Status of and Plans for Light-Element Standards Evaluations at LANL

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Status of Light-Element R-matrix Analyses/Evaluations

- n-p (N-N system) scattering up to 100 MeV
- n+^{3}He (^{4}He system) cross sections up to 20 MeV
- n+^{6}Li (^{7}Li system) cross sections up to 8 MeV
- n+^{10}B (^{11}B system) cross sections up to 1 MeV – work just started with Ian Thompson (LLNL)
- n+^{12}C (^{13}C system) scattering up to 16 MeV

Charge-Independent Analysis of N-N System up to 100 MeV

Channel	a_c (fm)	l_{max}
p+p	3.26	3
n+n	3.26	3
n+p	3.26	3
γ+d	84.6	1

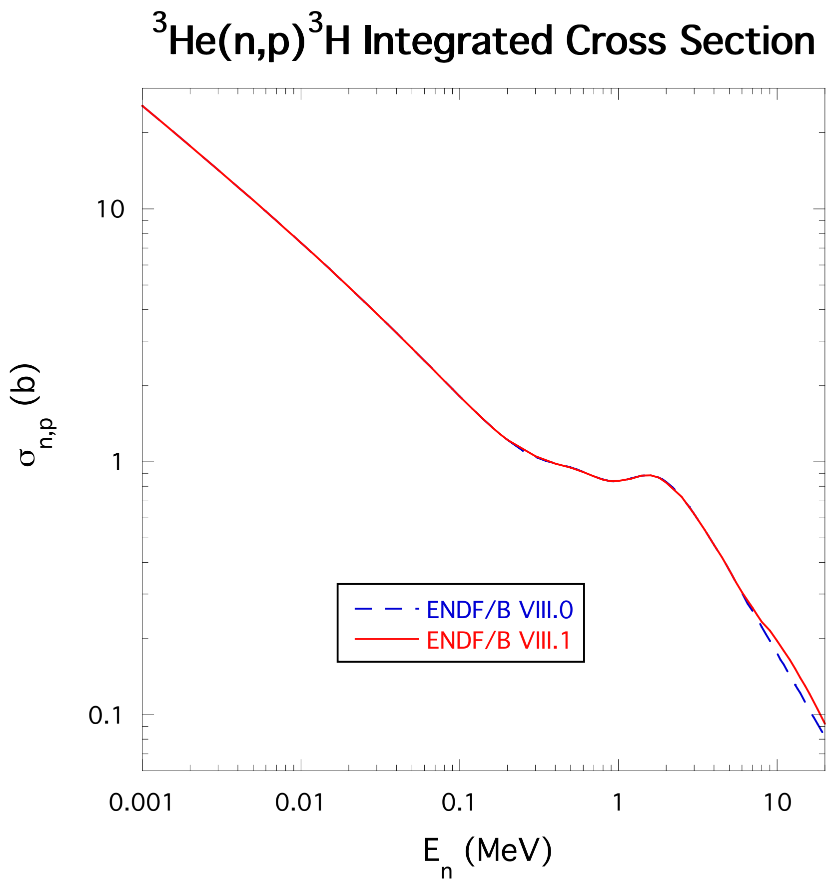
Reaction	# Pts.	χ^2	Observable Types
p(p,p)p	667	1218	$\sigma(\theta)$, $A_y(p)$, $C_{x,x}$, $C_{y,y}$, $K_x^{x'}$, $K_y^{y'}$, $K_z^{x'}$
n(n,n)n	1	0	σ_{int} (a_0)
p(n,n)p	5260	4687	σ_T, $\sigma(\theta)$, $A_y(n)$, $C_{y,y}$, $K_y^{y'}$
p(n,γ)d	82	133	σ_{int}, $\sigma(\theta)$, $A_y(n)$
d(γ,n)p	84	106	σ_{int}, $\sigma(\theta)$, $\Sigma(\gamma)$, $P_y(n)$
Total	6094	6144	19

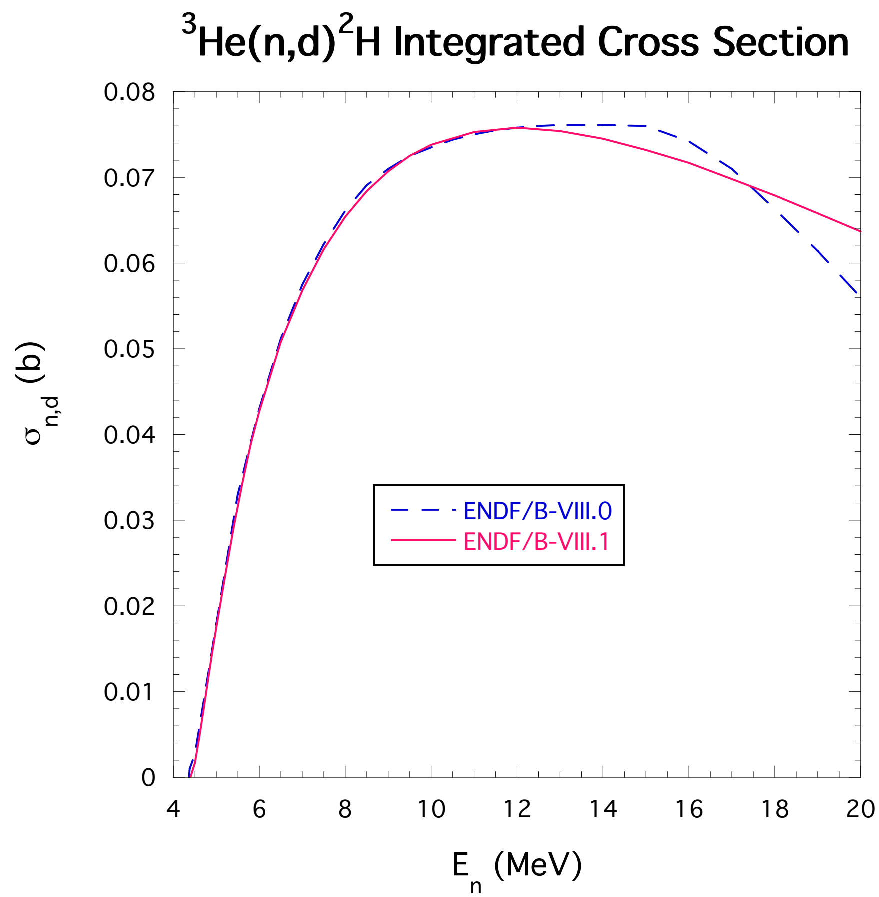
free parameters = 50 $\Rightarrow$ χ^2/degree of freedom = 1.0165

Extending N-N scattering to higher energies

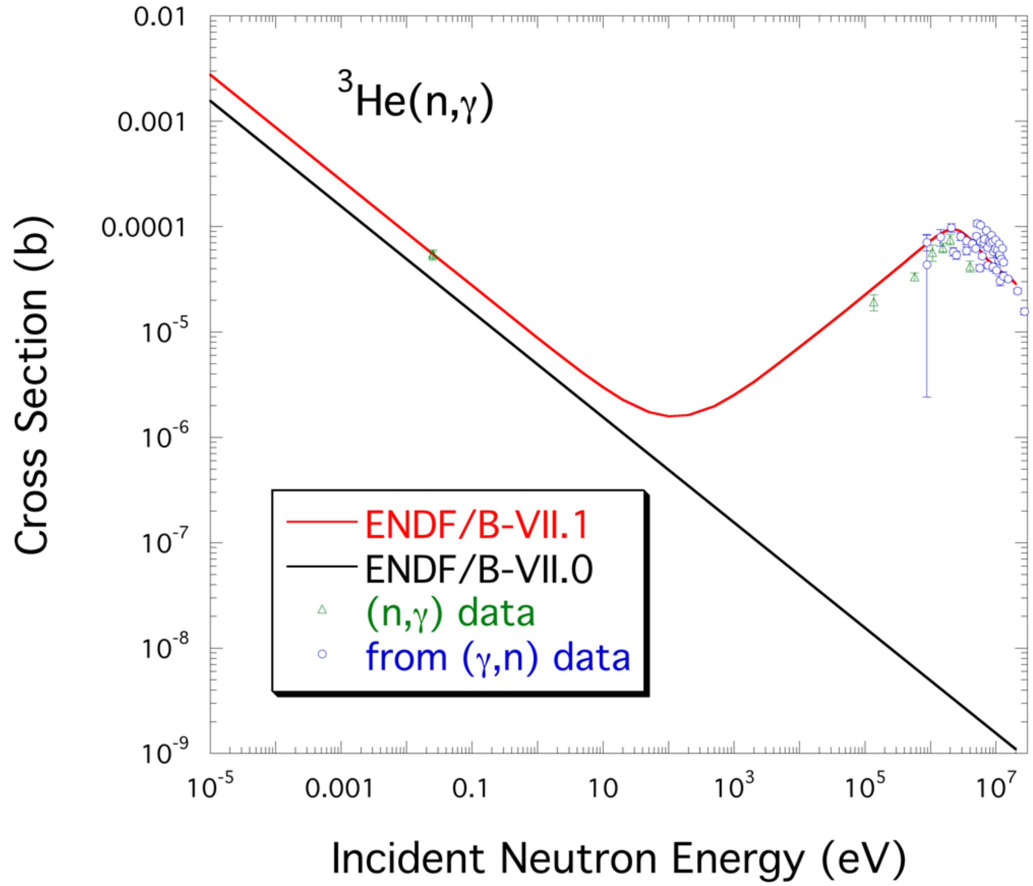
- 100 MeV seems to be the practical upper limit for an R-matrix pole expansion to work. Above that energy, some of the “background” poles remain in the energy range of the data, and cause non-smooth behavior of the phase shifts.
- One possibility is to match the 100-MeV solution to higher-energy phase shifts (e.g., one of the later solutions of Arndt’s group). This was tried before (at a lower matching energy), and it did not work very well because of discontinuities in the matching process.
- Another possibility is to base the parametrization over the whole energy range on $\mathbf{R}^{-1}$, rather than **R**. Then $\mathbf{R}^{-1}=\mathbf{A}+\mathbf{B}E$ (+pole terms in E). This approach was used by the Nijmegen group without the need for pole terms in their analysis of p-p scattering (but only up to 30 MeV).

Changes in the n+^{3}He Reaction Cross Sections

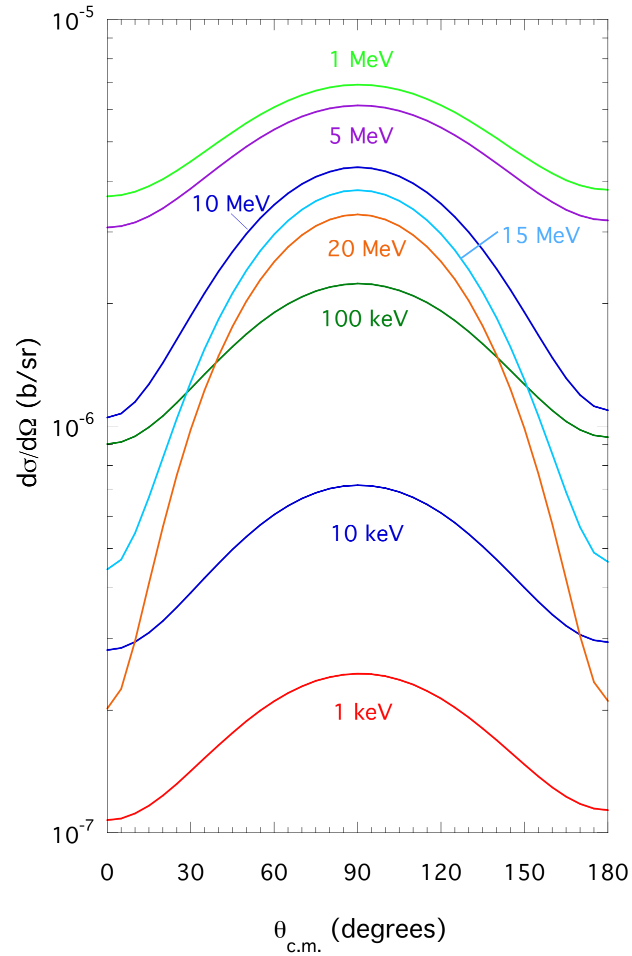




$^{3}He(n,\gamma)^{4}He$ Cross Section



Differential Cross Section

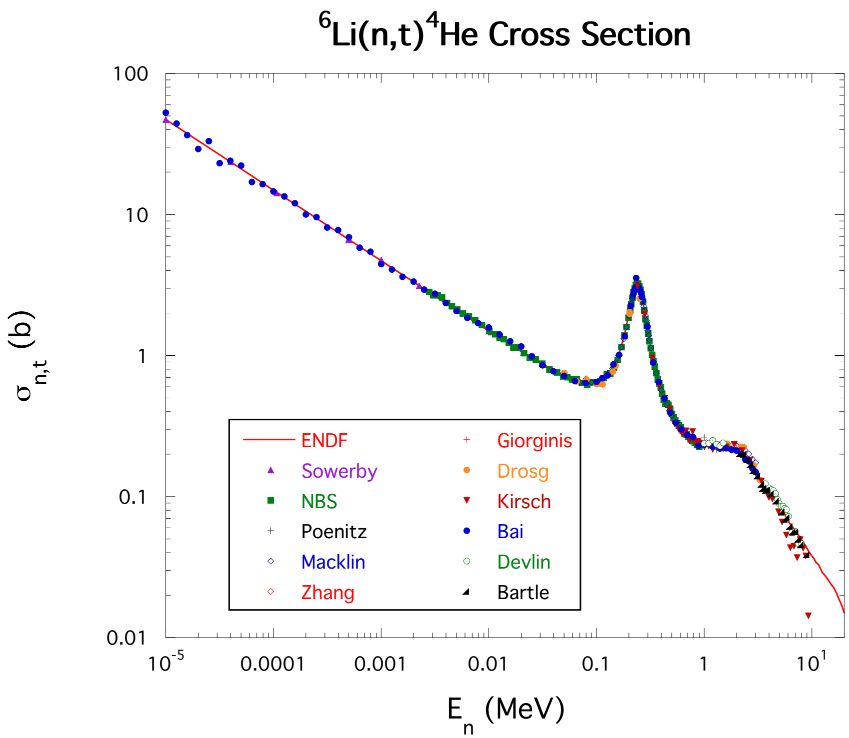


Summary of ^{7}Li R-matrix Analysis

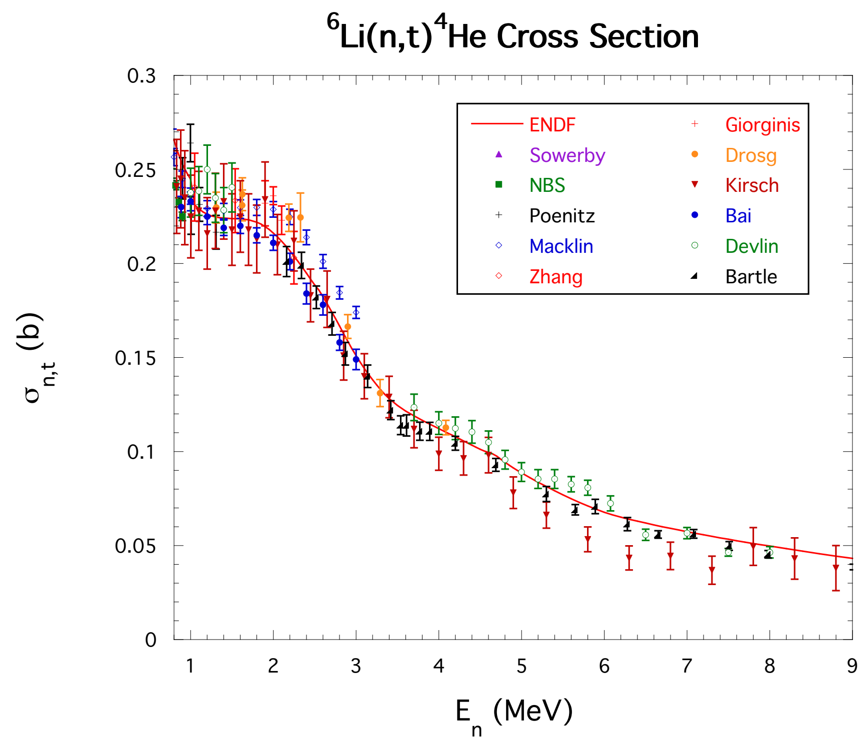
Channel	l_{max}	a_c (fm)
t+^{4}He	5	4.0
n+^{6}Li	3	5.0
d+^{5}He	1	7.5
n+^{6}Li*	1	5.0
p+^{6}He	1	5.0
n+^{6}Li**	1	5.5

Reaction	Energy range	Observables	# data points	χ^2/point
^{4}He(t,t)^{4}He	E_t = 3-17 MeV	$\sigma(\theta)$, $A_y(\theta)$	1689	1.03
^{4}He(t,n)^{6}Li	E_t = 8.75-14.4 MeV	$\sigma(\theta)$	39	1.14
^{4}He(t,n)^{6}Li*	E_t = 8.75-14.4 MeV	$\sigma(\theta)$	3	0.42
^{6}Li(n,t)^{4}He	E_n = 0-8 MeV	σ_{int} , $\sigma(\theta)$	2840	1.44
^{6}Li(n,n_0) ^{6}Li	E_n = 0-8 MeV	σ_{int} , σ_T, $\sigma(\theta)$, $P_y(\theta)$	1451	1.36
^{6}Li(n,d) ^{6}Li	E_n = 0-8 MeV	σ_{int} , $\sigma(\theta)$	28	11.9
^{6}Li(n,n_1) ^{6}Li*	E_n = 0-8 MeV	σ_{int} , $\sigma(\theta)$	175	2.11
^{6}Li(n,p) ^{6}He	E_n = 0-8 MeV	σ_{int} , $\sigma(\theta)$	92	1.58
^{6}Li(n,n_2) ^{6}Li**	E_n = 0-8 MeV	σ_{int}	41	0.30
Totals		17	6358	1.39*

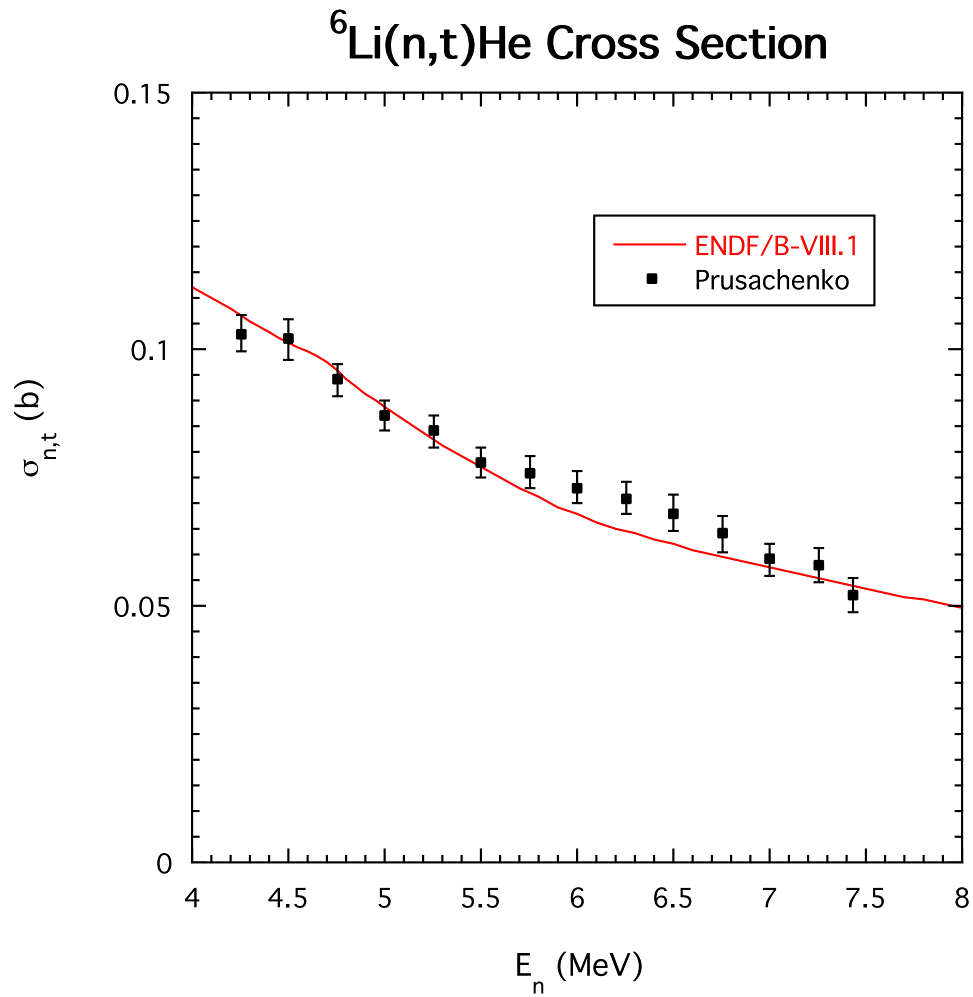
*For 170 free parameters, χ^2/ν = 1.43



6Li(n,t)4He Cross Section
100
10
1
0.1
0.01
10-5
0.0001
0.001
0.01
0.1
1
101
σ n,t (b)
En (MeV)
ENDF
Sowerby
NBS
Poenitz
Macklin
Zhang
Giorginis
Drosg
Kirsch
Bai
Devlin
Bartle



6Li(n,t)4He Cross Section
0.3
0.25
0.2
0.15
0.1
0.05
0
1
2
3
4
5
6
7
8
9
σ n,t (b)
En (MeV)
ENDF
Sowerby
NBS
Poenitz
Macklin
Zhang
Giorginis
Drosg
Kirsch
Bai
Devlin
Bartle



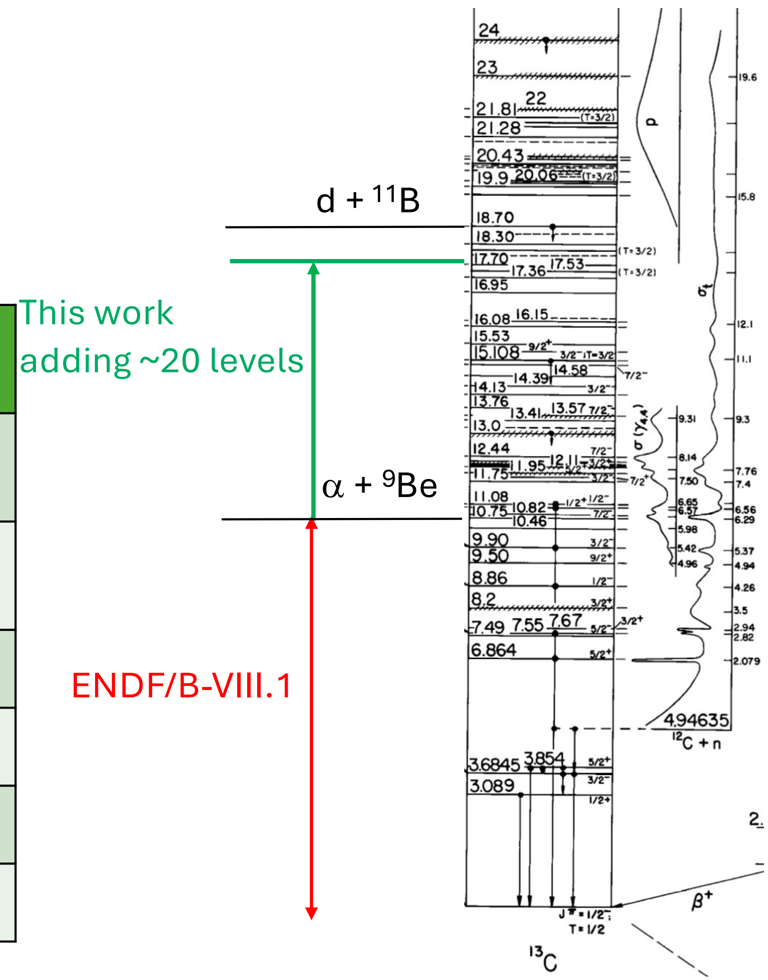
^{6}Li(n,t)He Cross Section
ENDF/B-VIII.1
Prusachenko
0.15
0.1
0.05
0
$\sigma_{n,t}$ (b)
4
4.5
5
5.5
6
6.5
7
7.5
8
E_n (MeV)

Summary of ^{13}C Analysis

Partition	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

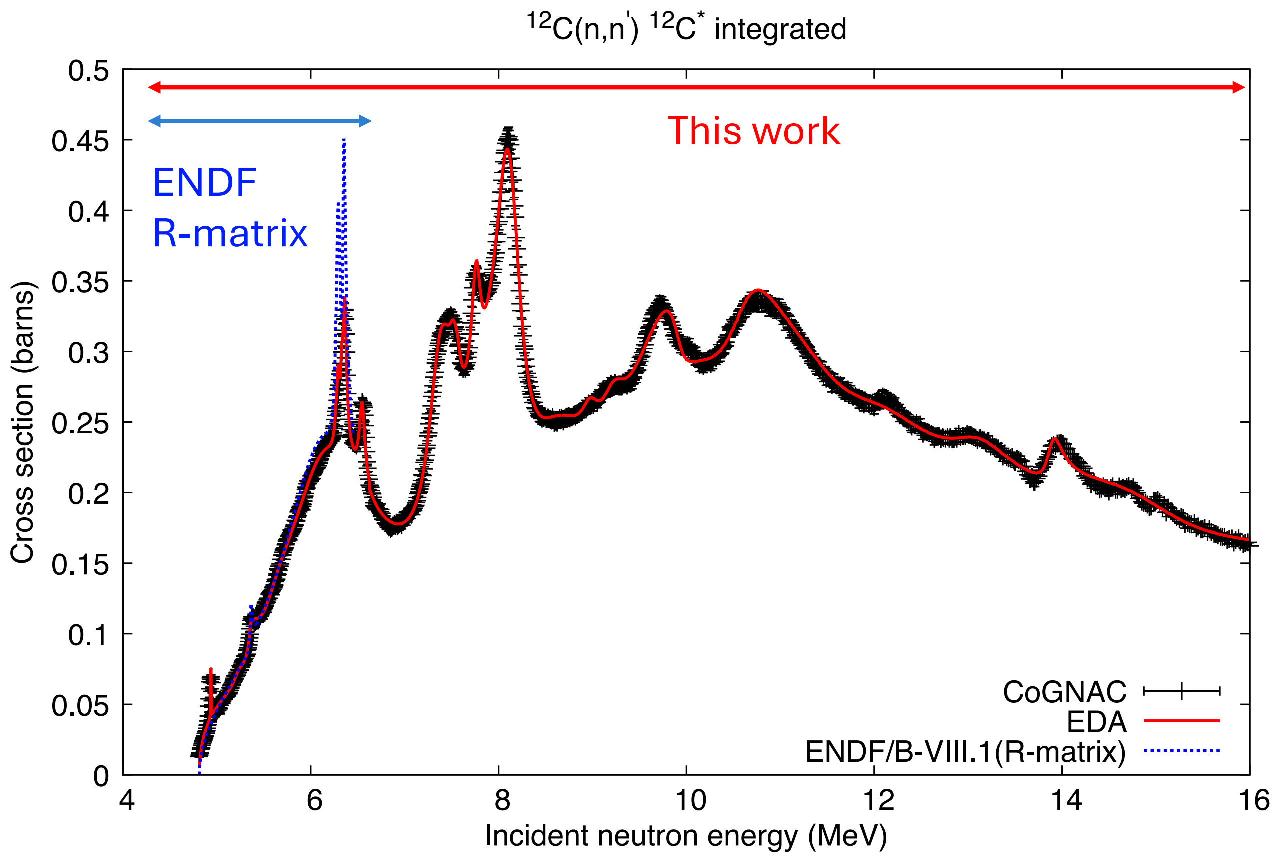
Reaction	Energy range (MeV)	# Exp data points	Observables
^{12}C(n,n$_0$)^{12}C	E_n = 0 – 16.0	8963	σ_{tot} , $d\sigma/d\Omega$, A_y(n)
^{12}C(n,n$_1$)^{12}C*	E_n = 4.81 – 16.4	2494	σ_{int}(CoGNAC), $d\sigma/d\Omega$
^{12}C(n,γ)^{13}C	E_n = 0 – 0.2	7	σ_{int}
^{12}C(n,α)^{9}Be	E_n = 7.24 – 20.0	149	σ_{int}
^{9}Be(α,n$_0$)^{12}C	E_α = 0.366 – 3.55	509	σ_{int}
^{9}Be(α,n$_1$)^{12}C*	E_α = 0.266 – 3.55	509	σ_{int}

Total	12631



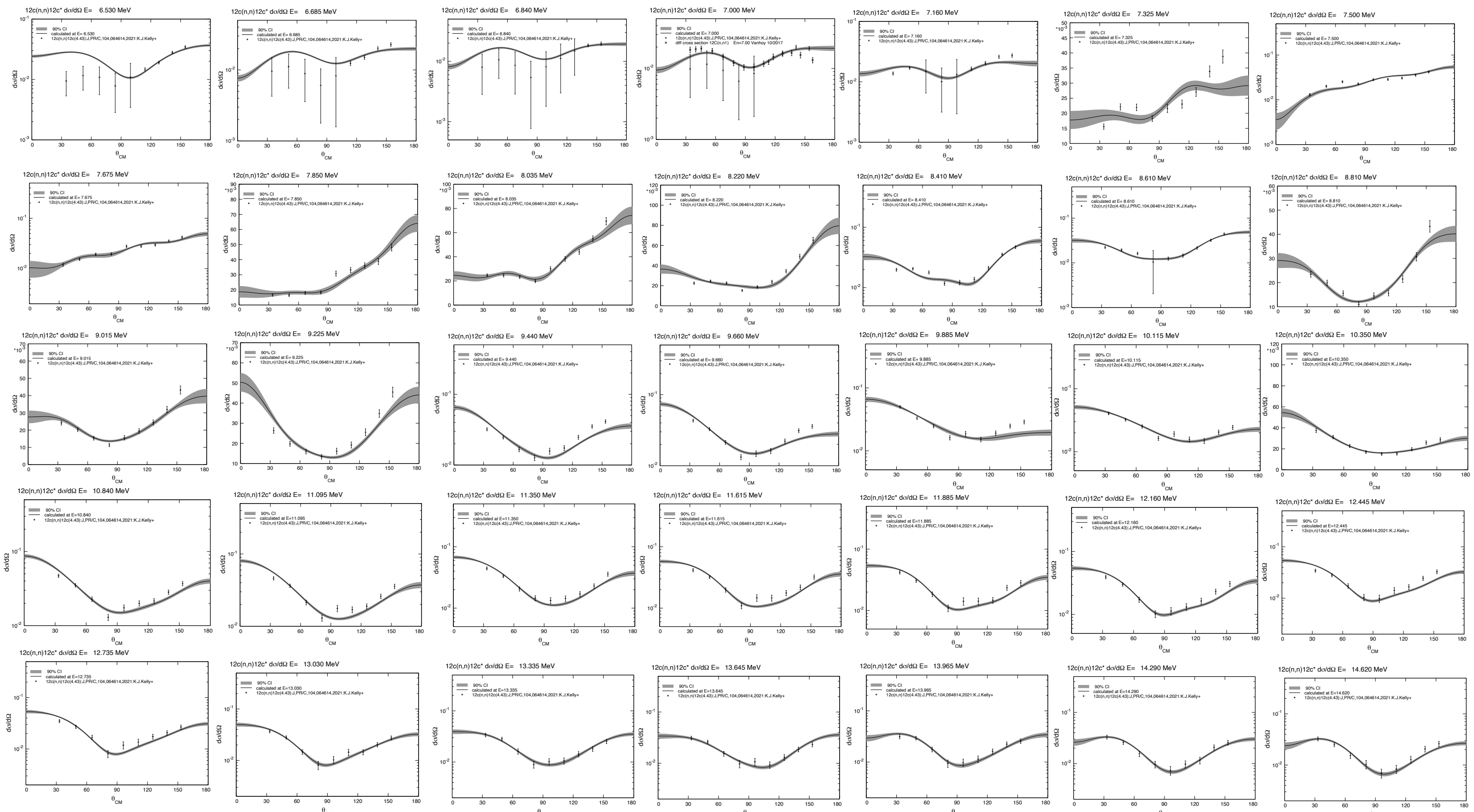
F. Ajzenberg-Selove, Nucl. Phys. A523 (1991) 1

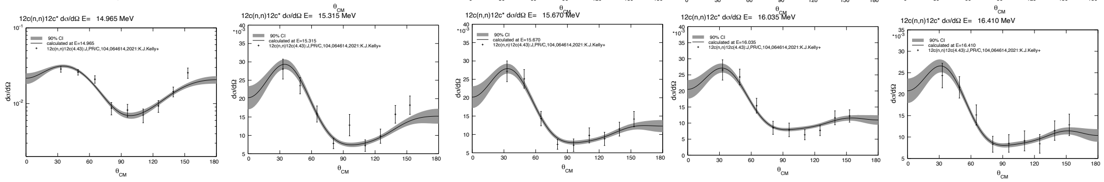
Integrated cross section of inelastic scattering



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

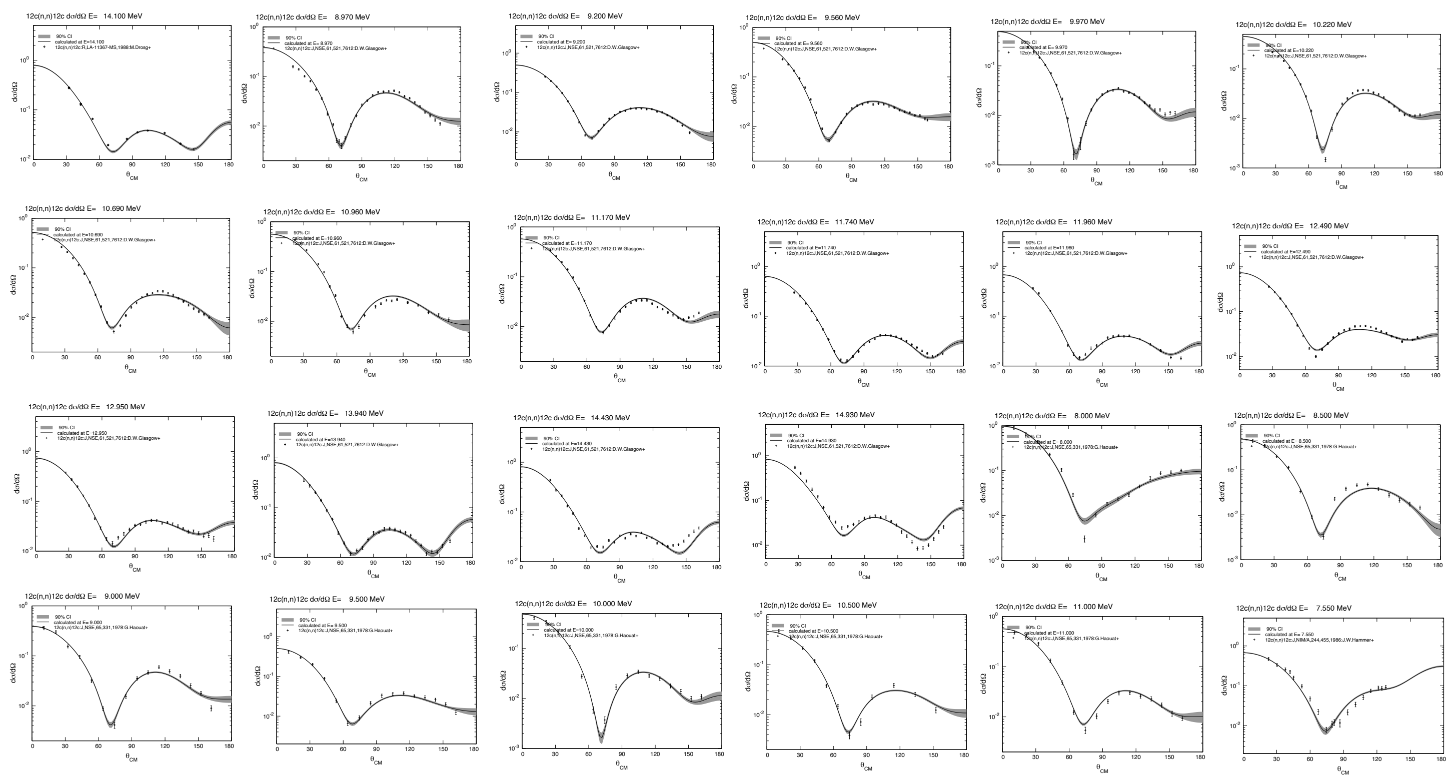
Inelastic differential cross sections (6.53-16.4 MeV)

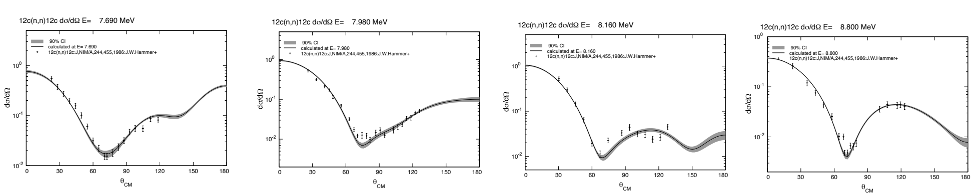




Keegan J. Kelly et al.,
PRC104, 064614 (2021)

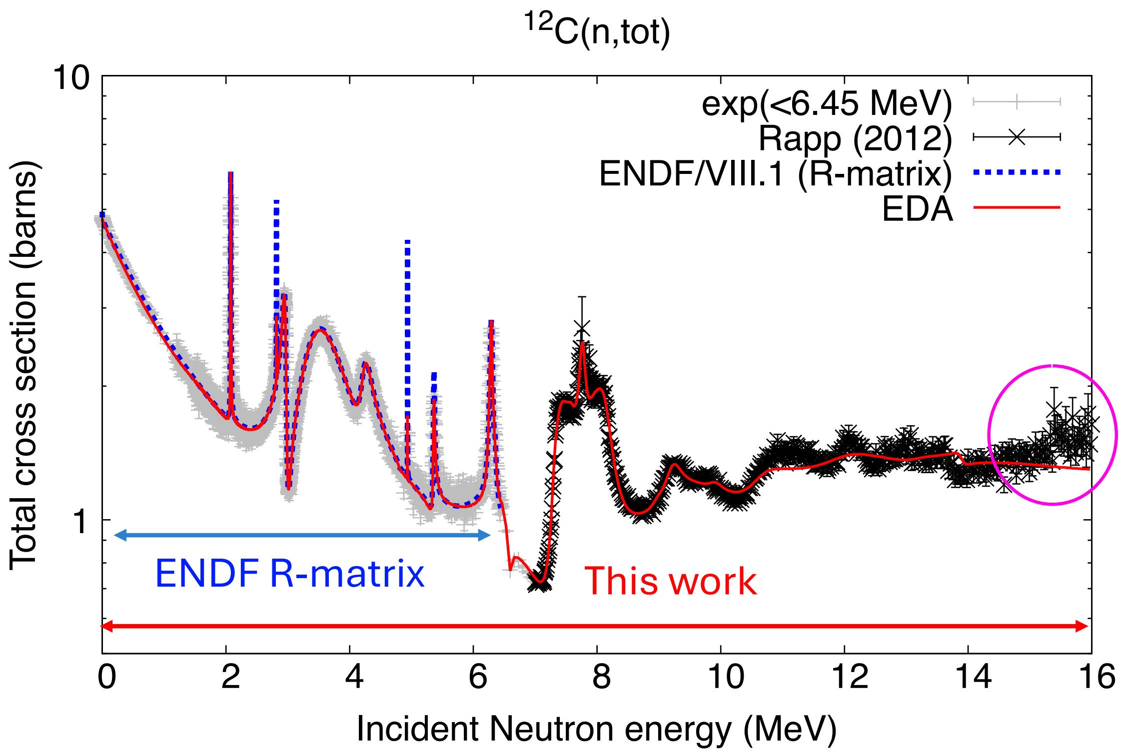
Elastic differential cross sections (7.55-14.93 MeV)





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)

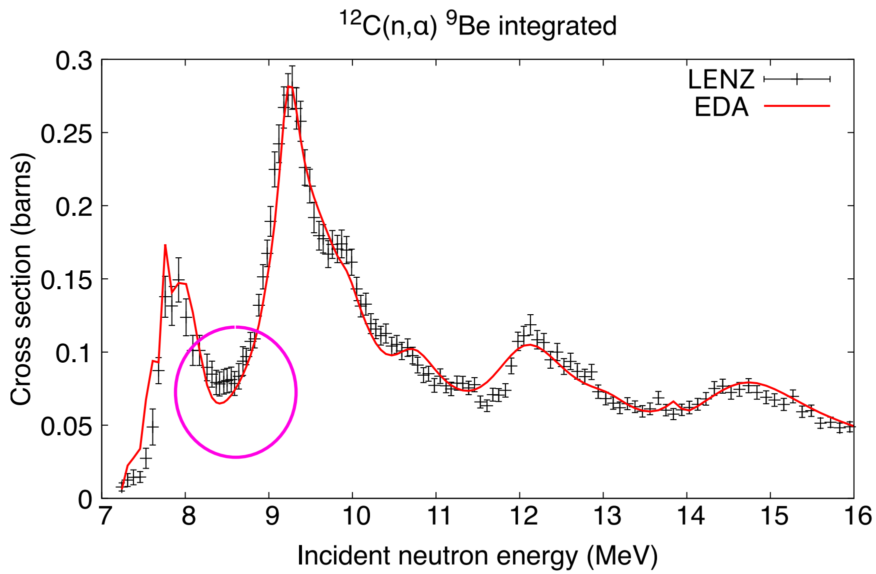
^{12}C+n Total Cross Section

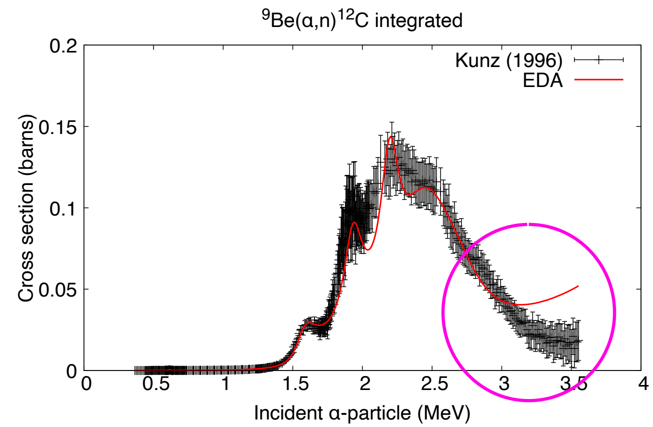


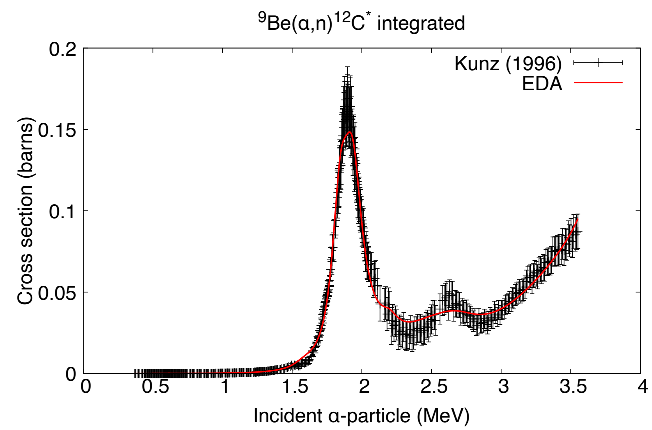
- EDA reproduces sharp peaks below 6.45 MeV
- EDA underestimates above 15 MeV

➡ 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,α) ^{12}C due to the restriction from ～8.5 MeV neutron in the inverse reaction

Plans for the coming year

- Decide on the best approach to extend the N-N analysis to 250 MeV.
- Add new data to the ^{7}Li analysis, and possibly extend its energy to 10 MeV.
- A lot of work needs to be done on the ^{11}B analysis, with help from Ian Thompson.
- Add new GALINA data to the ^{13}C analysis, and assess its suitability for a new evaluation of the n+C standard below 2 MeV. No new work is planned for n+^{13}C (^{14}C system).
- Implement a new approximate method for taking into account the width of an excited-state channel in R-matrix analyses.