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^{238}U CAPTURE AND INELASTIC CROSS-SECTIONS

A report by the Working Party
on International Evaluation Co-operation
of the NEA Nuclear Science Committee

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FOREWORD

A Working Party on International Evaluation Co-operation was established under the sponsorship of the OECD/NEA Nuclear Science Committee (NSC) to promote the exchange of information on nuclear data evaluations, validation, and related topics. Its aim is also to provide a framework for co-operative activities between members of the major nuclear data evaluation projects. This includes the possible exchange of scientists in order to encourage co-operation. Requirements for experimental data resulting from this activity are compiled. The working party determines common criteria for evaluated nuclear data files with a view to assessing and improving the quality and completeness of evaluated data.

The parties to the project are: ENDF (United States), JEF/EFF (NEA Data Bank Member countries), and JENDL (Japan). Co-operation with evaluation projects of non-OECD countries, specifically the Russian BROND and Chinese CENDL projects, are organised through the Nuclear Data Section of the International Atomic Energy Agency (IAEA).

Subgroup 4 of the working party was initiated with the objective to solve discrepancies in the capture and inelastic scattering cross-sections of ^{238}U, which are of primary importance for fast reactor systems. The initial discrepancies in the ^{238}U capture cross-sections are first reviewed, followed by a combined evaluation and measurement effort on the inelastic scattering cross-section. The latter work was performed in close co-operation with the NEA Nuclear Science Committee Working Party on International Nuclear Data Measurement Activities (WPMA).

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SUMMARY

Subgroup 4, dealing with ^{238}U capture and inelastic cross-sections, was established as a means of resolving noted discrepancies between the versions of the major evaluated files – ENDF/B-VI, JEF-2, JENDL-3 – available at the time. The discrepancies depend mainly on available experiments and theoretical nuclear reaction models calculations. There was a consensus concerning the need to review the existing evaluations and possibly revise them by taking into account new experiments and improved model calculations.

A consensus regarding the ^{238}U capture cross-section was achieved fairly quickly without any major difficulties on the basis of studies for the revision of the major evaluated files. Once these studies were completed, a report was prepared for the International Conference on Nuclear Data for Science and Technology, held at Jülich in 1991*. In turn, the first part of this report is derived from the paper presented at the Jülich conference. After examining the results of studies conducted since 1991, it is reasonable to say that the conclusions reached by the Subgroup at that time also remain valid today.

The work involving ^{238}U inelastic cross-sections did not proceed as quickly as expected, as neither available experimental results nor model calculations gave any clear indications that lead to an immediate resolution of the discrepancies. Thanks to a close co-operation with the NEA Nuclear Science Committee Working Party on International Nuclear Data Measurement Activities (WPMA), new experiments could be launched, providing the necessary information to draw a certain number of conclusions so as to bring the work of the Subgroup to an end. The contributions of the WPMA subgroup have been extremely helpful in this regard.

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* Y. Kanda, *et al.*, "A Report on Evaluated ^{238}U (n,γ) Cross-Section", Proceedings of the International Conference on Nuclear Data for Science and Technology, S.M. Qaim, ed., Jülich (1991). The article is integrated into the present report with the express permission of the publisher.

^{238}U CAPTURE AND INELASTIC CROSS-SECTIONS

1. Evaluated $^{238}U(n,\gamma)$ cross-section

1.1 Introduction

The neutron capture cross-section of ^{238}U in unresolved resonance regions is an important quantity for reactor calculations. A long-standing difficulty in this regard, however, is that earlier evaluations had resulted in higher capture cross-sections than expected from reactor physics analysis. This was a common problem in three major evaluated data files – ENDF/B-V, JEF-1 and JENDL-2. The available differential measurements on which they were scattered by more than 15% depending on the neutron energy region. As shown in Figure 1 there were substantial discrepancies even in the careful experiments, e.g. Moxon [1] and de Saussure, *et al*. [2] which had been undertaken to solve the problem. Evaluators recommended mean values of experiments as the best cross-section values as there was to modify the experimental results. Nevertheless, the new versions of the major files, ENDF/B-VI, JEF-2 and JENDL-3 have now adopted smaller capture cross-sections in the unresolved region than the previous versions.

In Figure 1, as a typical example, JENDL-3 is shown in comparison with the experiments and the previous version (JENDL-2). As can been seen from this figure, JENDL-3 follows the lowest values of experimental data, while JENDL-2 follows the average values.

To have a full understanding of the smaller capture cross-sections adopted in the new major files, the subgroup on ^{238}U capture and inelastic scattering cross-sections was established by the NEACRP/NEANDC Working Group on International Evaluation Co-operation. The problems concerning the capture cross-sections have been intensively studied and resolved. The results are reported here. The project on the inelastic scattering cross-section is in progress.

1.2 Validity of the new versions of the three major files

1.2.1 The resolved resonance range

It is believed that measurements of the ^{238}U capture cross-sections made with white neutron sources (e.g. linacs) can be accurate. Normally these are normalised at very low energies using resonances where the neutron width Γ_n is much smaller than the capture width Γ_γ and the sample is "black" so that at the resonance peak the capture yield gives directly the normalisation constant. Therefore, the measurements with white neutron sources must be renormalised when it is found that incorrect values of Γ_n and Γ_γ were used in their original data procedures.

1.2.2 Sowerby, *et al.* [3,4] and Moxon, *et al.* [5,6]

The NEANDC Task Force on ^{238}U was set up to deal with two problems: the neutron widths of the resolve resonances above 1.4 keV and the capture cross-section in the resolved and unresolved resonance regions. In the task force, the new evaluation was carried out over the whole energy range below 10 keV using the shape analysis code REFIT [7]. This code can simultaneously analyse both capture and transmission data. The shape analysis is able to identify errors in background and normalisation in both the measurements. It should be noted that previous evaluations are mainly based on area analysis.

The normalisation of capture data is no longer necessary to consider only very low energy resonances as in principle the experiments can be normalised at any resonance where both Γ_n and Γ_γ are well known. The peak height in a capture measurement and its capture area can be derived from the resonance parameters obtained from transmission measurements. For resonances which are isolated and do not overlap with others the derived quantity is accurate and hence can be used to normalise the experiment. As a result of this ability, it was found that the capture cross-sections of de Saussure, *et al*. [2] were inconsistent with the parameters obtained from the transmission data and assumed values of Γ_γ (23~223.5 meV) unless the capture data were renormalised by a factor of ~0.9 near 1.8 keV neutron energy. This renormalisation is correct for a wide range of resonance neutron widths from $\Gamma_n << \Gamma_\gamma$ to $\Gamma_n >> \Gamma_\gamma$. The original normalisation is correct at the first resonance at 6.67 eV, where the measured data were normalised by the authors, but at higher resonance energies the capture yields calculated from transmission data increasingly deviate from the experimental values. The average capture cross-sections published by de Saussure, *et al*. [2] must be corrected by multiplying by the following correction factor *F*:

$$F = 0.845\ \exp\left(0.38421\sqrt{E}\right)$$

where E is in eV [8]. It is probable that this tendency will continue in the unresolved resonance region. This correction brings the data of de Saussure, *et al*. into good broad agreement with the data of Moxon [1,9] as seen in Figure 2. The reason for the above correction factor is uncertain. It is worth noting that the normalisation of the Moxon data [1] has also been checked by the same method and it was found that the normalisation was correct.

1.3 The unresolved resonance region

1.3.1 Evaluation by Fröhner [10-12]

The evaluation in the unresolved resonance region (~10 to 300 keV) is based on simultaneous fits with the FITACS code [13], which employs Hauser-Feshback theory with width fluctuation and the generalised (Bayesian) least squares technique, to a large body of total (five sets), inelastic scattering (four sets) and capture cross-section data (27 sets), and on rigorous (Bayesian) inclusion of prior knowledge from resolved resonances and from optical model fits at higher energies. Multiple scattering corrections applied to capture yield data produced lower capture cross-sections, consistent with the resolved resonance analysis.

Utilisation of theory permits simultaneous description of all the observations in terms of average resonance parameters. Since this theory relates averaged cross-sections for all reaction channels, a coherent evaluation of all information provides powerful physical constraints and reduces uncertainties.

1.3.2 Evaluation by Poenitz [14-16]

The evaluation of the ^{238}U capture cross-section was part of a simultaneous evaluation of ten cross-sections and later combination with an R-matrix analysis of additional data for five of these cross-sections [16]. For ^{238}U the average capture cross-sections in the resolved resonance region as well as data above the unresolved resonance range were used in addition to the cross-section for the unresolved region. The resulting evaluated cross-section lies on the lower side of the bulk of the available measurements and is accurate to ~ ±2-5% or better over most of the energy range between 10 keV and 500 keV (as shown in Figure 3).

1.4 Contents of three major libraries

1.4.1 ENDF/B-VI and JEF-2

These two files adopted the same evaluation in the resolved and unresolved resonance region [17]. For the resolved resonance region from 10^{-5} eV to 10 keV the evaluation by Moxon and Sowerby [3-6] was used. Fröhner's evaluation was adopted in the unresolved resonance region 10 to 149 keV [10,11]. The evaluation from 149 keV to 20 MeV is taken directly from the simultaneous standards evaluation [14,16].

1.4.2 JENDL-3

The resolved resonance region from 10^{-5} eV to 4 keV. For the unresolved resonance region, the measurement by Kazakov, *et al*. [18] was adopted because it was a recent experiment with good resolution and in addition it was consistent with reactor physics analysis. Although the ^{238}U capture cross-section was included in the original simultaneous evaluation for JENDL-3 performed by Kanda, *et al*. [19], the renormalisation of the average cross-section in the resolved resonance region could not be utilised since the simultaneous evaluation was made only on the basis of the data above 50 keV. The recent measurement of Quang and Knoll [20] also agrees with the new evaluations.

1.5 Impact on integral parameters

The lower capture cross-section of ^{238}U has been required from the reactor analysis. Hence it is interesting to know how the present change to lower values impacts on various integral characteristics of reactors. Some results of sensitivity analysis on JENDL-3 are presented here as an example. The sensitivity coefficients were calculated for the ZPPR-9 critical assembly, which is a clean homogeneous physical mock-up core of a large demonstration fast breeder reactor.

The sensitivity coefficients of ^{238}U capture cross-section in the energy range from 1 keV to 500 keV are particularly significant to k_{eff} and the reaction rate of ^{238}U capture to ^{239}Pu fission (or ^{235}U fission). The differences of ^{238}U capture cross-section from JENDL-2 to JENDL-3 cause an increase in k_{eff} by 0.4% and a decrease of the ^{238}U capture to ^{239}Pu fission rate ratio by 1.3%. Contributions from the other energy regions are negligible.

1.6 Conclusions

The subgroup has studied the reason why the recent evaluated data of the ^{238}U capture cross-section are lower than the average of the available measured data. Sowerby and Moxon found in their shape analysis of resolved resonances that some of the measured capture data should be renormalised. After the renormalisation, the measured data converge to the lower values, with which the recent evaluated data agree. The lower values could be reproduced with fitting the theoretical model to available experiments by Fröhner. From the multiple scattering effect it is understood why many of the old capture data sets were too high: this confirms and explains Poenitz's renormalisation based on the resolved-resonance analysis. Furthermore, the lower capture cross-section of ^{238}U has significant influence on the integral parameters of fast reactors, whose direction has been predicted by reactor physicists. Thus the subgroup concludes that the capture cross-section of ^{238}U in the unresolved resonance region, which was adopted in three of the recent major files, i.e. ENDF/B-VI, JEF-2 and JENDL-3, are reasonable and the earlier evaluation should be superseded.

2. Inelastic scattering cross-section

In this second section of the report, the progress in the experiments and evaluations for ^{238}U inelastic scattering cross-sections conducted within the WPEC Subgroup 4 (SG4) and the ^{238}U(n,n′) subgroup of the WPMA are summarised. Several new experiments were conducted after the subgroups were established. Newly obtained data greatly contributed to the reduction of uncertainties in experimental data, and provided a refined database for new evaluations. Evaluations undertaken with improved models and parameters derived from the new experimental data consistently described the experimental data. It is now concluded that the problems which were the basis for creating SG4 have been eliminated.

2.1 Introduction

SG4 was set up in 1989 with the aim to update the data on ^{238}U inelastic scattering and capture cross-sections. Neutron inelastic scattering provides a major neutron moderation mechanism in fast reactors and dominates neutron energy spectra in the reactors. Therefore, neutron inelastic scattering has great effects on important reactor physics parameters, i.e. criticality k_{eff}, reaction rates, sample worth, Doppler coefficients, void worth and so on. In particular, the inelastic scattering cross-section of ^{238}U is of prime importance in the design of fast and accelerator-based reactors.

There were, however, marked differences among evaluated data files in inelastic scattering cross-section and energy spectra of inelastic neutrons. Furthermore, experimental database was very poor, as is indicated by large differences among experiments and scarcity of experimental data for some reaction channels, i.e. higher levels and continuum levels. Such a situation was mainly attributed to difficulties in theoretical calculations and experiments for inelastic scattering due to complex nuclear structure and very narrow level spacing, respectively, as shown in Figure 4.

The status and progress in the experiment and evaluation until 1994 were discussed in Inter-Laboratory Collaboration (ILC) meeting held during the Gatlinburg Nuclear Data Conference [21], and thereafter regularly at WPEC/WPMA meetings. Discussions at the meetings contributed to information exchange and helped clear up various problems. Accordingly, several new experiments were conducted to obtain new data, and evaluations were also undertaken with updated models and parameters. Owing to these activities, experimental data with much reduced uncertainty became available for updated evaluation, and the newest version of the evaluated data seems to be satisfactory, though several problems still remain to be solved in the near future.

This report summarises the progress and the present status of the cross-section data of ^{238}U neutron inelastic scattering. In the following, the latest version of three major files (ENDF/B-VI, JEF-2.2, JENDL-3.2) and Maslov's new evaluation are discussed in comparison with experimental data. The data of JEF-2.2, however, are essentially equivalent with JENDL-3.1 for the inelastic scattering of ^{238}U, except for the region below ≈350 keV, and thus are not presented explicitly.

2.2 Scope of SG4

First, the scope and the goal of the SG4 are discussed. In the discussion of inelastic scattering cross-section, total inelastic cross-sections are frequently argued with first priority. It should be emphasised, however, that reactor physics parameters are affected not only by the inelastic cross-section but also, to an even greater extent, by the energy distribution of inelastic neutrons as indicated by the example below. Therefore, the energy spectrum should be considered as well as the inelastic cross-section.

2.2.1 Importance of energy distribution of inelastic neutrons

The effect of the inelastic scattering cross-section and neutron spectrum or slowing down matrix in the reactor physics parameters was discussed by

Kikuchi [22]. He reported calculated k_{eff} in ZPPR-9 for the combinations of the inelastic scattering cross-section σ_{in} and the slowing down matrix M(E,E′) as presented in Table 1.

As shown in Figure 5, inelastic scattering cross-section is very different between JENDL-2 and JENDL-3(.1), but the calculated k_{eff} in Table 1 is very close. On the other hand, the calculation with different slowing down matrices (Case 0 vs. Case 2, Case 1 vs. Case 3) resulted in marked differences. The results indicate that the reactor physics parameters are very largely affected by the slowing down matrix M(E,E′), in addition to the inelastic scattering cross-section itself. Therefore, for the inelastic scattering cross-section, the energy spectrum of emitted neutrons should be treated accurately, as should the total inelastic scattering cross-sections. Besides, it should be noted that experimental total inelastic scattering cross-sections have uncertainties associated with the yield extrapolation to zero energy, subtraction of fission neutrons and the cross-section estimation of low-lying levels included in the elastic peak in the experiment. Therefore, data comparison should be made in the form of neutron emission spectrum or energy differential cross-section rather than total inelastic scattering cross-section.

2.2.2 Status of the data

The required data accuracy is defined in terms of the uncertainty in the reactor physics parameters introduced by the data error. According to the 1998 High Priority Request List of the NEA/NSC, the requirement for the ^{238}U inelastic cross-section is ±5%.

The evaluated total inelastic scattering cross-section of ^{238}U is shown in Figure 5, along with experimental data. As seen in the figure, the values by JENDL-3.2, -3.1 and ENDF/B-VI are in agreement within 10% except for larger discrepancies in the region from 5-6 MeV. Therefore, as long as the total inelastic scattering cross-section is concerned, the requirement is almost satisfied. There are, however, very large differences in neutron spectrum between the evaluations as shown in Figure 6 [23]. These differences may introduce serious problems in reactor calculations, as noted above. The differences between JENDL-3.1 and ENDF/B-VI proved to be due to the continuum spectrum. Such a difference still exists between JENDL-3.2 and ENDF/B-VI, as shown in Figure 7.

Due to improvements in models, theoretical calculation can obtain ^{238}U inelastic cross-sections using coupled channel and statistical models which consider coupling between ground state rotational bands and vibrational bands.

The calculations, however, still require the help of experimental data to determine model parameters that can not be determined *a priori* with sufficient accuracy.

On the other hand, measurement of inelastic scattering cross-section to each level with the TOF method is also difficult and uncertain because of very narrow level spacing. Systematic experimental data for each level were, therefore, restricted to those of the University of Lowell [24], and were exclusively referred to in the evaluation. However, the experimental error for each level was not small. Measurement by γ-ray detection is also uncertain because of ambiguities in γ-ray branching ratio and decay scheme, and of very high internal conversion coefficients. The experiment by γ-ray detection resulted in very large overestimation of inelastic scattering cross-sections as shown in Figure 6.

For reactor calculations, on the other hand, data for each level are not required, but the slowing down matrix is problematic. Therefore, practical solutions for data improvement include using medium resolution experimental data (Figure 6) as well as high resolution data.

2.2.3 Goal of SG4

From the above arguments, it should be understood that an accurate "energy differential inelastic cross-section" is the goal of the present work. The neutron spectrum of ^{238}U shows a characteristic shape as shown in Figure 6. Therefore, for detailed and quantitative data comparison, it is reasonable to categorise the inelastic cross-section of ^{238}U into the following four groups:

1) Ground states rotational band (Ex = 45, 148 keV, 307 keV, etc.).

2) Vibrational levels between Ex = 680 and 827 keV.

3) Vibrational levels between Ex = 929 and 1 160 keV.

4) Higher discrete levels and the continuum due to evaporation process.

Process 1) provides a major moderating mechanism for a fast reactor and is a key quantity in theoretical calculation of inelastic scattering cross-sections. A fair amount of data was reported for the first level, but the scatter among the data is as large as 30-40%, in particular around 300-500 keV. Therefore, new data will be desirable to define the error band of the cross-section.

The contribution of 2)-4) increases with incident energy. As shown in Figure 6, processes 2) and 3) form apparent structures in the neutron emission spectrum, and the contribution of higher or continuum levels becomes dominant above ~3.5 MeV incident energy. These processes provide larger moderation of neutrons and stronger effects to the reactor physics parameters than low-lying states. In that sense, even for fast reactors, the inelastic scattering to 2)-4), and the shape of “evaporation spectrum” should be evaluated properly.

Additionally, it should be noted that fission neutrons pose a difficulty with regard to deriving the data for 2)-4) because inelastically scattered neutrons lie on the fission neutron “background” and are indistinguishable from the latter in the conventional neutron scattering experiment. The contribution of fission neutrons becomes larger with increasing incident neutron energy. Fortunately, ENDF/B-VI, JENDL-3 and experimental data are presently in agreement [23,25], but should be checked in more detail in the future. Therefore, in comparison with experimental data, it is better to compare the sum spectrum of the inelastic neutrons and fission neutrons.

For the reasons mentioned above, the experimental neutron spectrum were requested between 2-4 MeV where there were practically no experimental data according to [23].

2.3 New measurements

In Table 2, experimental data reported after SG4 was established (1989) are summarised with the method and quantities obtained. Supplemental comments are given below.

- Three sets of experimental data for the first level [26,27,28] are in fair agreement except for a few data points (Figures 8 and 9), and provided a firm experimental database for data evaluation with a much-reduced error band. These data cover energy points from threshold to 800 keV. The data at the highest energy levels are consistent with those of Lowell University [29]. Therefore, the combination of the three data sets mentioned above and those of Lowell University provides a consistent data set-up to around 3 MeV. These data are also useful to confirm the model parameters, i.e. optical model potential, deformation parameters, etc., which are basic parameters for theoretical calculation of ^{238}U cross-sections.

- The neutron emission data [23,30-33] provided neutron spectrum inclusive of both inelastic neutrons and fission neutrons. The experiments provided information on the gross structure of inelastically scattered neutron spectrum, and were used to derive cross-section values for vibrational states that were very uncertain and coupling parameters between the vibrational states and the ground state rotational band.

Data are given as the emission spectrum in [23,31,34] (Figure 10) or differential neutron yields per appropriate energy interval around 0.5 MeV [33] (Figures 11-13). Partial cross-sections were also derived for major structures, i.e. ground state rotational group, vibrational group around 700 and 1 200 keV excitation energy (Figures 12,13). They were used to adjust the evaluated data and to derive information from the coupling parameters. It is important to note that there are overlapping energy regions between experiments, and in those regions experimental data by each author show fair agreement.

- The experimental data by Smith and Chiba [35] provided extensive angular distribution data for elastic scattering and some inelastic neutrons of the ground state rotational band, and a comprehensive database to derive optical model potentials for data evaluation. The data are used to tune the parameters in the data evaluations and for development of the soft-rotator model mentioned below [36,37,38], though they did not provide direct information concerning the inelastic cross-section itself.

2.4 New evaluation

Since 1989, new evaluations were undertaken by T. Kawano, M. Fujikawa and Y. Kanda [39] for JENDl-3.2 and by Maslov [37], taking into account new experimental data and progress in modelling.

In the former evaluation, a coupled channel model was used for calculation of direct reaction cross-sections for vibrational levels as well as for ground state rotational band. A band coupling strength was chosen referring to experimental inelastic and neutron emission data. Data comparison with experimental DDX data is shown in Figure 10. Data improvement in JENDL-3.3 is currently in progress; problems in the continuum neutron spectra [40] are being eliminated, as is a slight disagreement with experimental DDX data.

In the latter evaluation, a statistical model and a coupled channel were employed. In the coupled channel model, a soft-rotator model is adopted for vibration band while a rigid-rotator scheme is adopted for the ground state rotational band [36,37]. A double-humped fission barrier model is employed for fission cross-section calculations. The evaluation was further revised [41] taking into account the new experimental data at Geel [33]. The former evaluation is shown in Figures 12 and 14 as MPHS98, and the new evaluation in Figures 13 and 15.

In Figure 16, the new evaluation [41] is compared with experimental neutron emission data. Very good overall agreement is confirmed.

In this evaluation, the cross-section of (n,γn′) process was explicitly estimated. The estimated cross-section is as high as ≈60 mb at most (around En = 3.5 MeV). This process may significantly affect the reactor physics parameters if the cross-section is sizeable because very low energy neutrons are emitted in this process [42,43]. Up to now, however, there has been no experimental confirmation of the (n,γn′) process, and it remains an open question to be solved in the future.

2.5 Status of the evaluated files

From the above argument, the data comparison is made for the following quantities to assess the quality of the evaluated file:

- Total inelastic scattering cross-section.
- Cross-section of the first and second levels.
- Vibrational levels between Ex = 680 and 827 keV.
- Vibrational levels between Ex = 929 and 1 160 keV.
- Neutron emission spectra inclusive of fission neutrons.

From the comparison among experiments and ENDF/B-VI, JENDL-3.2 and Maslov's evaluation in Figures 5-11, the following observations can be pointed out:

- As noted above, there is no large difference among evaluated data and experiments in the total inelastic scattering cross-sections, although ENDF/B-VI seems too high around the range 5-6 MeV. Therefore, the problem is in the partial inelastic cross-section and neutron emission spectra.
- The three new experimental data sets for the first level [26-28] are consistent with each other and also with the three evaluations except for a few data points (Figures 8, 9, 10). The data at the highest energy levels seem to be consistent with those of Lowell University [29] in the higher energy region. These experimental data support the three evaluations, although not in so definitive a manner as to recommend the

best one. For second and third levels, large scatter exists among the experimental data and there was no progress in experimental data during this period. However, the cross-section is not large compared with the first level, and this problem may be set aside for the future.

- For this level group, the three recent experiments [23,30,33] are consistent with one another. JENDL-3.2 and ENDF/B-VI are both in fair agreement with the experiments above 2.5 MeV, but seem too large in the lower energy region. In particular, the values of ENDF/B-VI are about two times as large as the experiment around 2 MeV. On the other hand, as shown in Figure 13, Maslov's evaluation reproduces the experimental data consistently while it gives slightly lower values than the data of Shao, *et al*. below 2 MeV.

- Experimental neutron spectrum data (Figure 10) and energy differential data (Figure 14) indicate that ENDF/B-VI and JENDL-3.2 overemphasise the values for the level group. In particular, the ENDF/B-VI values are too large throughout the energy region above ≈1.5 MeV, and the discrepancy becomes larger in the higher incident energy. Maslov's evaluation (Figure 14) took these new data into account, resulting in better agreement.

- For higher levels and continuum neutrons, JENDL-3.2 and Maslov's evaluation are in good agreement with experimental neutron emission spectra down to hundreds of keV, while JENDL-3.2 is markedly lower than the experiment in the 8-12 MeV region in 14 MeV data.

In summary, due to new experimental data and evaluations conducted under SG4, the data status of ^{238}U inelastic scattering cross-section has been markedly improved. At present, Maslov's evaluation [41], which took new experimental data into account, provides the best reproduction of experimental data. JENDL-3.2 also gives good reproduction except for slight disagreement. The refinement of JENDL-3.2 is now in progress. The JEF 2.2 data have the same problems as those pointed out for JENDL-3.1 [23], as the data are equivalent.

It should be pointed out that new evaluations by Maslov, *et al*. and Kawano, *et al*. are ongoing on the basis of recent experimental data and updated reaction models. The latter will appear in the near future as JENDL-3.3. These evaluations are expected to achieve better reproductions of recent experimental data in a more consistent manner. It is highly recommended to perform benchmark analyses of suitable reactor physics experiments. These analyses will indicate the predictability of the newest versions of evaluations and the influence of remaining problems.

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TABLES

Table 1. Effect of the inelastic-scattering cross-section and slowing down matrix of ^{238}U on k_{eff} and reaction ratios for ZPPR-9 [22]

	Case 0	Case 1	Case 2	Case 3
k_{eff}	0.9991	0.9995	1.015	0.9807

1) Case 0: σ_{in} of JENDL-2, M(E,E′) of JENDL-2.
2) Case 1: σ_{in} of JENDL-3, M(E,E′) of JENDL-3.
3) Case 2: σ_{in} of JENDL-2, M(E,E′) of JENDL-3.
4) Case 3: σ_{in} of JENDL-3, M(E,E′) of JENDL-2.

Table 2. New experiments on ^{238}U(n,n′) after 1989

Author	Year	Quantity	E_{in} (MeV)	θ	Ref.
Baba +	1990 1991	Neutron Emission	1.2, 2.0, 4.2, 6.1, 14.1, 18.0	30-150° (2-7)	[23] [34]
Moxon +	1994	(n,n_1)	0.68, 0.126, 0.182, 0.213	90°[2]	[26]
Kornilov & Kagalenko	1995	Neutron Emission	1.17, 1.79, 2.19	120°	[30]
Kornilov & Kagalenko	1996	(n,n_1)	0.313, 0.387, 0.474, 0.578	120°[3]	[27]
Smith & Chiba	1996	(n,n_{GSRB})[1] angular distribution	4.5-10 (≈0.5 step)	17-160° (>40)	[35]
Miura & Baba	1998	(n,n_1) & (n,n_0)	0.34, 0.40, 0.465, 0.55, 0.70, 0.855	125°[4]	[28]
Goddio +	1999	Neutron Emission	2.0, 2.5, 3.0, 3.5	35, 55, 125°	[33]
Miura & Baba	1999	Neutron Emission	2.6, 3.6, 11.8	30-145° (6)	[31]

1 Elastic and inelastic to the ground state rotational band (GSRB) member.
2 Angle-integrated by Hauser-Feshbach calculation.
3 Angle-integrated using-the angular distribution of ENDF/B-VI.
4 Angle-integrated using the angular distribution of JENDL-3.2.

The results agree with that using ENDF/B-VI distribution within 5%.

\+ Data analysis is in progress for the experiment at LANSCE/WNR using a γ-ray detector array GEANIE as reported by R.C. Haight at WPEC meeting in 1998.

FIGURES

Figure 1. Comparison of evaluated data with experiments for ^{238}U capture cross-sections in unresolved resonance region. JENDL-3 and JENDL-2 are shown as the typical examples of a new version and previous one of the major files, respectively. There are also typical experiments in available ones.

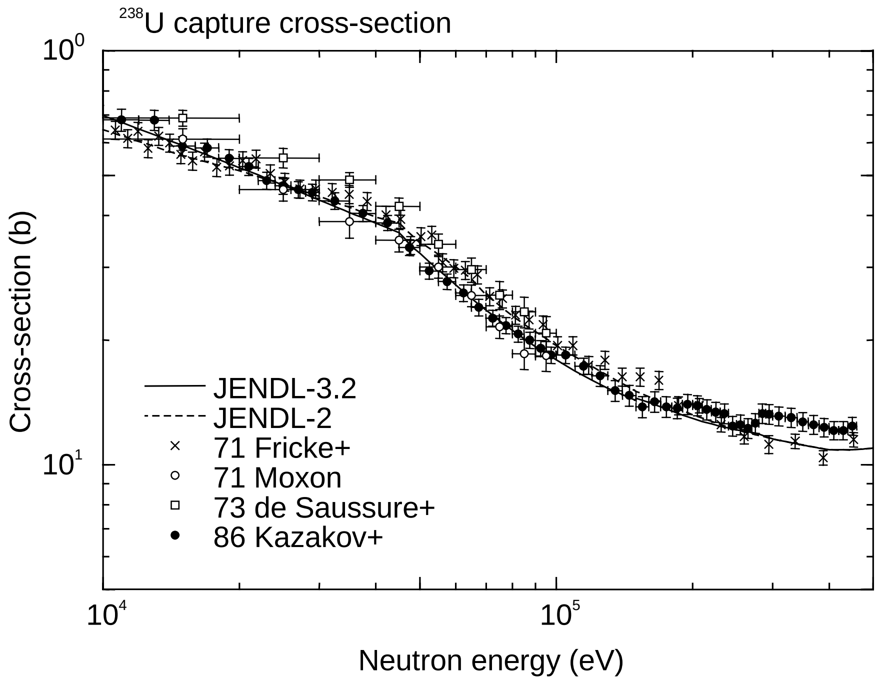


Figure 2. Comparison of ratios of the original de Saussure, *et al*. data [2] **and the de Saussure, *et al*. ones renormalised by Moxon** [9] **to the Moxon measurement** [1]

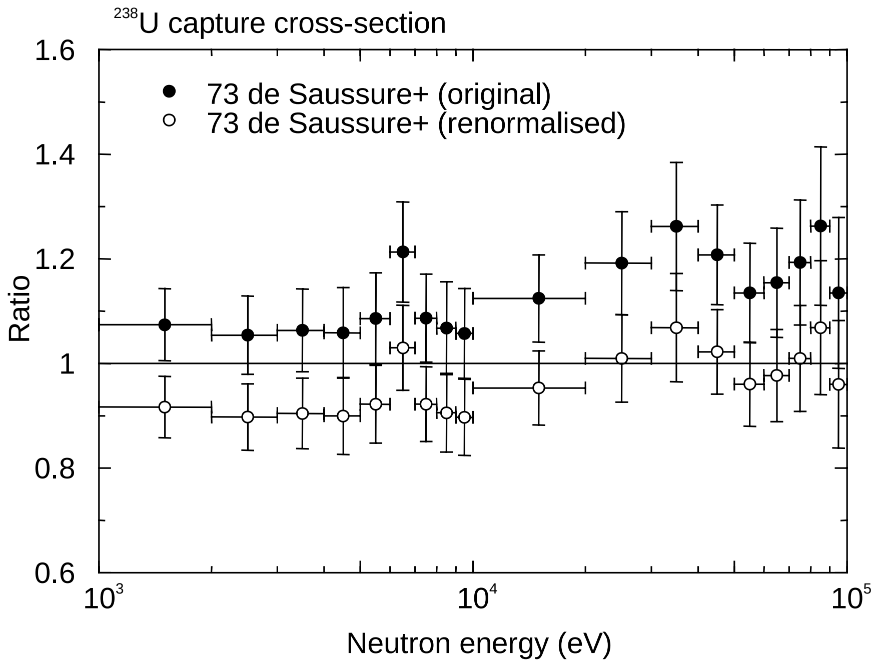


Figure 3. Comparison of the new versions of the major files with the experiments of Moxon renormalised by de Saussure, *et al*. and Kazakov, *et al.*

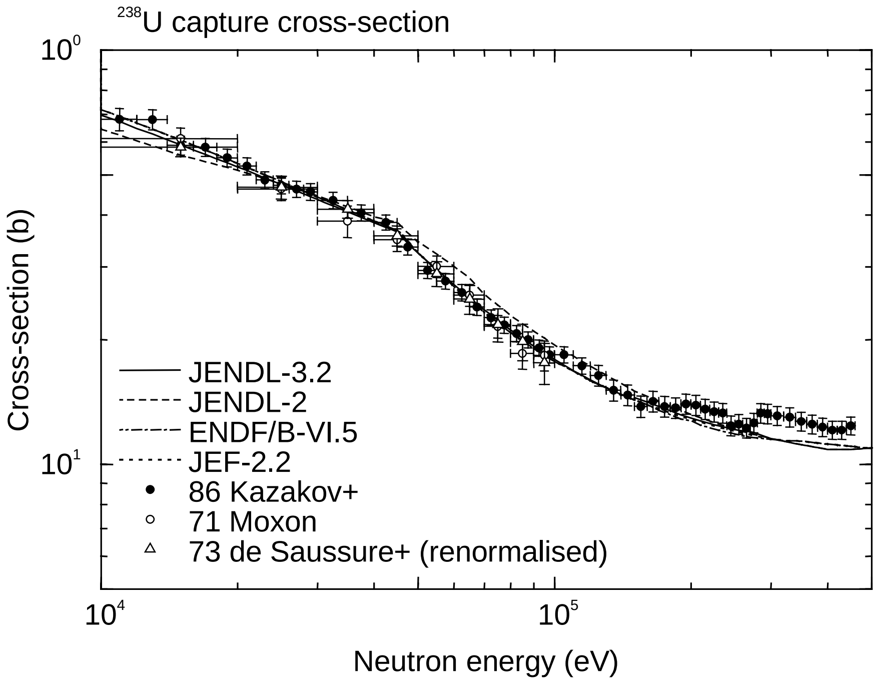


Figure 4. Level scheme of ^{238}U [44]

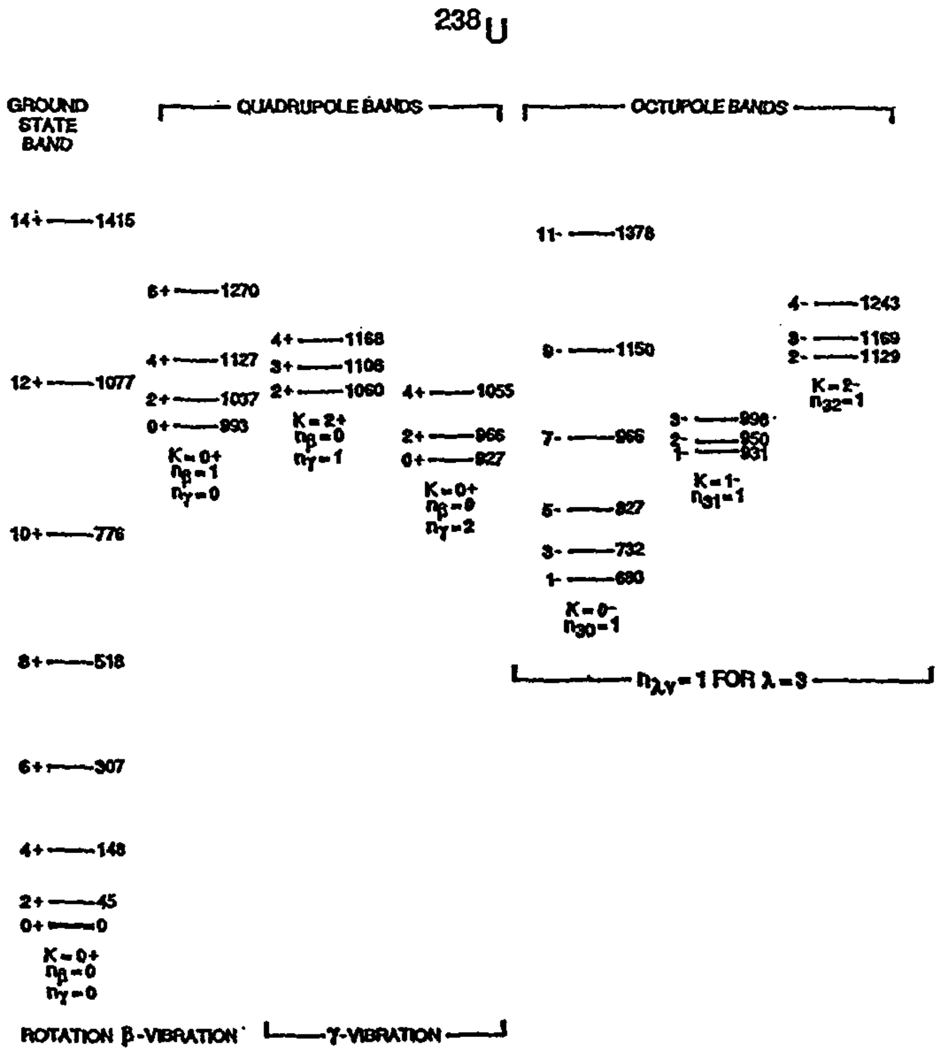


Figure 5. Total inelastic scattering cross-section [45]

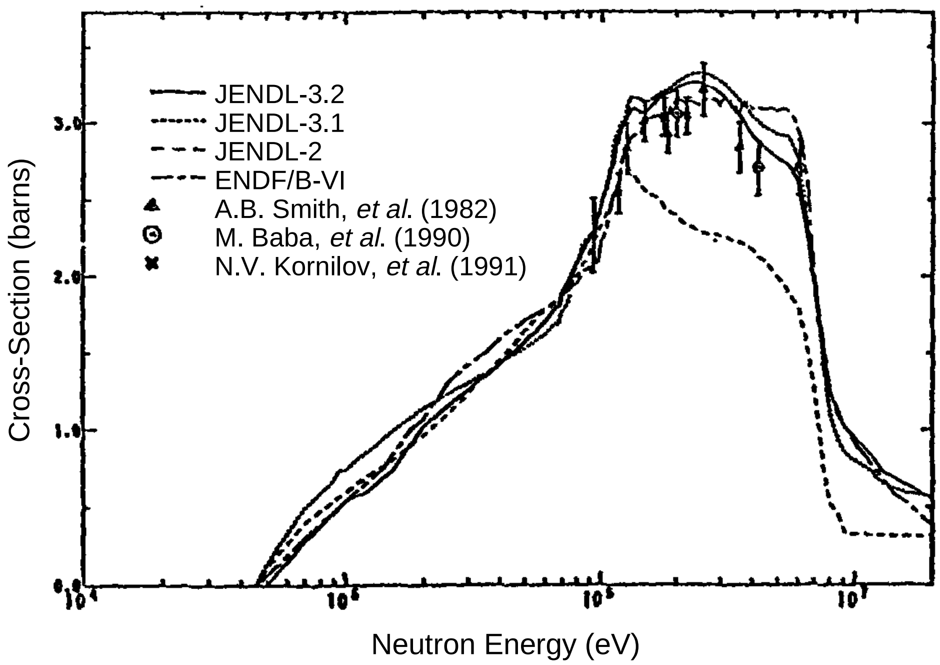
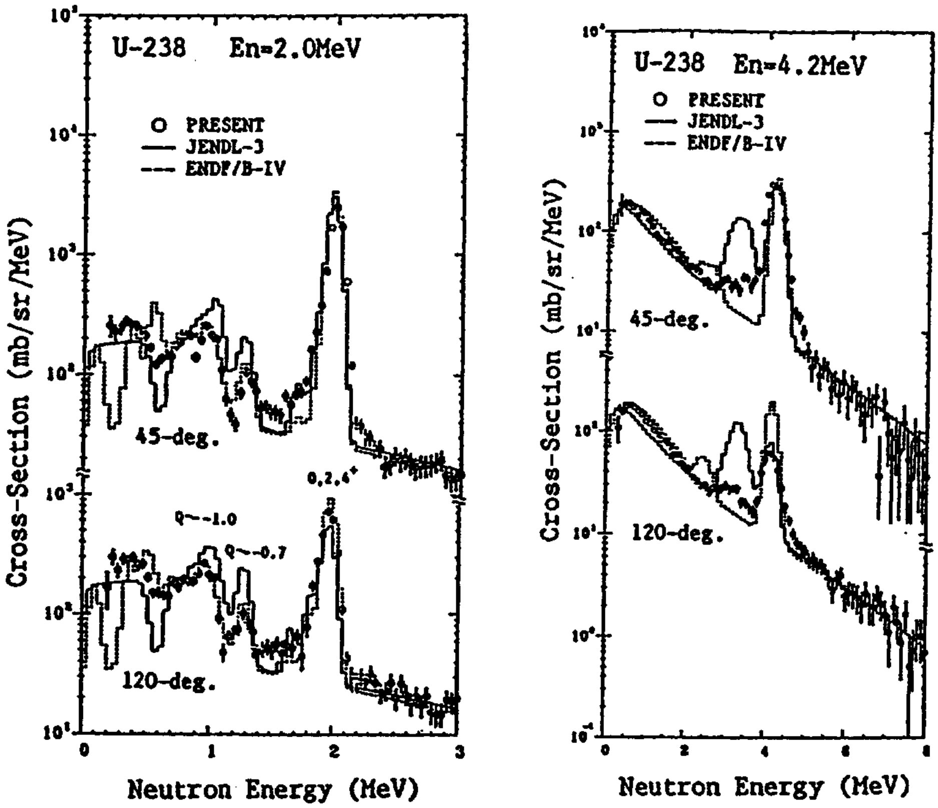


Figure 6. Comparison of experimental neutron spectrum data with the evaluation [23]

"JENDL-3"corresponds to JENDL-3.1 data



(b) 2.0 MeV (c) 4.2 MeV

Figure 7. Comparison of continuum neutron spectrum

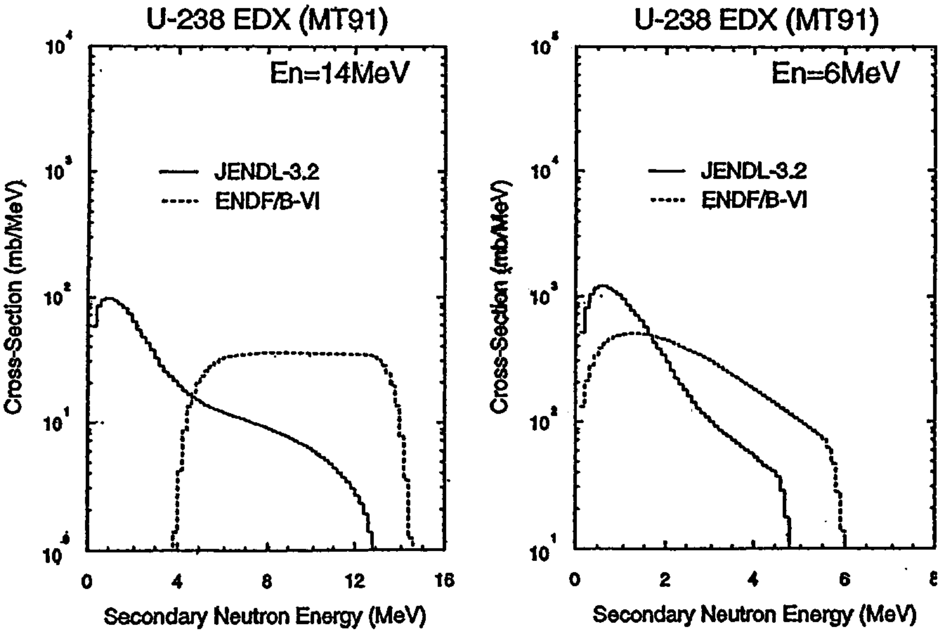


Figure 8. Experimental data of the ^{238}U(n,n′) to the first level [26]

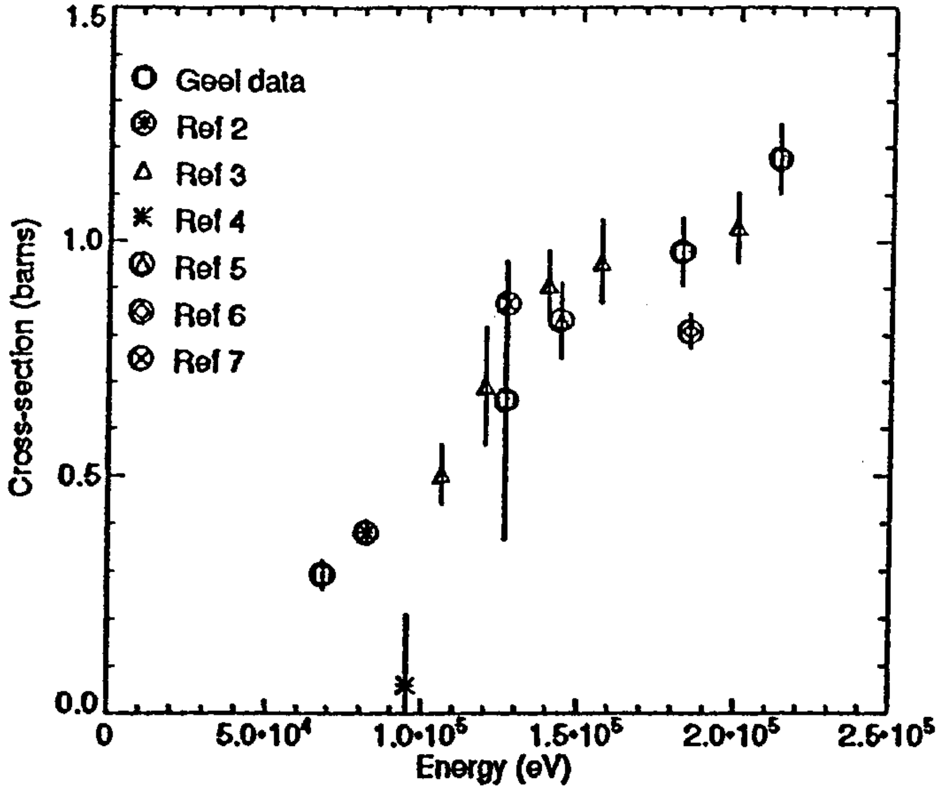


Figure 9. ^{238}**U(n,n′) cross-section to the first level** [28]

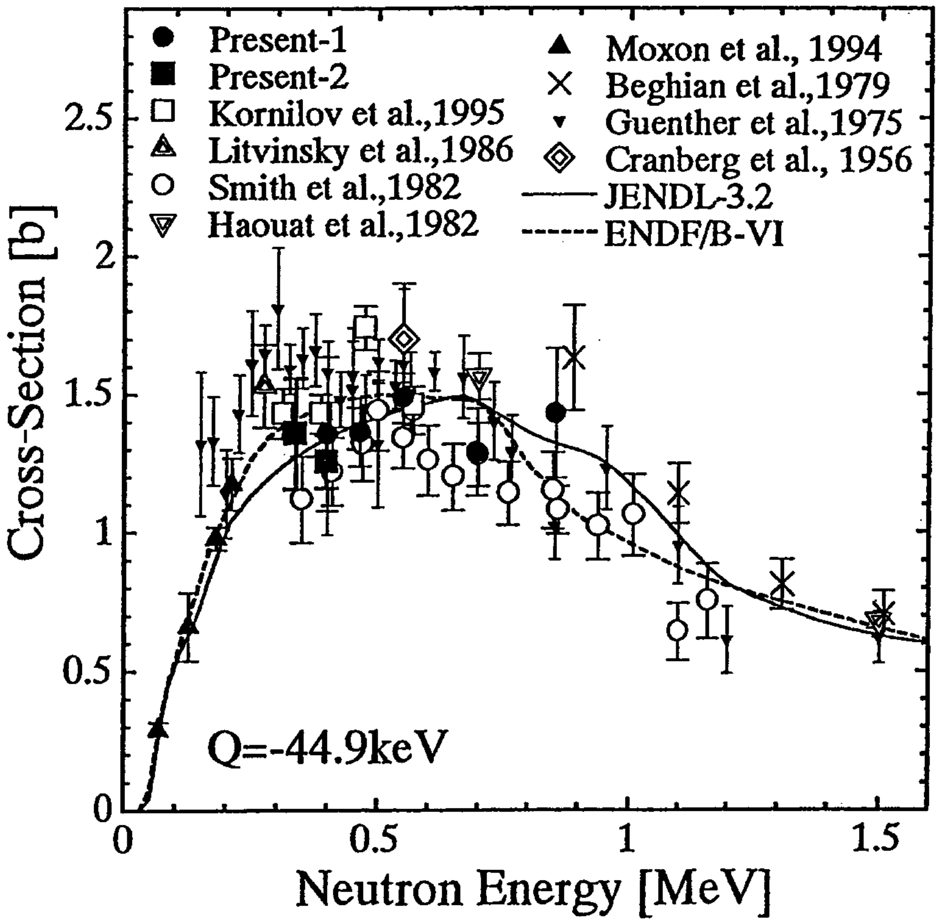


Figure 10. Comparison of neutron emission spectra [23,31]

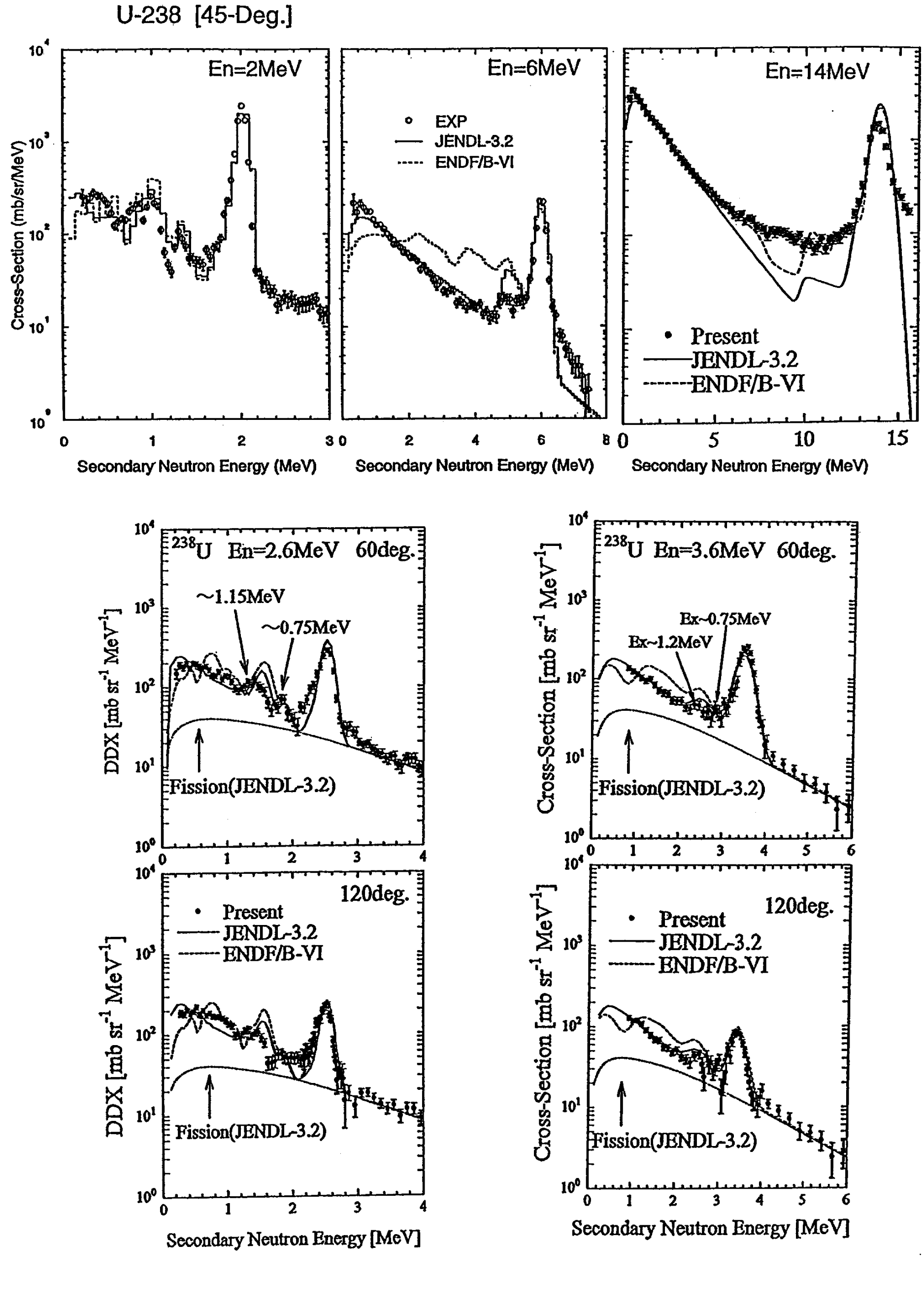


Figure 11. Neutron emission spectrum data for 3.5 MeV incident neutrons [33]

The solid line shows Monte Carlo calculation using the ENDF/B-VI data

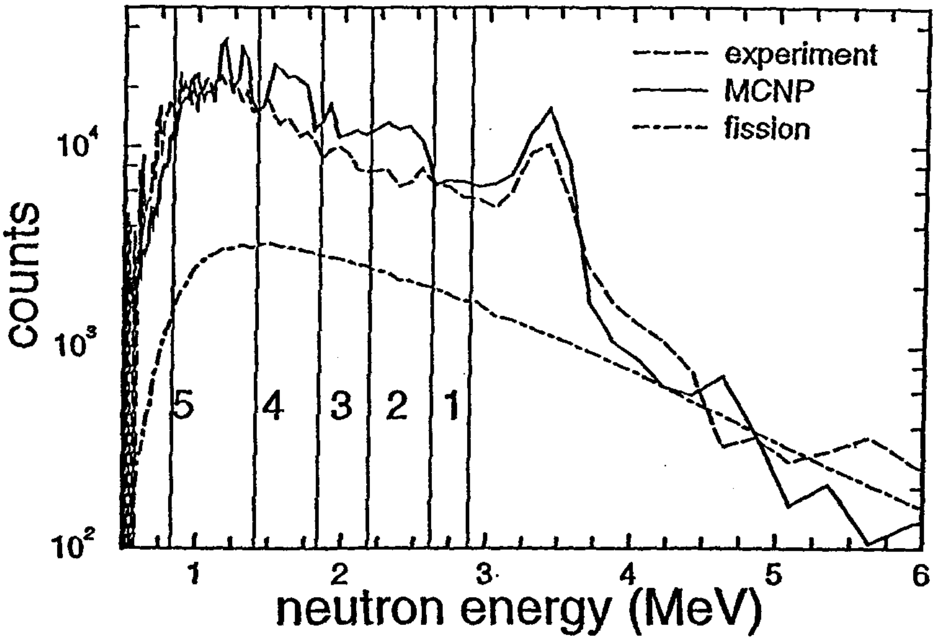


Figure 12. Partial inelastic cross-section for Group 1 region in Figure 11 [33]

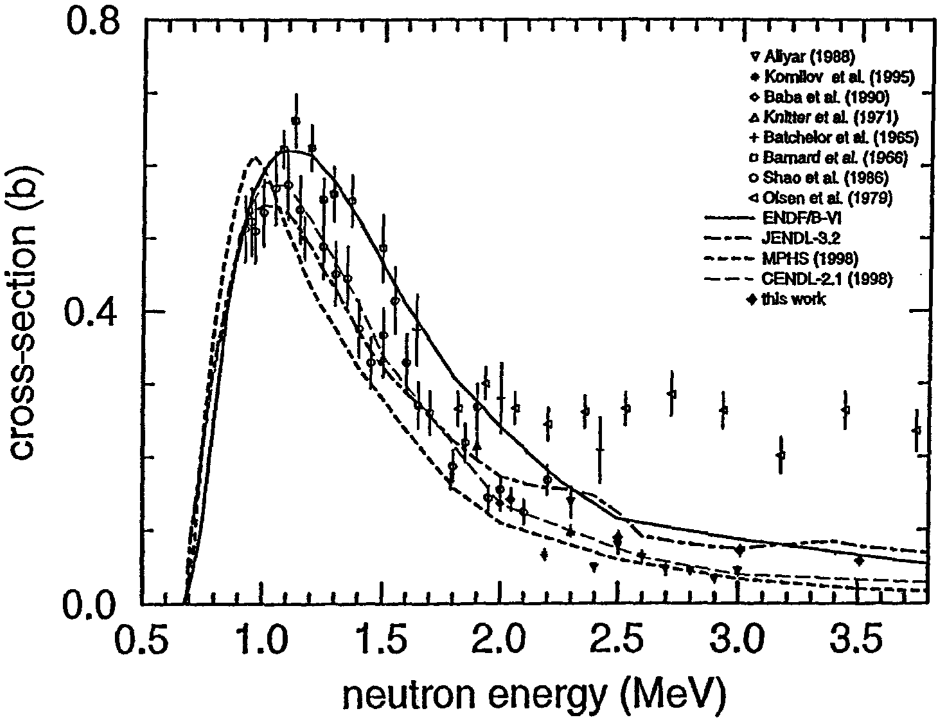


Figure 13. Same as Figure 12, but experimental data are compared with Maslov's new evaluation [41]

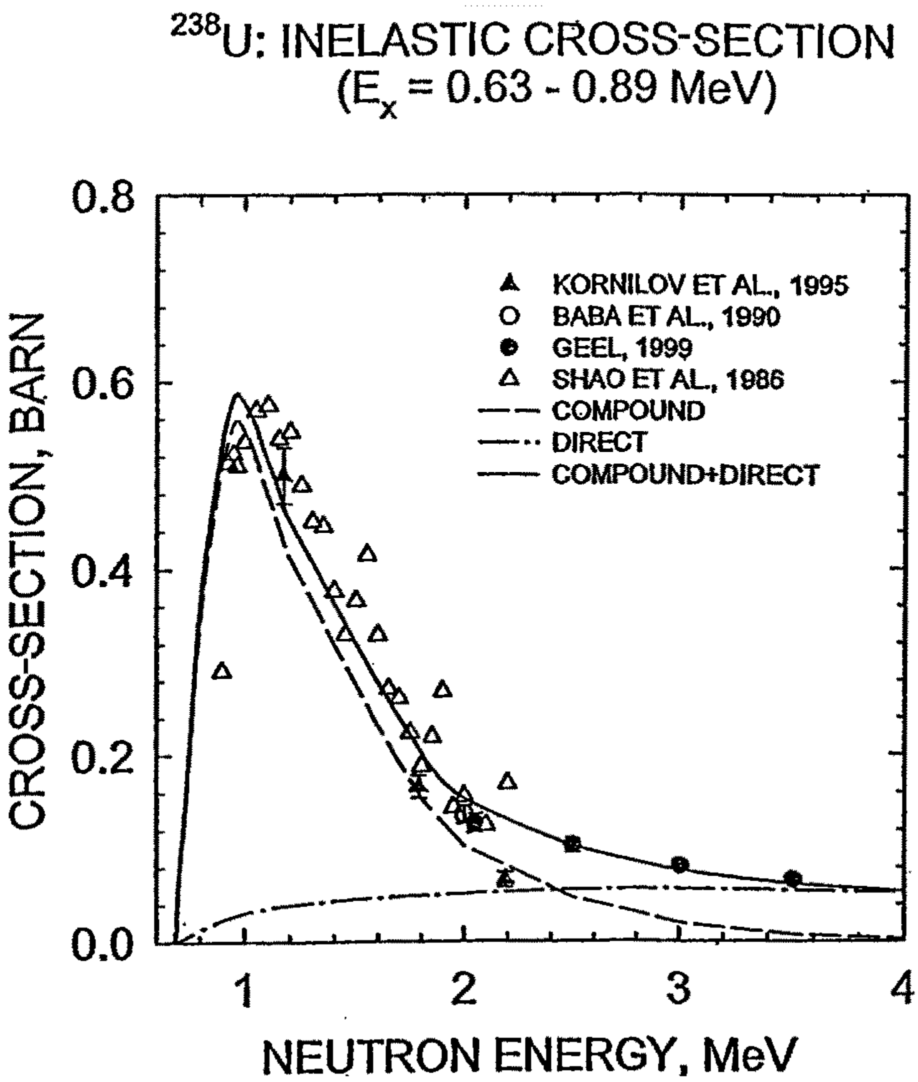


Figure 14. Partial inelastic cross-section for Group 2 region in Figure 11 [33]

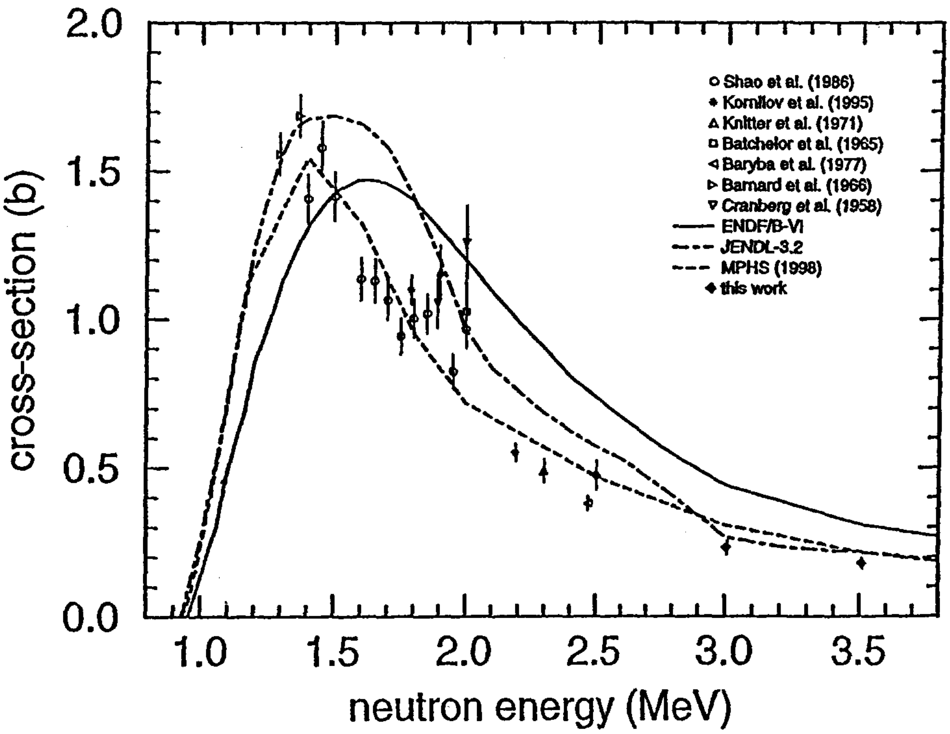


Figure 15. Same as Figure 14, but experimental data are compared with Maslov's new evaluation [41]

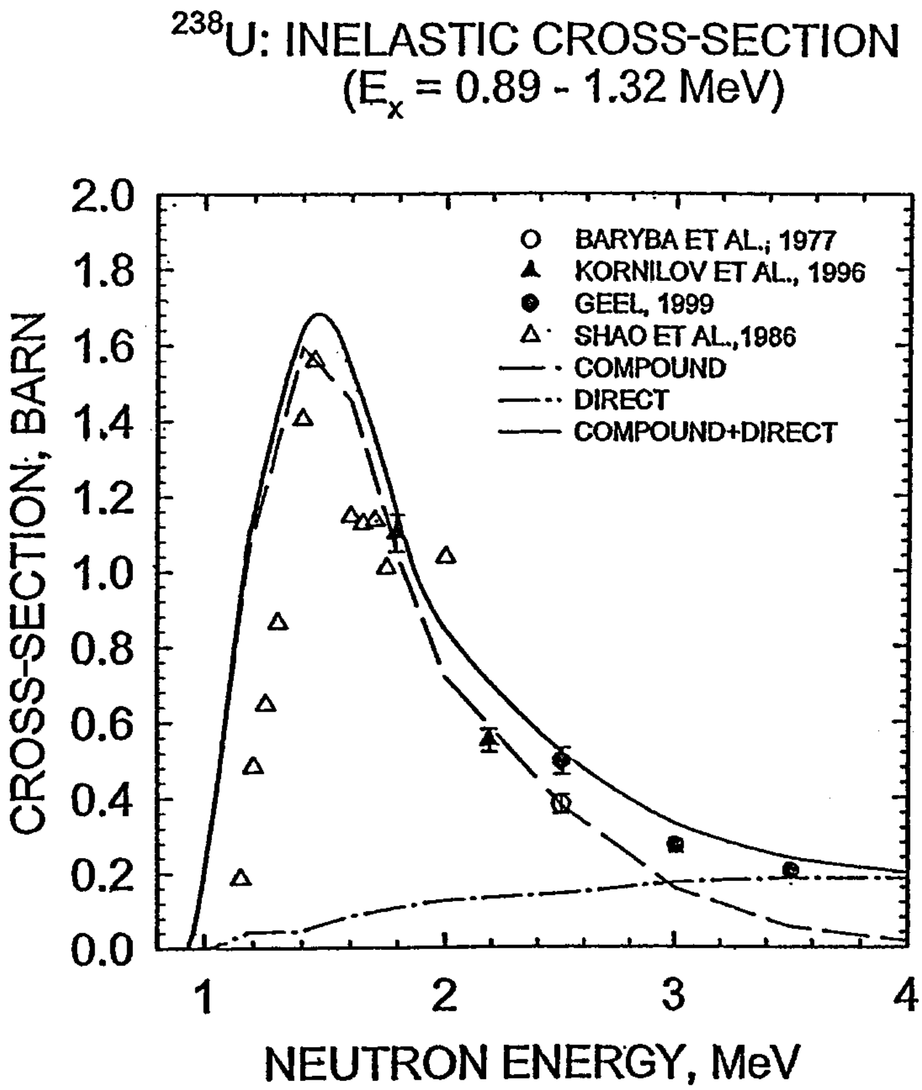


Figure 16. Neutron emission spectra evaluated by Maslov, *et al.* [37]