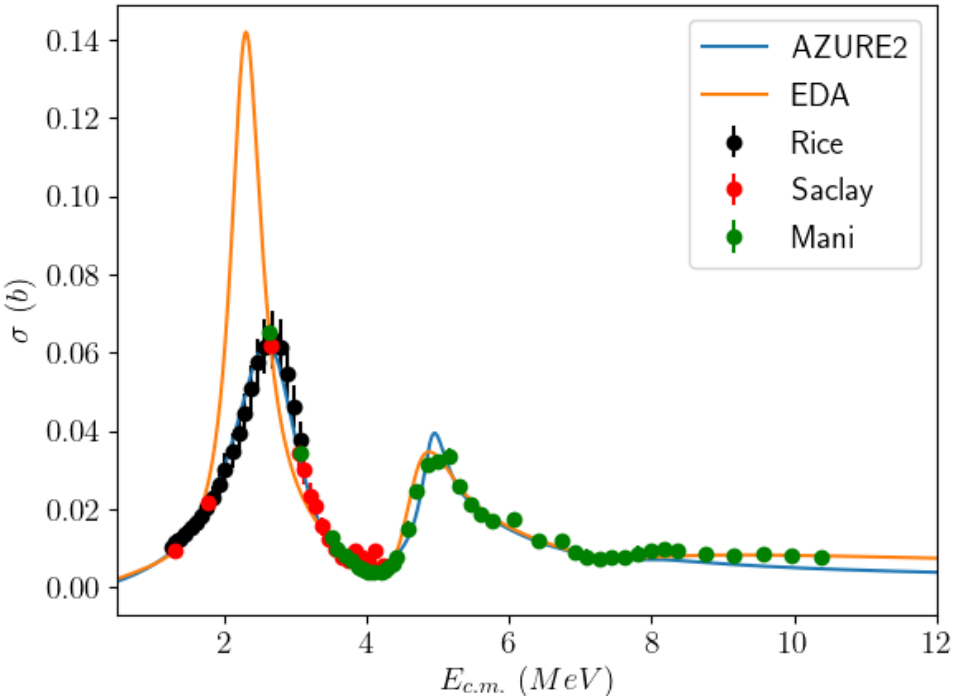




Scaling Factors:
Mani: 0.5
Foteinou: 0.5

Data Used: Integrated Cross Section: Mani *et al.* (Proceedings of the Physical Society , Vol.85, 1965)
McClenahan *et. al.* (Physical Review, Part C, Nuclear Physics, Vol.11, 1975)
Gould *et. al.* (Nuclear Science and Engineering, Vol.55, 1974)
Elwyn *et. al.* (Physical Review, Part C, Nuclear Physics, Vol.16, 1977)
: Angular distribution data: Foteinou *et. al.* (Nucl. Instrum. Methods in Physics Res., Sect.B, Vol.269, 2011)

$^{7}Li(p,\alpha)\alpha$



Scaling Factors

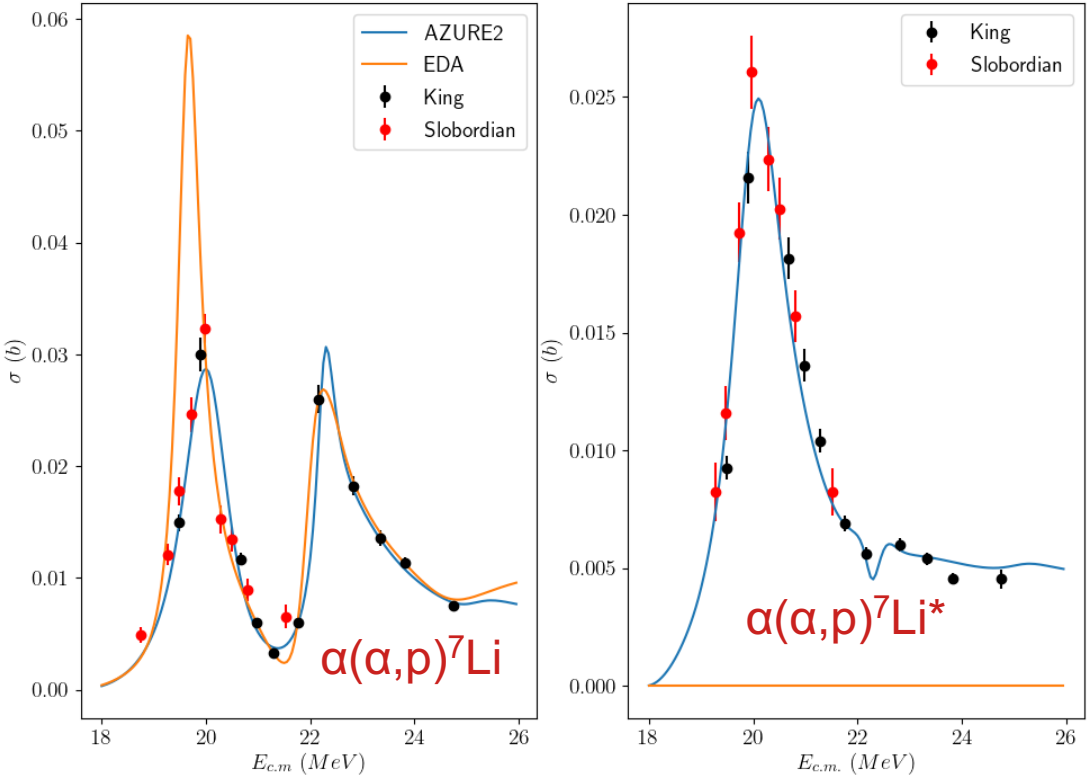
Mani: 0.5

Rice and Saclay: (10/7)*0.5

(Erratum: Nuclear Physics 41 (1963) 176)

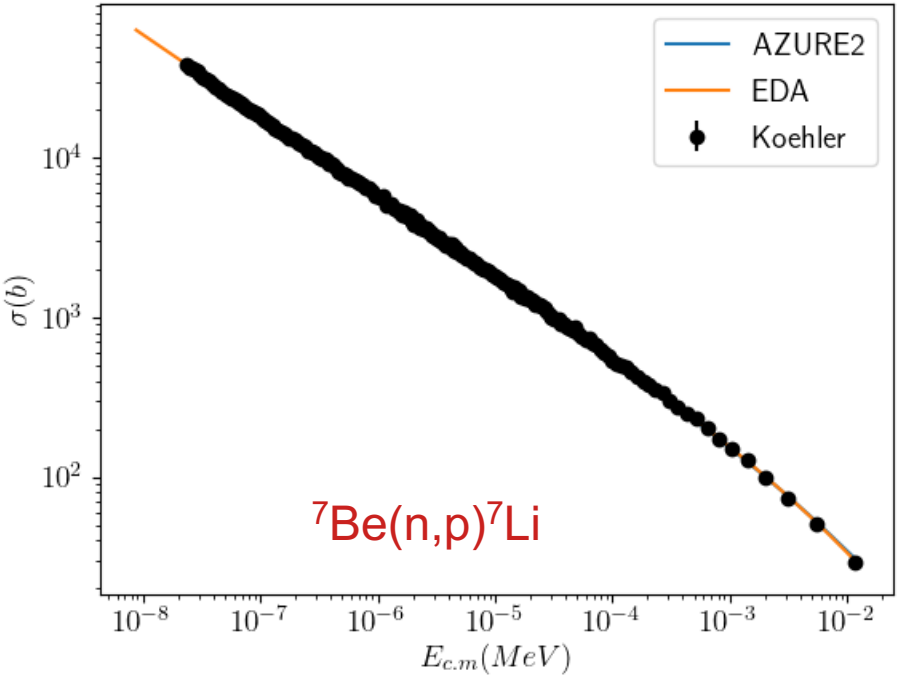
Data Used: ^{7}Li(p,α)α :Integrated cross section: Rice: Cassagnou *et. al.* (Nuclear Physics, Vol.33, Issue.3, p.449 (1962))
Mani *et . al.* (Nuclear Physics, Vol.60, Issue.4, p.588 (1964))
Saclay:Cassagnou *et. al.* (Nuclear Physics, Vol.33, Issue.3, p.449 (1962))

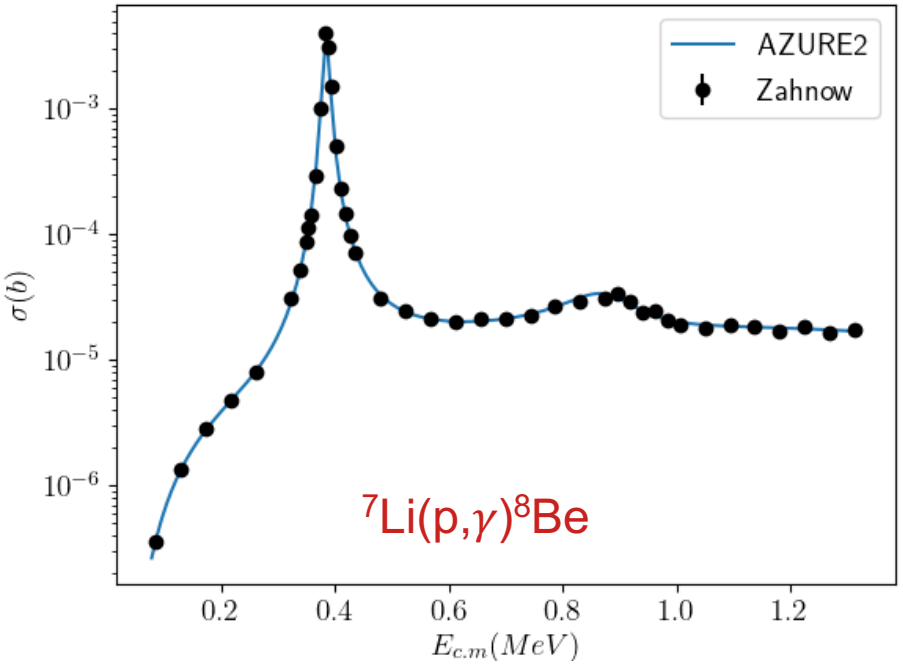
$\alpha(\alpha,p)^7Li$ and $\alpha(\alpha,p)^7Li^*$



Data Used: α(α,p)^{7}Li,^{7}Li* : Partial cross section: *C.H.King et. al.* (Phys. Rev. C,16, 1712, 1977)
: Partial cross section: R. J. Slobodrian et. al. (Zeitschrift fuer Physik A, Hadrons and Nuclei, Vol.308, Issue.1, p.15 (1982)

^{7}Be(n,p)^{7}Li and ^{7}Li(p,γ)^{8}Be





Data Used: ^{7}Be(n,p)^{7}Li : Integrated cross section: Koehler *et. al.* (Phys. Rev. C, 37, 917, 1988)
^{7}Li(p,γ)^{8}Be: Partial Cross section: D. Zahnow et. al. (Zeitschrift fuer Physik A, Hadrons and Nuclei, Vol.351, p.229 (1995))

Summary/Future Work

- Preliminary results from *R*-matrix analysis of ^{8}Be system with AZURE2 was compared with EDA calculations.
- Use AZURE2 parameters as reference while updating EDA evaluations for ^{8}Be system.
- Sensitivity studies for channel radius and background level dependence.
- Estimate the uncertainty bands.
- Check for overfitting and see if the parameters are actually constrained by the data.
- Angular distribution data for ^{6}Li(d,n)^{7}Be from new measurement will be added to the fits.

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