On the Selection of the Differential ^{235}U PFNS Experimental Data

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Background

A Coordinated research project (CRP) of the International Atomic Energy Agency (IAEA) to evaluate standard reaction cross sections and spectra is in progress. One of the objectives is also to evaluate the thermal-neutron induced prompt fission neutron spectrum of ^{235}U. Furthermore, this spectrum is also of interest within the CIELO project, which is the Subgroup-40 (SG40) of the Working Party on Evaluation Cooperation (WPEC) of the OECD. The first task in the evaluation process is the review the available experimental information and the assessment of its quality, which is the primary purpose of the present report.

Available experimental data

The primary source of experimental data is the EXFOR database, maintained by the Nuclear Reaction Data Centre Network (NRDC) and is available on-line from the main data centres (e.g.: "http://www-nds.iaea.org"). A search in the database was made with the following search criteria, which include "Reaction Sub-Fields" to more precisely define the search:

Target:	U-235	
Reaction:	*,f	(needed to include ratios to ^{252}Cf spontaneous fission spectrum)
SP4	^MASS	(exclude mass distribution data)
SP58:	,NU/DE*;PR,NU/DE*	(additional reaction qualifier parameter).

With this choice of parameters we retrieved 24 reactions and 51 datasets. We believe we retrieved all relevant measurements that are available in the database. The qualifier SP58 refers to combined fields PR5 to PR8 in the EXFOR nomenclature. This form of the search criteria was used to capture labelled explicitly prompt-fission neutron spectra, as well as some older data, which do not have the "PR" qualifier defined I the field SP6. From the retrieved parameters we selected those that correspond to incident neutron energies <100 eV. The final list of datasets is given in Table I.

The data in EXFOR are given in different representation, which makes it difficult to compare different data sets. To bring all data on the same basis, each data set was converted to “shape” spectrum and scaled to match a chosen basis function by minimising the squares of the relative differences between the measured values and the basis function. The basis function was defined, which consists of a linear combination of a Watt function and a Maxwellian function, which was found to represent the data reasonably well. This function is used only as a tool for a more objective assessment of experimental data.

$$f(E) = w_M f_M(E, E_M) + w_W f_W(E, a_W, b_W).$$

Parameter values of the basis function were as follows:

w_M = 0.7424

w_W = 1 - w_M

E_M = 1.316E+06 (eV)

a_W = 6.859E+05 (eV)

b_W = 9.366E-06 (1/eV)

In all comparison plots that follow, the experimental data are scaled to match the basis function as described above, and expressed as ratios to a Maxwellian spectrum with a temperature of 1.32 MeV.

Table I: Final retrieval of the EXFOR data sets

EXFOR No.	Year	Author	EXFOR Reaction Code
13810002	1952	D.L. Hill	92-u-235(n,f),,nu/de,,mxw/rel
13824002	1956	L. Cranberg+	92-u-235(n,f),,nu/de,,mxw/rel
20616003	1972	H. Werle+	92-u-235(n,f),,nu/de,,mxw/rel
20616008	1972	H. Werle+	92-u-235(n,f),,nu/de,,mxw/msc
20616009	1972	H. Werle+	92-u-235(n,f),,nu/de,,mxw/msc
22464006	1998	K. Nishio+	(92-u-235(n,f),pr,nu/de,hf,fct/mxw)+ (92-u-235(n,f),pr,nu/de,lf,fct/mxw)
30426002	1977	A. Lajtai+	92-u-235(n,f),pr,nu/de,,mxw/fct
30704003	1985	A. Lajtai+	92-u-235(n,f),pr,nu/de,,mxw/rel
31692002	2010	N. Kornilov+	92-u-235(n,f),pr,nu/de,,npd/mxw
31692005.3	2010	N. Kornilov+	92-u-235(n,f),pr,nu/de,,npd/mxw
31692005.2	2010	N. Kornilov+	92-u-235(n,f),pr,nu/de,,npd/mxw
31692005.1	2010	N. Kornilov+	92-u-235(n,f),pr,nu/de,,npd/mxw
31692006	2010	N. Kornilov+	(98-cf-252(0,f),pr,nu/de)/ (92-u-235(n,f),pr,nu/de)
32587002	1989	Wang Yufeng+	92-u-235(n,f),pr,nu/de,,mxw/rel
40871007	1983	V.N. Nefedov+	92-u-235(n,f),pr,nu/de,,mxw
40871008	1983	V.N. Nefedov+	92-u-235(n,f),pr,nu/de,,mxw
40871011	1983	V.N. Nefedov+	(98-cf-252(0,f),pr,nu/de)/ (92-u-235(n,f),pr,nu/de,,mxw)
40871012	1983	V.N. Nefedov+	(98-cf-252(0,f),pr,nu/de)/ (92-u-235(n,f),pr,nu/de,,mxw)
40872004	1983	B.I. Starostov+	92-u-235(n,f),pr,nu/de,,mxw
40872007	1983	B.I. Starostov+	(98-cf-252(0,f),pr,nu/de)/ (92-u-235(n,f),pr,nu/de,,mxw)
40873004	1983	A.A. Boytsov+	92-u-235(n,f),pr,nu/de,,mxd
40930006	1985	B.I. Starostov+	92-u-235(n,f),pr,nu/de,,mxd
41502002	2004	O.A. Batenkov+	(92-u-235(n,f),pr,nu/de)/ (98-cf-252(0,f),pr,nu/de)
41516007	2010	A.S. Vorobyev+	92-u-235(n,f),pr,nu/ de,,mxd/msc
41516008	2010	A.S. Vorobyev+	92-u-235(n,f),pr,nu/de,,mxd/msc
41516017	2010	A.S. Vorobyev+	(98-cf-252(0,f),pr,nu/de)/ (92-u-235(n,f),pr,nu/de)
41597002	2013	A.S. Vorobyev+	(92-u-235(n,f),pr,nu/de)/ (98-cf-252(0,f),pr,nu/de)
41597003	2013	A.S. Vorobyev+	92-u-235(n,f),pr,nu/de

Cranberg, Hill

The data in the entry 13810002 by Hill are rather old and scattered in excess of the experimental uncertainty. The data in the entry 13824002 by Cranberg seem to be more consistent, but compared to more recent measurements their uncertainties are rather large. Neither of these data sets would improve the quality of the evaluated spectrum through a fitting procedure, therefore these data can be excluded from further consideration (see Fig. 1).

Werle

The data consist of measurements by two detectors: a proton-recoil detector and a ^{3}He spectrometer detector. The data at low neutron energies measured with the ^{3}He detector differ significantly from the measurements with the proton recoil detector. Both have a relatively high uncertainty and would not add quality if these old measurements were included in the fitting procedure (see Fig. 2 and note the scale on the axes), therefore these data can be excluded from further consideration.

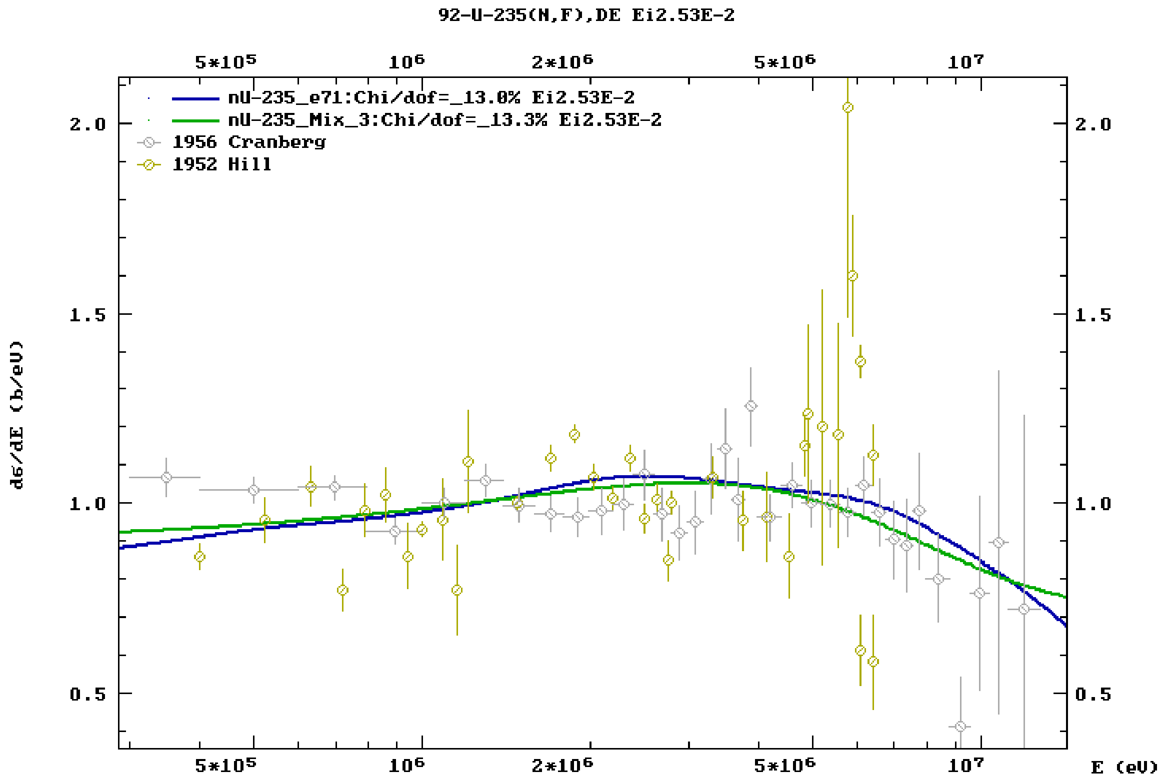

Figure 1: Comparison of the ^{235}U PFNS data by Cranberg and by Hill to ENDF/B-VII (labelled e71) and the IAEA MIX_3 fit.

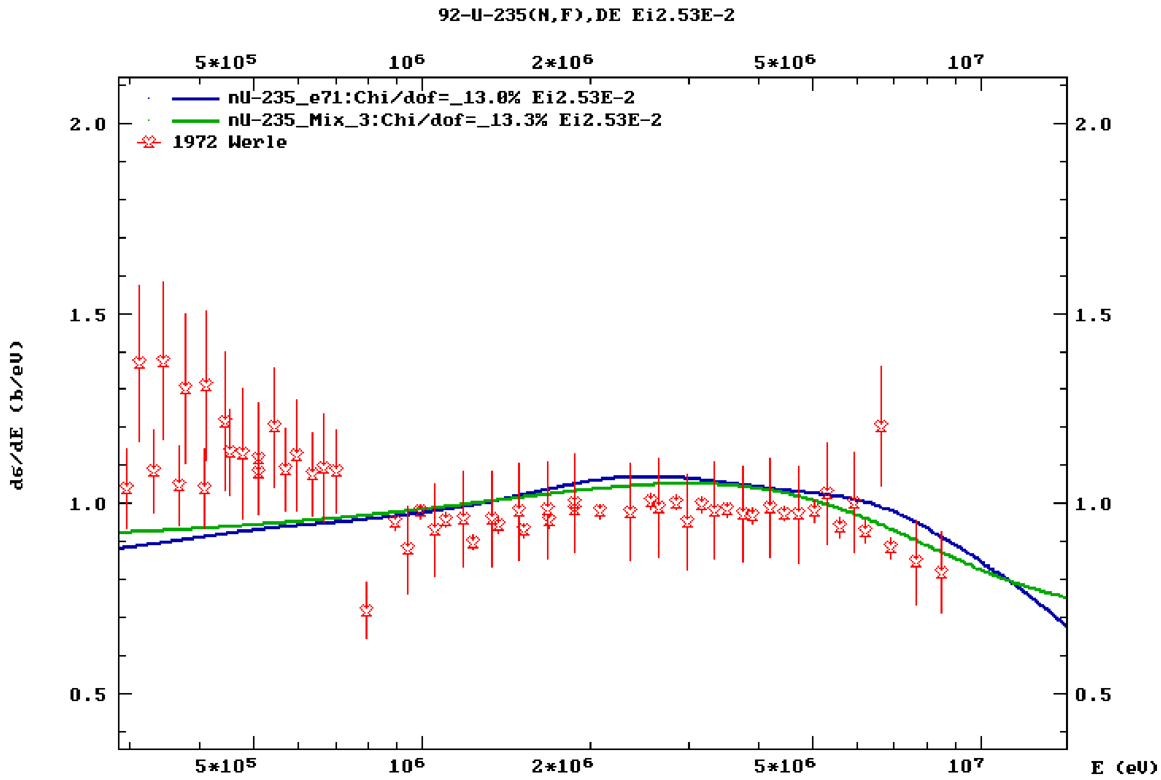

Figure 2: Comparison of the ^{235}U PFNS data by Werle to ENDF/B-VII (labelled e71) and the IAEA MIX_3 fit.

Lajtai

The measurements are very well documented in the reference paper. The lithium glass detector was used to detect neutrons. However, from the paper it is evident that corrections in the region from about 0.2 MeV to 1.2 MeV involve very large corrections. What remains is a relatively small data set, which in addition seems to be discrepant with other measured data and has large uncertainties. Therefore, this data set is considered less suitable for inclusion in the fitting procedure.

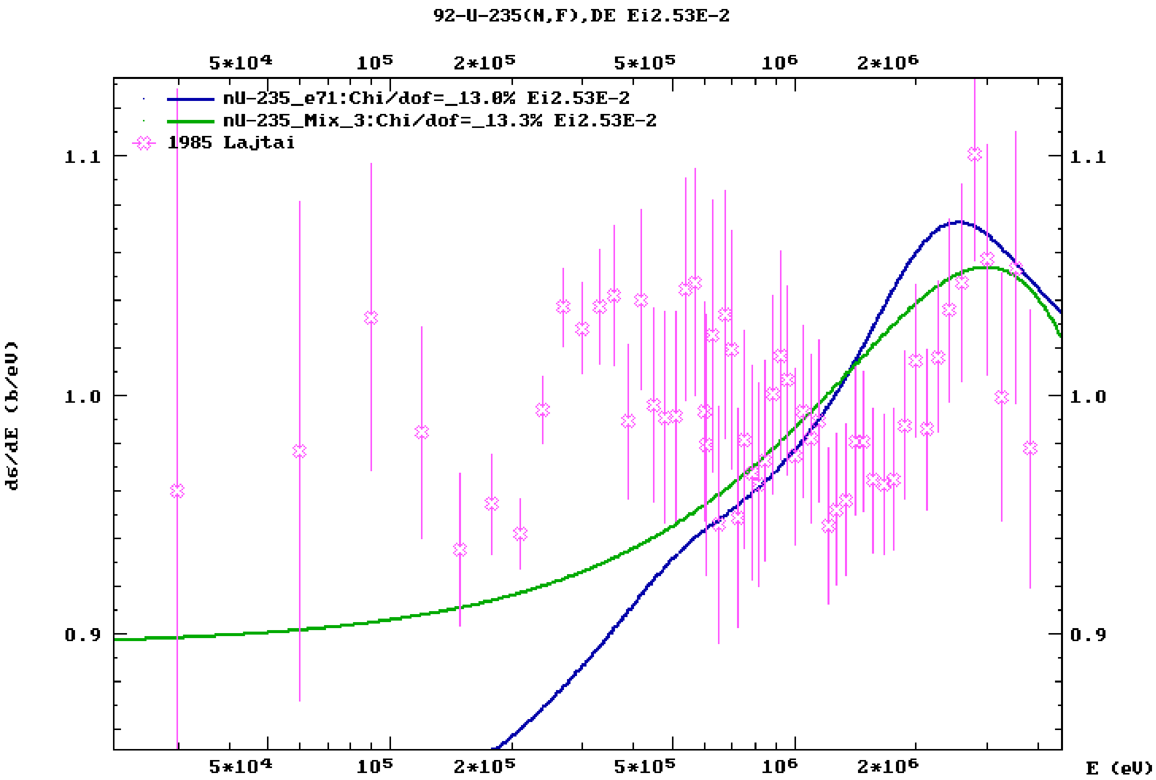

Figure 3: Comparison of the ^{235}U PFNS data by Werle to ENDF/B-VII (labelled e71) and the IAEA MIX_3 fit.

Wang Yufeng

The data seem to have an unphysical bump below 1.3 MeV. The data below this energy are to be excluded from the fitting procedure.

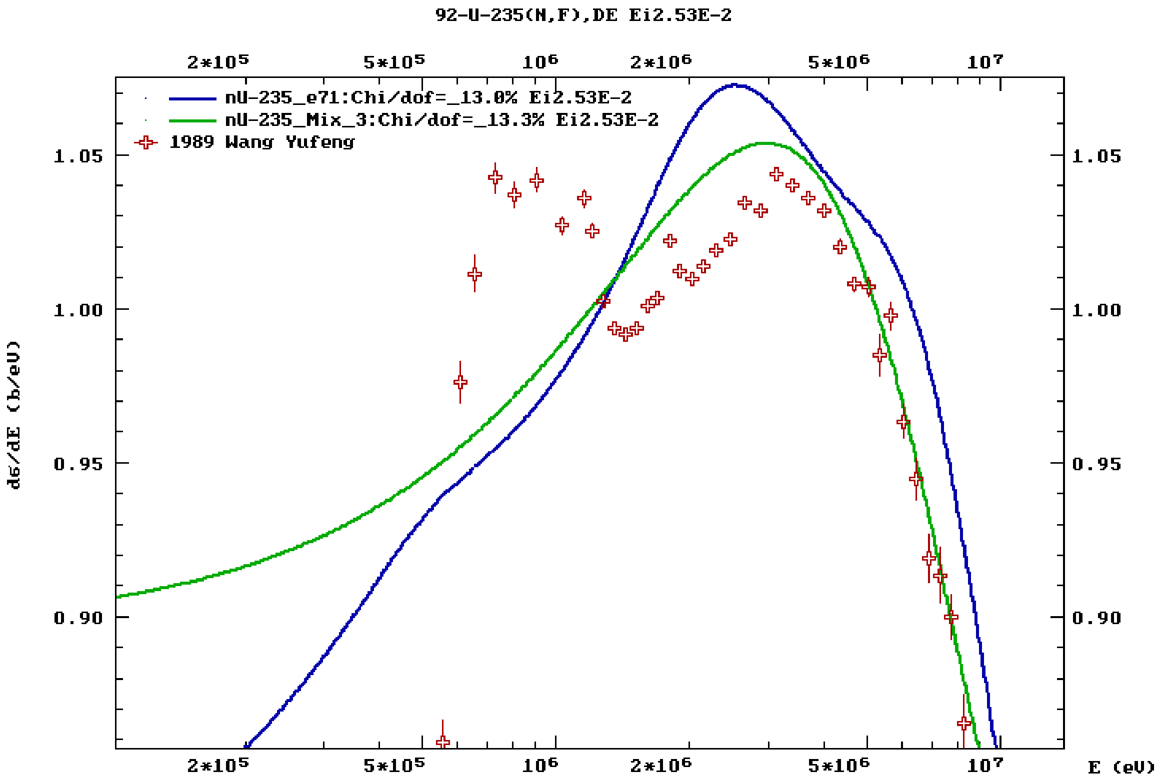

Figure 4: Comparison of the ^{235}U PFNS data by Wang Yufeng to ENDF/B-VII (labelled e71) and the IAEA MIX_3 fit.

Nefedov

Four sets of data are given in the EXFOR entry No. 40871, as seen from Table 1. The first two subentries 7 and 8 (see Fig. 5) give the spectra directly, while the second two subentries 11 and 12 (see Fig. 6) give the ratio with the ^{252}Cf spectrum. When the data are brought on the same basis (Figs. 7 and 8), there seems to be no correspondence between different data sets. Since the measurements were done relative to the ^{252}Cf spontaneous fission spectrum, we consider subentries 11 and 12 to be the primary data; subentries 7 and 8 are ignored. Note that the co-authors in the main reference are Starostov and Boytsov.

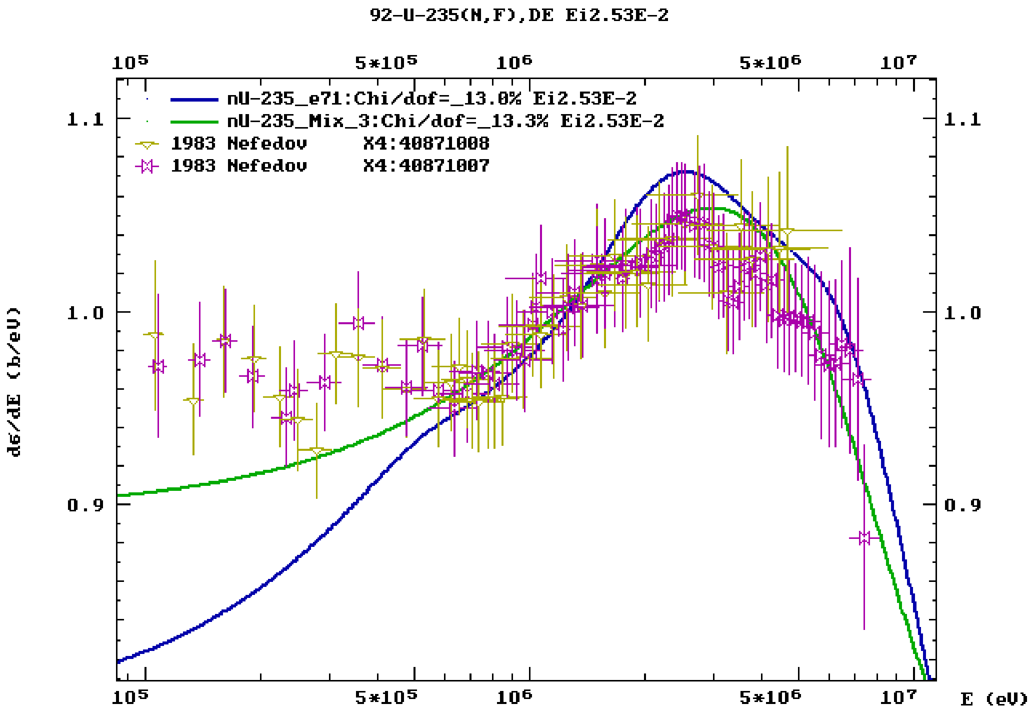

Figure 5: Comparison of the ^{235}U PFNS data by Nefedov to ENDF/B-VII (labelled e71) and the IAEA MIX_3 fit.

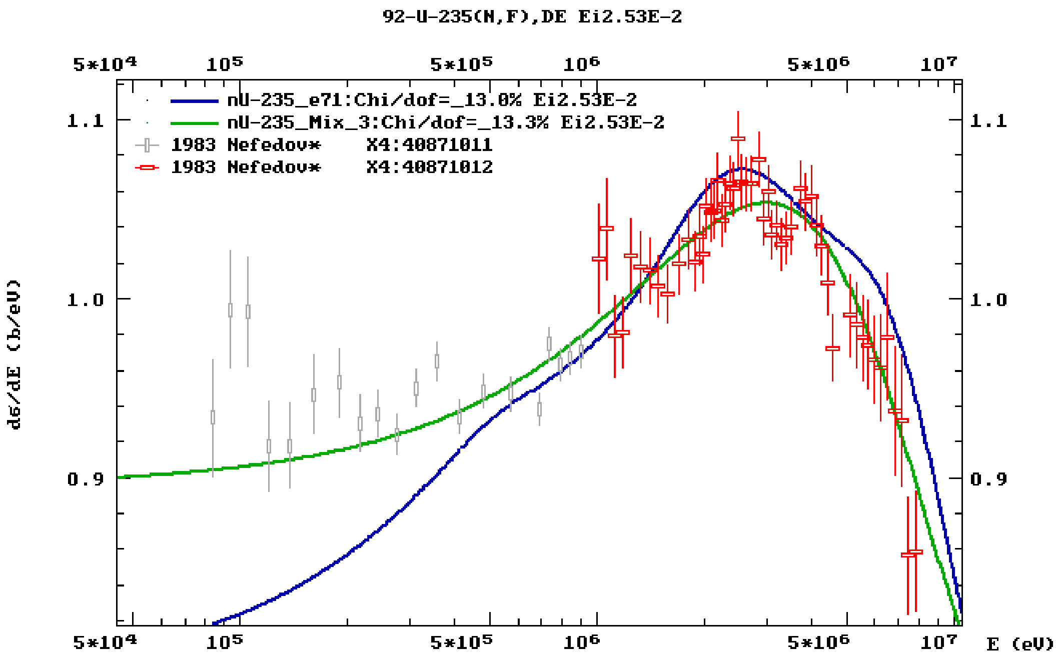

Figure 6: Comparison of the ^{235}U PFNS data by Nefedov (calculated from the ratio with ^{252}Cf spontaneous fission spectrum) to ENDF/B-VII (labelled e71) and the IAEA MIX_3 fit.

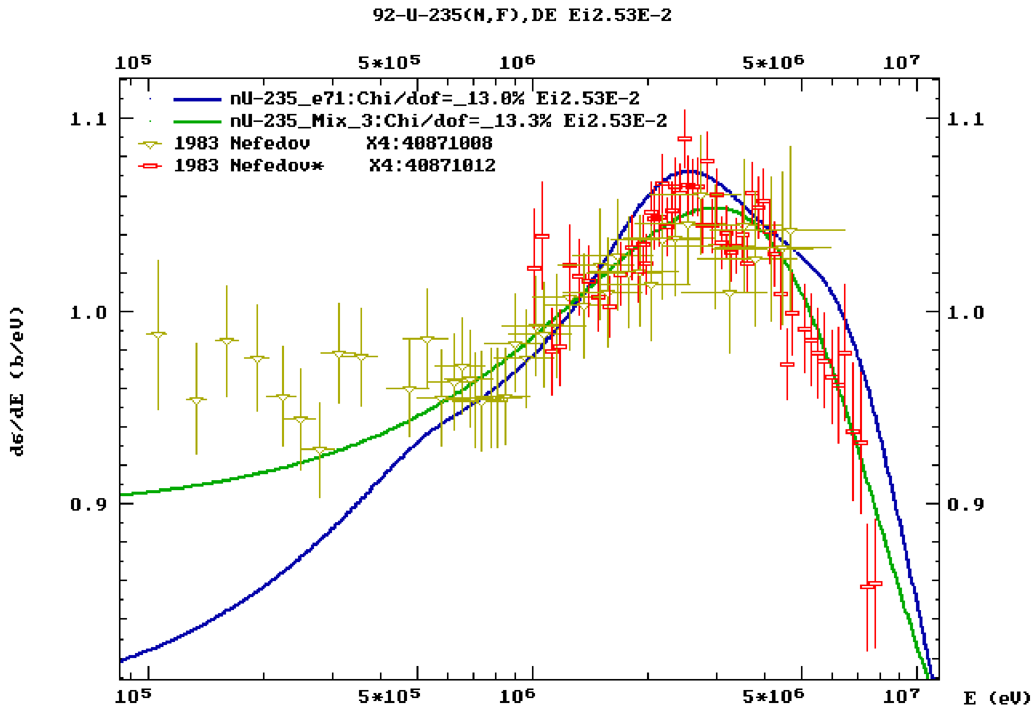

Figure 7: Comparison of the ^{235}U PFNS data by Nefedov to ENDF/B-VII (labelled e71) and the IAEA MIX_3 fit. The data given directly as measured spectra are compared to the data derived from the ratio with the ^{252}Cf spontaneous fission spectrum.

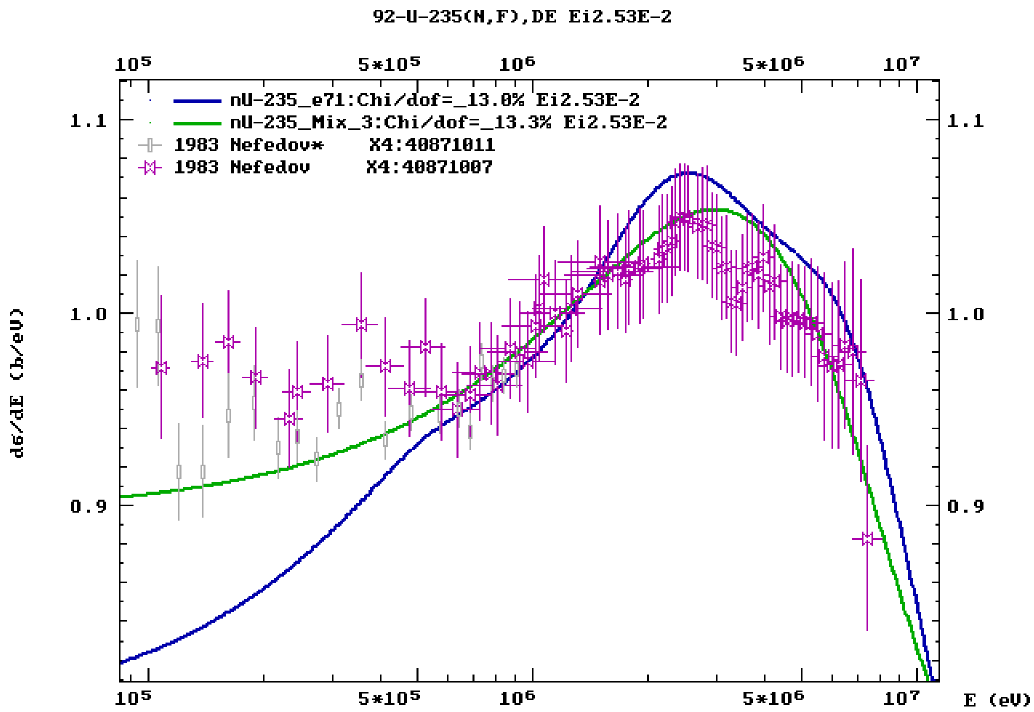

Figure 8: Comparison of the ^{235}U PFNS data by Nefedov to ENDF/B-VII (labelled e71) and the IAEA MIX_3 fit. The data given directly as measured spectra are compared to the data derived from the ratio with the ^{252}Cf spontaneous fission spectrum.

Starostov

There are two EXFOR entries with Starostov as the first author: 40872 published in 1983 and 40930 published in 1985. The EXFOR entry 40872 contains two data sets. Subentry 4 is given as the absolute spectrum, while subentry 7 is given as the ratio to ^{252}Cf. Since the measurements were done relative to the ^{252}Cf spontaneous fission spectrum, we consider subentry 7 to be the primary data; subentry 4 is ignored.

The EXFOR subentry 40930006 is a complicated case. There are four sets of results given in the same data block, distinguished by a flag for each measurement. From the reference it is evident that this is a re-analysis of the older measurements. The sets flagged 1, 2 and 3 correspond to measurements in the first campaign using different detectors. Measurement 4 corresponds to the second campaign. The measurements were normalised to each other in the overlapping regions to produce a single set covering a broad energy range. However, as evident from Fig. 9, the overall shape of the spectrum is in strong contradiction with what we believe to be a reasonable shape of the spectrum (especially at higher energies), as well as with the data of the same author in the subentry 40872007. The comparison plot is included in Fig. 9.

To understand better the situation with the data, the single entry was split into separate subentries 16, 26, 36 and 46, respectively, where the leading digit corresponds to the flag in the original subentry 6. The result is shown in Fig. 10. Evidently, subentries 16 and 46 (measured with the same detector) are consistent, while the subentries 26 and 36 show an unphysical trend, rising strongly up to about 7 MeV and then dropping of sharply. Subentry 46 originates from the measurement of the second campaign and is considered suitable for inclusion in the fitting procedure. Judging by the given energy range and the general trend of the data, subentry 16 is likely to be from the same measurement as given in the subentry 40871011; the comparison is shown in Figure 10a. Differences may be attributed to the fact that the latter is reconstructed from the ration to 252Cf, which is considered primary information and hence more reliable. Similarly, subentry 26 seems to be related to 40871012, but has an unphysical bump near 7 MeV, as seen from Figure 10b. Likewise, subentry 36 might be related to the Starostov entry 40872007, shown in Figure 10c. The split subentries 16, 26 and 36 are rejected. For subentry 46 see the comments on the Bojtsov measurement.

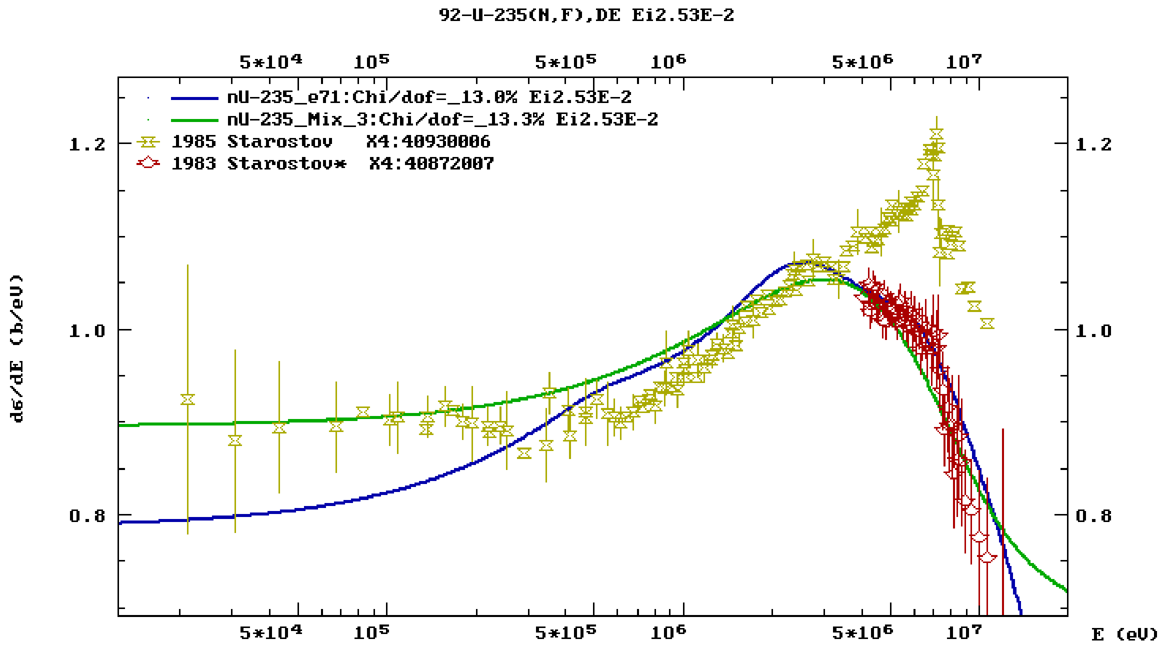

Figure 9: Comparison of the ^{235}U PFNS data by Starostov to ENDF/B-VII (labelled e71) and the IAEA MIX_3 fit. The combined data from three measurements given directly as measured spectra in EXFOR entry 40930006 are compared to entry 4072007 by the same author.

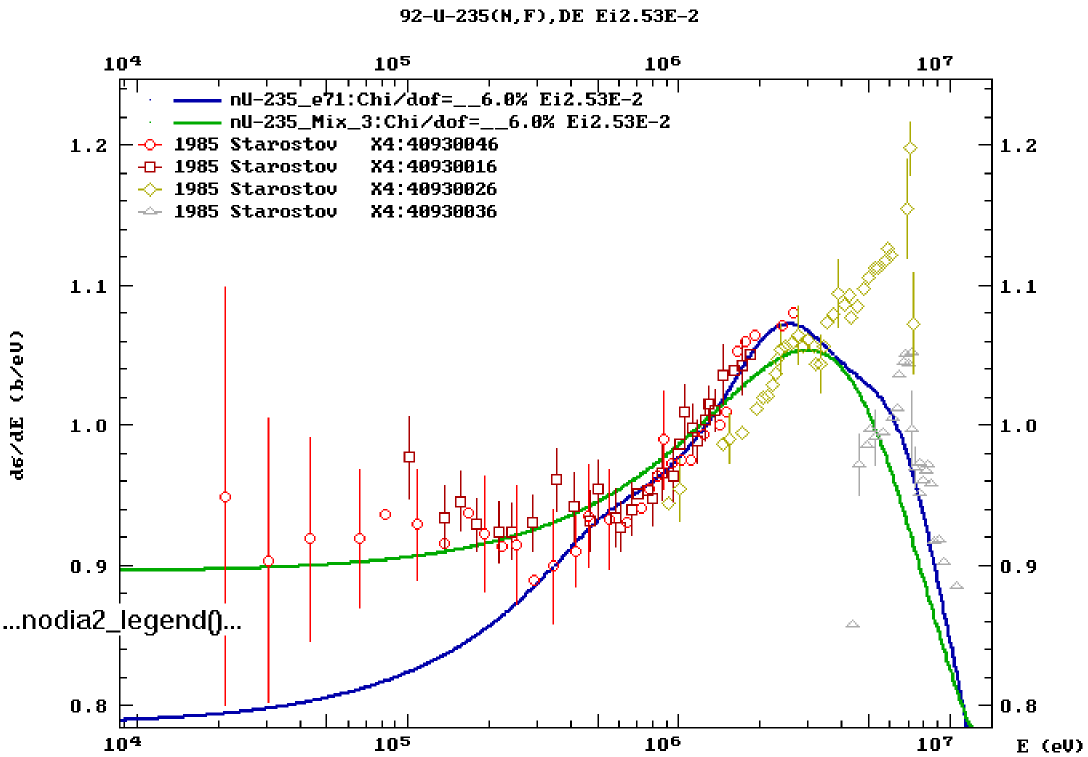

Figure 10: Comparison of the ^{235}U PFNS data by Starostov to ENDF/B-VII (labelled e71) and the IAEA MIX_3 fit. The data from the three measurements given directly as measured spectra in EXFOR entry 40930006 are normalised independently.

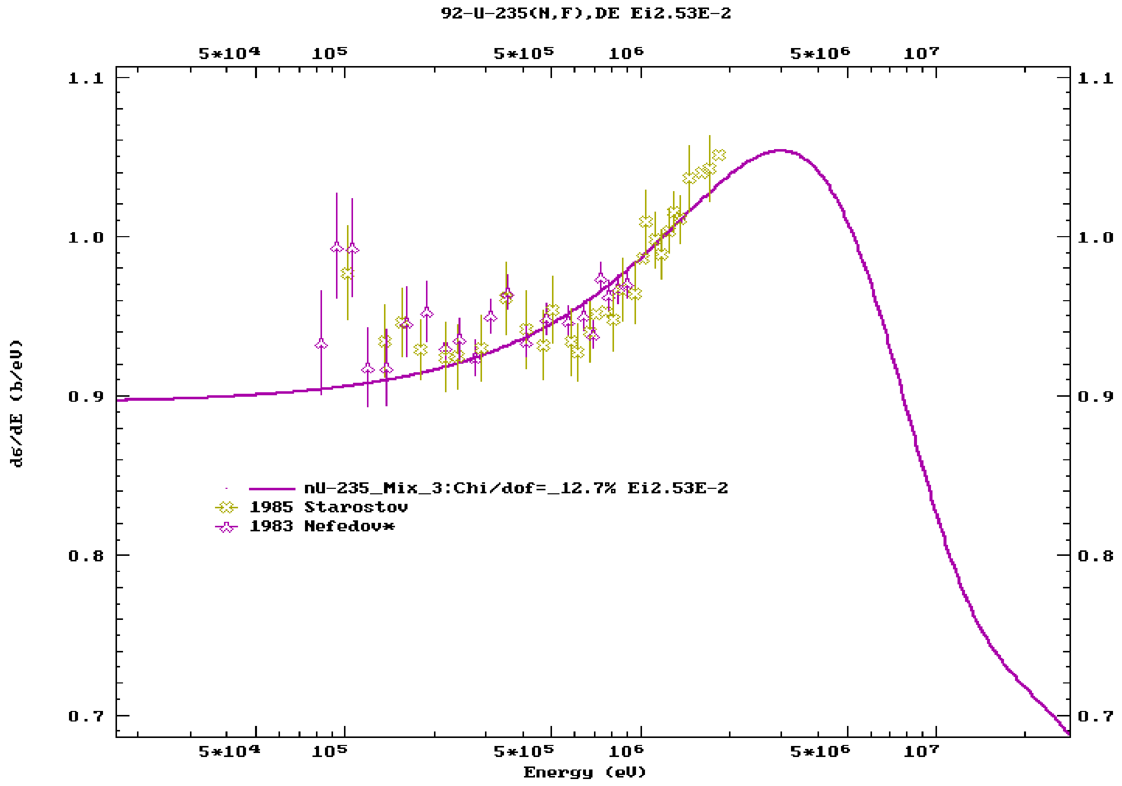

Figure 10a: Comparison of the ^{235}U PFNS data by Starostov (split subentry 16) and Nefedov (entry 40871011) to ENDF/B-VII (labelled e71) and the IAEA MIX_3 fit.

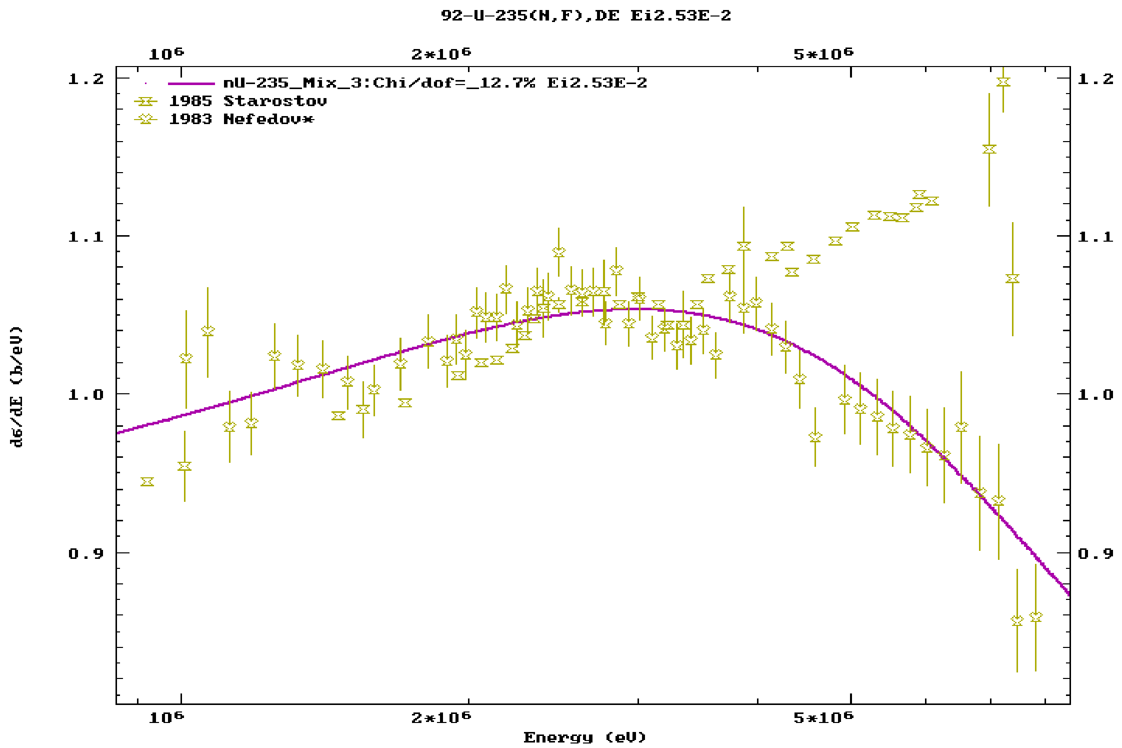

Figure 10b: Comparison of the ^{235}U PFNS data by Starostov (split subentry 26) and Nefedov (entry 40871012) to ENDF/B-VII (labelled e71) and the IAEA MIX_3 fit.

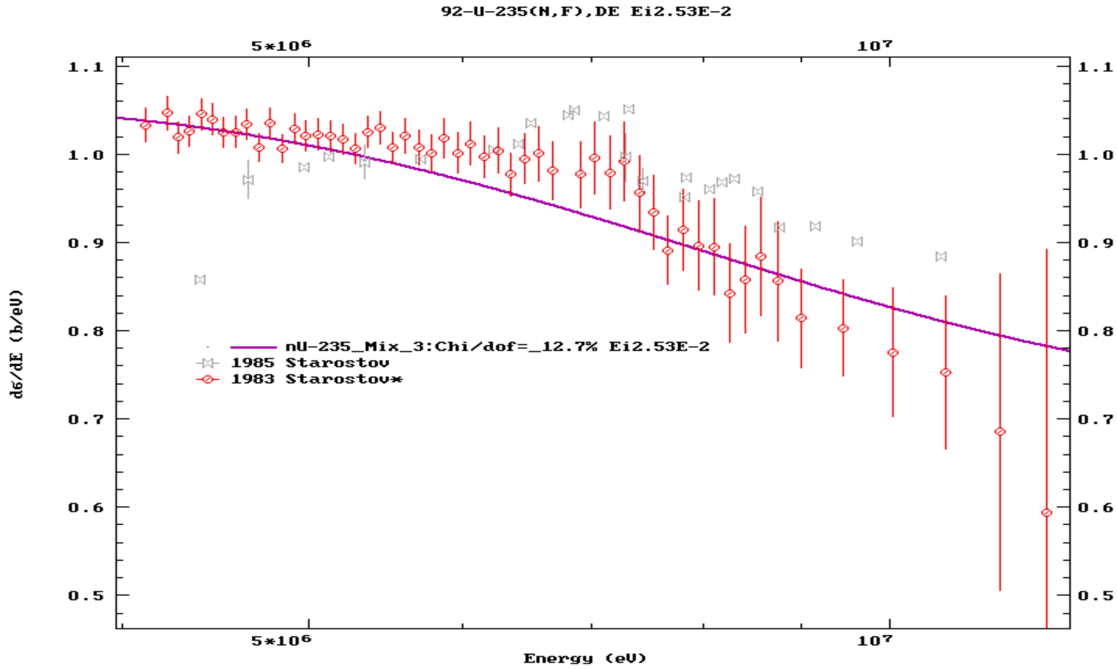

Figure 10c: Comparison of the ^{235}U PFNS data by Starostov (split subentry 36) and Starostov (entry 40872007) to ENDF/B-VII (labelled e71) and the IAEA MIX_3 fit.

Boytsov

The EXFOR subentry 40873004 refers to the same original measurements as Starostov; Nefedov and Starostov are the co-authors of the paper. The similarity of data points between the data sets by Boytsov and by Starostov in Fig. 11 indicates that this is not an independent measurement. The data set by Starostov is more recent by date, but it is obtained by digitisation of the published figure while the Boytsov data are presumably supplied by the author in numerical form. Due to the similarity of both data sets the choice between the two is rather arbitrary.

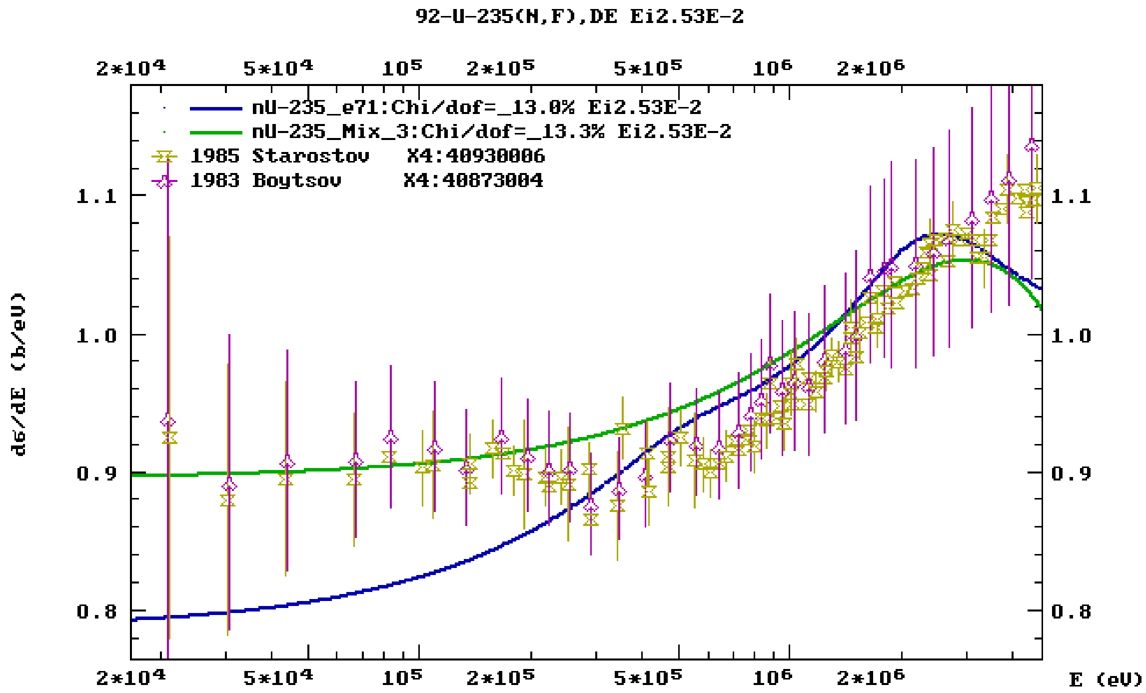

Figure 11: Comparison of the ^{235}U PFNS data by Boytsov to ENDF/B-VII (labelled e71) and the IAEA MIX_3 fit. The data are compared to the corresponding data by Starostov in the EXFOR entry 40930006.

Batenkov

There is obviusly something wrong with the interpretation of the EXFOR entry 41502002 by Batenkov, as evident from Figure 12. At present, the data cannot be included in the fitting procedure.

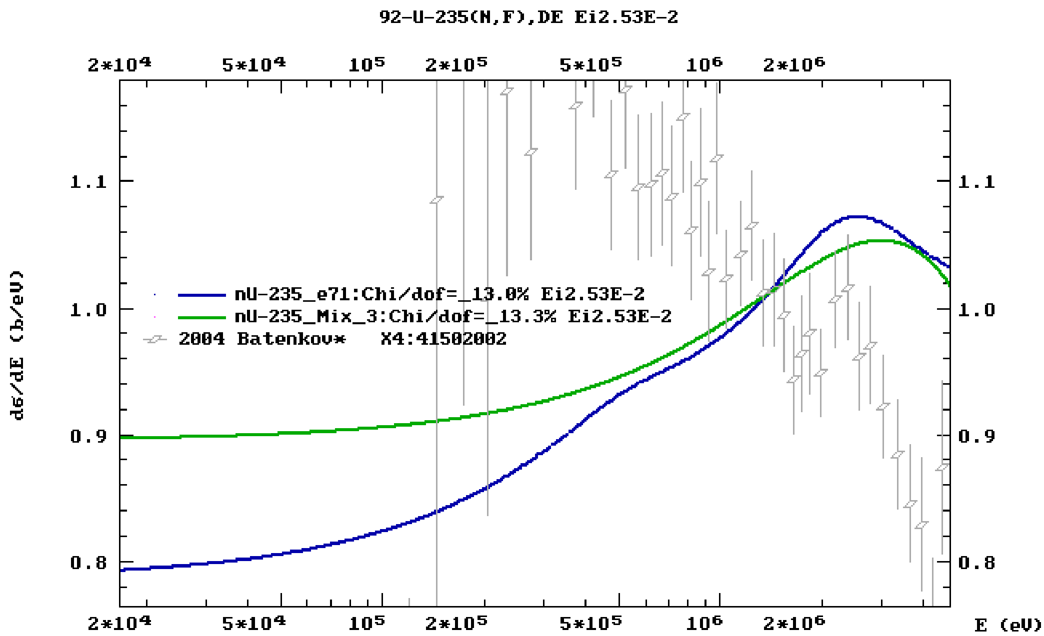

Figure 12: Comparison of the ^{235}U PFNS data by Batenkov to ENDF/B-VII (labelled e71) and the IAEA MIX_3 fit.

Kornilov

The EXFOR entry 31692006 by Kornilov is shown in Fig. 13. The data in EXFOR are given as ratio to ^{252}Cf.

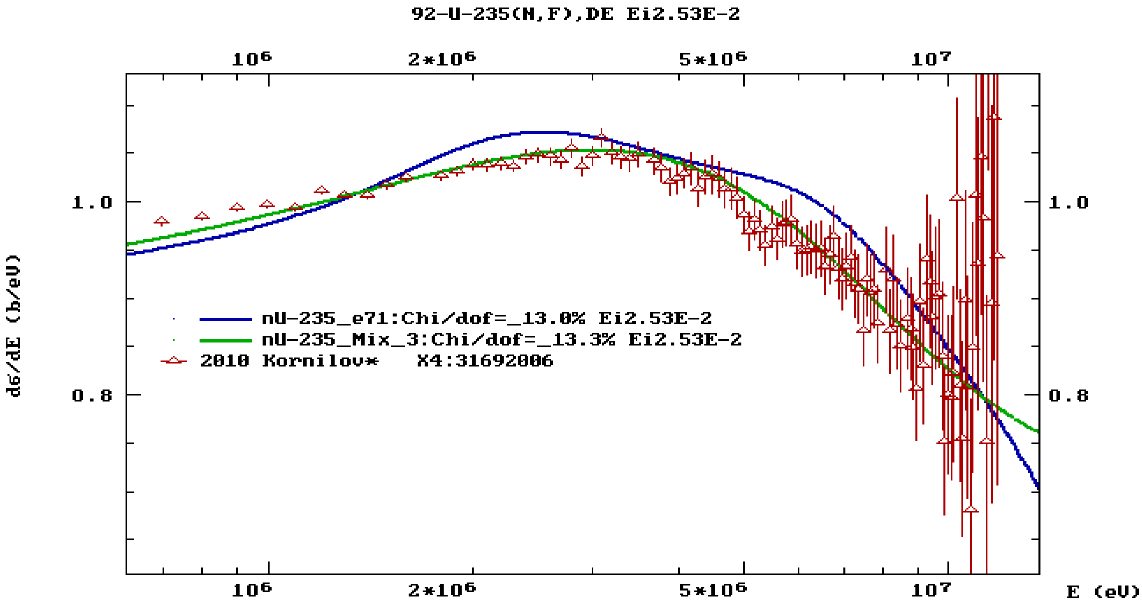

Figure 13: Comparison of the ^{235}U PFNS data by Kornilov to ENDF/B-VII (labelled e71) and the IAEA MIX_3 fit.

Vorobyev

The EXFOR entry 41597 includes subentries 2 and 3, which contain the spectrum and the ratio to ^{252}Cf, which are in perfect agreement with each other, assuming the ^{252}Cf spectrum evaluated by Mannhart and contained in the IRDFF-v1.04 library. There is also EXFOR entry 41516017 from a preliminary analysis, which differs very slightly and should be marked as superseded. The data are shown in Fig. 14.

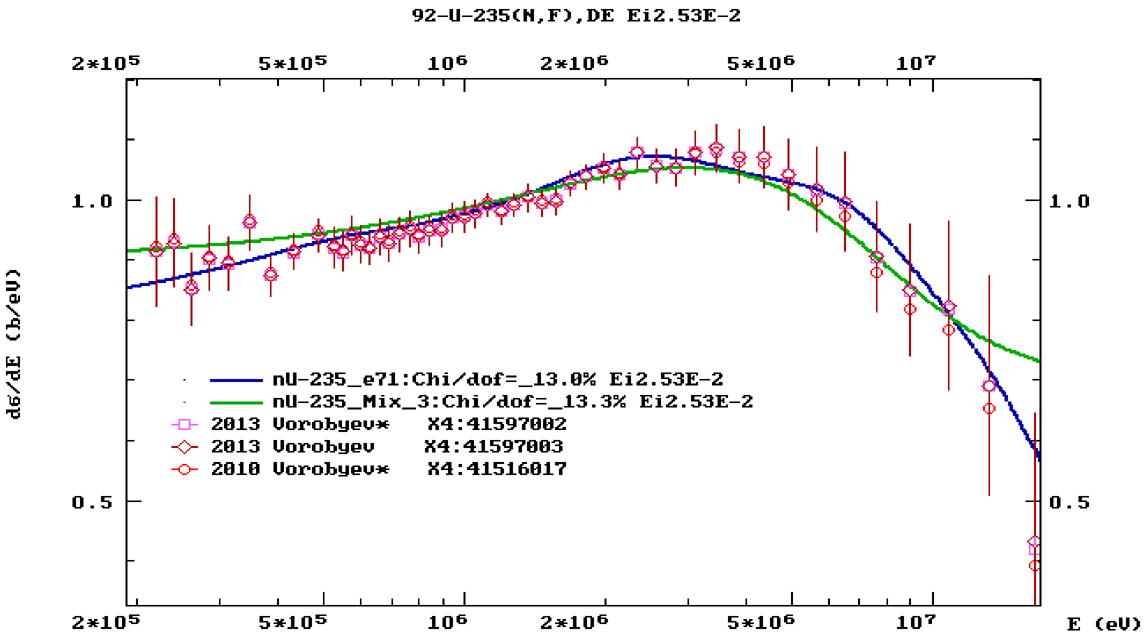

Figure 14: Comparison of the ^{235}U PFNS data by Vorobyev to ENDF/B-VII (labelled e71) and the IAEA MIX_3 fit.

Conclusions

The following data sets are recommended for fitting the shape of the thermal-neutron induced prompt-fission neutron spectrum of ^{235}U

Table 2: Selected EXFOR data sets

EXFOR No.	Year	Author	Comment
30704003	1985	A. Lajtai+	Below 0.2 MeV
31692006	2010	N. Kornilov+	
32587002	1989	Wang Yufeng+	Above 1.3 MeV
40871011	1983	V.N. Nefedov+	
40871012	1983	V.N. Nefedov+	
40872007	1983	B.I. Starostov+	
40873004	1983	A.A. Boytsov+	An alternative to #40930006 by Starostov (1985)
41597002	2013	A.S. Vorobyev+	