Status of the Evaluation of the Neutron Spectrum of $^{235}U + n_{th}$

Wolf Mannhart

PTB Braunschweig

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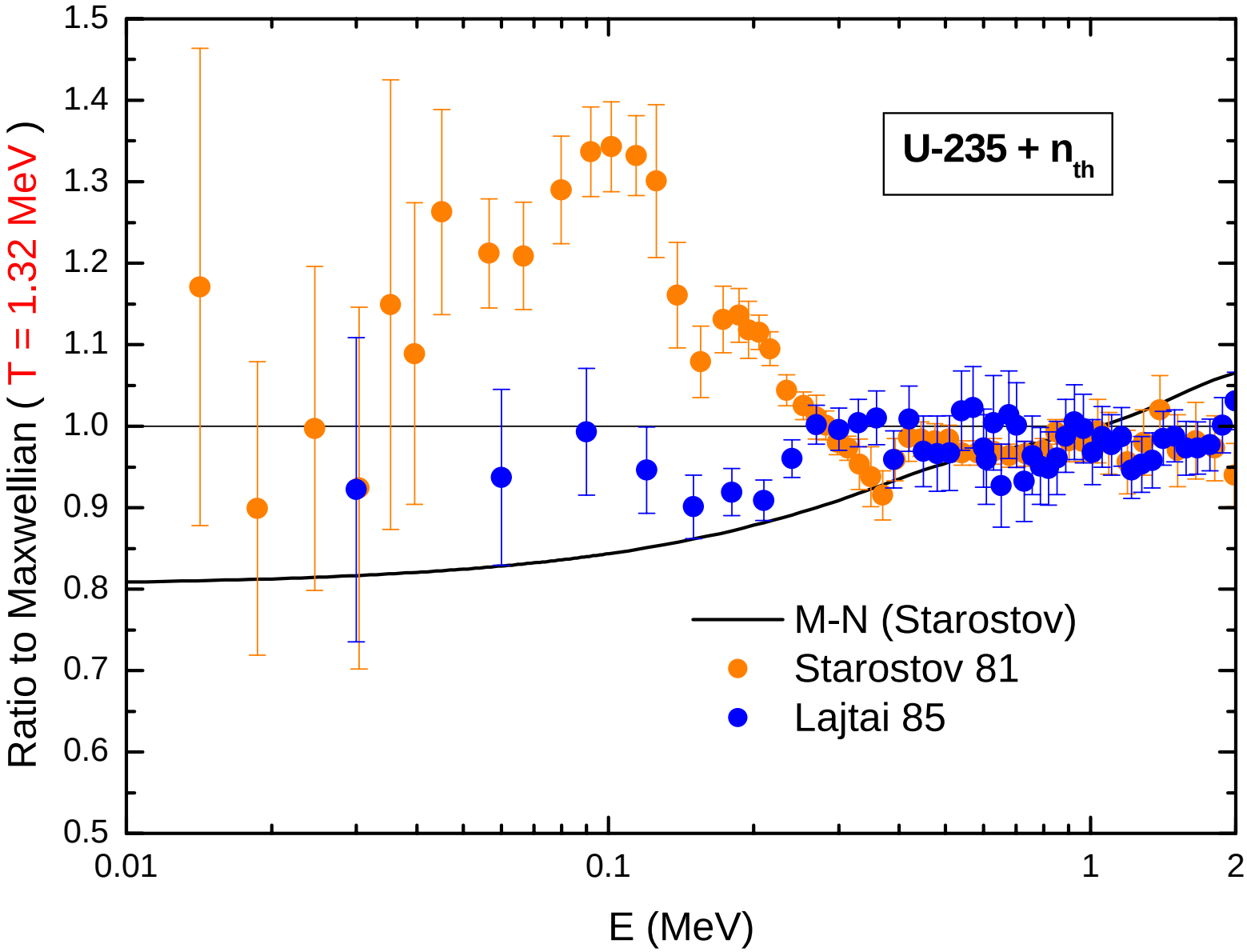
Topics

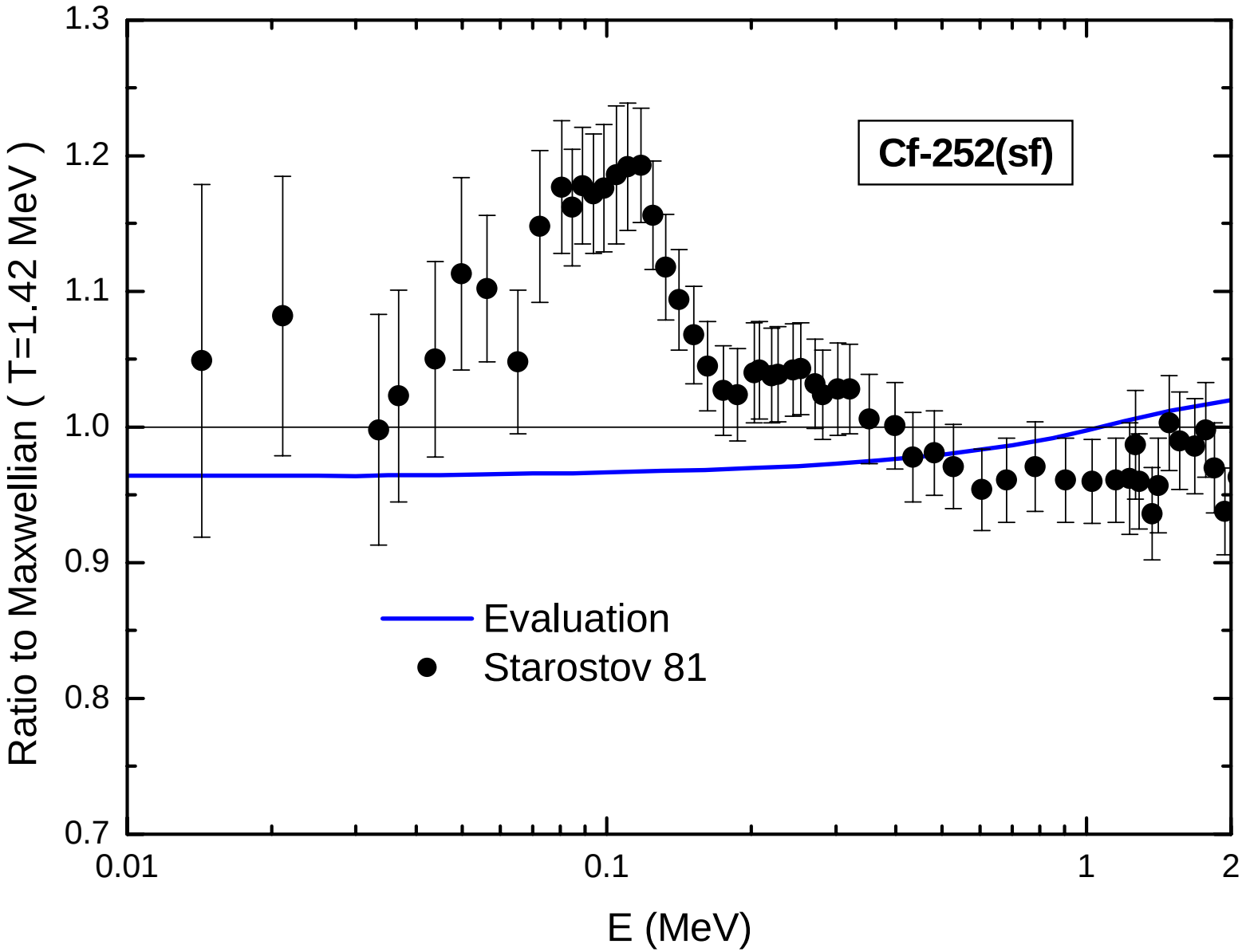
1. Experimental database
2. Comparison of the data with various versions of the Madland-Nix model (see report NEA/WPEC-9 (2003))
3. Comparison with high-threshold integral data
4. Spectrum-averaged cross sections
   a) Evaluation of the experimental database
   b) Comparison with calculated data
   c) Comparison of $\langle\sigma\rangle_{U\text{-}235}$ with $\langle\sigma\rangle_{Cf\text{-}252}$ (data verification)
5. Summary and conclusions

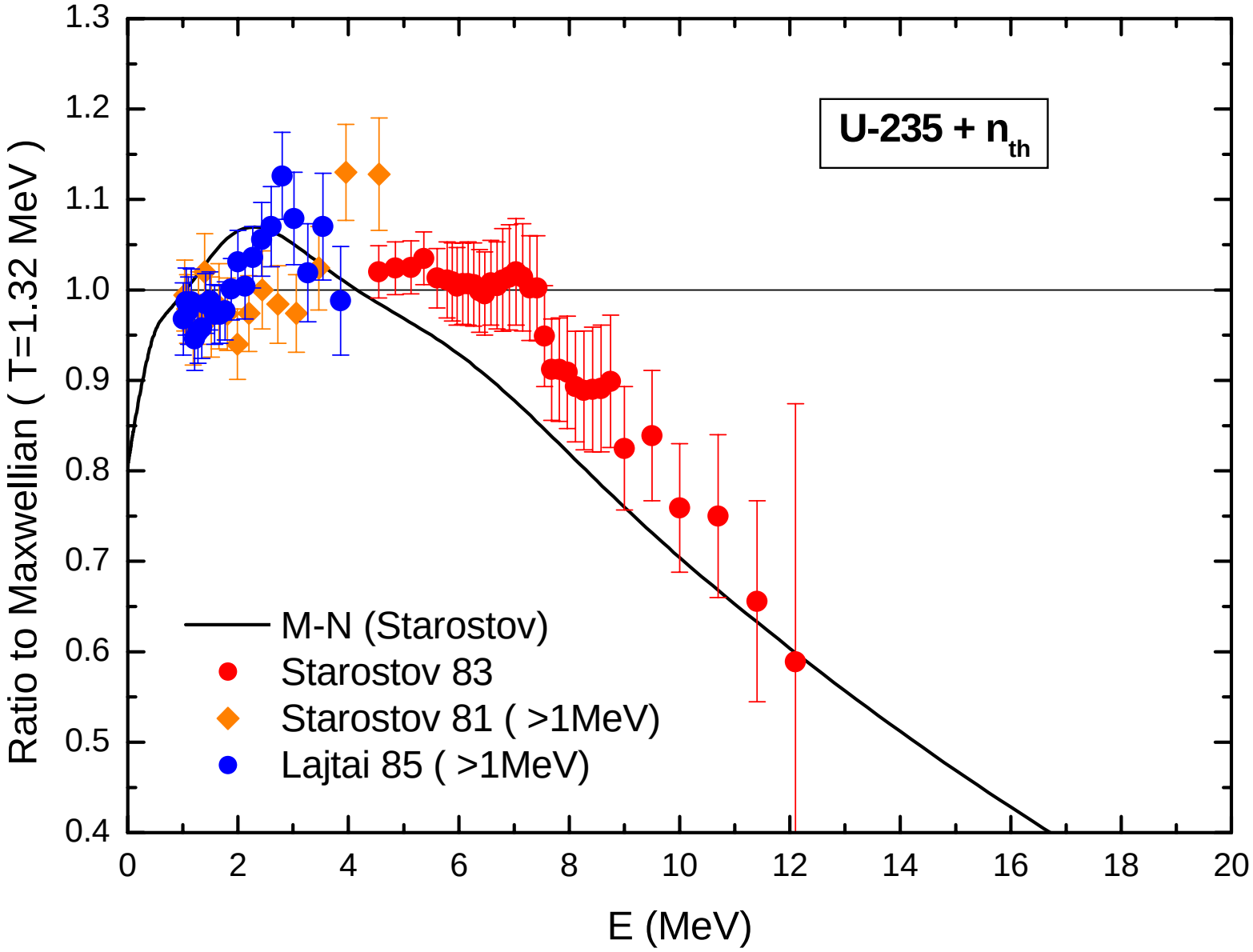
Experimental Database

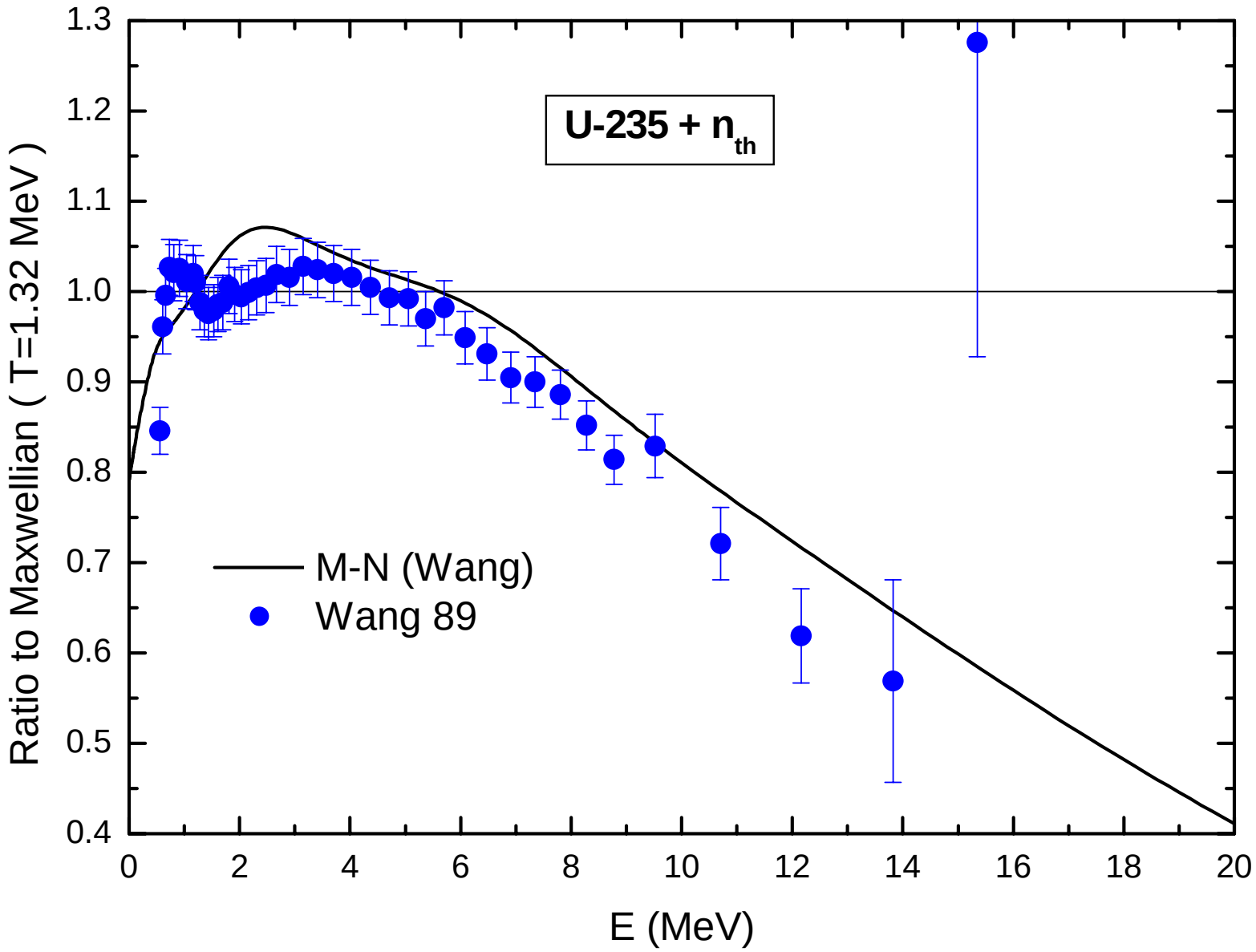
TOF in m

Authors	References	TOF	Range (MeV)
Kravchenko et al.	Nuclear Data Conf., Santa Fe (2004) Vol. 1, p.737	**PR**	2.00 - 14.00
Wang et al.	CNP 11 (1989) 47	3.17	0.56 – 15.35
Lajtai et al.	Nuclear Data Conf., Santa Fe (1985) Vol. 1, p.613	0.30	0.030 – 3.86
Starostov et al.	6th All Union Conf. Kiev (1983) Vol. 2, p. 290	6.11	4.55 – 12.10
Nevedov et al.	ibid. (1983) Vol. 2, p. 285	2.31	0.108 – 7.49
Bojcov et al.	ibid. (1983) Vol. 2, p. 294	0.40	0.021 – 4.50
Starostov et al.	INDC(CCP)-164 (1981)	0.40	0.014 – 4.56
Werle et al.	JNE 26 (1972) 165	**PR**	0.104 – 9.50


U-235 + n th
M-N (Starostov)
Starostov 81
Lajtai 85
Ratio to Maxwellian (T = 1.32 MeV)
E (MeV)
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.01
0.1
1
2


Cf-252(sf)
Evaluation
Starostov 81
Ratio to Maxwellian (T=1.42 MeV)
E (MeV)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.01
0.1
1
2


U-235 + n th
M-N (Starostov)
Starostov 83
Starostov 81 (>1MeV)
Lajtai 85 (>1MeV)
Ratio to Maxwellian (T=1.32 MeV)
E (MeV)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0
2
4
6
8
10
12
14
16
18
20


U-235 + n th
M-N (Wang)
Wang 89
Ratio to Maxwellian (T=1.32 MeV)
E (MeV)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0
2
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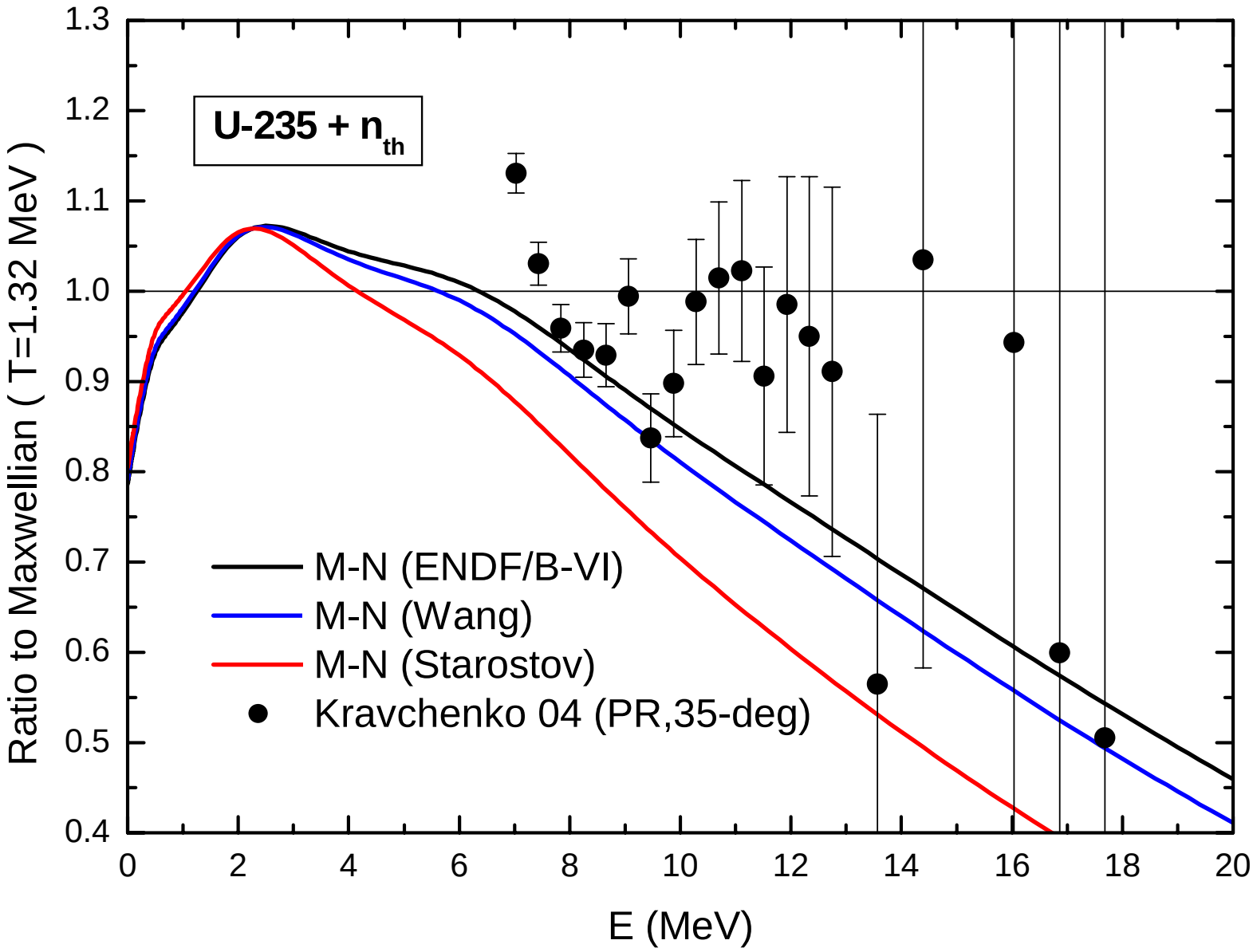
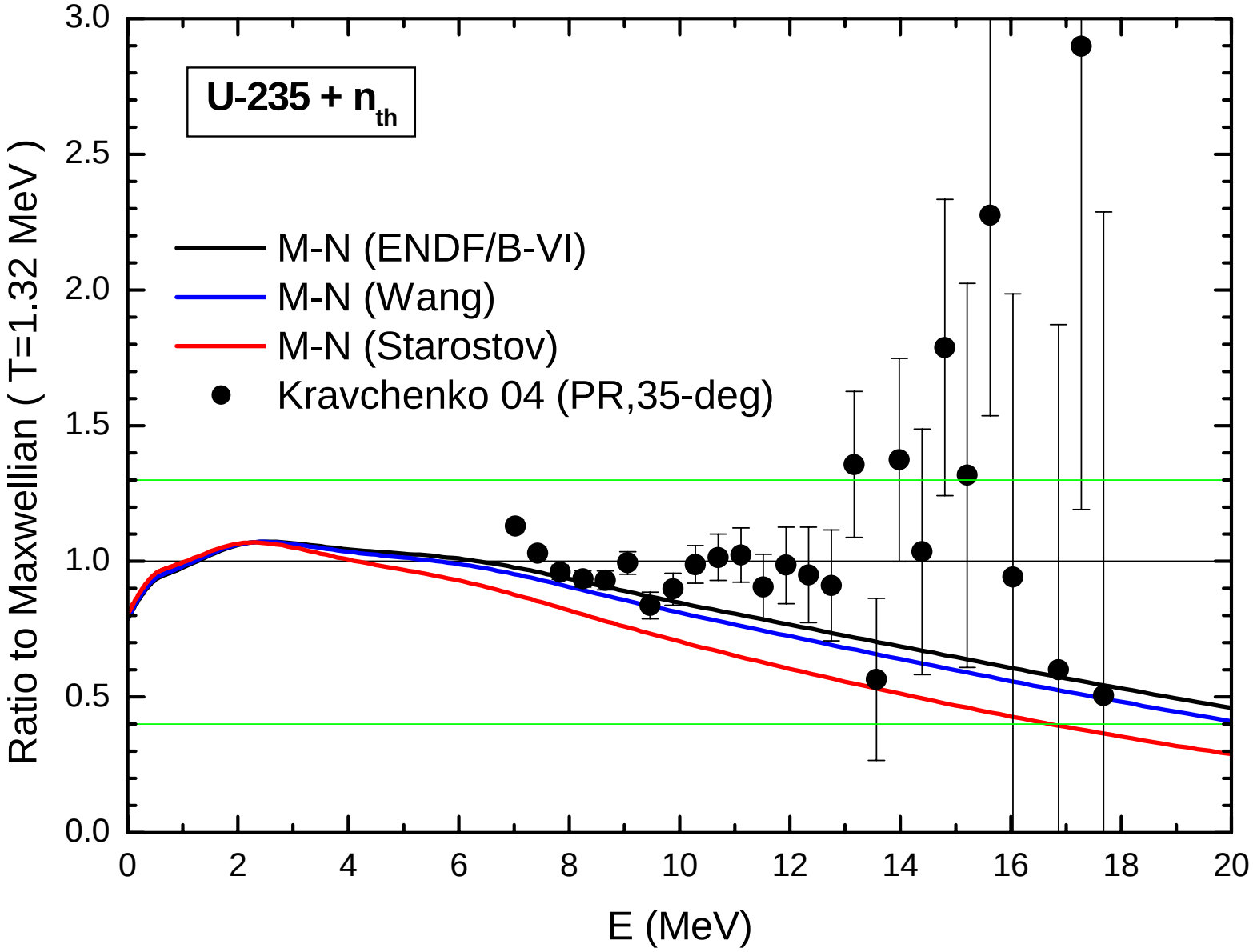
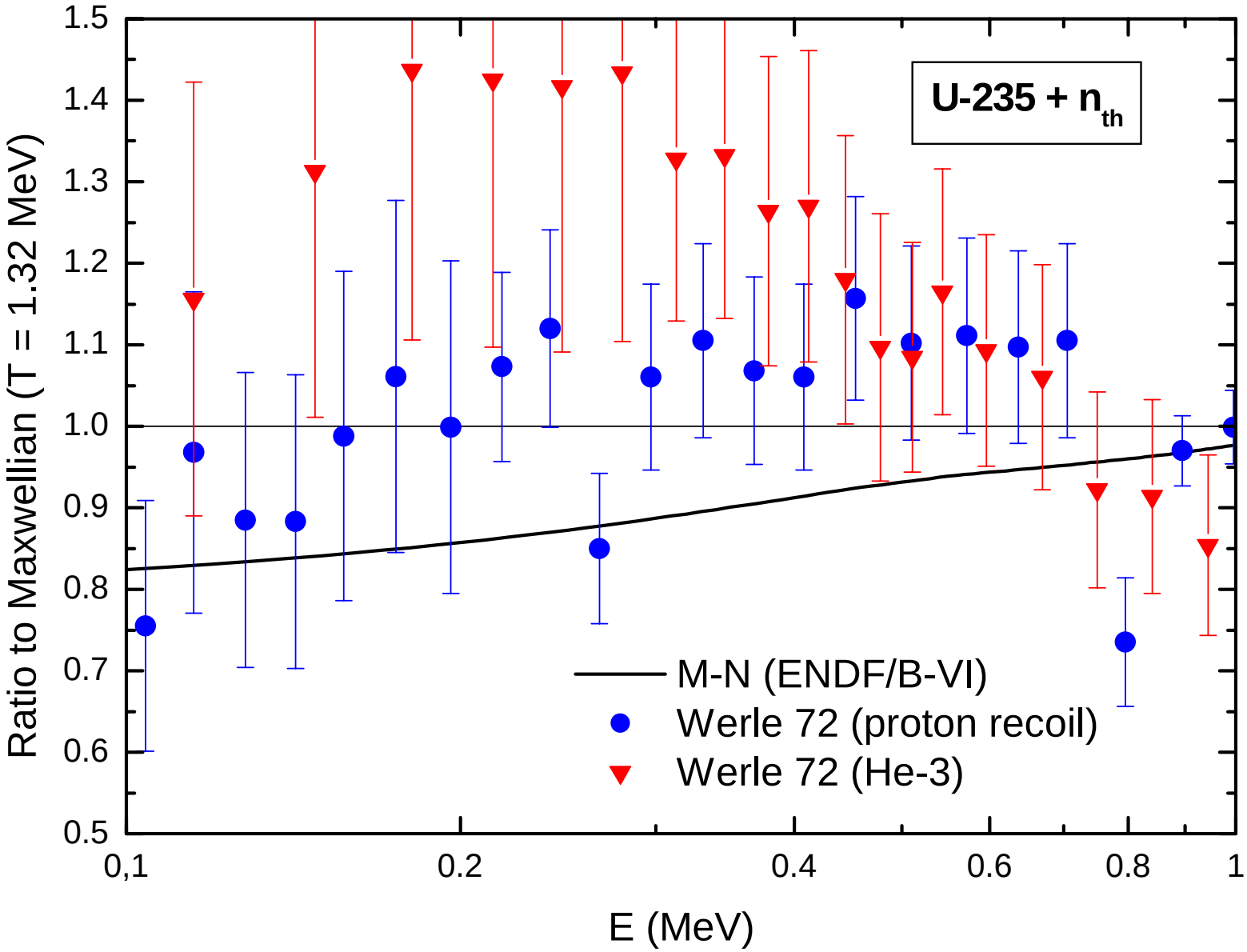
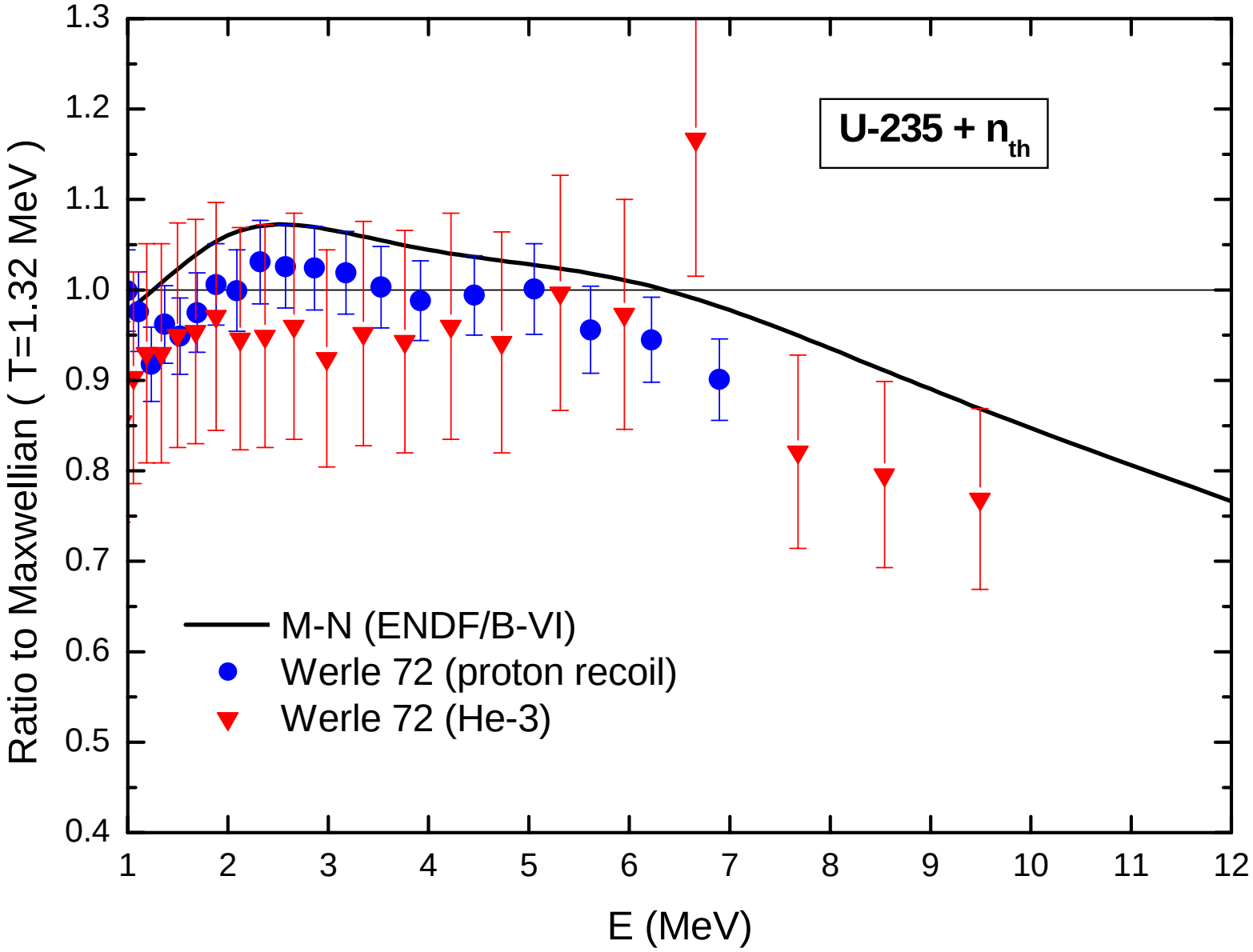

U-235 + n th
M-N (ENDF/B-VI)
M-N (Wang)
M-N (Starostov)
Kravchenko 04 (PR,35-deg)
Ratio to Maxwellian (T=1.32 MeV)
E (MeV)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0
2
4
6
8
10
12
14
16
18
20


U-235 + n th
M-N (ENDF/B-VI)
M-N (Wang)
M-N (Starostov)
Kravchenko 04 (PR,35-deg)
Ratio to Maxwellian (T=1.32 MeV)
E (MeV)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
2
4
6
8
10
12
14
16
18
20


U-235 + n th
M-N (ENDF/B-VI)
Werle 72 (proton recoil)
Werle 72 (He-3)
Ratio to Maxwellian (T = 1.32 MeV)
E (MeV)
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0,1
0.2
0.4
0.6
0.8
1


U-235 + n th
M-N (ENDF/B-VI)
Werle 72 (proton recoil)
Werle 72 (He-3)
Ratio to Maxwellian (T=1.32 MeV)
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1.0
0.9
0.8
0.7
0.6
0.5
0.4
1
2
3
4
5
6
7
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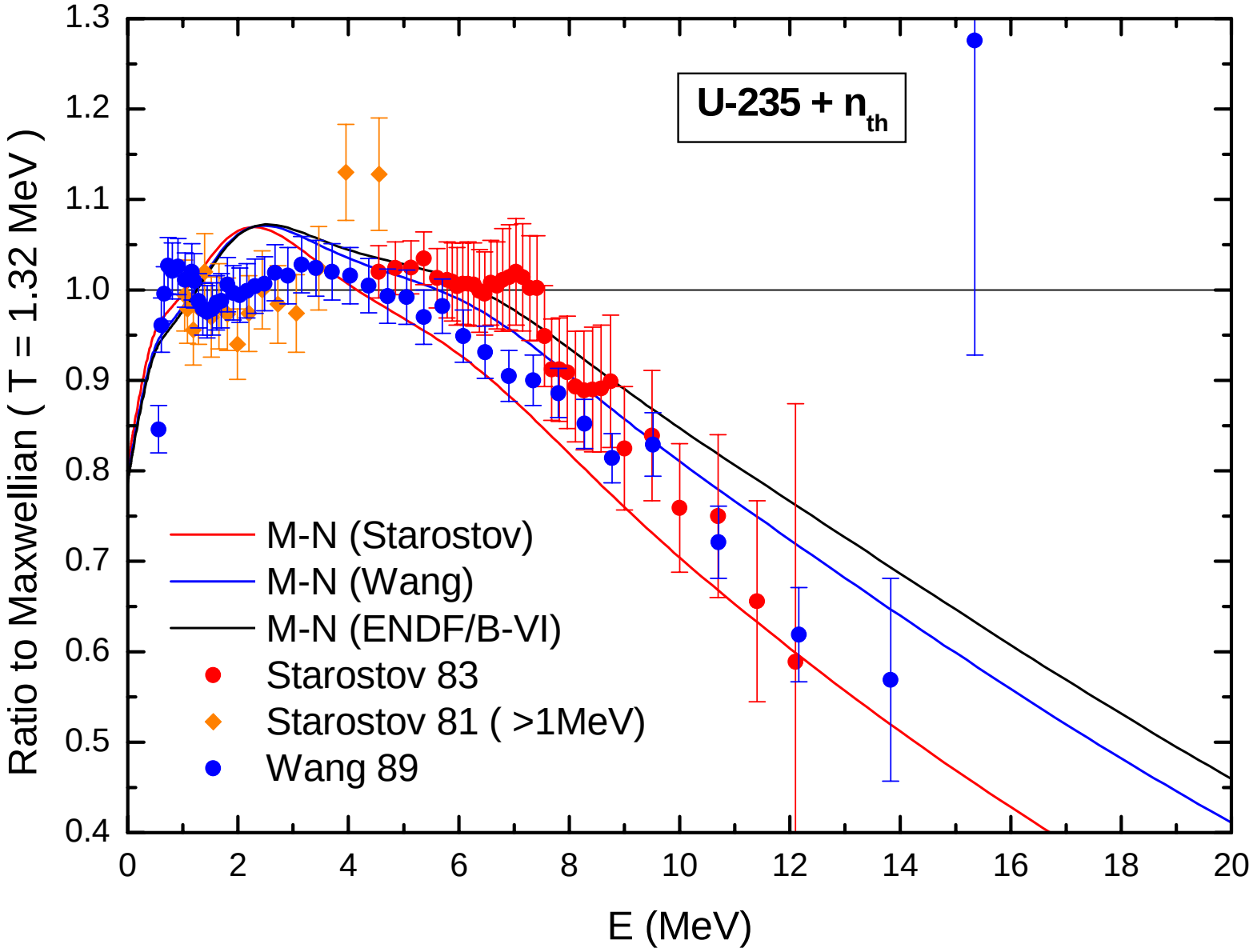
9
10
11
12


U-235 + n th
M-N (Starostov)
M-N (Wang)
M-N (ENDF/B-VI)
Starostov 83
Starostov 81 (>1MeV)
Wang 89
Ratio to Maxwellian (T = 1.32 MeV)
E (MeV)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0
2
4
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Comparison of various versions of the Madland-Nix model with high-threshold integral data in the $^{235}U + n_{th}$ neutron field

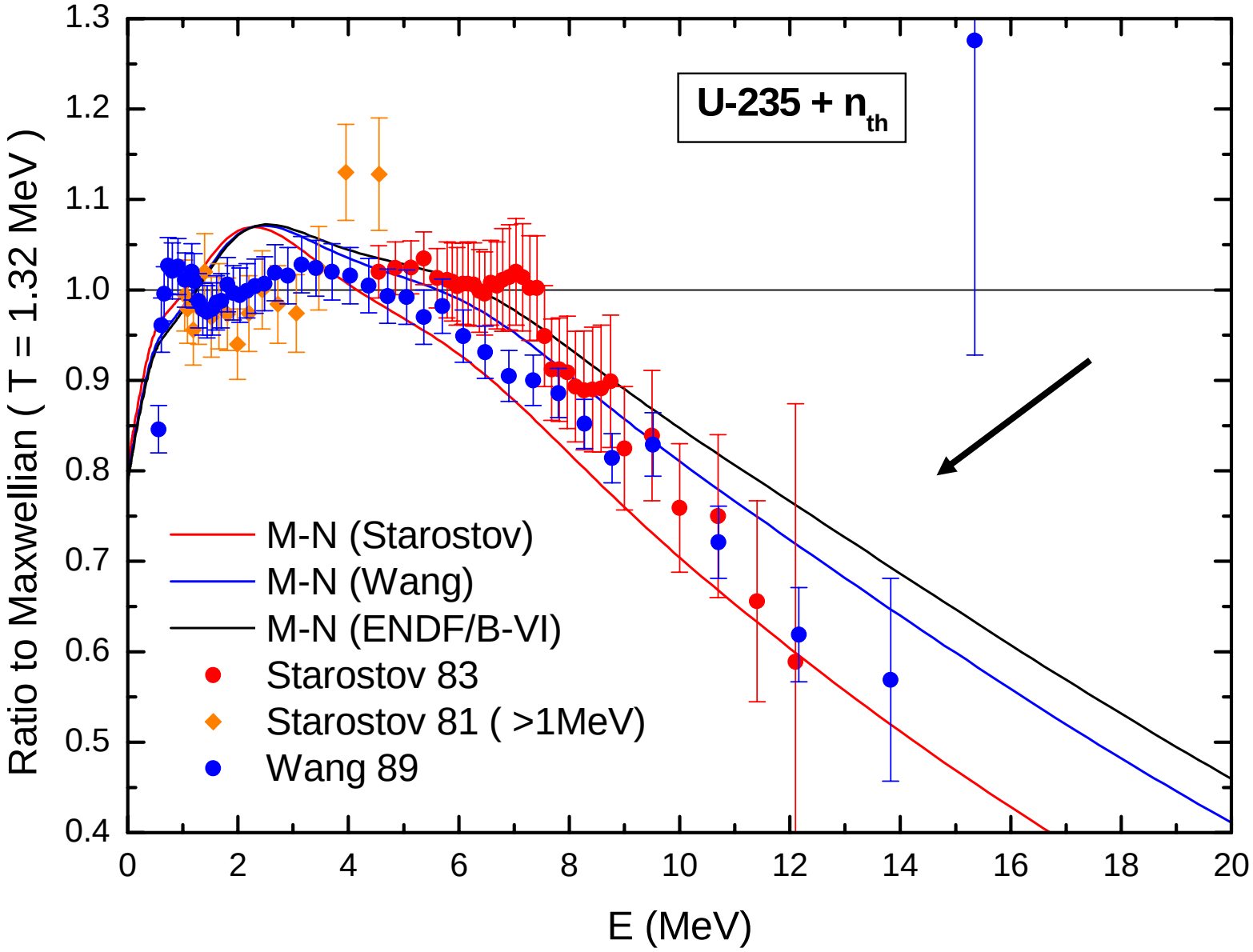
Reaction used: $^{58}Ni(n,2n)^{57}Ni$

Response range: 13.03 – 17.73 MeV

$E_{50\%}$: 14.71 MeV

Neutron spectrum, N(E)	<σ>calc. / <σ> exp.	C/E = 1
Madland-Nix (Starostov)	**0.608 ± 0.025**	N(E) * 1.64
Madland-Nix (Wang)	**0.777 ± 0.032**	N(E) * 1.29
Madland-Nix (ENDF/B-VI)	**0.841 ± 0.035**	N(E) * 1.19

A similar deviation is observed in the ^{235}U + n(0.5 MeV) experiment of Kornilov et al. (2007).


U-235 + n th
M-N (Starostov)
M-N (Wang)
M-N (ENDF/B-VI)
Starostov 83
Starostov 81 (>1MeV)
Wang 89
Ratio to Maxwellian (T = 1.32 MeV)
E (MeV)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0
2
4
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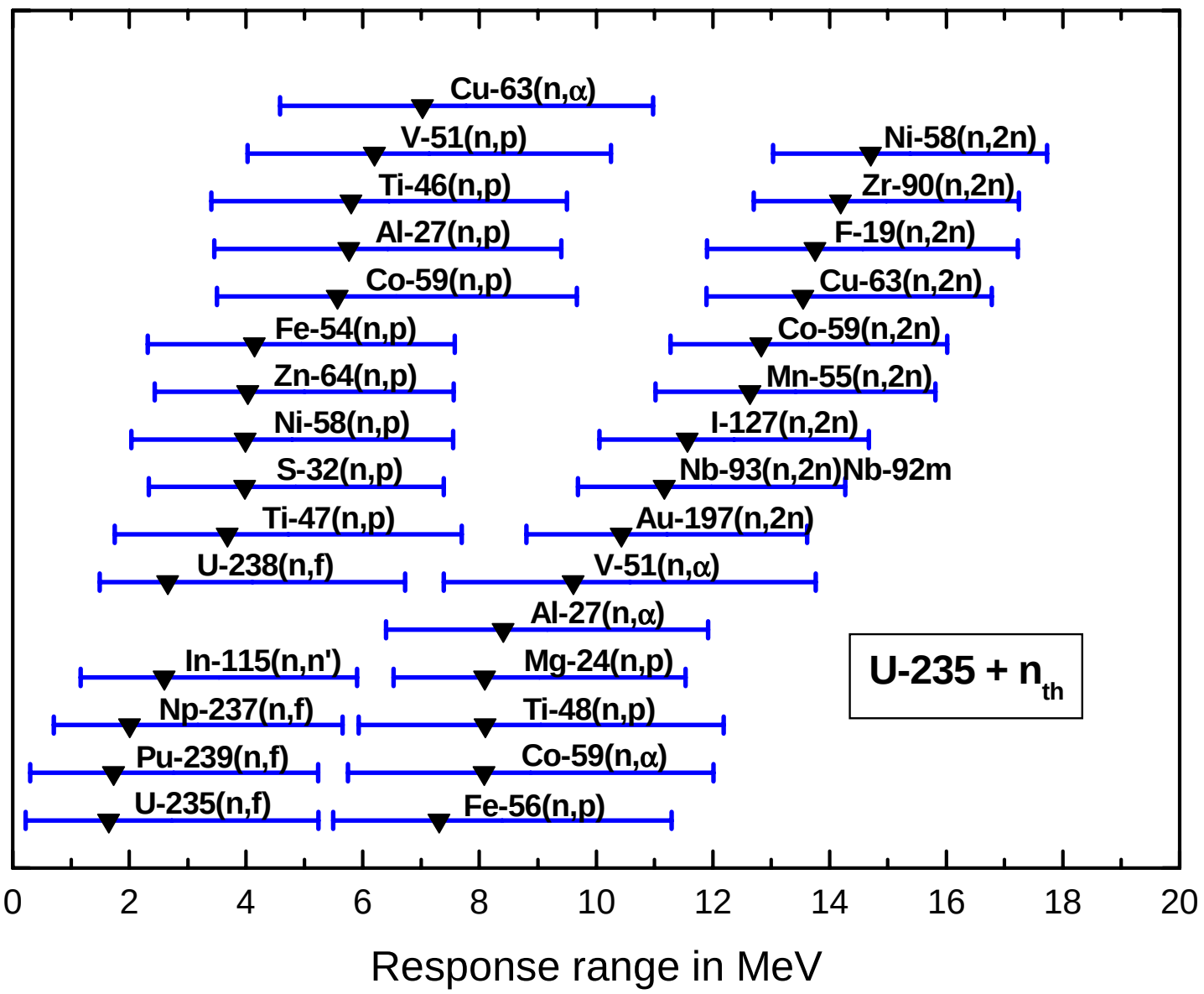
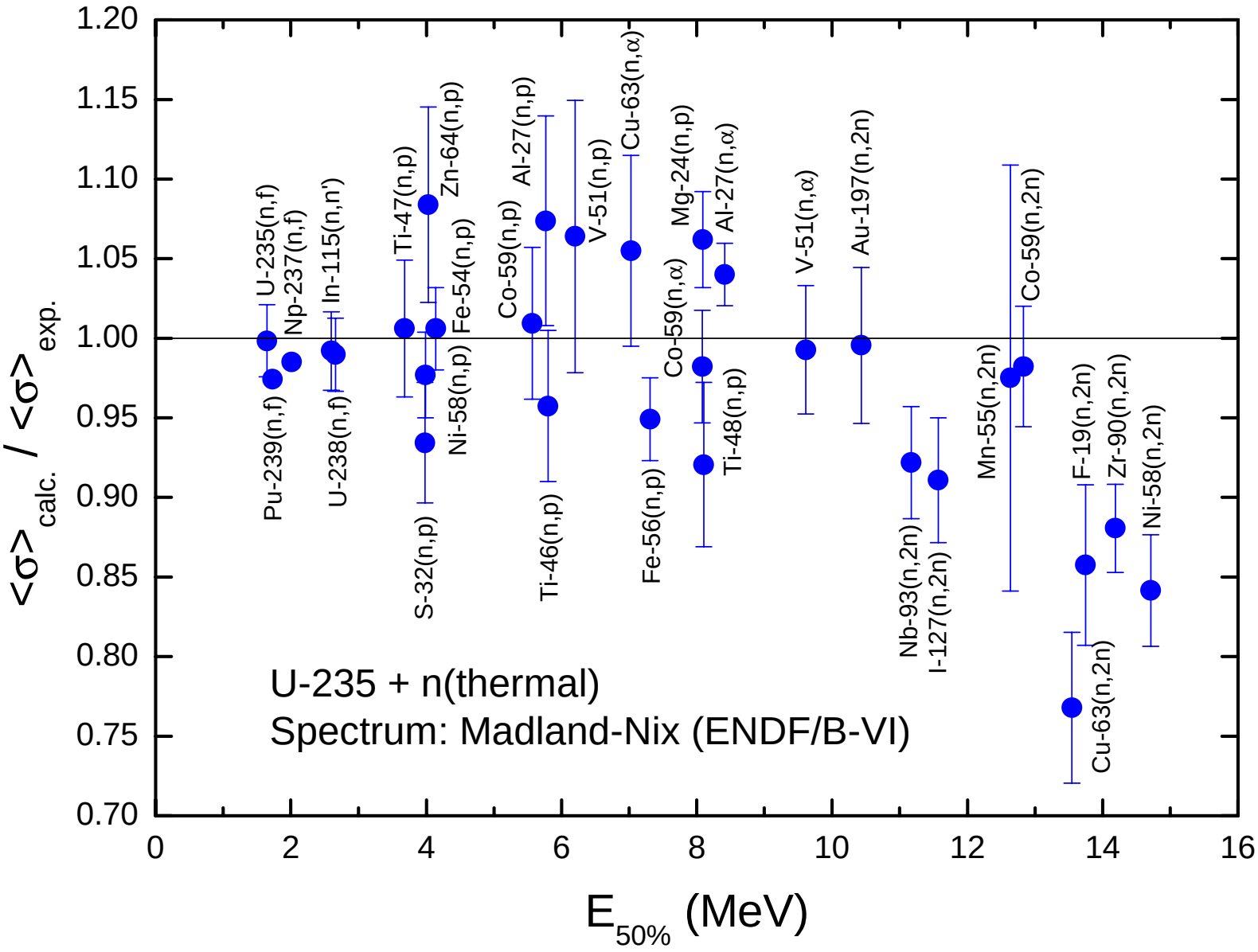
Evaluation of $\langle\sigma\rangle_{exp}$ data in the neutron field of $^{235}U + n_{th}$

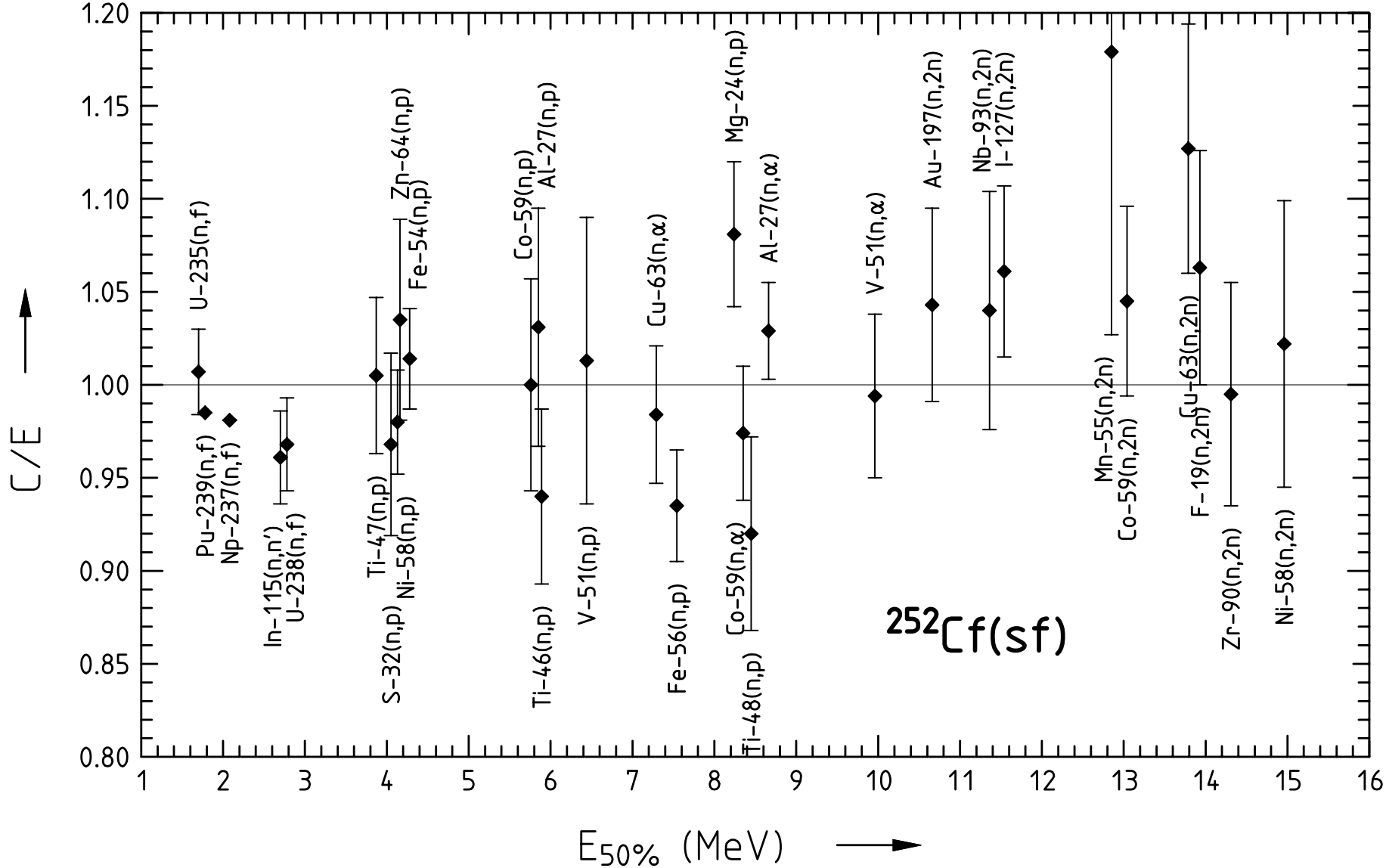
No. of experiments:	**35**	
No. of data:	**200**	**(only 4 absolute)**
Data rejected:	**25**	
No. of reactions:	**30**	**(with covariance matrix)**
Value of χ^2/f :	**0.71**	

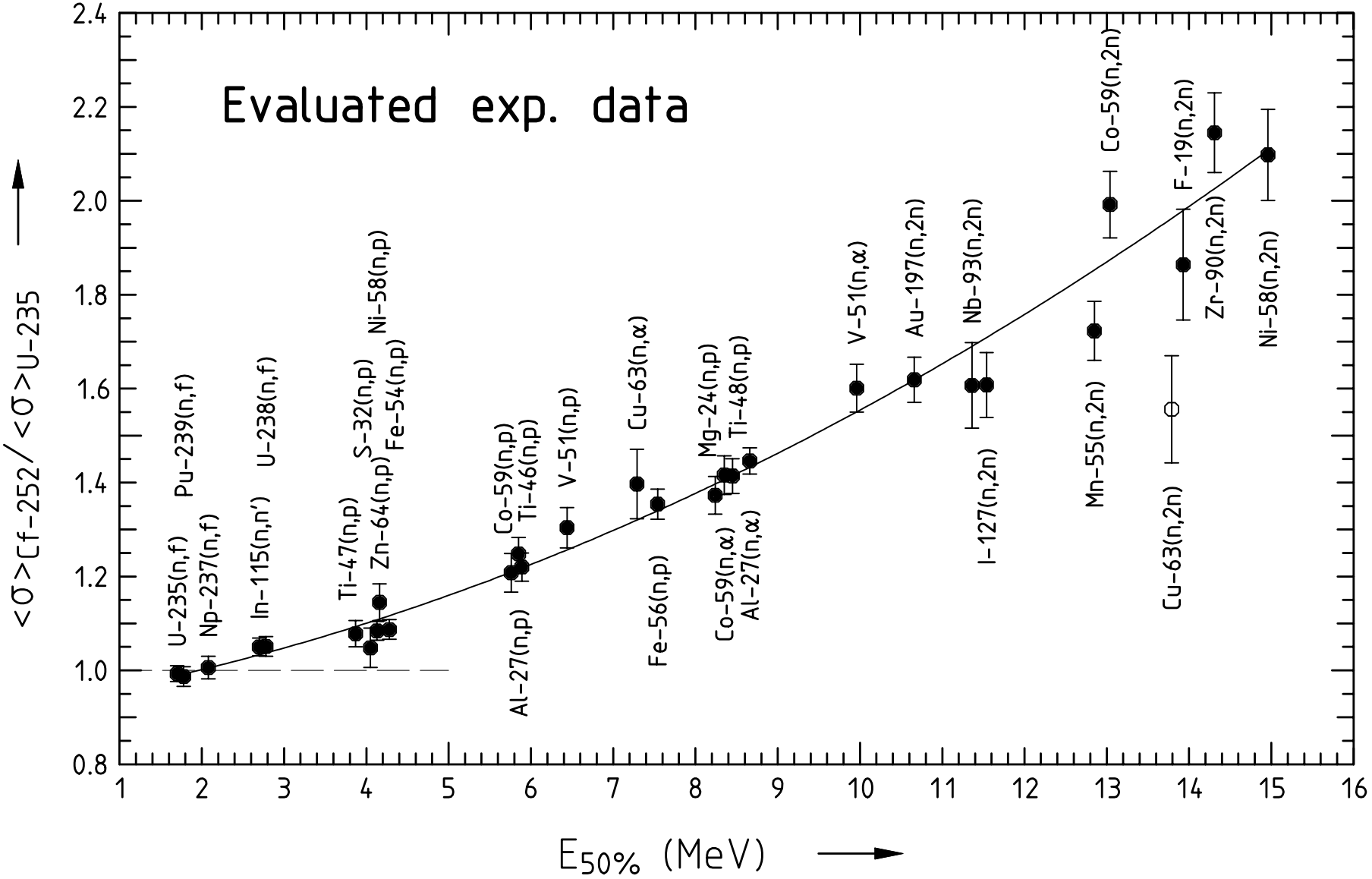
References:	Iteration	Δ (%)
Progress Report NEA/NSC/DOC(99)10 (1999) p. 40	no	
Present data (2004, unpublished)	yes	0.16 – 0.70

U-235 + n(thermal)		new evaluation		N(E) = Madland-Nix (ENDF/B-VI)						
Reaction	E(50%) (MeV)	Experiment < σ > (mb)	error (%)	Calculation < σ > (mb)	total error (%)	σ(E) error (%)	N(E) error (%)	C/E	Δ C/E	Source σ(E)
U-235(n,f)	1.65	1.217E+03	1.12	1.215E+03	1.98	1.98		0.998	0.023	B-6 NDO
Pu-239(n,f)	1.73	1.831E+03	1.65	1.784E+03				0.974		B-6
Np-237(n,f)	2.01	1.350E+03	1.78	1.330E+03				0.985		B-6
In-115(n,n')	2.60	1.878E+02	1.23	1.863E+02	2.16	2.16		0.992	0.025	B-6 MF=10
U-238(n,f)	2.66	3.094E+02	1.13	3.062E+02	2.03	2.03		0.990	0.023	B-6 NDO
Ti-47(n,p)	3.68	1.784E+01	1.99	1.795E+01	3.77	3.77		1.006	0.043	IRDF-90.2
S-32(n,p)	3.98	6.908E+01	1.97	6.454E+01	3.55	3.55		0.934	0.038	IRDF-90.2
Ni-58(n,p)	3.99	1.082E+02	1.30	1.057E+02	2.44	2.44		0.977	0.027	B-6
Zn-64(n,p)	4.03	3.539E+01	3.02	3.836E+01	4.80	4.80		1.084	0.061	IRK-90
Fe-54(n,p)	4.14	7.967E+01	1.38	8.015E+01	2.18	2.18		1.006	0.026	B-6
Co-59(n,p)	5.57	1.396E+00	2.36	1.409E+00	4.10	4.10		1.009	0.048	B-6
Al-27(n,p)	5.77	3.902E+00	1.77	4.190E+00	5.87	5.87		1.074	0.066	B-6 NAV
Ti-46(n,p)	5.80	1.151E+01	1.70	1.102E+01	4.67	4.67		0.957	0.048	IRK-96
V-51(n,p)	6.20	4.968E-01	2.62	5.286E-01	7.60	7.60		1.064	0.086	B-6
Cu-63(n,α)	7.03	4.918E-01	4.91	5.189E-01	2.86	2.86		1.055	0.060	B-6
Fe-56(n,p)	7.31	1.079E+00	1.54	1.024E+00	2.27	2.27		0.949	0.026	B-6
Mg-24(n,p)	8.09	1.451E+00	1.59	1.541E+00	2.34	2.34		1.062	0.030	IRK-90
Co-59(n,α)	8.08	1.563E-01	2.25	1.535E-01	2.81	2.81		0.982	0.035	B-6
Ti-48(n,p)	8.10	2.996E-01	1.79	2.758E-01	5.32	5.32		0.921	0.052	IRK-96
Al-27(n,α)	8.41	7.007E-01	1.28	7.288E-01	1.39	1.39		1.040	0.020	IRK-90
V-51(n,α)	9.61	2.429E-02	2.29	2.411E-02	3.36	3.36		0.993	0.040	B-6
Au-197(n,2n)	10.43	3.392E+00	2.35	3.377E+00	4.32	4.32		0.996	0.049	IRK-90
Nb-93(n,2n)Nb-92m	11.17	4.645E-01	2.52	4.282E-01	2.87	2.87		0.922	0.035	IRK-90
I-127(n,2n)	11.57	1.279E+00	3.37	1.165E+00	2.69	2.69		0.911	0.039	IRDF-90.2
Mn-55(n,2n)	12.64	2.362E-01	2.80	2.303E-01	13.42	13.42		0.975	0.134	B-6
Co-59(n,2n)	12.83	2.028E-01	2.51	1.992E-01	2.92	2.92		0.982	0.038	IRK-90
Cu-63(n,2n)	13.55	1.184E-01	5.91	9.091E-02	1.81	1.81		0.768	0.047	IRK-90
F-19(n,2n)	13.75	8.624E-03	5.37	7.395E-03	2.43	2.43		0.857	0.051	IRK-90
Zr-90(n,2n)	14.19	1.027E-01	2.69	9.044E-02	1.63	1.63		0.881	0.028	IRK-90
Ni-58(n,2n)	14.71	4.257E-03	2.90	3.582E-03	2.99	2.99		0.841	0.035	IRK-90


Cu-63(n,α)
V-51(n,p)
Ti-46(n,p)
Al-27(n,p)
Co-59(n,p)
Fe-54(n,p)
Zn-64(n,p)
Ni-58(n,p)
S-32(n,p)
Ti-47(n,p)
U-238(n,f)
In-115(n,n')
Np-237(n,f)
Pu-239(n,f)
U-235(n,f)
Ni-58(n,2n)
Zr-90(n,2n)
F-19(n,2n)
Cu-63(n,2n)
Co-59(n,2n)
Mn-55(n,2n)
I-127(n,2n)
Nb-93(n,2n)Nb-92m
Au-197(n,2n)
V-51(n,α)
Al-27(n,α)
Mg-24(n,p)
Ti-48(n,p)
Co-59(n,α)
Fe-56(n,p)
U-235 + n th
0
2
4
6
8
10
12
14
16
18
20
Response range in MeV


1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0
2
4
6
8
10
12
14
16
<σ>calc. / <σ>exp.
E50% (MeV)
U-235 + n(thermal)
Spectrum: Madland-Nix (ENDF/B-VI)
U-235(n,f)
Np-237(n,f)
In-115(n,n')
Pu-239(n,f)
U-238(n,f)
Ti-47(n,p)
Zn-64(n,p)
Fe-54(n,p)
Ni-58(n,p)
S-32(n,p)
Co-59(n,p)
Al-27(n,p)
V-51(n,p)
Ti-46(n,p)
Cu-63(n,α)
Mg-24(n,p)
Co-59(n,α)
Al-27(n,α)
Fe-56(n,p)
Ti-48(n,p)
V-51(n,α)
Au-197(n,2n)
Nb-93(n,2n)
I-127(n,2n)
Mn-55(n,2n)
Co-59(n,2n)
F-19(n,2n)
Cu-63(n,2n)
Zr-90(n,2n)
Ni-58(n,2n)


C/E
E50% (MeV)
252Cf(sf)
U-235(n,f)
Pu-239(n,f)
Np-237(n,f)
In-115(n,n')
U-238(n,f)
Ti-47(n,p)
S-32(n,p)
Ni-58(n,p)
Zn-64(n,p)
Fe-54(n,p)
Co-59(n,p)
Al-27(n,p)
Ti-46(n,p)
V-51(n,p)
Cu-63(n,α)
Fe-56(n,p)
Mg-24(n,p)
Co-59(n,α)
Ti-48(n,p)
Al-27(n,α)
V-51(n,α)
Au-197(n,2n)
Nb-93(n,2n)
I-127(n,2n)
Mn-55(n,2n)
Co-59(n,2n)
F-19(n,2n)
Cu-63(n,2n)
Zr-90(n,2n)
Ni-58(n,2n)


Evaluated exp. data
<σ>Cf-252 / <σ>U-235
E50% (MeV)
U-235(n,f)
Pu-239(n,f)
Np-237(n,f)
In-115(n,n')
U-238(n,f)
Ti-47(n,p)
S-32(n,p)
Zn-64(n,p)
Ni-58(n,p)
Fe-54(n,p)
Co-59(n,p)
Ti-46(n,p)
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V-51(n,p)
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Fe-56(n,p)
Mg-24(n,p)
Co-59(n,α)
Ti-48(n,p)
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V-51(n,α)
Au-197(n,2n)
Nb-93(n,2n)
I-127(n,2n)
Mn-55(n,2n)
Co-59(n,2n)
Cu-63(n,2n)
F-19(n,2n)
Zr-90(n,2n)
Ni-58(n,2n)

Summary

- The experimental database is very small (only three TOF experiments).
- The level of documentation is poor (insufficient for the evaluation).
- The proton recoil experiments do not contribute to the solution of the below mentioned problems.
- **At low neutron energies, the data of Starostov 81 and Lajtai 85 are incompatible with each other.**
- **At high neutron energies, the data of Starostov 83 and Wang 89 are incompatible with the integral data.**
- It must be assumed (is suspected) that the available TOF data at high neutron energies are wrong due to missing or incomplete corrections.
- **Considering all that, it seems obsolete to perform a qualified evaluation of the existing database.**