Evaluation of Cross Sections for Fast Ion Reactions with Beryllium in Helium and Hydrogen Fusion Plasmas

Andrej Žohar, Andrej Trkov, Anders Hjalmarsson, Žiga Štancar, Gašper Žerovnik, Jan Malec*, Luka Snoj

Jožef Stefan Institute, Uppsala University, UKAEA

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Overview

1. **Motivation, theory and current status**
2. **^{9}Be(p,nγ)^{9}B**
3. **^{9}Be(^{3}He,nγ)^{11}C**
4. **^{9}Be(p,d)2α**
5. **^{9}Be(p,α)^{6}Li**
6. **^{9}Be(d,nγ)^{10}B and ^{9}Be(α,nγ)^{12}C**

Figure: Elemental Beryllium

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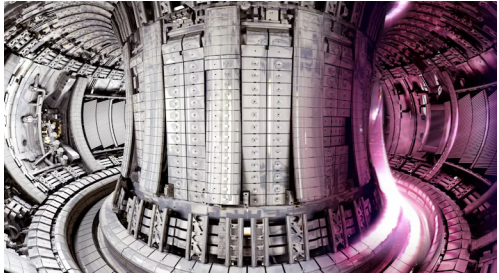
Motivation

- Early tokamak phases use hydrogen/helium plasmas (non-DT)
- Fast ions interact with Be impurities $\rightarrow$ neutron/gamma emission [Johnson et al., 2010]
- Important for:
  - Detector commissioning
  - Safety assessments
  - Validation of transport simulations in PFPO operation



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Objectives

- Evaluate cross sections for:
  - ^{9}Be(p,nγ)^{9}B
  - ^{9}Be(^{3}He,nγ)^{11}C
  - ^{9}Be(p,d)2α, ^{9}Be(p,α)^{6}Li
- Propose inclusion in FENDL library
- Evaluate uncertainties and generate covariance data
- paper: [Žohar et al., 2024]

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Reactions

Table: Reactions of interest for neutron emission from interactions between plasma ions and beryllium impurity in tokamak plasmas.

Reaction	Q [keV]	Nuclear data library
^{9}Be(p,nγ)^{9}B	-1850	ENDF/B-VIII.0 TENDL-2021 FENDL-3.2b
^{9}Be(^{3}He,nγ)^{11}C	7558	TENDL-2021
^{9}Be(p,d)2α	560	/
^{9}Be(p,α)^{6}Li	2125	/
^{9}Be(d,nγ)^{10}B	4362	TENDL-2021
^{9}Be(α,nγ)^{12}C	5802	JENDL-5 TENDL-2021

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Model: Cross Section Formula

$$\sigma(E) = \frac{S(E)}{E} \mathrm{e}^{-B_g/\sqrt{E}} \tag{1}$$

- $S(E)$: Astrophysical S-function
- B_g: Gamow factor
- Separates strong energy dependence (Coulomb barrier and quantum tunneling)

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S-function Parametrization

The astrophysical S-function isolates the nuclear interaction component from rapidly varying Coulomb effects, can be described as [Nocente et al., 2010]:

$$S(E) = \frac{A_0 + A_1 E + A_2 E^2 + \ldots}{1 + B_1 E + B_2 E^2 + \ldots} \tag{2}$$

- Used to fit experimental data
- Flexible for various resonant structures

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Uncertainty Evaluation

- Discarded $<0.1\%$ unphysical results
- Derived covariance matrices by Monte Carlo sampling of fit parameters
- Added 2% systematic uncertainty to account for model defficiency

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Reaction: ^{9}Be(p,nγ)^{9}B – Background and Library Comparison

- Threshold energy: 2.0 MeV, with notable resonance around 2.5 MeV
- Existing libraries (ENDF/B-VIII.0, TENDL, FENDL) provide identical cross sections
- Significant disagreement with experimental EXFOR data

Fitting model:

$$\sigma(E) = \frac{S(E)}{E} e^{-B_g/\sqrt{E}}, \quad S(E) = \frac{A_0 + A_1 E + \ldots}{1 + B_1 E + \ldots}$$

Fit performed in two regions due to the 2.5 MeV resonance.

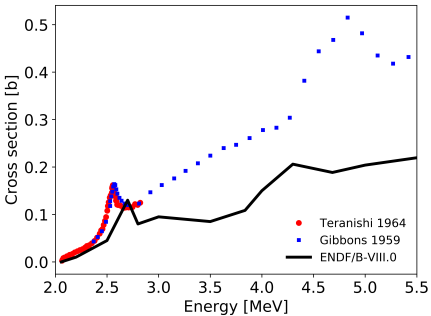

Figure: Comparison of ^{9}Be(p,nγ)^{9}B from ENDF/B-VIII.0 and experimental data.

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Reaction: ^{9}Be(p,nγ)^{9}B – Results

- Cross section evaluated using two sets of experimental data
- Fitted in two energy regions: below and above resonance at 2.5 MeV
- Covariance matrix generated using Monte Carlo sampling

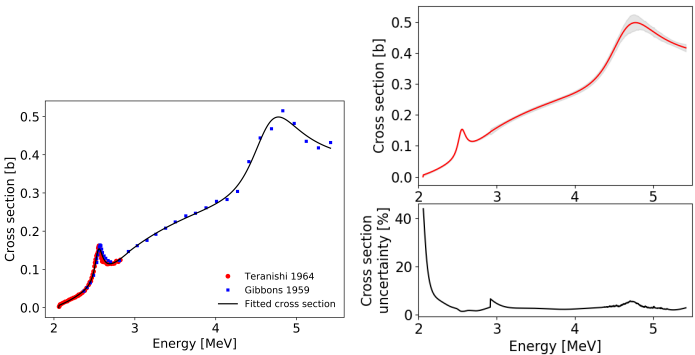

Figure: Fitted cross sections and associated uncertainties

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Covariance Matrix: ^{9}Be(p,nγ)^{9}B

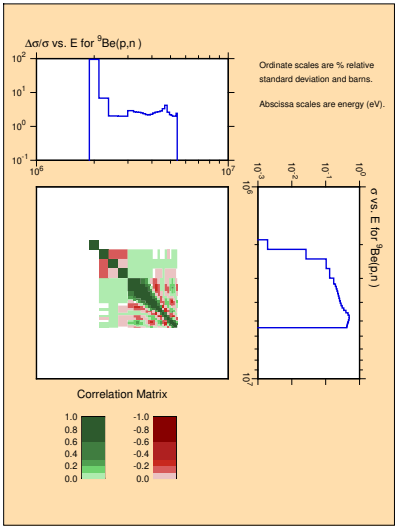

Figure: Covariance matrix of the generated cross sections for the neutron emission in reaction ^{9}Be(p,nγ)^{9}B.

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Reaction: ^{9}Be(^{3}He,nγ)^{11}C – Background

- Only available in TENDL-2019 and TENDL-2021 libraries
- Three EXFOR experimental datasets available (1966–1984)
- No clear resonance structure observed in data
- $$S(E) = \frac{A_0 + A_1 E}{1 + B_1 E + B_2 E^2} \qquad (3)$$
- Extrapolated to threshold at 1.32 MeV (no data below 1.95 MeV)

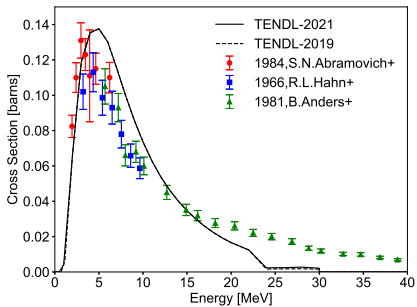

Figure: Measurement and cross-section for ^{9}Be(^{3}He,nγ)^{11}C.

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Results: ^{9}Be(^{3}He,nγ)^{11}C

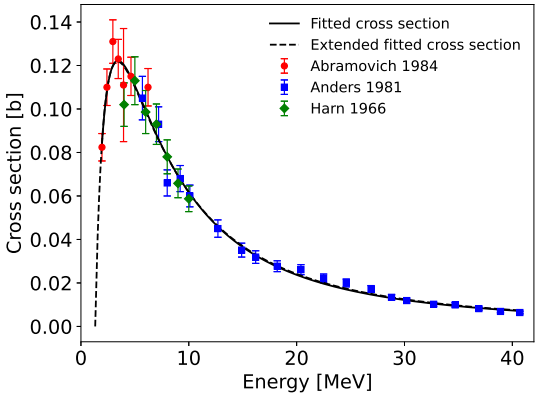

Figure: Experimental data and fitted cross section

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Uncertainty: ^{9}Be(^{3}He,nγ)^{11}C

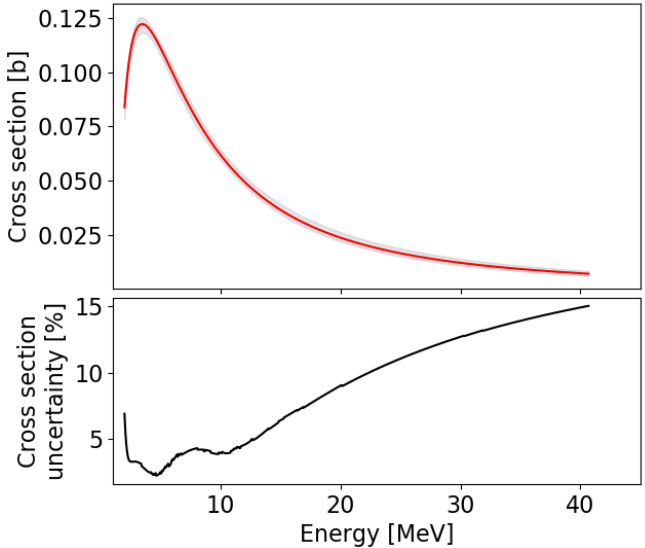

Figure: Cross section uncertainty from Monte Carlo parameter sampling for reaction ^{9}Be(^{3}He,nγ)^{11}C.

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Covariance Matrix: ^{9}Be(^{3}He,nγ)^{11}C

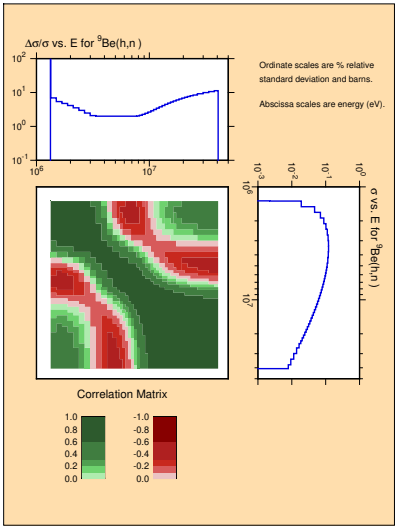

Figure: Covariance matrix for the cross sections of the ^{9}Be(^{3}He,nγ)^{11}C reaction.

Reaction: ^{9}Be(p,d)2α – Model and Resonances

- Reaction produces a fast deuteron and an unstable ^{8}Be, which decays into two α particles
- Present in JENDL-5.0, ENDF/B-VIII.0, and TENDL-2021 nuclear data libraries
- Stored implicitly as deuteron-production data in MF6/MT5 format (ENDF terminology)
- Data from libraries represent total deuteron emission
- Experimental data at lower energies show significant deviations and are not used for current evaluation
- Two prominent resonance peaks observed in the measured cross sections

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Results: ^{9}Be(p,d)2α

S-function fits by energy range:

$$S_1(E) = \frac{A_0 + A_1E + A_2E^2 + A_3E^3 + A_4E^4}{1 + B_1E + B_2E^2}$$

$$S_2(E) = \frac{A_0 + A_1E + \ldots + A_5E^5}{1 + B_1E + B_2E^2}$$

$$S_3(E) = \sum_{l=0}^{12} A_l P_l\left(\mu(E)\right)$$

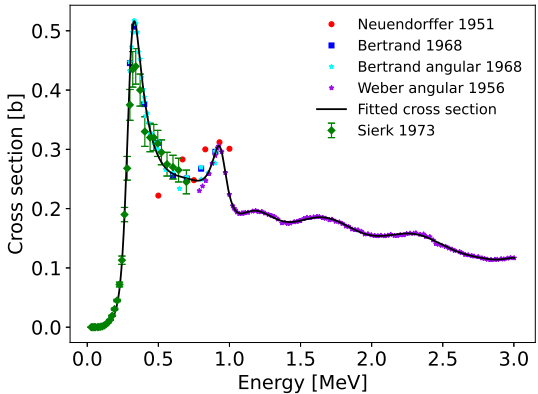

Figure: Measurements and cross section for ^{9}Be(p,d)2α.

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Uncertainty: ^{9}Be(p,d)2α

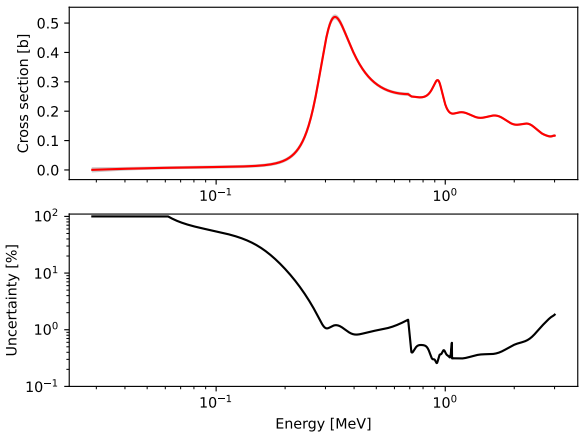

Figure: Uncertainty of generated total cross section for reaction ^{9}Be(p,d)2α calculated by the Monte Carlo technique from the uncertainties of the fitted polynomial coefficients.

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Covariance Matrix: ^{9}Be(p,d)2α

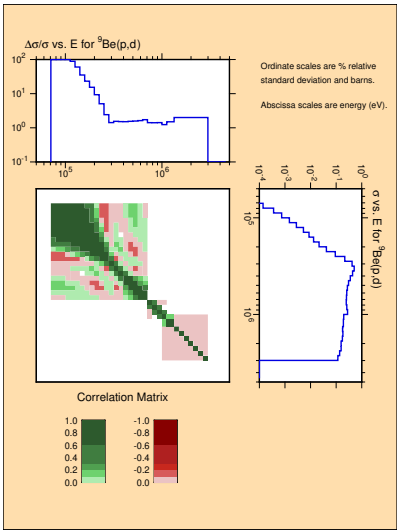

Figure: Covariance matrix of the cross sections for ^{9}Be(p,d)2α reaction.

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Reaction: ^{9}Be(p,α)^{6}Li – Model and Resonances

- Produces fast α and ^{6}Li
- Not well evaluated in nuclear data libraries (only total α production in MF6/MT5)
- Experimental data shows two prominent resonance peaks

S-function fits by energy range:

$$S_1(E) = \frac{A_0 + A_1 E + \ldots + A_5 E^5}{1 + B_1 E + B_2 E^2 + B_3 E^3}$$

$$S_2(E) = \frac{A_0 + A_1 E + \ldots + A_5 E^5}{1 + B_1 E + B_2 E^2}$$

$$S_3(E) = \frac{A_0 + A_1 E + \ldots + A_4 E^4}{1 + B_1 E + B_2 E^2}$$

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Results: ^{9}Be(p,α)^{6}Li

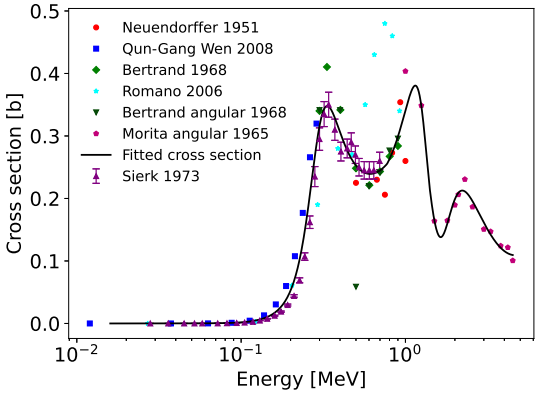

Figure: Measurements for ^{9}Be(p,α)^{6}Li.

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Uncertainty: ^{9}Be(p,α)^{6}Li

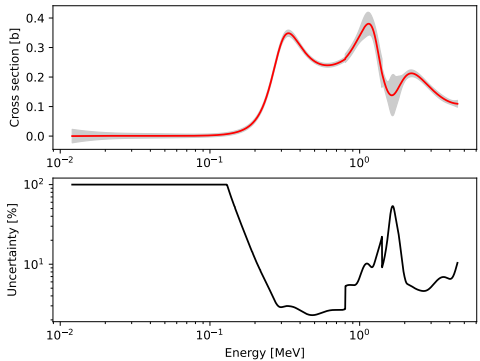

Figure: Uncertainty of generated total cross section for reaction ^{9}Be(p,α)^{6}Li calculated by the Monte Carlo technique from the uncertainties of the fitted polynomial coefficients

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Covariance Matrix: ^{9}Be(p,α)^{6}Li

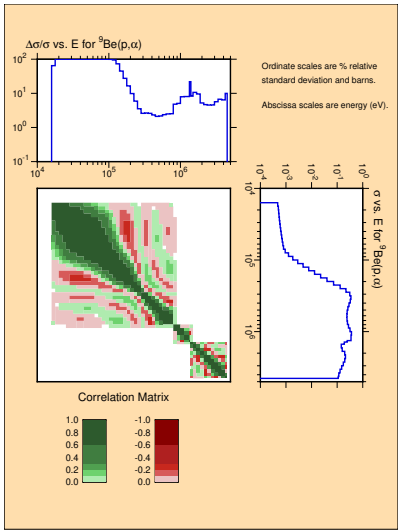

Figure: Covariance matrix of the cross sections for ^{9}Be(p,α)^{6}Li reaction.

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Reactions: ^{9}Be(d,nγ)^{10}B and ^{9}Be(α,nγ)^{12}C – Background

- Fast d and α particles from earlier reactions can produce secondary neutrons via:
  - ^{9}Be(d,nγ)^{10}B
  - ^{9}Be(α,nγ)^{12}C
- Relevance: further contributes to neutron diagnostics during non-DT phases
- Data libraries: TENDL-2021 (both), JENDL-5 (only α-induced)

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Reaction: ^{9}Be(d,nγ)^{10}B – Data and Comparison

- Sparse experimental data available
- Peak around 1.5 MeV seen in some measurements (e.g. Siemssen 1965)
- TENDL-2021 includes evaluation, but deviations observed
- Due to low data density, current evaluation in TENDL is the best available

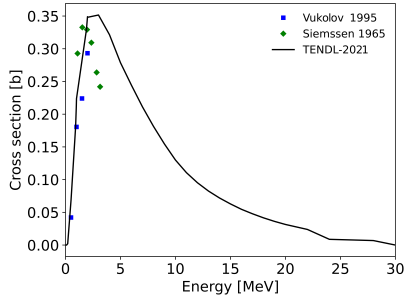

Figure: Experimental measurements vs TENDL-2021 cross section for ^{9}Be(d,nγ)^{10}B.

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Reaction: ^{9}Be(α,nγ)^{12}C – Data Status

- Several experiments exist (Wrean, Kunz, Ramström, Gibbons)
- JENDL-5 provides accurate fit up to 5 MeV
- TENDL-2021 fails to reproduce key resonant features
- Reaction important as threshold is relatively low (1.8 MeV)

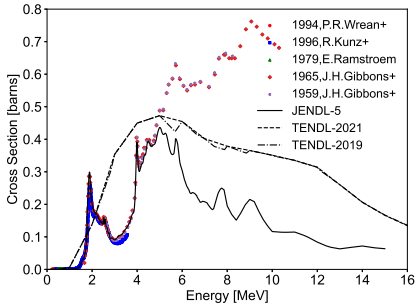

Figure: Experimental measurements vs JENDL-5 and TENDL-2021 for ^{9}Be(α,nγ)^{12}C.

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Conclusion

- Developed evaluated cross sections for Be reactions
- Covered key channels for PFPO neutron/gamma sources
- Data proposed for FENDL inclusion
- New measurements recommended for validation and extension

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