R-matrix Analysis of ^{8}Be System

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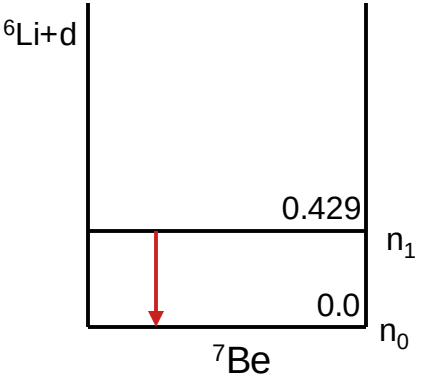
CSEWG Meeting 2024

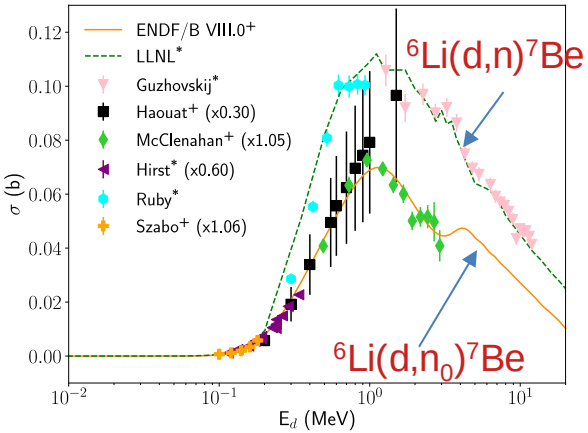
Outline

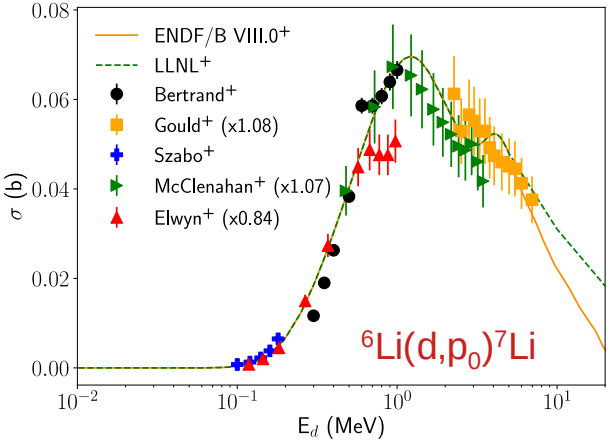
- Motivation
- *R*-matrix analysis of ^{8}Be
  - Results from AZURE2 analysis
  - Updates on Energy Dependent Analysis (EDA) analysis of ^{8}Be system.

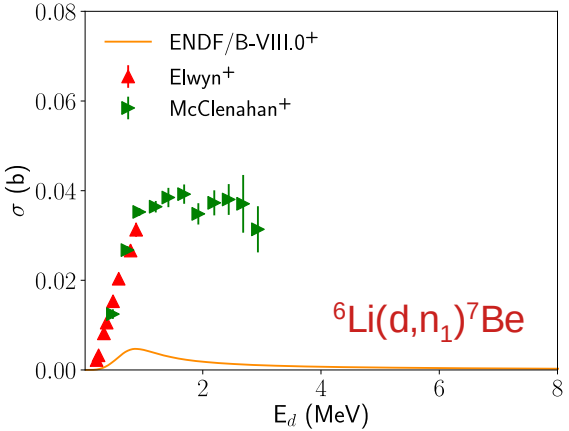
Motivation

- Charged particle-induced reactions on light nuclei are important for nuclear astrophysics and nuclear applications.
- *R*-matrix code EDA code from LANL is used for light charged particle evaluations results of which are reported to ENDF data library.
- For the case of ^{8}Be compound system, the ENDF/B-VIII.0 evaluation only included data for reaction channels resulting in the ground state of residual nucleus such as ^{6}Li(d,n_0)^{7}Be, ^{6}Li(d,p_0)^{7}Li and excluded the data for reactions resulting the residual nucleus in excited state such as ^{6}Li(d,n_1)^{7}Be, ^{6}Li(d,p_1)^{7}Li, etc.
- This work: Used AZURE2 code to perform a new complete *R*-matrix analysis with a subset of data available in literature including the recent measurement from S. N. Paneru et al., Phys. Rev. C 110, 044603 (2024).



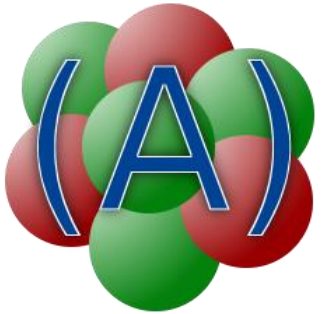






S. N. Paneru *et al.*, Phys. Rev. C 110, 044603 (2024)

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



- Multilevel-Multichannel *R*-matrix analysis to describe the ^{8}Be system.
- Channel radius values for different channels are taken from EDA calculations for comparison purposes.
- Data included 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}Li(p,γ)^{8}Be
^{7}Be(n,α) α	^{6}Li(d,n_{0+1})^{7}Be
^{7}Li(p,n_{0+1})^{7}Be	

R	Channel	Channel radius (fm)
1	$^{6}Li + d$	6.4639
2	$^{7}Li + p$	4.15
3	$^{7}Li^{*} + p$	5.0
4	$^{7}Be + n$	4.15
5	$^{7}Be^{*} + n$	5.0
6	$\alpha + \alpha$	4.0
7	$^{8}Be + \gamma$	0.0

- Red: Data for reactions channels were not included in existing ENDF/EDA analysis
- ^{8}Be+ γ partition is not included in existing ENDF/EDA analysis

^{8}Be Levels Information

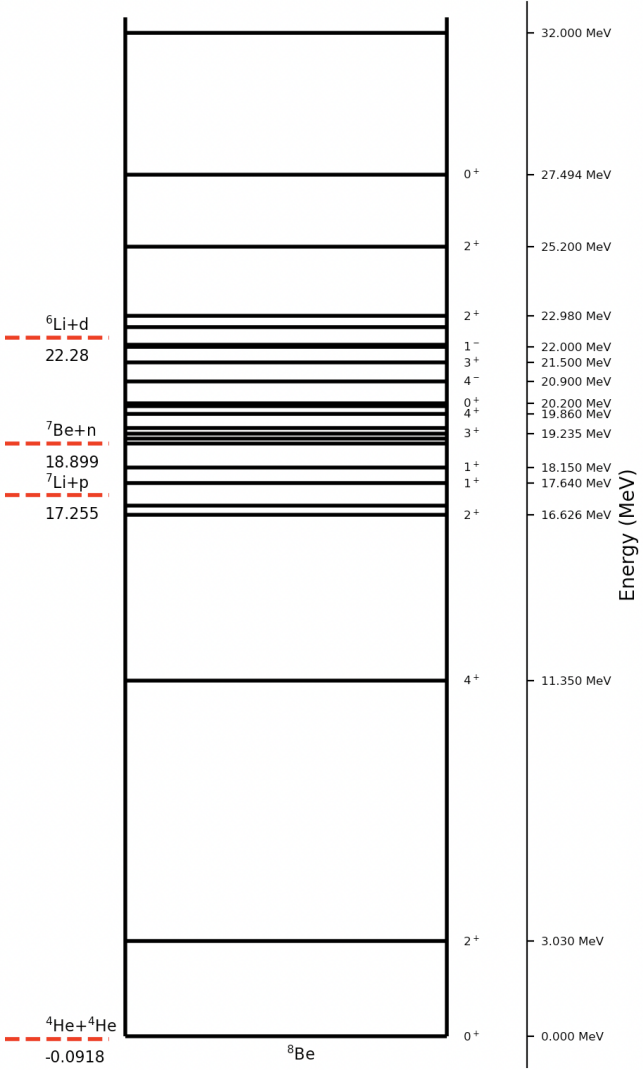
- Taken from NNDC/ENSDF.
- The 22.63 MeV level was assigned 1^+ spin and parity.
- The 22.98 MeV level was assigned 2^+ spin and parity
- The 21.5 MeV state was assigned 3^+ spin and parity.
- Max orbital angular momentum, l=4

Background Levels

- 0^+ at 32 MeV
- 2^+ at 32 MeV
- 4^+ at 32 MeV

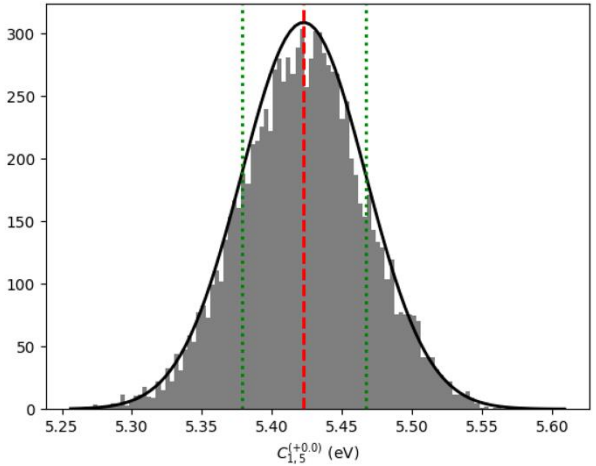
Data Sources:

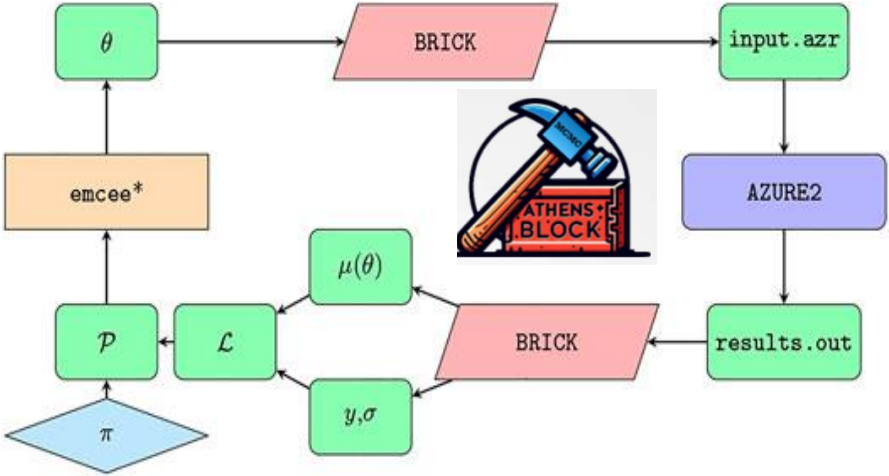
- EXFOR
- And recent measurement of deuteron induced reactions on ^{6}Li. (S. N. Paneru *et al.*, Phys. Rev. C 110, 044603 (2024))



Uncertainty quantification

- We used Bayesian analysis to infer the uncertainties in the *R*-matrix parameters and the calculated cross sections.
- Bayesian *R*-matrix Inference Code Kit (BRICK) was used for uncertainty quantification.
- BRICK acts as an intermediate state to communicate between the Markov chain Monte Carlo Python routine *emcee* and AZURE2.
- Uniform priors were chosen for reduced width amplitudes and the ANC's while log normal distributions were chosen as priors for the normalization parameter.
- Simultaneous fitted 2523 data points including all reactions channel with AZURE2.
- All together 227 parameters were used in the analysis.

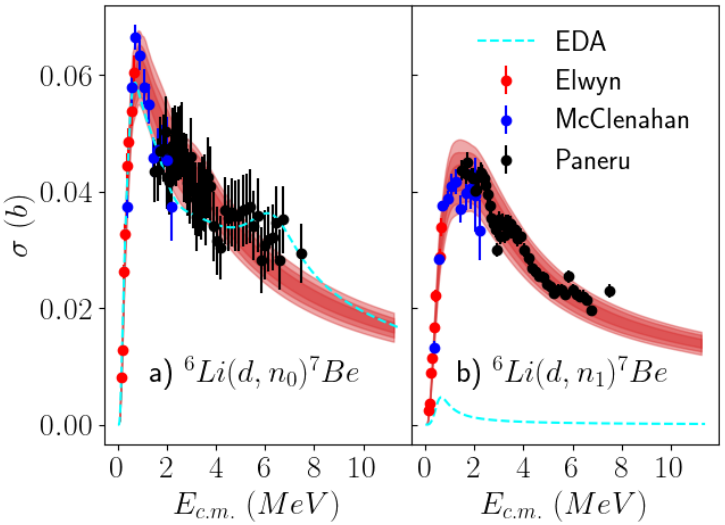


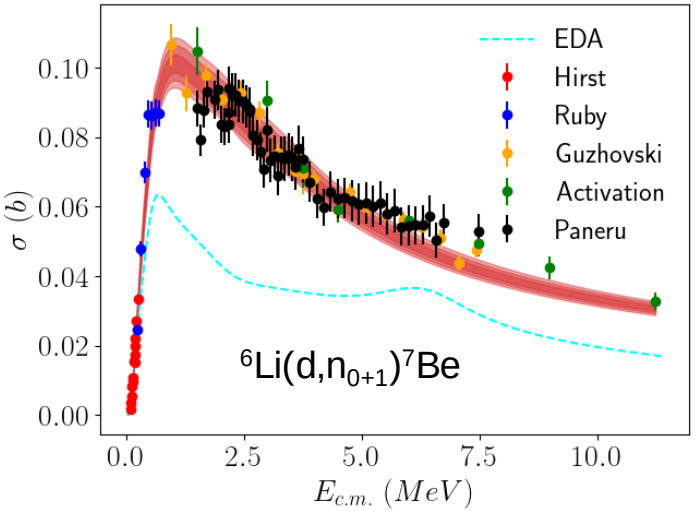


BRICK: D. Odell *et al.*, Front. Phys., 88476, 2022.

Results and comparisons with EDA

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

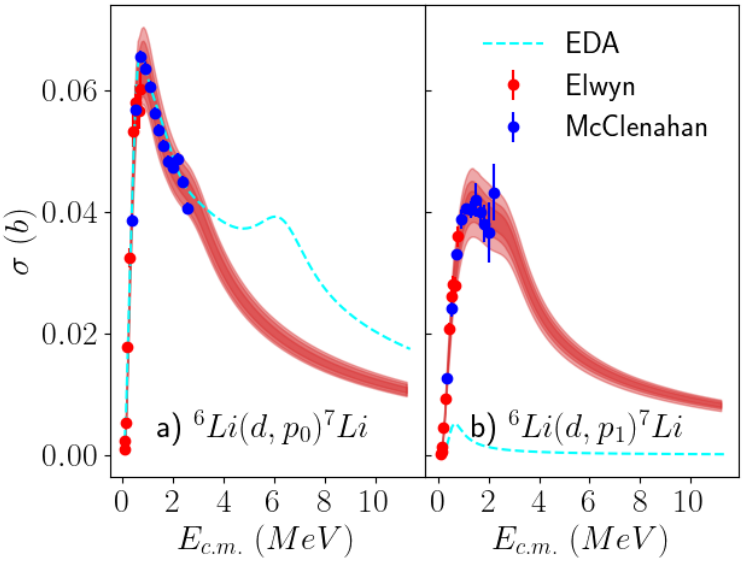


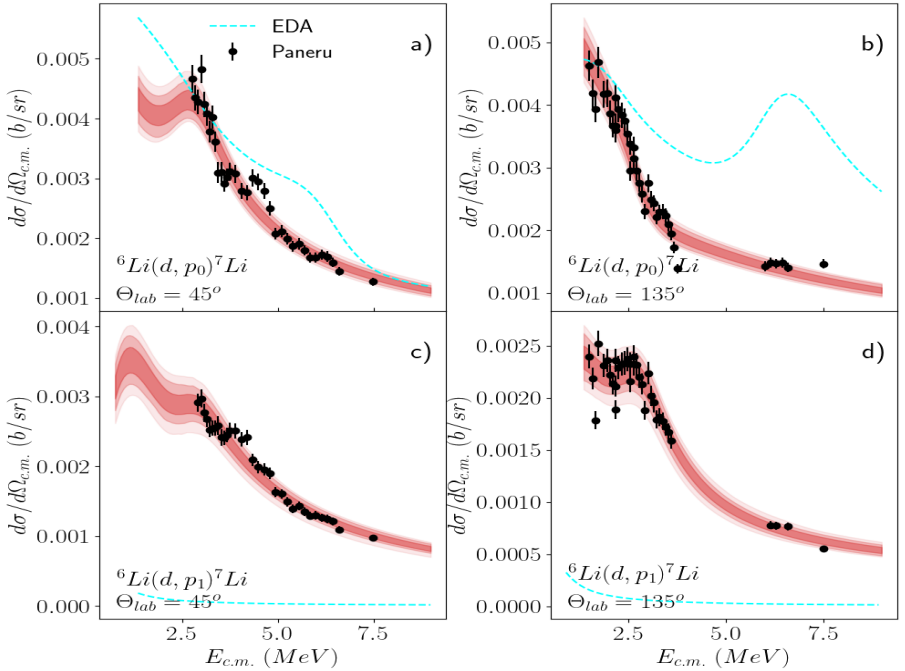


- Paneru *et al.* data provided additional constraints to the $^{6}Li(d,n_{0,1})^{7}Be$ fits at higher energies.
- The enhancement of cross section around $E_{c.m.}$=6 MeV is not supported by this work.
- The non-zero cross sections observed from EDA calculations is due to *l*=0 partial wave (s-wave) that was introduced for these excited state partitions.

Elwyn *et al.* (Phys. Rev. C, 16, 1977) , McClenahan *et al.* (Nucl. Phys, 11, 1975), 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)), S. N. Paneru *et al.*, Phys. Rev. C 110, 044603 (2024) (for activation and Paneru)

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





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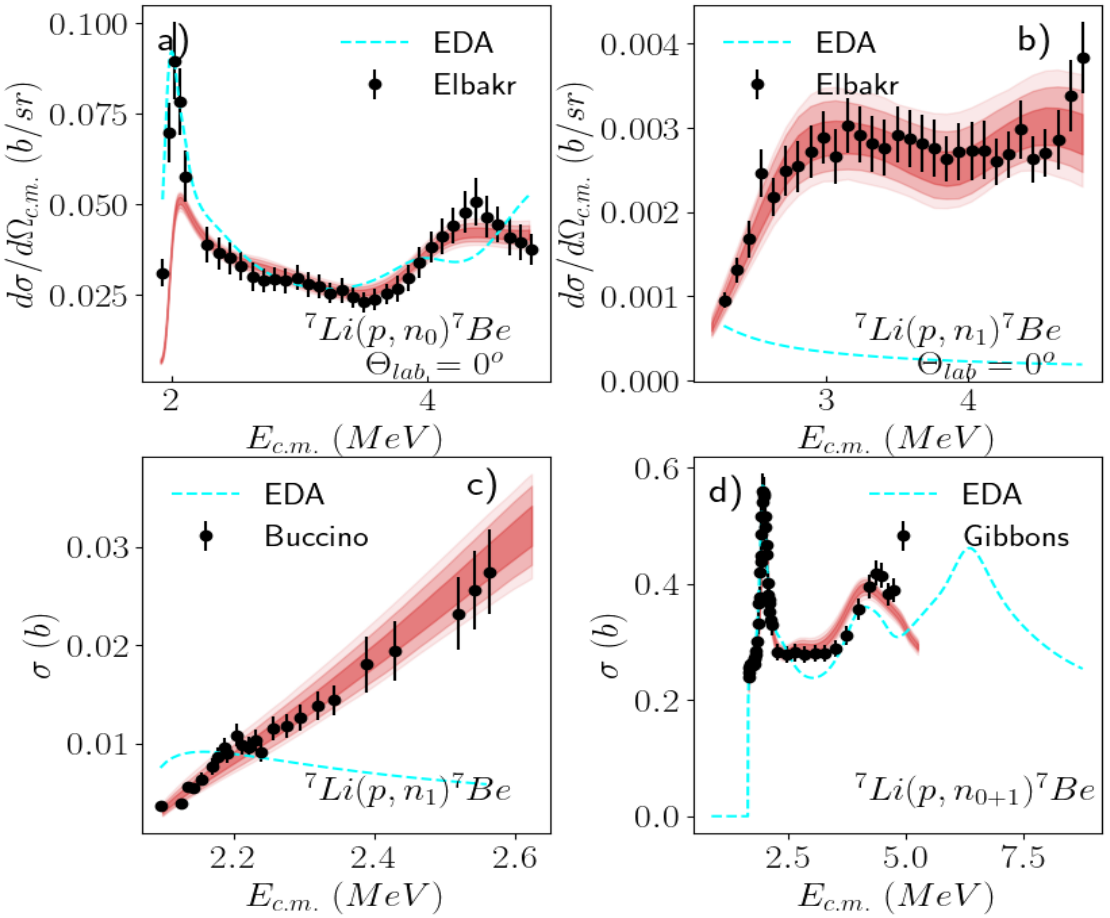
Elwyn *et al.* (Phys. Rev. C, 16, 1977) , McClenahan *et al.* (Nucl. Phys, 11, 1975), S. N. Paneru *et al.*, Phys. Rev. C 110, 044603 (2024)

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

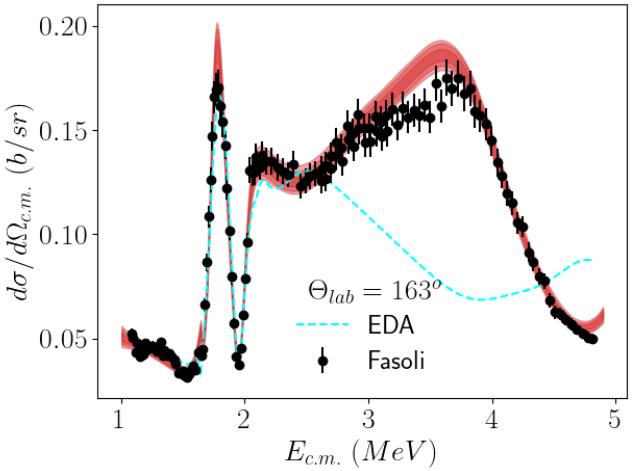
- $^{7}Li(p,n)^{7}Be$ is widely used as mono-energetic neutron source.
- The resonance at $E_{c.m.}$=4.4 MeV is strongly affected by the properties of 21.5 MeV state for which parity is not assigned.
- Use of either 3^{+} or 3^{-} for 21.5 MeV state produces fits of similar quality. Could be the interference effect of two nearby resonances.
- Angular distributions data are well reproduced except for the near threshold data from Elbakr *et al.* at θ_{lab}=0°.



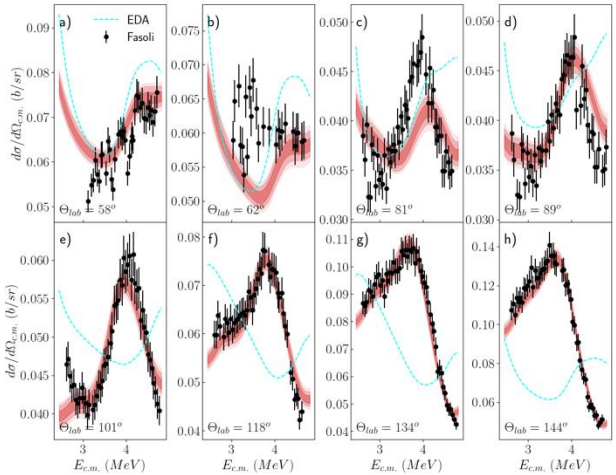
Elbakr *et al.* (Nuclear Instrum.and Methods in Physics Res., Vol.105, p.519 (1972)), Buccino *et al.* (Nuclear Physics, Vol.53, Issue.3, p.375 (1964), Gibbons *et al.* (Physical Review, Vol.114, p.571 (1959))

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

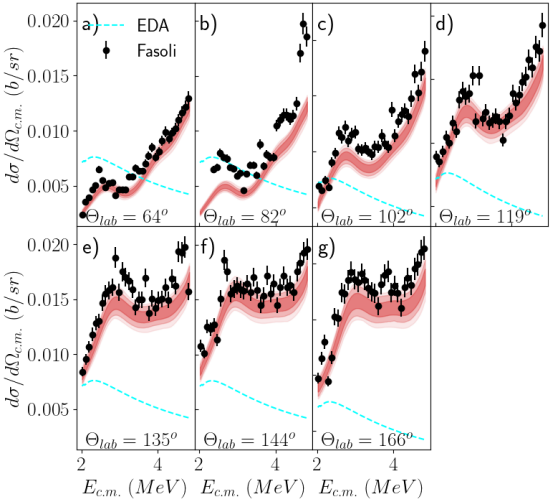
- This work included the ^{7}Li(p,p)^{7}Li* reaction data in the analysis.
- Elastic scattering data at high $E_{c.m.}$ was added into the analysis.



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



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



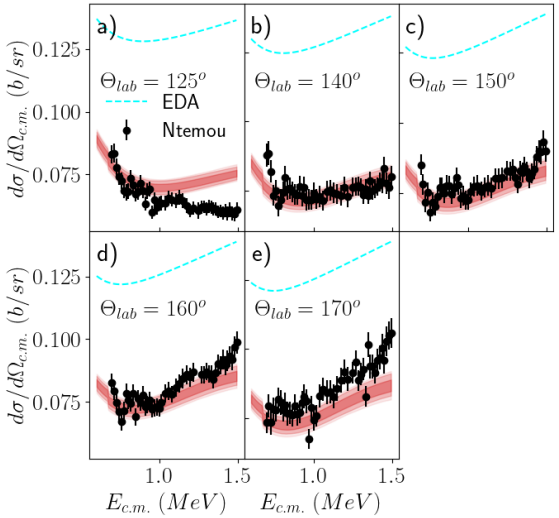
^{7}Li(p,p)^{7}Li*

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

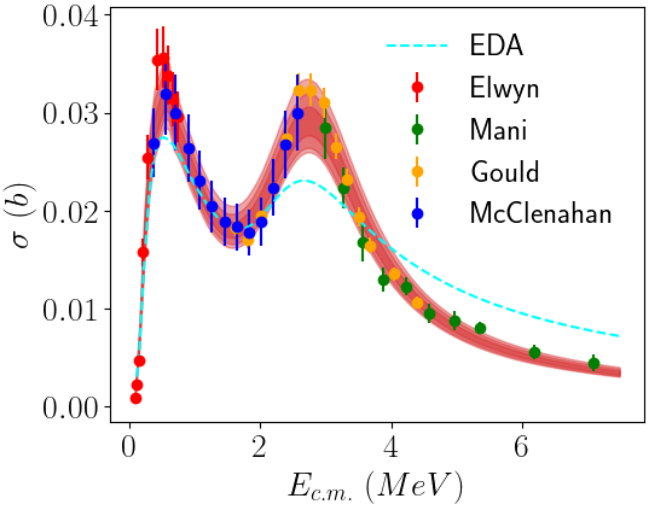
- EDA introduces data at high energies which AZURE2 couldn't fit.
- Only used elastic scattering data below deuteron breakup threshold.
- Lack of spin and parity assignments at high excitation energies in ^{8}Be limits to fit the elastic scattering data at high energies.

^{6}Li(d,α)α

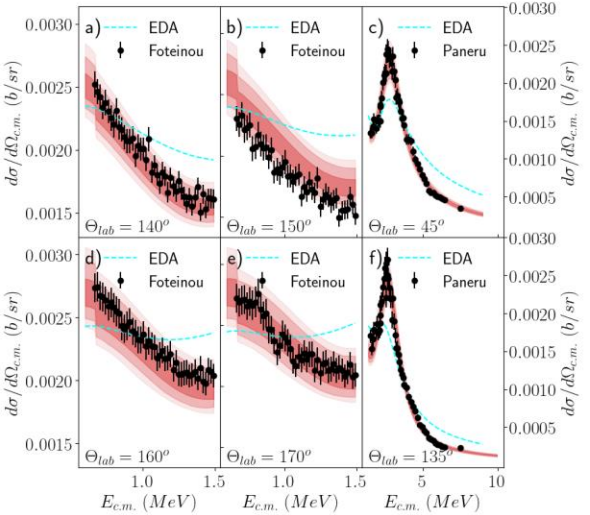
- A scaling factor of ½ have been applied to α-production data to convert it into reaction cross section data for reaction channels with identical particles.



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



^{6}Li(d,α)α

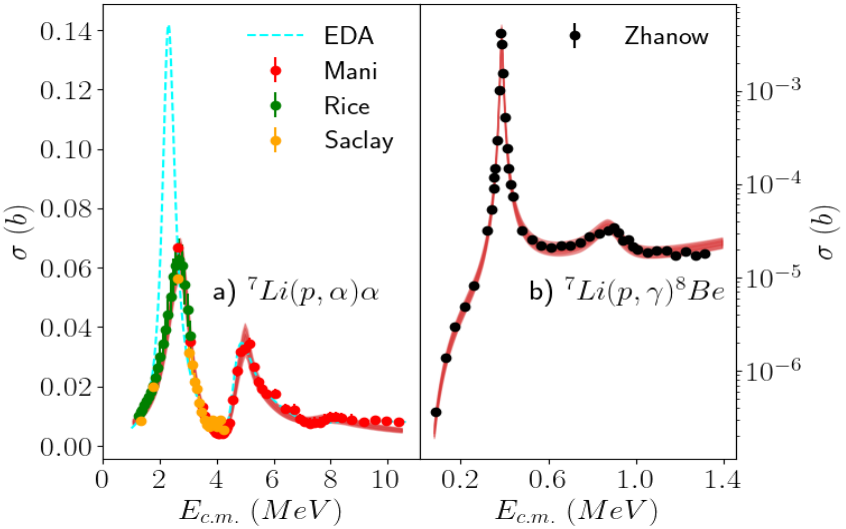


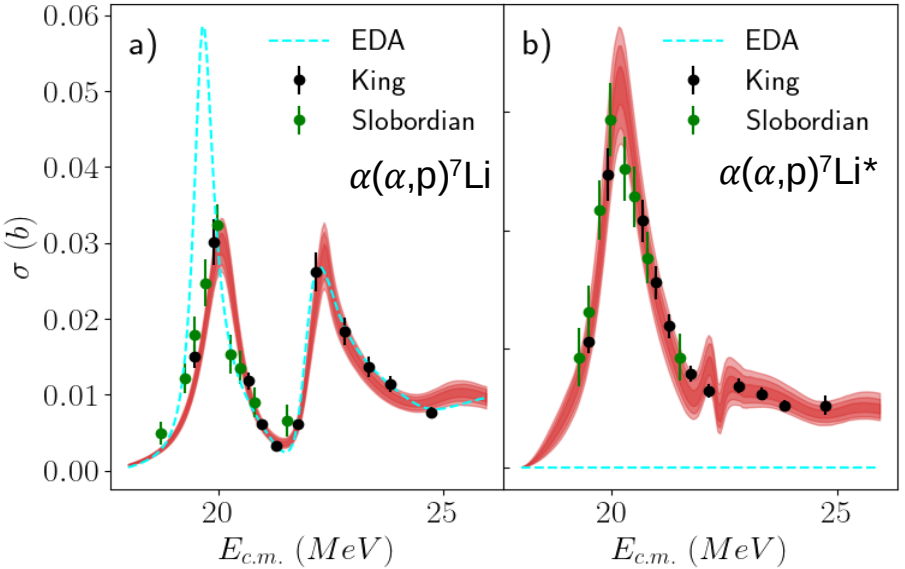
^{6}Li(d,α)α

Ntemou *et al.* (Nucl. Instrum. Methods in Physics Res., Sect.B, Vol.407, p.34 (2017), 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), Foteinou *et al.* (Nucl. Instrum. Methods in Physics Res., Sect.B, Vol.269, 2011)

$^{7}Li(p,\alpha)\alpha$, $^{7}Li(p,\gamma)^{8}Be$ and $\alpha(\alpha,p)^{7}Li$

- $^{7}Li(p,\gamma)^{8}Be$ is important for physics beyond the standard model.
- Over prediction of cross section in current evaluation for both $^{7}Li(p,\alpha)\alpha$ and $\alpha(\alpha,p)^{7}Li$ reactions are related to properties of E_x=19.86 MeV state in ^{8}Be.

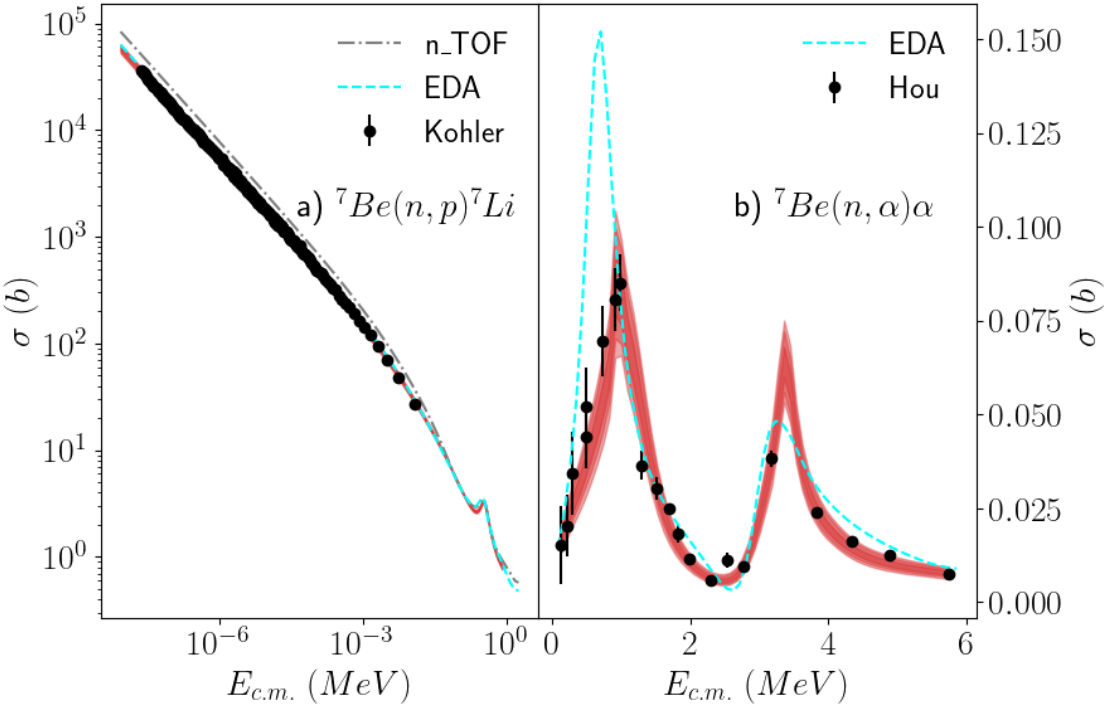




Rice: Cassagnou *et al.* (Nuclear Physics, Vol.33, Issue.3, p.449 (1962)), Mani *et al.* (Nuclear Physics, Vol.60, Issue.4, p.588 (1964)), Saclay:Cassagnou *et al.* (Nuclear Physics, Vol.33, Issue.3, p.449 (1962)), D. Zahnow *et al*. (Zeitschrift fuer Physik A, Hadrons and Nuclei, Vol.351, p.229 (1995)), *C.H.King et al.* (Phys. Rev. C,16, 1712, 1977), 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 $^{7}Be(n,\alpha)\alpha$

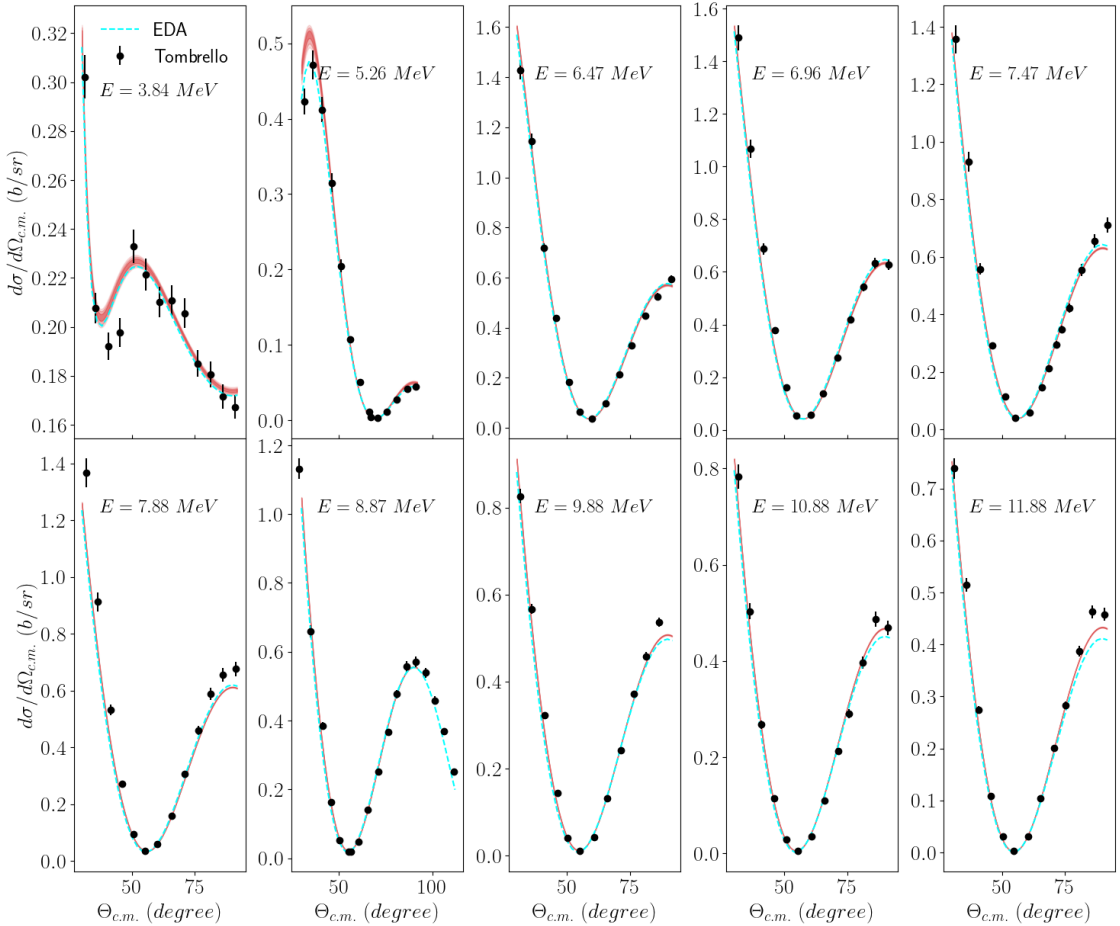
- $^{7}Be(n,p)$ and $^{7}Be(n,\alpha)\alpha$ are important for cosmological lithium problem.
- Kohler *et al*. data for $^{7}Be(n,p)$ differs from the latest n_TOF data by 40%.
- Both data sets for $^{7}Be(n,p)$ complements the $^{7}Li(p, n)^{7}Be$ data at high energies quite well.
- New measurement required to sort out the differences.
- Limited data sets available for $^{7}Be(n,\alpha)\alpha$.



Koehler *et al.* (Phys. Rev. C, 37, 917, 1988), S. Q. Hou et al. (Phys. Rev. C, 91,055802, 2015)

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

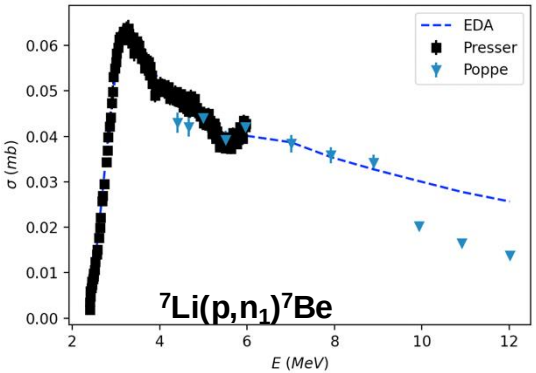
- $\alpha(\alpha,\alpha)\alpha$ is important for 'triple-alpha' process.
- AZURE2 in its open access form does not calculate the identical particle scattering cross section.
- The source code was modified to calculate the cross section from the phase shifts.
- Only 0+, 2+, and 4+ states in ^{8}Be was used to constrain the fits to $\alpha(\alpha,\alpha)\alpha$ cross section data.
- Γ=5.42 ± 0.04 eV consistent with previous evaluations.

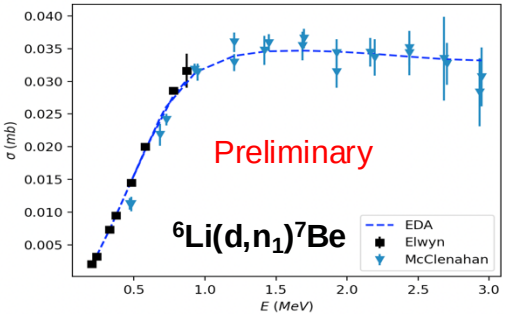


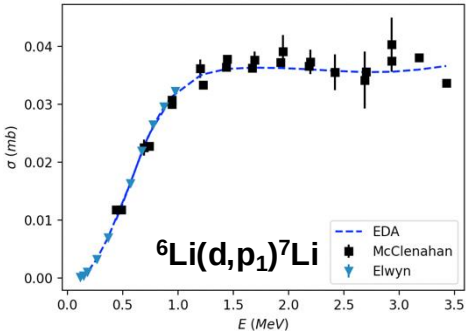
T.A. Tombrello *et al.* (Phys. Rev. 129,2252,1963)

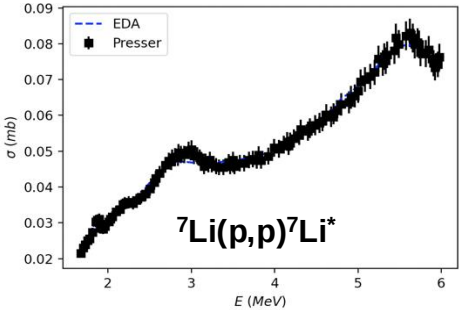
Updates on ^{8}Be evaluation using EDA

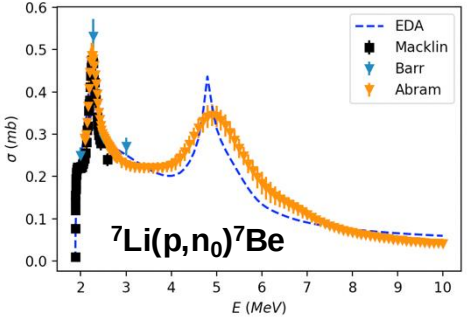
- Added data in existing evaluation for the reaction channels leading to excited state nucleus in residual nucleus.
- Data for ^{6}Li(d,d)^{6}Li below $E_{c.m.}$=4 MeV is added into the evaluation.
- Maximum orbital angular momentum have been increased to 4 to better explain the angular distribution data for various charged particle reaction channels.
- Preliminary results for some of the channels are shown.
- Ongoing Work: Add more data into evaluation and optimize the parameters to explain all reaction channels. The results will be reported to ENDF-IX.











Summary

- Preliminary results from *R*-matrix analysis of ^{8}Be system with AZURE2 was compared with EDA calculations.
- Bayesian analysis was used to infer the uncertainties in *R*-matrix parameters and the calculated cross sections.
- Lessons learned from this work is being implemented into an ongoing effort to update the ^{8}Be evaluation using EDA code.
- The new evaluation will be reported to ENDF-IX.

Collaborators

H.Y. Lee[1], R. J. deBoer[2], M. Paris[1], G. M. Hale[1], M. Febbraro[3], E. A. Bennett[1], C. Fichtl[1], N. A. Gibson[1], C. Hamilton[1], S. A. Kuvin[1], K. Manukyan[2], M. Mosby[1], C. Prokop[1], D. Robertson[2], H. Sasaki[1], and E. Stech[2]

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Thank You.