^{12}C+n evaluation work extending to 16 MeV neutron

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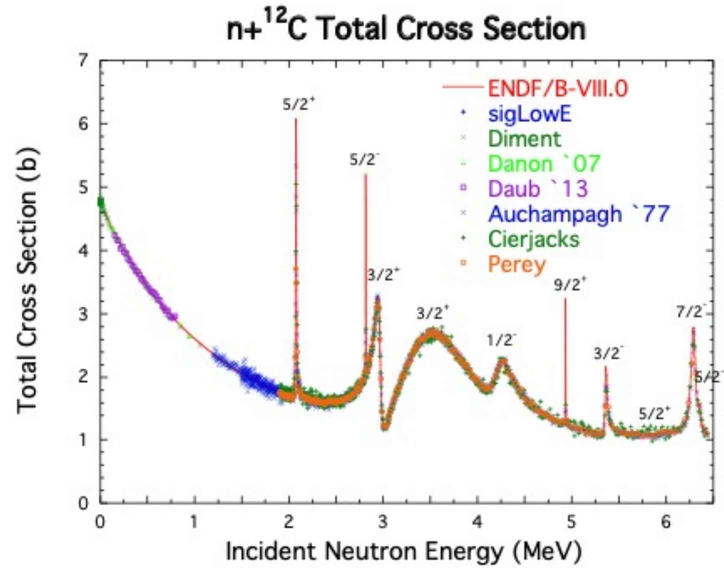
^{12}C+n evaluation in ENDF

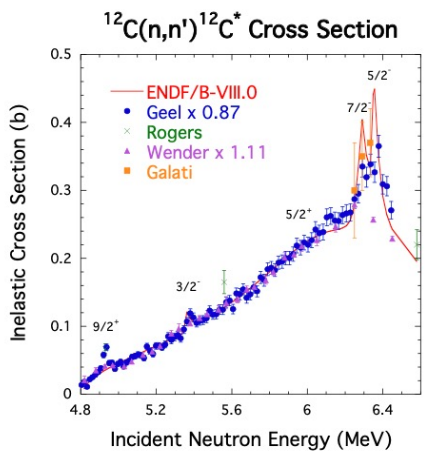
- R-matrix evaluation has been done up to 6.5 MeV neutron in the current ENDF/B-VIII.1 library

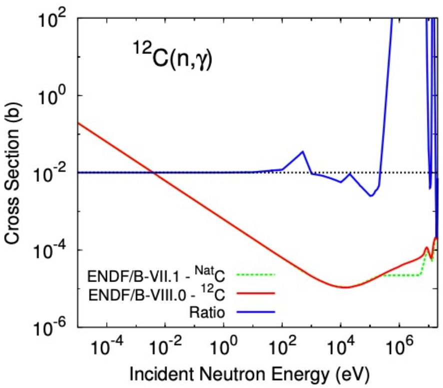


- Extending the upper neutron energy is important for applications in nuclear energy, nuclear criticality safety, nuclear security and basic science

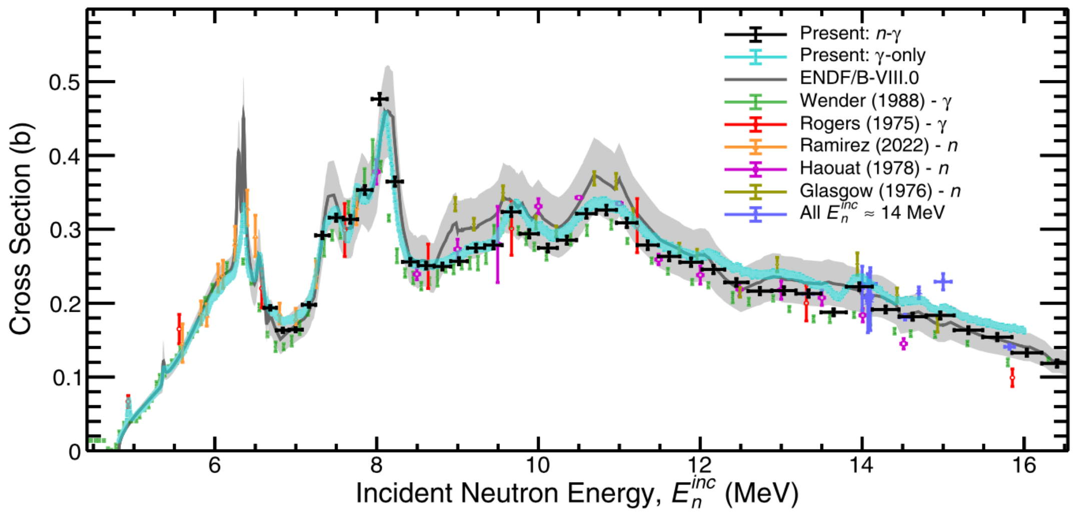
- R-matrix evaluation up to high neutron energy can benefit for the future ENDF

- We present preliminary results of our evaluation work extending to 16 MeV neutron



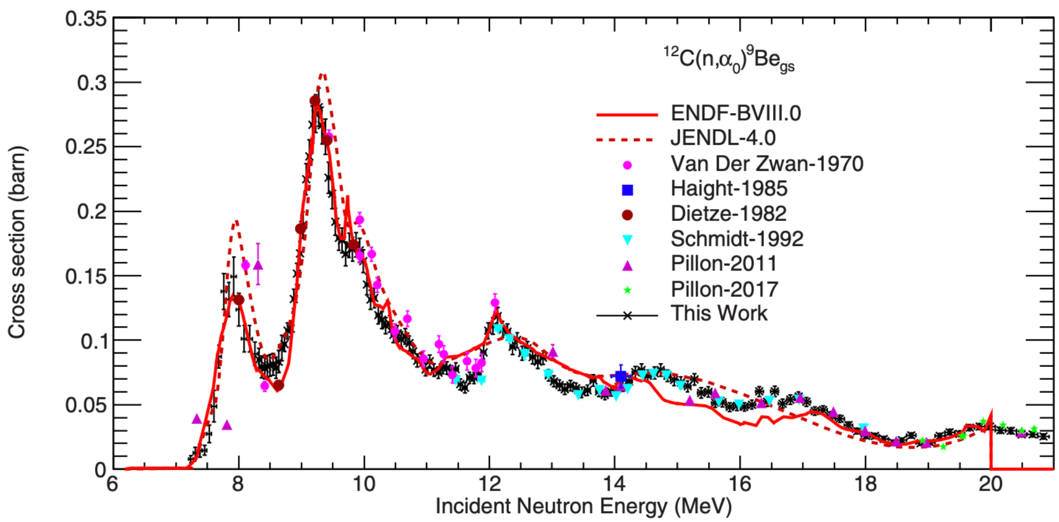


Recent (n,n'γ) and (n,α) measurements at LANSCE



$^{12}C(n,n'\gamma)^{12}C^*$ @CoGNAC

Keegan Kelly et al., PRC108, 014603 (2023)



$^{12}C(n,\alpha)^9Be$ @LENZ

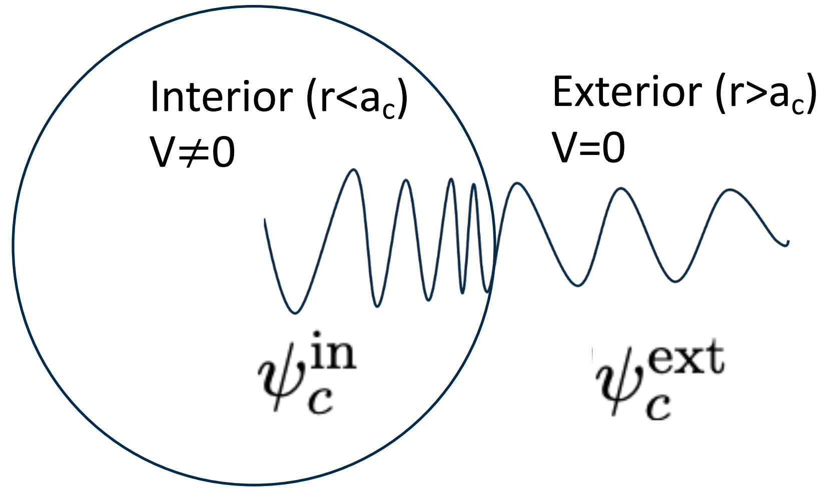
Sean Kuvin et al., PRC104, 014603 (2021)

We have new data applicable for the evaluation up to 16 MeV

R-matrix theory

- Schrödinger equations of two different regions

$$\begin{cases} (H_0 + V)\psi_c^{\rm in} = E\psi_c^{\rm in} & (r < a_c) \\ H_0\psi_c^{\rm ext} = E\psi_c^{\rm ext} & (r > a_c) \end{cases}$$



V… Nuclear force

c… channel

General solution in r>a_c :

$$\psi_c^{\rm ext} = \{\delta_{cc'} I_{c'}(r) - \underline{S_{cc'}} O_{c'}(r)\}\, \phi_{c'}$$

S-matrix

- Observables (cross sections, polarizations,..) are calculated from S-matrix that is defined on the surface of the boundary at r=a_c

- (Phenomenological) R-matrix theory describes the S-matrix with the R-matrix below instead of solving the Schrödinger equation in r< a_c

$$\underline{R_{cc'}} = \sum_\lambda \frac{\gamma_{\lambda c}\gamma_{\lambda c'}}{E_\lambda - E}$$

R-matrix

λ… level

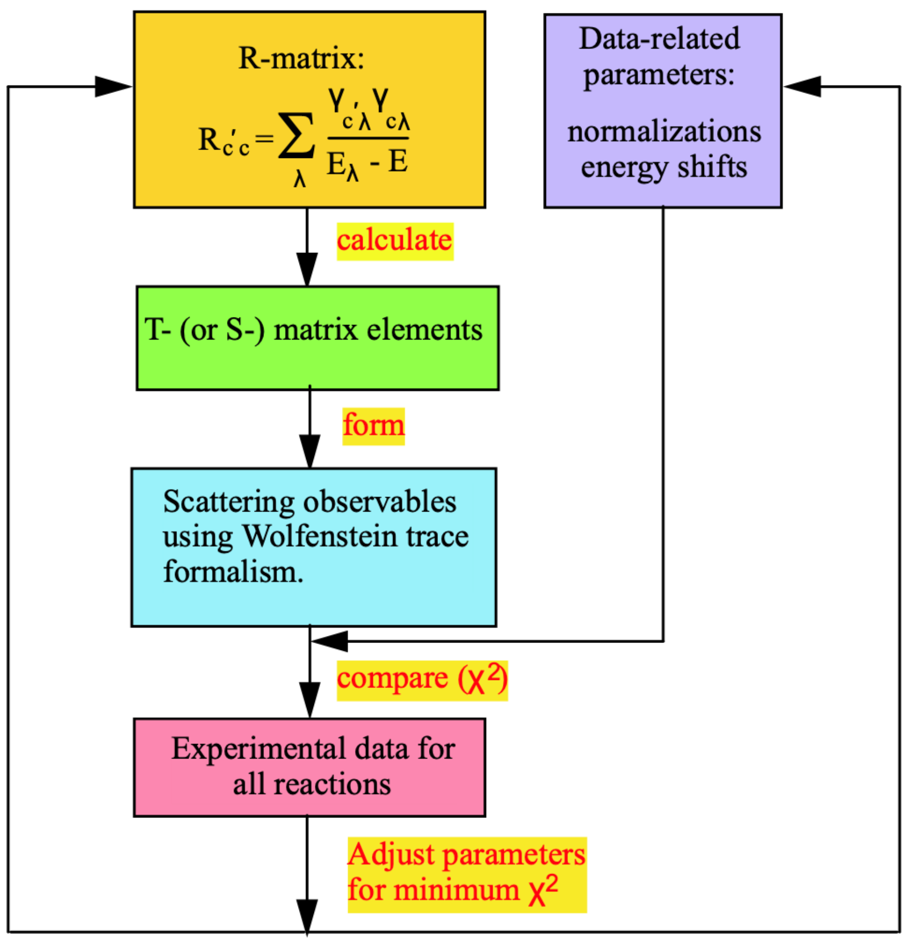
$$\gamma_{\lambda c} \propto \int_{r=a_c} \mathrm{d}S\ \phi_c^* X_\lambda$$

$$(H_0 + V)X_\lambda = E_\lambda X_\lambda$$

➡ R-matrix analysis searches for suitable R-matrix parameters {E_λ , $\gamma_{\lambda c}$}

R-matrix analysis with EDA

We use Energy Dependence Analysis (EDA) code for the R-matrix evaluation



- Construct R-matrix with R-matrix parameters $\{E_\lambda, \gamma_{\lambda c}\}$
- Calculate T- (or S-) matrix and form observable quantities
- Estimate χ^2 and compare the calculation and experimental data with data-related parameters
- Update R-matrix and data-related parameters $\{p_i\}$ to minimize χ^2 (**p**) based on a variable metric method

$$\delta \mathbf{p} = -H^{-1}\mathbf{g} \qquad g_i = \frac{\partial \chi^2(\mathbf{p})}{\partial p_i}$$

$$H_{ij} = \frac{\partial^2 \chi^2(\mathbf{p})}{\partial p_i \partial p_j}$$

G.M.Hale, Nuc.Data sheets 109 (2008)2812

Input of EDA

Partition β	L_{max}	a_c (fm)
n + ^{12}C	4	4.47
n + ^{12}C*(2^+)	3	6.10
γ + ^{13}C	1	50.0
α+ ^{9}Be	3	5.00

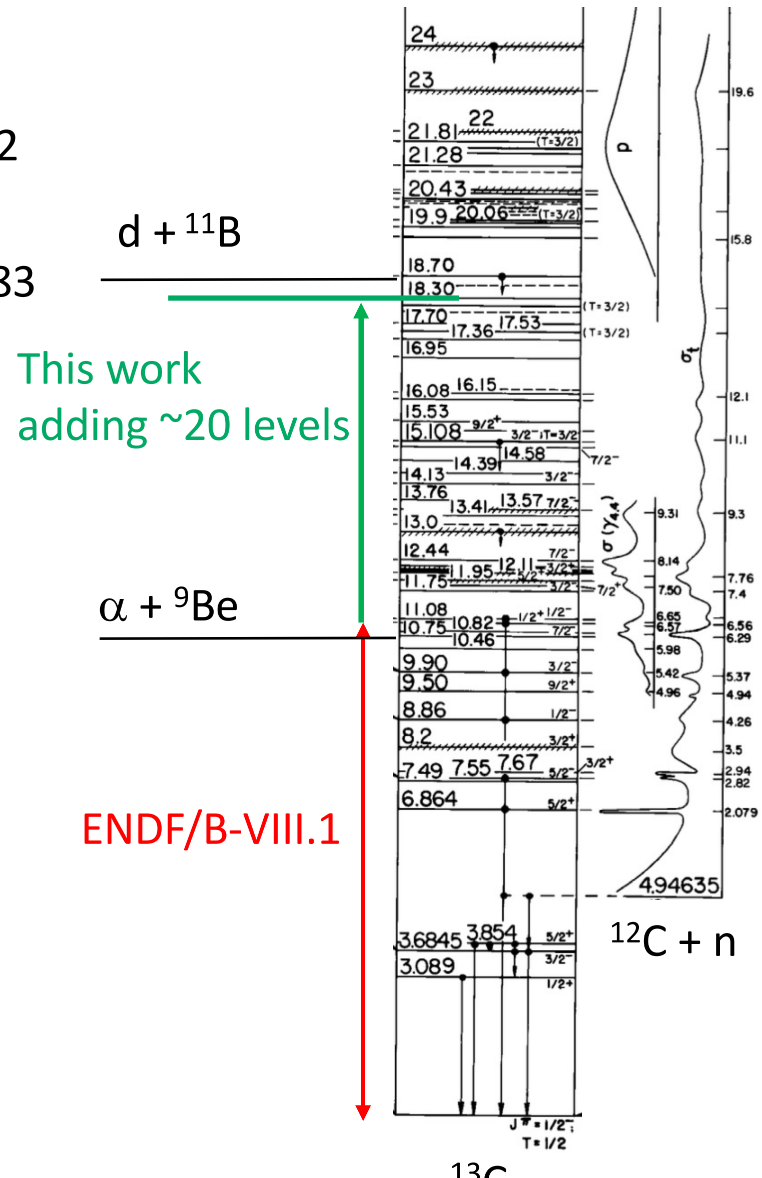
R-matrix parameters

# of channel c=(β,s,L,J^π)...... 52

# of level λ 50

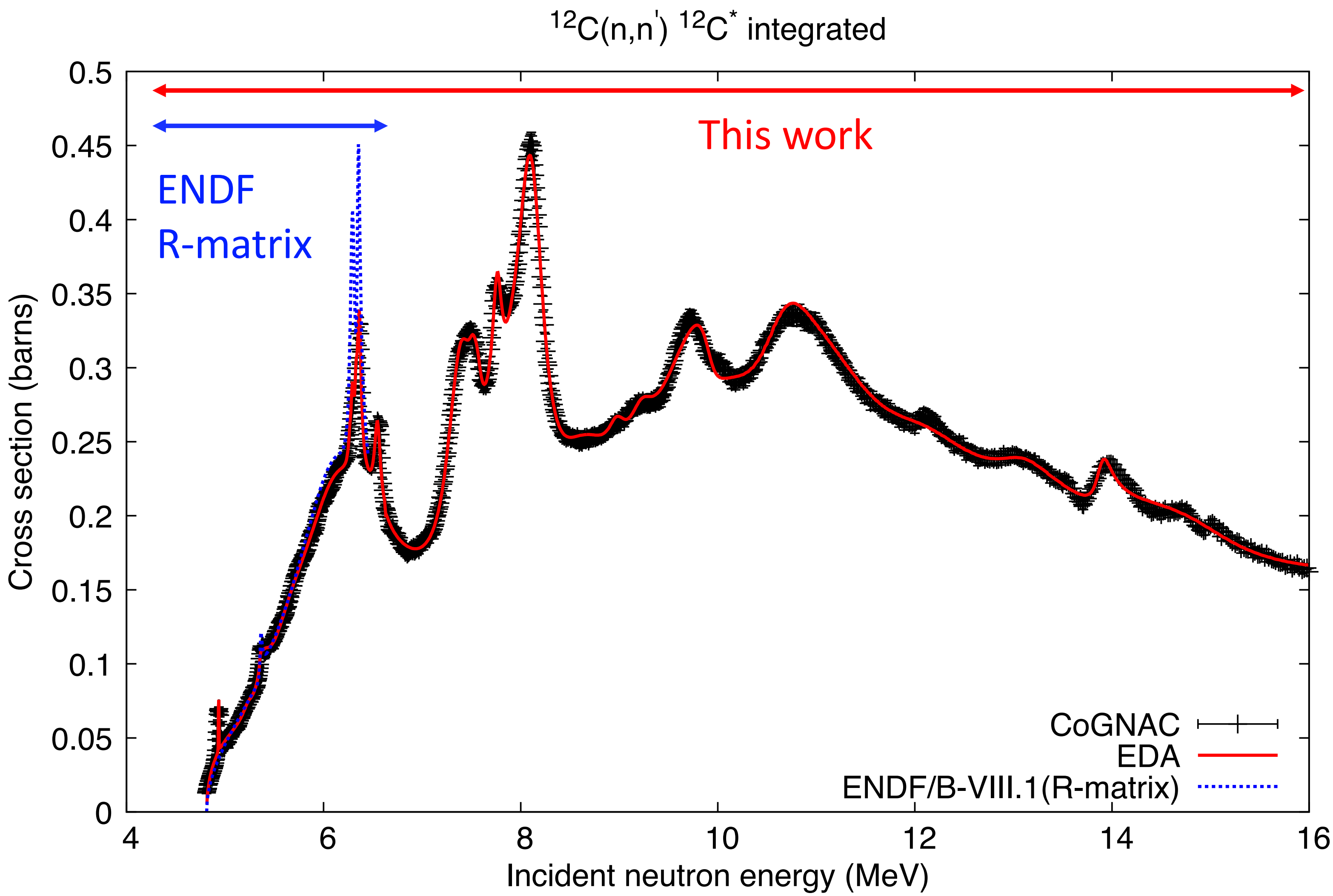
# of reduced width $\gamma_{\lambda c}$ 283

Reaction	Energy range (MeV)	# Exp data points	Observables
^{12}C (n,n) ^{12}C	E_n = 0 – 16.0	8963	σ_{tot} , dσ/dΩ, A_y(n)
^{12}C (n,n) ^{12}C*	E_n = 4.81 – 16.4	2494	σ_{int}(CoGNAC) , dσ/dΩ
^{12}C (n,γ) ^{13}C	E_n = 0 – 0.2	7	σ_{int}
^{12}C (n,α) ^{9}Be	E_n = 7.24 – 20.0	149	σ_{int}
^{9}Be(α,n) ^{12}C	E_α = 0.366 – 3.55	509	σ_{int}
^{9}Be(α,n) ^{12}C*	E_α = 0.266 – 3.55	509	σ_{int}
	Total	12631	



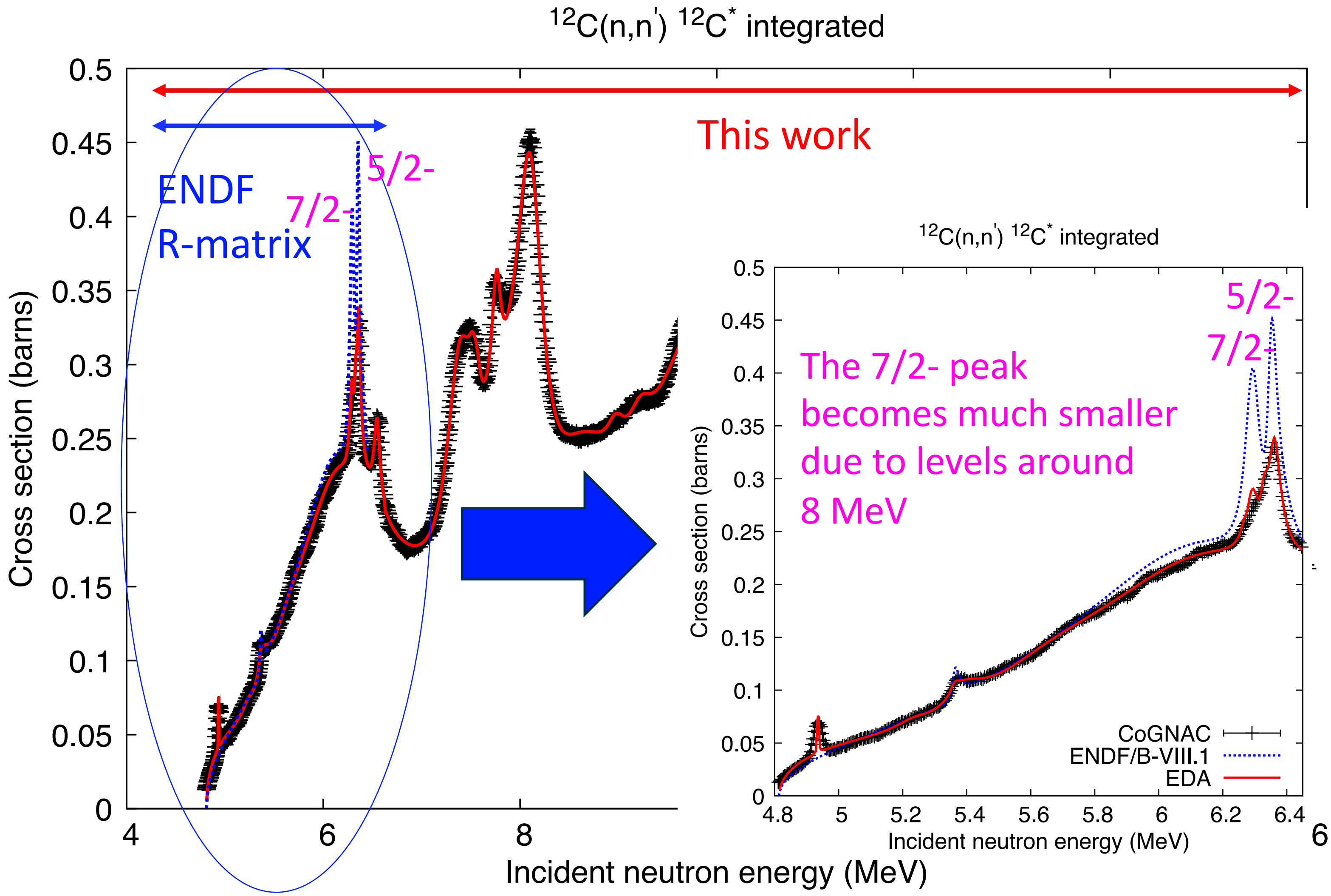
F.Ajzenberg-Selove, Nucl. Phys. A523 (1991) 1

Integrated cross section of inelastic scatterings



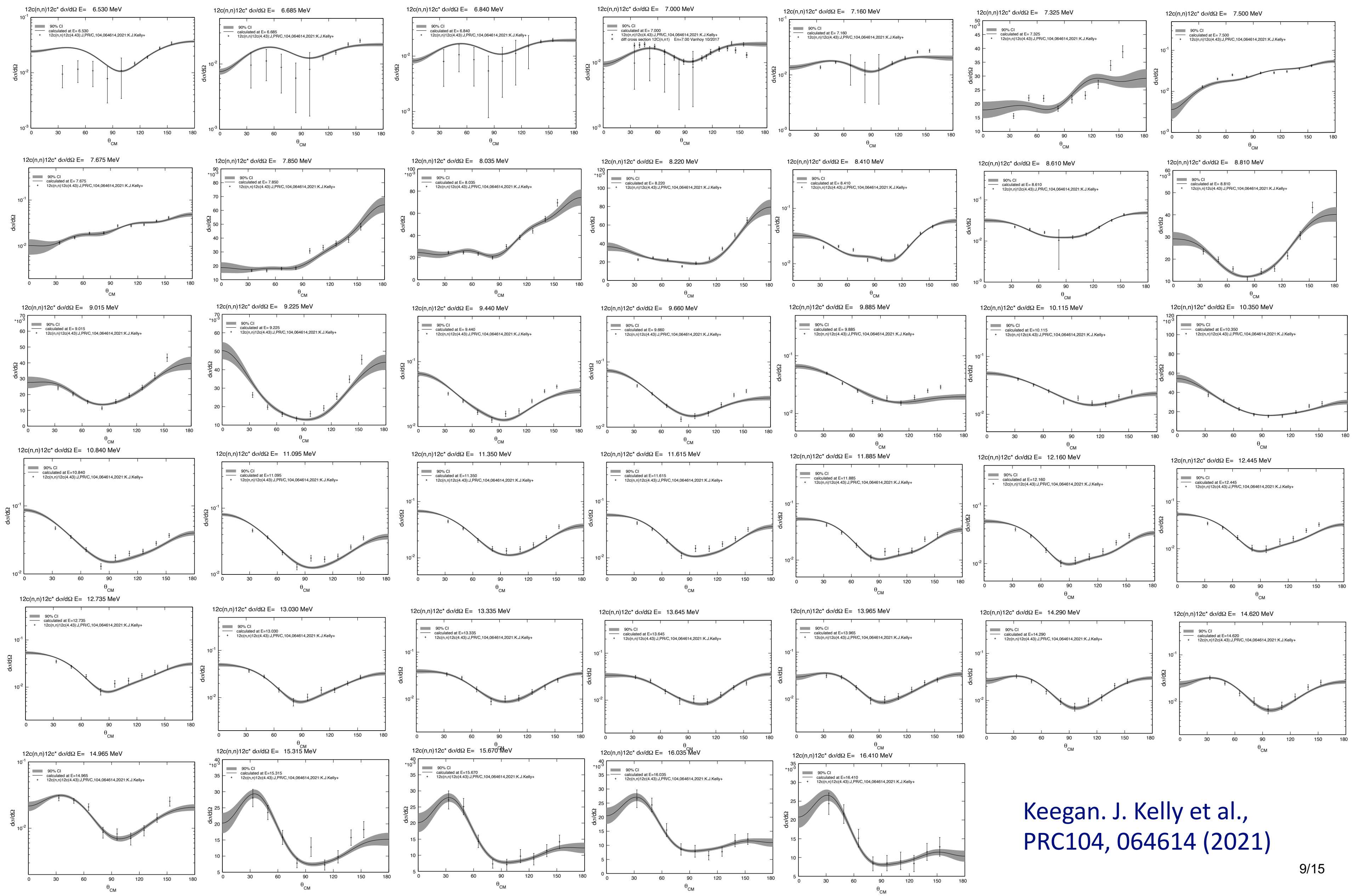
We found R-matrix parameters reproducing CoGNAC data up to 16 MeV neutron

Integrated cross section of inelastic scatterings



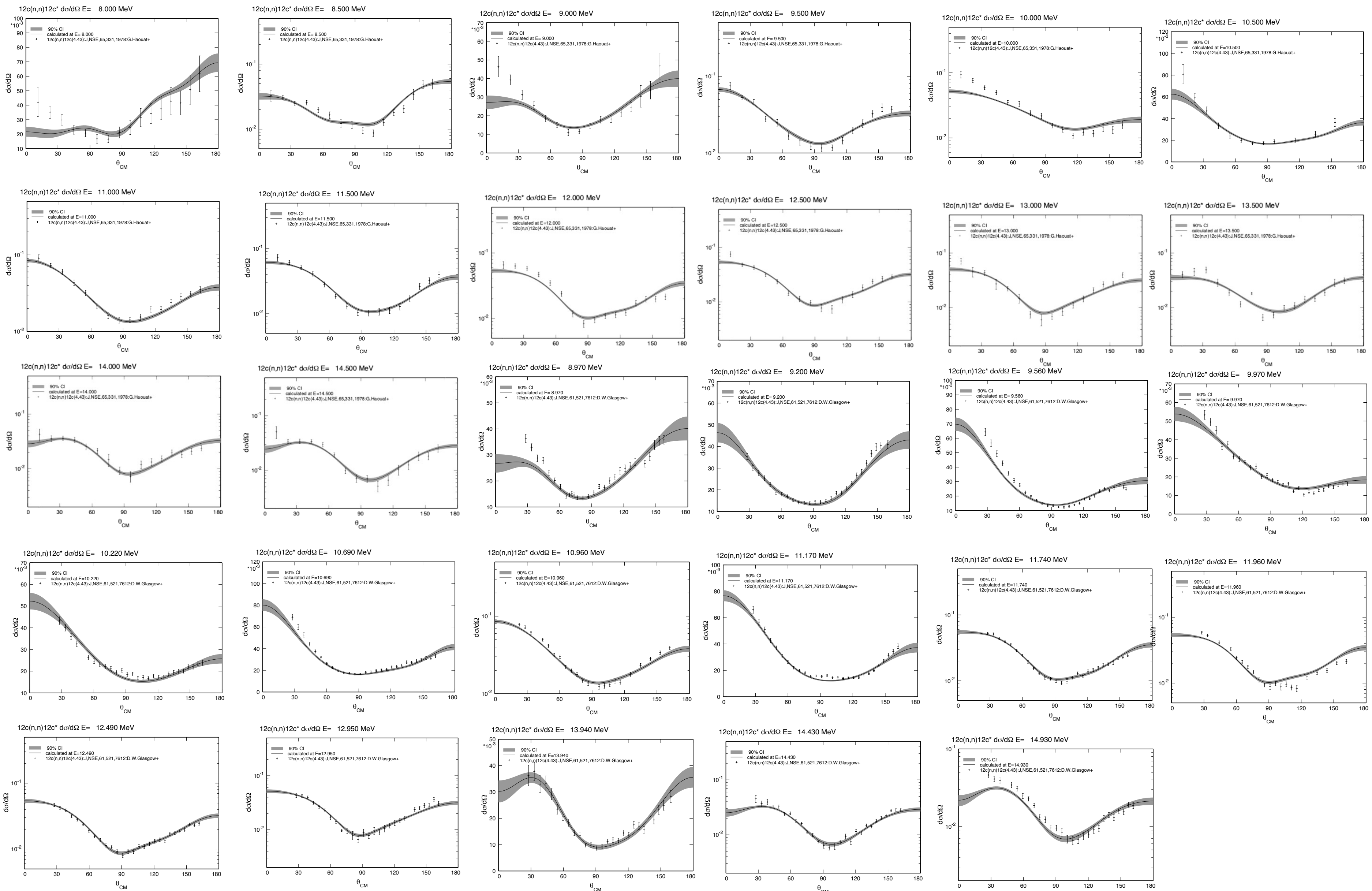
We found R-matrix parameters reproducing CoGNAC data up to 16 MeV neutron

Inelastic differential cross sections (6.53-16.4 MeV)



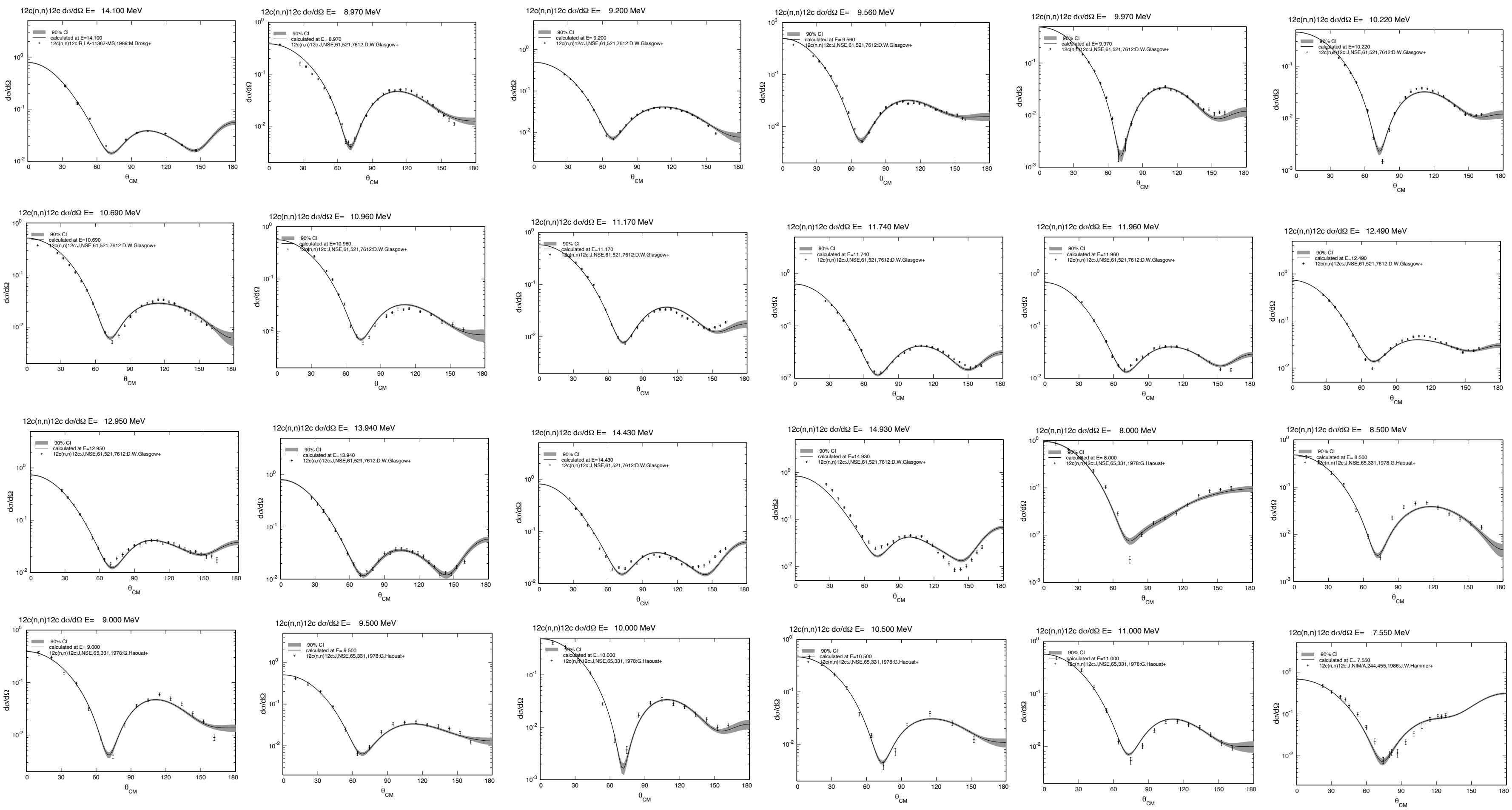
Keegan. J. Kelly et al.,
PRC104, 064614 (2021)

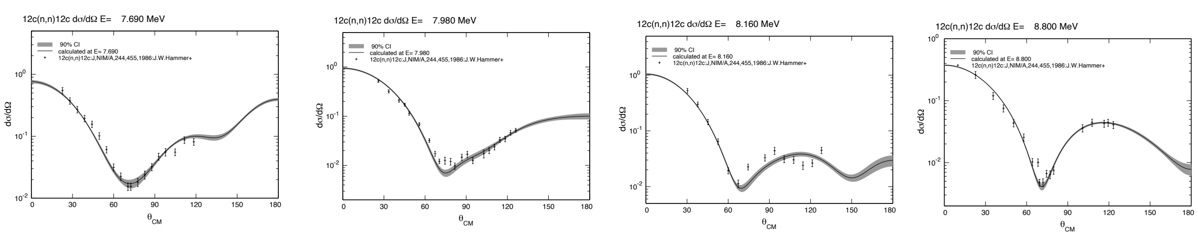
Other inelastic DA data (8.00-14.9 MeV)



D.W. Glasgow et al.,NSE61,521 (1976)   G. Haouat et al.,NSE65,331 (1978)

Elastic differential cross sections (7.55-14.93 MeV)





D. W. Glasgow et al.,NSE61,521 (1976)

G. Haouat et al.,NSE65,331 (1978)

M. Drosg et al., Rad.eff.,92,145(1988)

J. W. Hammer et al., J.NIM/A,244, 455 (1986)

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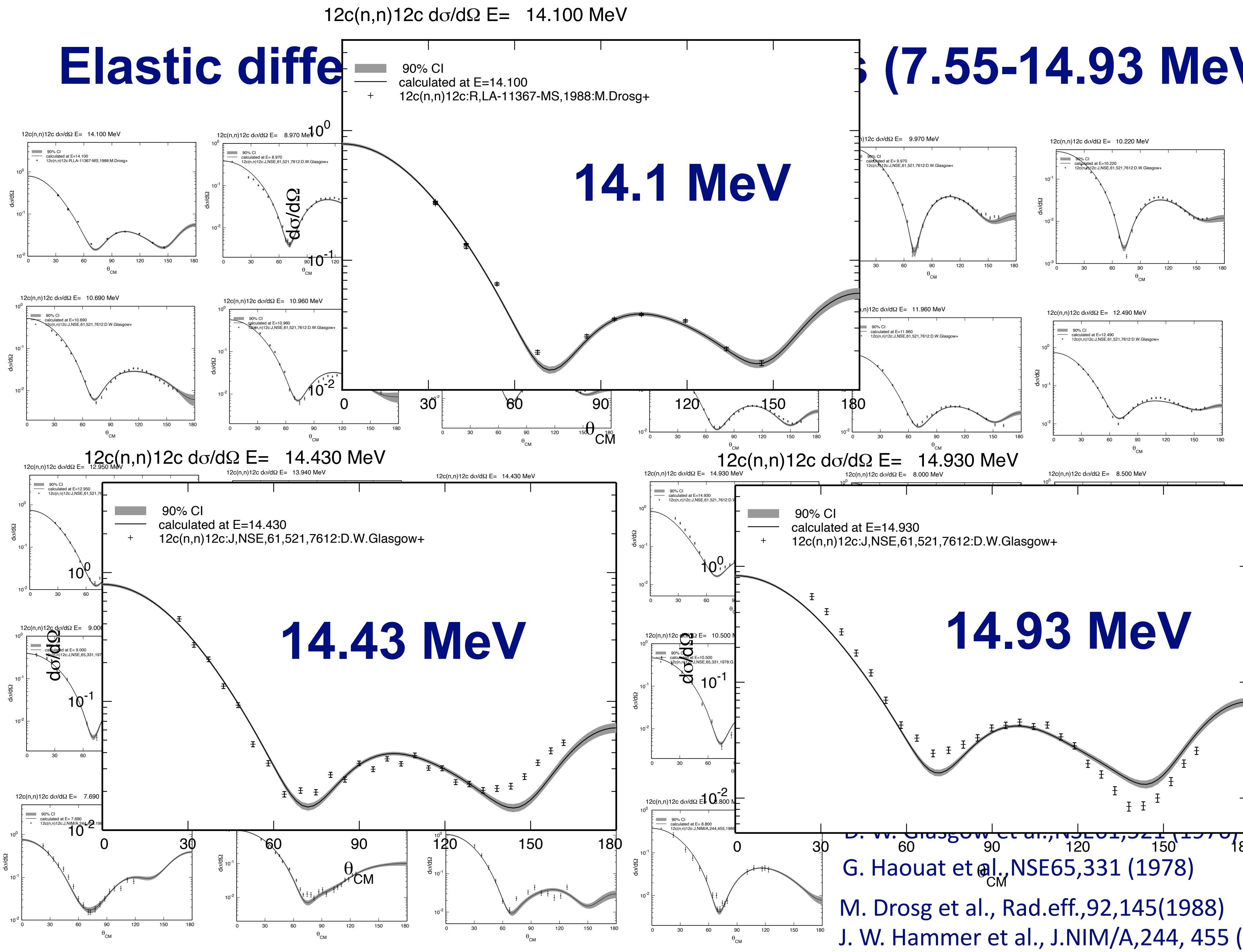

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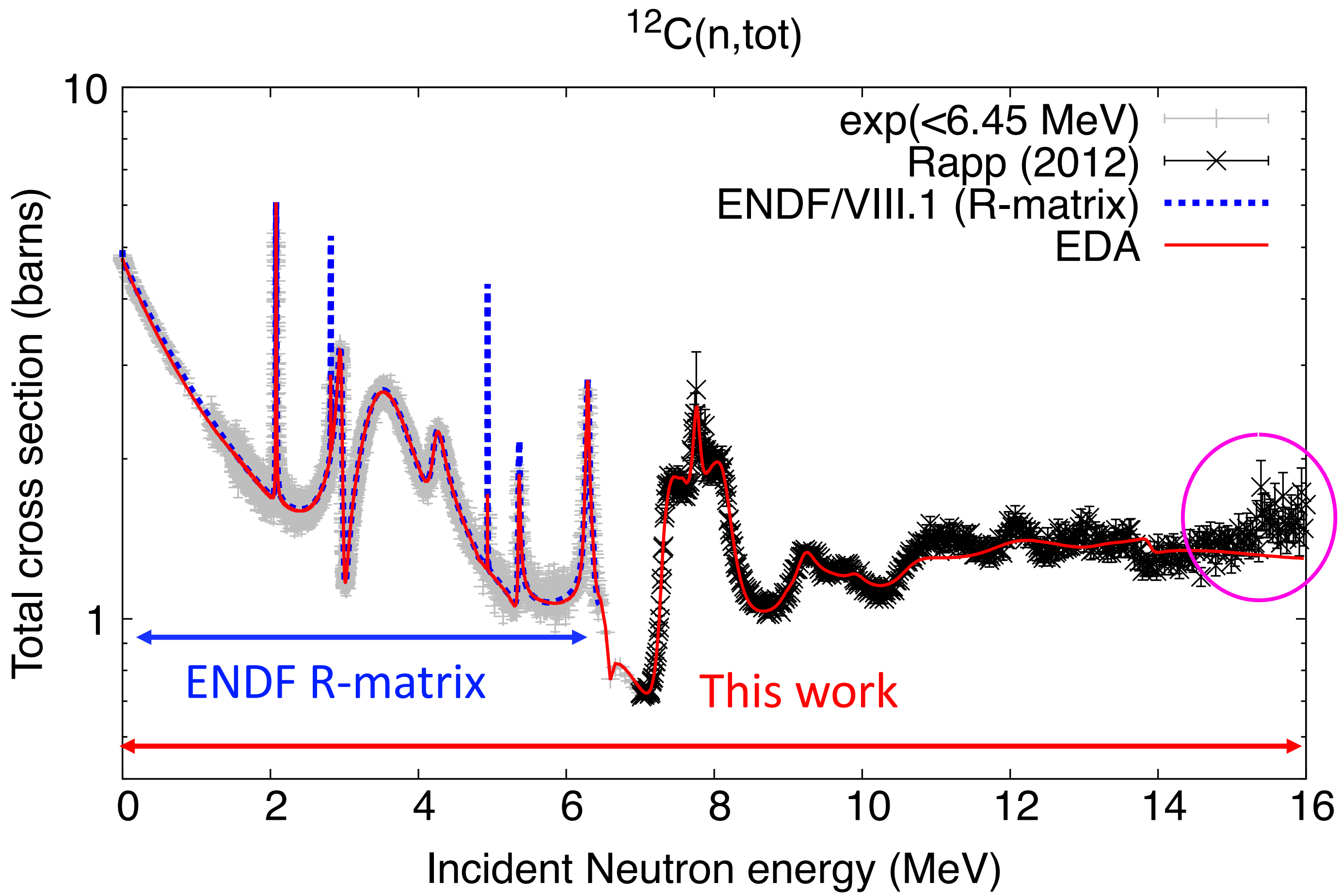
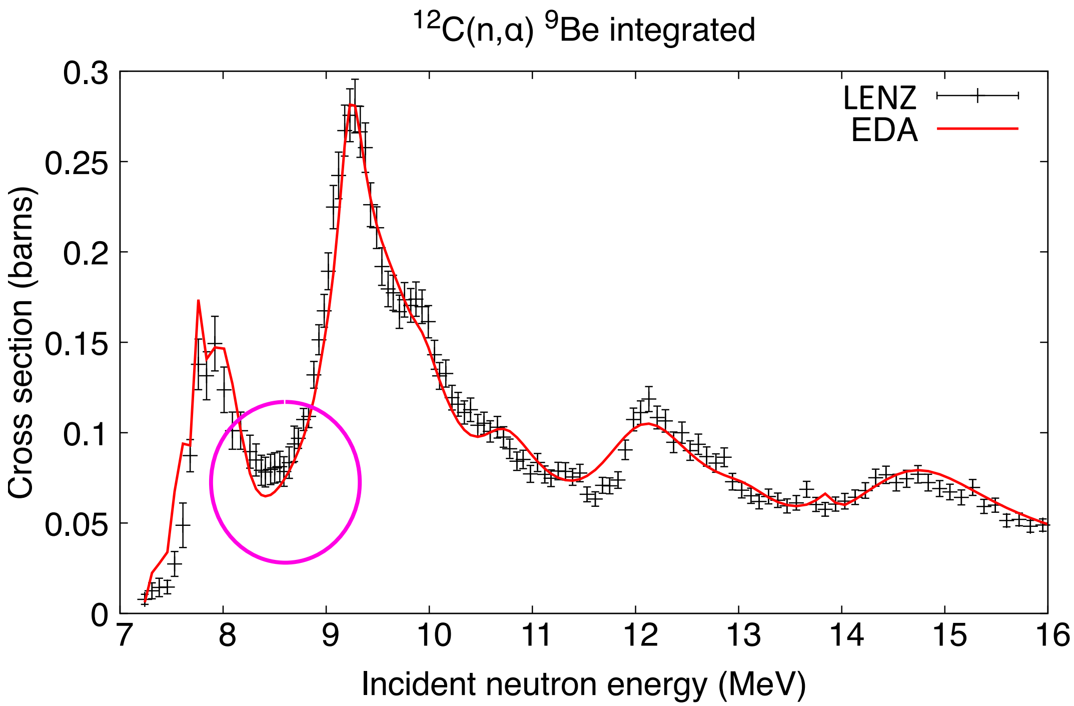
^{12}C+n Total cross section

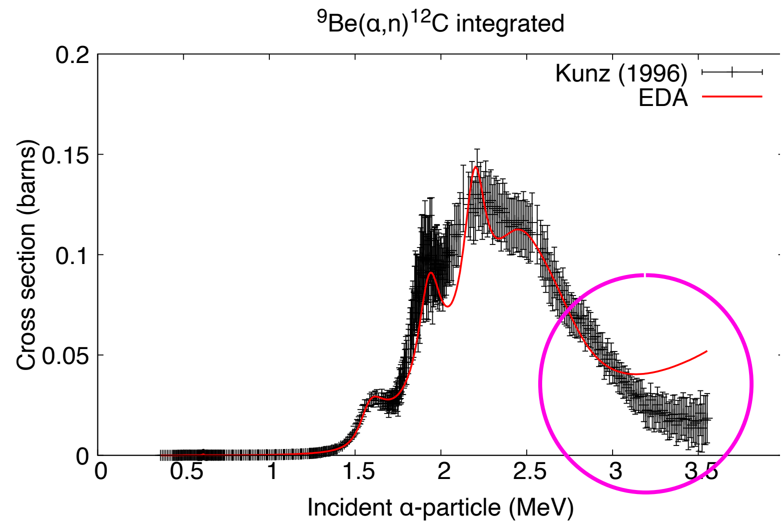


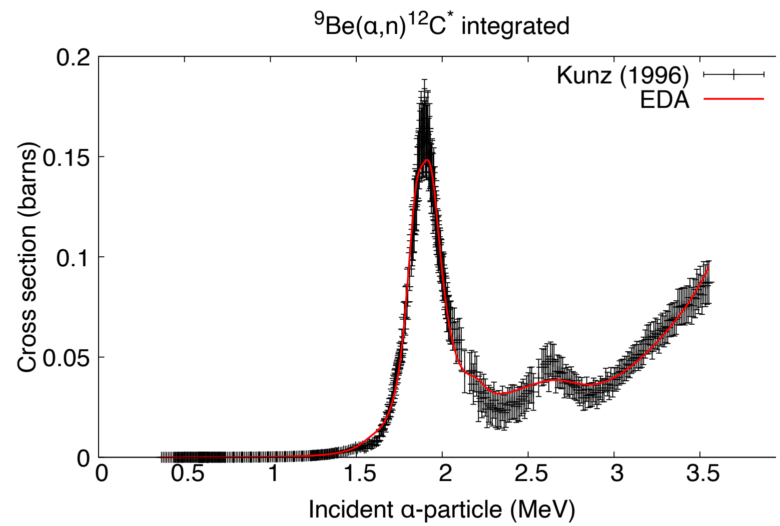
- EDA reproduces sharp peaks below 6.45 MeV
- EDA underestimates above 15 MeV

➡ More elastic scattering data above 15MeV reduces the discrepancy?
Contributions from the breakup ^{12}C(n,n′ 2α) α (～30%) and ^{12}C(n,p)^{12}B (< 5%) ?

Integrated cross sections of $^{12}C^{(*)}$ +n ⇄ ^{9}Be+^{4}He







EDA can reproduce overall structure of $^{12}C(n,^{4}He)^{9}Be$ and that of $^{9}Be(^{4}He,n)$ $^{12}C^{(*)}$

The fit does not work well around 3.5 MeV α-particle for $^{9}Be(n,\alpha)$ ^{12}C due to the restriction from ∼8.5 MeV neutron in the inverse reaction

Summary

- We extended the ^{12}C+n evaluation based on EDA R-matrix analysis from 6.45 MeV to 16 MeV neutron
- We found good R-matrix parameters to reproduce recent LANSCE measurements of inelastic scatterings and (n,α) channels
- The fit well works for the elastic and total cross section data up to 14 MeV neutron
- The discrepancy of ^{9}Be(n,α) ^{12}C is relevant to the fit of the reverse reaction

Thanks to
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Sean Kuvin (LANL/P-3)

Outlook

- Further optimization of R-matrix parameters for the better convergences and for decreasing the value of current χ^2 per degree of freedom (= 2.60)
- More integrated or reaction cross section data from various measurements
- Derivation of resonance parameters and covariances
- Development of the nuclear model to include the breakup reaction ^{12}C(n,n$'$ 2α) α