Neutron Thermal Cross Sections and Constants Evaluation

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Results of evaluation of the neutron cross section and constants at 0.0253 eV neutron energy and their thermal Maxwellian spectrum averaged values obtained since 1982 are summarized.

Neutron cross sections and constants considered

A) values at point 0.0253 eV (microscopic)

σ_f – fission cross section

σ_γ – capture cross sections

$\sigma_a=\sigma_f + \sigma_\gamma$ – absorption cross section

σ_s – elastic scattering cross section

$\sigma_t=\sigma_a + \sigma_s=\sigma_s + \sigma_f + \sigma_\gamma$ – total cross section

ν_t – total number of neutrons emitted per fission

$\alpha=\sigma_\gamma/\sigma_f$ – alpha constant

$\eta=\nu_t\, \sigma_f/\sigma_a$ – total number of neutrons emitted per neutron absorbed

$K1=(\nu_t - 1)\sigma_f - \sigma_\gamma$ – K1 constant as good indicator of k_{eff} value

B) integral values as cross sections and constants averaged on thermal (Maxwellian) neutron spectrum T=20.4 °C (Maxwellian).

g_f – Westcott g-factor for fission

g_a – Westcott g-factor for absorption

$g_\gamma =(g_a\sigma_a - g_f\, \sigma_f)/\sigma_\gamma$ – Westcott g-factor for capture

$<\sigma_f>=g_f\sigma_f$

$<\sigma_\gamma>=g_\gamma\sigma_\gamma$

$<\sigma_a>=<\sigma_f> + <\sigma_\gamma>$

$<\nu_t>=\nu_t$ – is considered usually as energy independent

$<\alpha>=<\sigma_\gamma>/<\sigma_f>=(g_\gamma\sigma_\gamma)/(g_f\, \sigma_f)=(g_\gamma/g_f)\alpha$ – because separate registrations of fission and capture

$<\eta>=<\nu_t\sigma_f>/<\sigma_a>=\nu_t<\sigma_f>/<\sigma_a>=(g_f/g_a)\eta$

$<K1>=(\nu_t - 1)<\sigma_f > - <\sigma_\gamma>=(\nu_t - 1)g_f\sigma_f - g_\gamma\sigma_\gamma=\nu_t<\sigma_f> - <\sigma_a>$

Results included in intercomparison

AXTON1982: European Appl. Res Rept.-Nucl. Sci. Technol., Vol.5, No.4, pp.609-676 (1984).

No integral data are considered.

Microscopic cross sections their ratios and constants are fitted for ^{233}U, ^{235}U, ^{239}Pu and ^{241}Pu nuclides basing on LSM with full error propagation law.

Fitted experimental data for all nuclides above if nuclide is not explicitly mentioned: σ_f, σ_a, σ_γ, σ_s, σ_t, ν_t, $\nu_t(^{252}Cf)$, $\nu_t/\nu_t(^{252}Cf)$, mean fission neutron spectrum energy, η, Sulphur thermal capture and ratios between some cross sections.

Fitted and calculated parameters: σ_f, σ_a, σ_γ, ν_t, $\nu_t(^{252}Cf)$, $\nu_t/\nu_t(^{252}Cf)$, η, $(1+\alpha)$, Sulphur thermal capture.

DIVADEENAM1982: Ann. Nucl. Energy, Vol.11, No. 8, pp. 375-404 (1984), Report IEAE-TECDOC-335, p.238 (1984).

Microscopic and integral data are included for ^{233}U, ^{235}U, ^{239}Pu, ^{241}Pu and $\nu_t(^{252}Cf)$. Correlations between experimental data were only partially accounted.

Fitted data for all nuclides above: σ_f, σ_a, σ_γ, σ_s, σ_t, ν_t, mean fission neutron spectrum energy, $<\alpha>$, $<\eta>$ and many other ratios and combinations of microscopical cross sections and integral data (including Hardy’s evaluation of integral thermal constants based on analysis of critical assembly).

Fitted and calculated parameters: g_f, σ_f, g_a, σ_a, σ_s, σ_γ, ν_t, η, α.

AXTON1984: Report IEAE-TECDOC-335, p.214 (1984).

Small revision of microscopic data used in AXTON1982, integral (Maxwellian spectrum averaged) data compiled as in DIVADEENAM1982 are added to the fit.

DIVADEENAM1984A: as given in Table 4a in paper by E.J. Axton, Report IEAE-TECDOC-335, p.214 (1984)

Probably some another fitting, difference with DIVADEENAM1982 is unclear.

AXTON1986: CBNM Report GE/PH/01/86, private communication to W.P. Poenitz (1986).

All microscopic and integral data (29 types), including <K1>

The result of AXTON1986 fit is used in general GMA fit of standard cross sections.

ENDF/B-VI, Standards (1987): ENDF/B-VI Standards evaluation, report NISTR-5177 (1993).

ENDF/B-VI, Releases 6 – 8, 1997.

Evaluation is based on Bayesian fit of microscopic cross sections with R-matrix code SAMMY and with sequential inclusion of thermal values taken from ENDF/B-VI Standards and integral data in the fit. Final minor adjustment of ν_t was done to get <K1> value equal to value 722.7 recommended by Hardy.

ENDF/B-V: values given in Table are taken from DIVADEENAM1982.

GMA2004 (with no new data): still not frozen new Standards evaluation. Least square fit of data included in Standards database with GMA code. AXTON1986 results are part of this database. No new experimental data for thermal values are added in the GMA fit.

GMA2004 (with new data): still not frozen new Standards evaluation. Least square fit of data included in Standards database with GMA code. AXTON1986 results are part of this database. The following new experimental data for thermal values are added in the GMA fit: M.Arif et al., (1987) X4=13118002, nuclear elastic scattering cross section at 0.0253 eV (14.00+-0.22 barn) and shown in Fig. 1 is obtained as sum of bound coherent component measured by Arif with high accuracy and estimated small bound incoherent component; R.Reed et al. data (1972), X4=10427, Nu-prompt for ^{233}U(n,f) and ^{235}U(n,f) measured relative ^{252}Cf as energy dependent values. Uncertainty of the data is large (1.4%), but they are rather consistent with results of other microscopic cross section measurements. They are shown on Fig. 2 and 3 together with other data.

GMA2004 (with new data, GWIN's NU-prompt taken with an uncertainty 0.12%) the fit of the same data as above – GMA2004(with new data) for exclusion that small uncertainty 0.12% was assigned to Gwin1984 data measured as energy dependent ratio of ν_p for ^{235}U(n,f) to ν_p for ^{252}Cf(sf) (see Fig. 3 and 2). The reason of this is give in next chapter.

HARDY79: Results of the analysis of Gwin-Magnusson uranyl nitrate critical assembles. The analysis includes nuclear data for other nuclides, depends from standards and approximations of neutron transport theories. As believed, it gives the best estimation of <K1> integral parameters. Value given in Table below is taken from MF=1, MT=451 (free text) in ENDF/B-VI, Rel.6 – 8.

Reasons of discrepancies with Hardy's value <K1>=722.7

There are known discrepancies between microscopic and integral data for ^{235}U. They are demonstrated in Table by comparing fitting made by Divadeenam (DIVADEENAM82) with only microscopic or only integral data included and with AXTON86 when integral data are excluded from the fit. Even if discrepancies are in the limits of the uncertainties of evaluated data, inclusion of integral data substantially reduces <K1> value. The problem of obtaining <K1> value as seems is not resolved up to now but as we see some closer value is obtained if new data for scattering (M. Arif et al.) are added. Fig. 3 presents the results of ratio ν_p for ^{235}U(n,f) to ^{252}Cf(sf) measurements grouped on method how the data are reduced to the value at 0.0253 eV. First group of data (extrapolated) presents the results of extrapolation (linear) to the 0.0253 eV point the ratios measured usually above tens keV. As seems this method is not accurate enough, because as we know now, ν_p for ^{235}U first is decreasing in eV – tens keV region and only then begins rather linear increase with energy. Thermal values obtained by linear extrapolation way will be low. Generally ν_p can vary from resonance to resonance and because there is no good averaging on resonances at 0.0253 eV point, using any extrapolation procedure can introduce a large additional uncertainty. Because of lack averaging, it may happen that ν_p can vary with energy near 0.0253 eV point and cause the difference between point microscopic and integral Maxwellian values. Fig. 2 does not show substantial energy dependence, which may be a cause of this difference (and the reason of this difference ~ 0.6% is not so clear), but as we see from Fig. 3 integral $< \nu_p>$ is below ν_p measured at the point 0.0253 eV. These "point" values are the highest and they present results of most direct measurements of ν_p at 0.0253 eV point. In AXTON86 evaluation experimental data by R.Gwin et al. presenting results of 3 sets of measurements were introduced with a modest uncertainty. If we think that uncertainty of "extrapolated" or "thermal" data shown in Fig. 3 are too small and this leads to too low value of ν_p we can reduce their influence by introducing in the GMA fit once more Gwin1984 value (0.647) with a small uncertainty (0.12%) which is probably lowest possible estimation of uncertainty for this work. We obtain <K1>=721.35 in this case. GMA evaluation in this case is very close to ENDF/B-VI. Rel. 6 (compare $<\sigma_f>$=570.77 (GMA) and 571.06 (B-VI), $<\sigma_\gamma>$=98.12 (GMA) and 97.77 (B-VI) and for others).

We should also recognize, that B-VI fit of elastic and capture cross sections with SAMMY is probably not an ideal as we see from Fig. 1 and Fig. 4, where Weigmann1990 data compared with B-VI fit.

Table. Comparison of cross sections and constants obtained in different evaluations for ^{235}U.

Evaluation	g_f	σ_f	g_γ	σ_γ	ν_t	$<\alpha>$	$<\eta>$	<K1>
AXTON1982	-	584.7 +-1.7	-	96.8 +-1.8	2.427 +-0.005	0.1680*	2.078*	718.7*
DIVADEEN1982 All data	0.9761 +-0.0012	582.6 +-1.1	0.9948	98.3 +-0.8	2.4251 +- 0.0034	0.1720	2.0692	712.6
DIVADEEN1982 only Maxwellian exp. data	-	580.9 +-1.5	-	99.1 +-1.2	2.4239 +-0.0042	0.1739**	2.0649**	708.8**
DIVADEEN1982 only microscopic exp.data	-	584.2 +-1.3	-	97.6 +-1.1	2.4225 +-0.0037	0.1703**	2.0700**	714.1**
DIVADEEN1984A	0.9766	582.9	0.9908	98.6	2.4287	0.1716	2.0730	715.6
AXTON1984	0.9765 +-0.0012	582.78 +-1.24	0.9917	98.67 +-0.84	2.4316 +-0.0039	0.1719	2.0748	716.85
AXTON1986 (GMA2004 input)	0.9774 +-0.0008	582.8 +-1.17	0.9877	99.05 +-0.74	2.4330 +-0.0036	0.1717	2.0764	718.57 +-2.22
AXTON1986 only microscopic exp. data	0.9778 +-0.0008	585.06 +-1.62	0.9841	96.10 +-1.74	2.4261 +-0.0046	0.1653	2.0819	721.24
ENDF/B-VI Standards, 1987	0.9771 +-0.0009	584.25 +-1.11	0.99022	98.96 +-0.74	2.4320 +-0.0036	0.1717	2.0758	719.7
ENDF/B-VI, Rel.6-8, 1997	0.9764	584.88	0.9910	98.66	2.4367 +-0.0005	0.1712	2.0805	722.69
ENDF/B-V	0.9775	583.5	0.9817	98.4	2.4370	0.1694	2.0817	723.02
GMA2004 (with no new data)	0.9773 +-.0008	583.47 +-1.11	0.9888	99.03 +-0.74	2.4325 +-0.0036	0.1717	2.0760	718.93
GMA2004 (with new data)	0.9773 +-.0008	584.17 +-1.11	0.9876	99.33 +-0.74	2.4324 +-0.0036	0.1718	2.0757	719.67
GMA2004 (with new data, GWIN's NU-prompt taken with an uncertainty 0.12%)	0.9774 +-.0008	583.97 +-1.02	0.9868	99.44 +-0.72	2.4358 +-0.0023	0.1719	2.0785	721.35
HARDY79	-	-	-	-	-	-	-	722.7 +-3.9

* - if g_f=0.9764 and g_γ=0.9910 are taken (as B-VI, Rel.6-8)

** - if g_f=0.9761 and g_γ=0.9948 are taken (as in DIVADEENAM1982 all data fit)

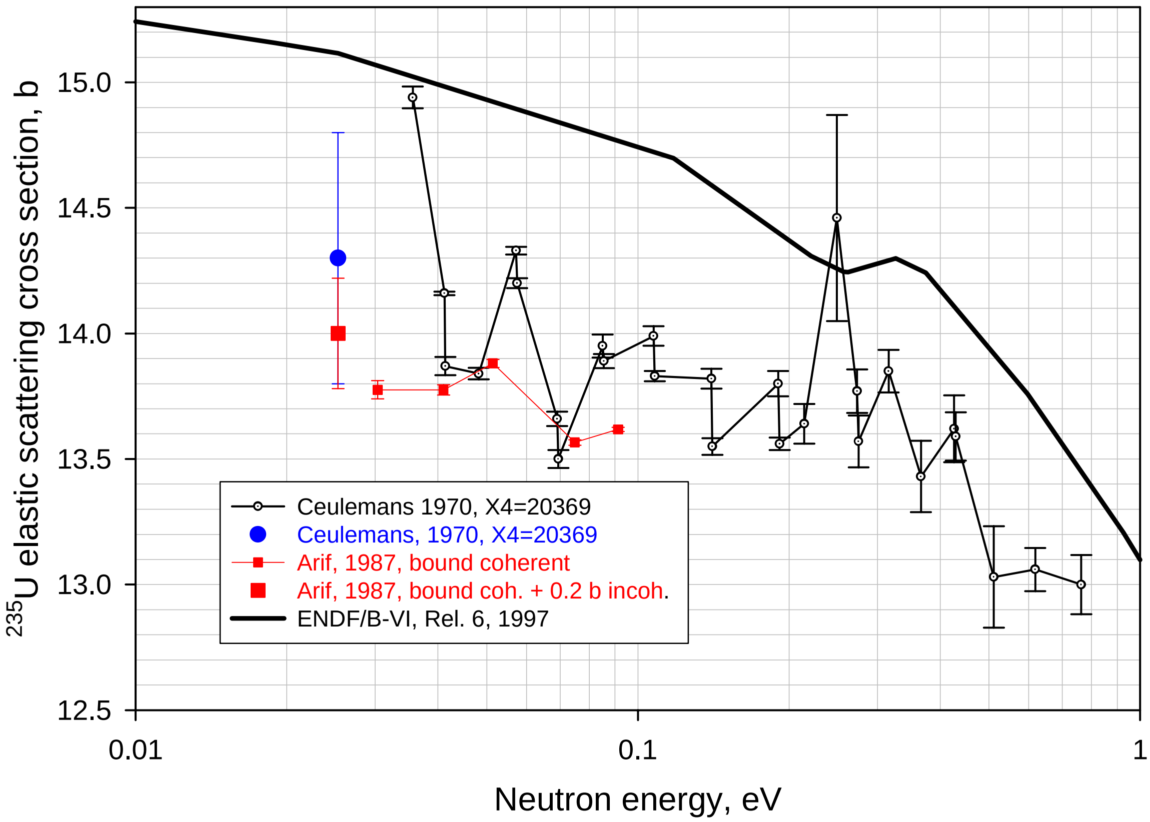

^{235}U elastic scattering cross section, b
15.0
14.5
14.0
13.5
13.0
12.5
0.01
0.1
1
Neutron energy, eV
Ceulemans 1970, X4=20369
Ceulemans, 1970, X4=20369
Arif, 1987, bound coherent
Arif, 1987, bound coh. + 0.2 b incoh.
ENDF/B-VI, Rel. 6, 1997

Fig. 1

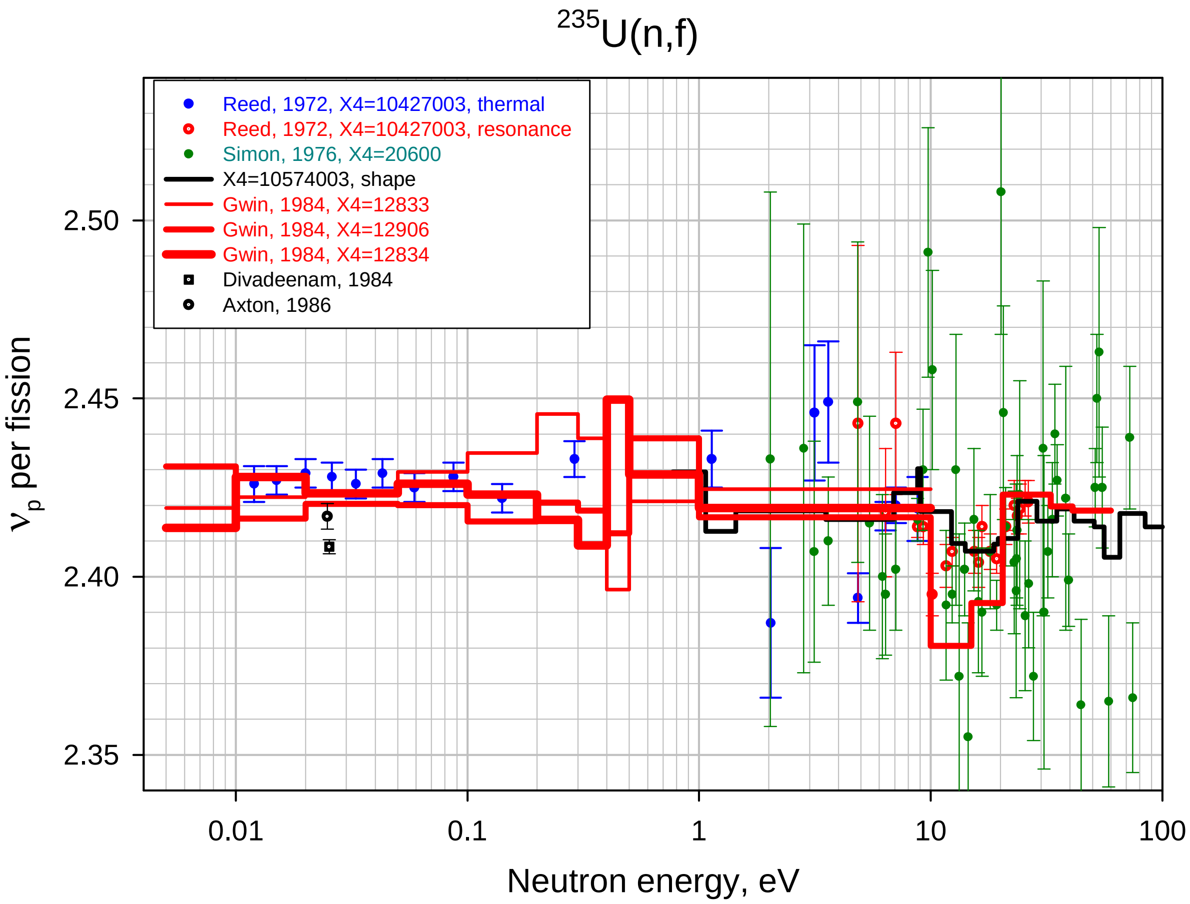

^{235}U(n,f)
ν_p per fission
2.50
2.45
2.40
2.35
0.01
0.1
1
10
100
Neutron energy, eV
Reed, 1972, X4=10427003, thermal
Reed, 1972, X4=10427003, resonance
Simon, 1976, X4=20600
X4=10574003, shape
Gwin, 1984, X4=12833
Gwin, 1984, X4=12906
Gwin, 1984, X4=12834
Divadeenam, 1984
Axton, 1986

Fig. 2

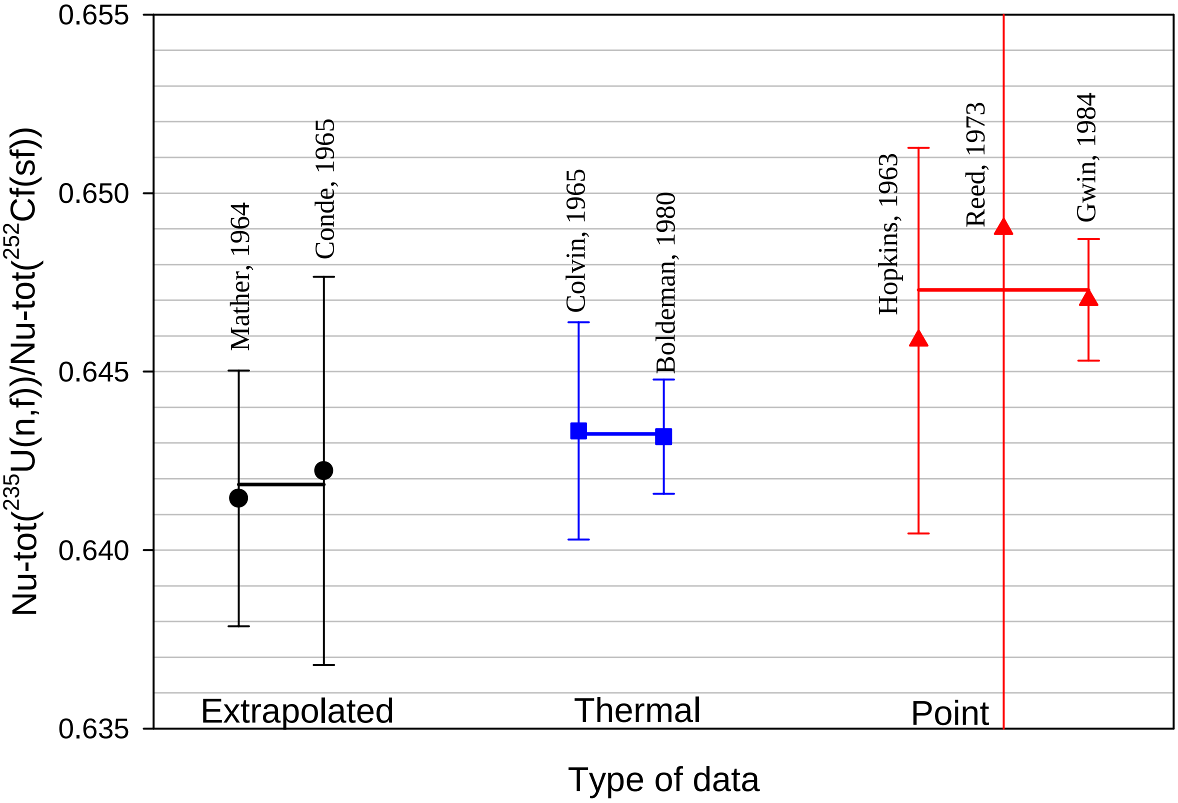

0.655
0.650
0.645
0.640
0.635
Nu-tot(235U(n,f))/Nu-tot(252Cf(sf))
Mather, 1964
Conde, 1965
Colvin, 1965
Boldeman, 1980
Hopkins, 1963
Reed, 1973
Gwin, 1984
Extrapolated
Thermal
Point
Type of data

Fig .3

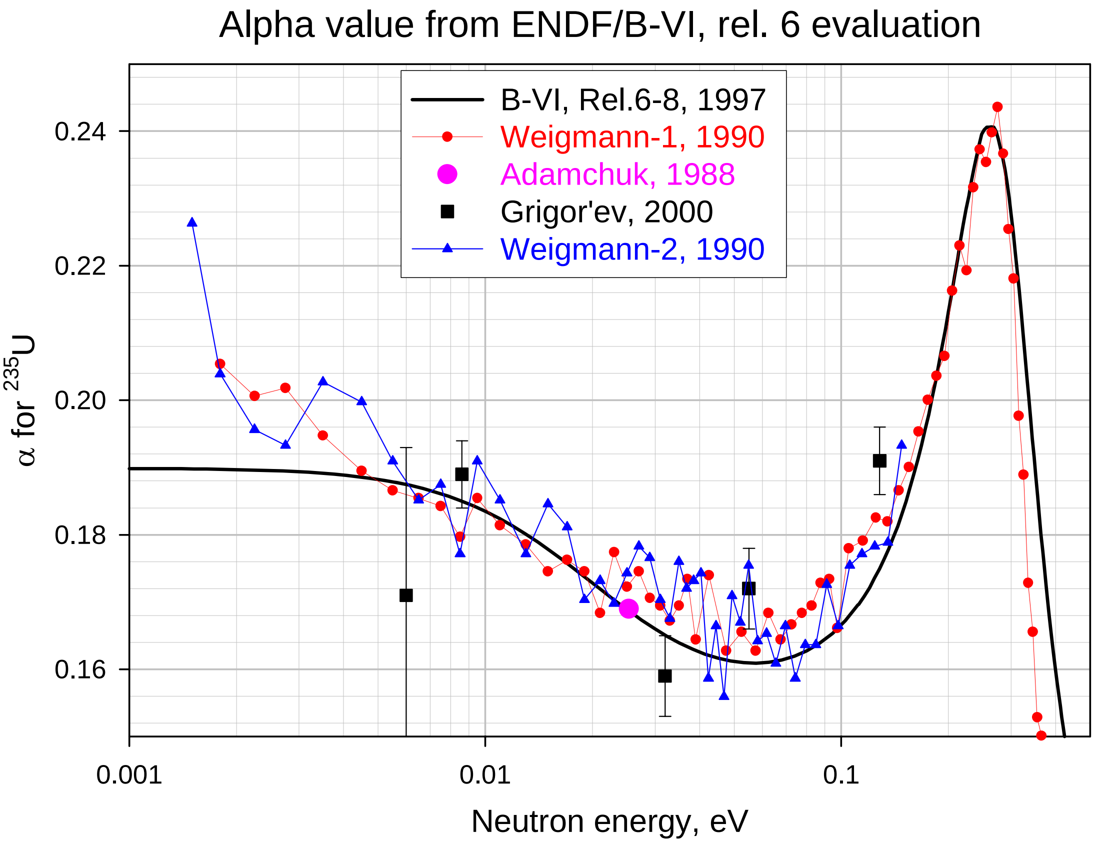
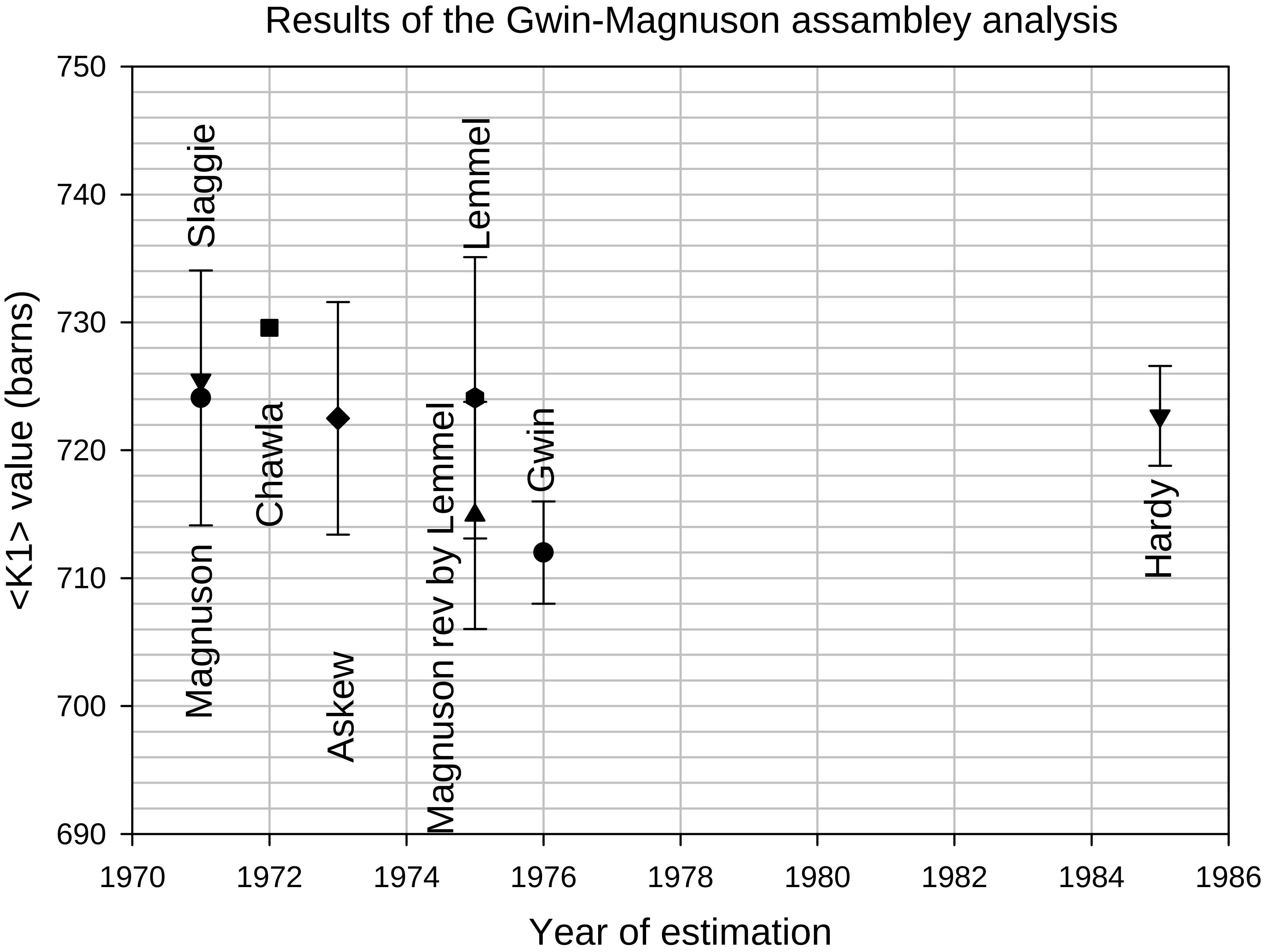

Alpha value from ENDF/B-VI, rel. 6 evaluation
B-VI, Rel.6-8, 1997
Weigmann-1, 1990
Adamchuk, 1988
Grigor'ev, 2000
Weigmann-2, 1990
0.24
0.22
0.20
0.18
0.16
α for 235U
0.001
0.01
0.1
Neutron energy, eV

Fig. 4


Results of the Gwin-Magnuson assambley analysis
<K1> value (barns)
750
740
730
720
710
700
690
Year of estimation
1970
1972
1974
1976
1978
1980
1982
1984
1986
Slaggie
Magnuson
Chawla
Askew
Lemmel
Magnuson rev by Lemmel
Gwin
Hardy