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Evaluations and Calculations of Neutron Reactions on ^{238}U up to 20 MeV

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1. Introduction

As an important fissile material nucleus, ^{238}U is highly sensitive in macro examination. In order to improve the quality of neutron data of ^{238}U in CENDL, considering the impact of adding new measurements, a brand-new evaluation of the complete set of neutron induced ^{238}U reaction data up to 20 MeV has been performed recently. Important reactions, such as average number of fission neutrons, (n,tot), (n, γ), (n,f), (n,2n) and (n,3n) cross sections have been evaluated based on experimental data analysis. Also, using existing optical potential parameters, new theoretical calculations based on Hauser-Feshbach and pre-equilibrium has been carried out. Resonance parameters from ENDF/B-VIII.0 have been adopted and an ENDF formatting file has been obtained. Under the guidance of integral benchmark, the inelastic cross section and radiation capture cross section have been adjusted and optimized repeatedly. The benchmark results have been well improved. This work is still in progress.

2. Methods and Results

In this section the evaluated results are described, including experimental evaluation method and results of important reactions, theoretical models and calculations, with the calculated covariance in an individual sub-section, and results of integral benchmark.

2.1 Evaluated reactions

In reactor research, the neutron production and disappearance reactions of ^{238}U have received great attention. Furthermore, experiments on these reactions have been widely reported. In CENDL-3.2[1], most of the neutron induced ^{238}U cross sections were evaluated in 1990. Based on existing experimental data taken from EXFOR [2, 3], the main excitation function on n+^{238}U reactions are evaluated in the 0.1-20 MeV energy region. In order to obtain accurate evaluation results from numerous divergent experimental data, data measured under advantageous experimental conditions, which including purpose, method, neutron source, detector, sample quantification, standard cross section selection, data correction, and uncertainty analysis, etc., are totally recommended. The excited function curves are based on these highly recommended experimental data.

The total cross section measurement mostly adopts the transmission method or a combination of transmission method and time–of–flight technique (TOF), and the basic idea is to obtain the full cross-section of neutrons by measuring the transmittance.

More than 30 sets of measured (n,tot) cross section are collected, and noticed that their distribution has a certain width. Mainly based on experimental information such as neutron energy range, energy resolution, sample quantification, geometrical conditions, background correction, dead time correction, and uncertainty analysis etc., several sets of experimental data are recommended which are emphasized in Fig.1, while the un-recommended data are not marked in the figure, the same below. The present result is getting agreement with these data, as well as evaluations from ENDF/B-VIII.0[4], JENDL-5.0[5] and CENDL-3.2 evaluations. The present evaluated (n,tot) cross section is quite accurate, with an accuracy generally within 1%.

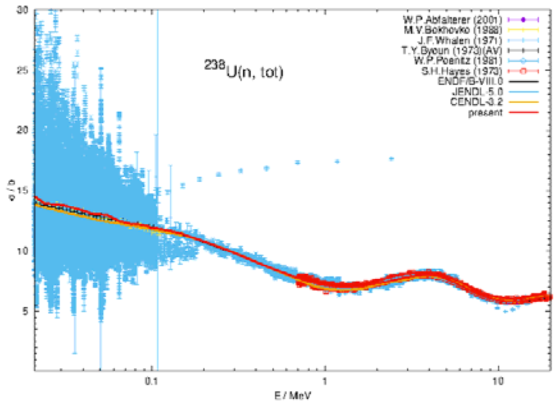

Fig. 1. Evaluated ^{238}U(n,tot) cross section

Neutron induced fission reactions can be marked by the measurement of fission fragments. The main equipment for measuring fission is the fission ionization chamber. The interference of α particle is a problem in traditional measurement of fission cross-section, and there are two ways to improve it. One is the fast fission ionization chamber, which reduces α particle collisions. Currently, the best equipment in the world is the fission chamber based on parallel plate avalanche ionization chamber (PPAC) detector technology developed by the European CERN nTOF cooperation group. The second is the coincidence measurement of two fragments combined with track tracking. Currently, the best equipment in the world is the Time Projection Chamber (TPC) detector from

LANL in the United States. The development of neutron sources also provides excellent experimental conditions for high precision measurement of fission cross sections.

48 subentries covered 1948-2014 of measured ^{238}U(n,f) cross section are collected and analyzed. The overall statistics of the data are basically consistent, but the central values are relatively different, with obvious discrepancy in the high energy region of >=20 MeV.

In order to obtain reliable data, the simultaneous evaluation technology is applied. That is, both the measured ^{238}U(n,f) cross section and the measured ratio cross sections of ^{238}U(n,f)/^{235}U(n,f) are considered. In nuclear data evaluation, relative measurement data can be used to improve the accuracy of evaluating nuclear data. The experimental data were classified, compared and analyzed according to experimental elements such as experimental purpose, neutron beam quality, neutron energy resolution, neutron flux calibration method, detector resolution, etc, and cross section and ratio data evaluated back-to-back. Then by Multiplying ratio data with the standard ^{235}U(n,f) cross section from IAEA, the two types of evaluated data were discussed for consistency. Fig. 2 shows the evaluated ^{238}U(n,f) cross section with experimental data and other evaluations.

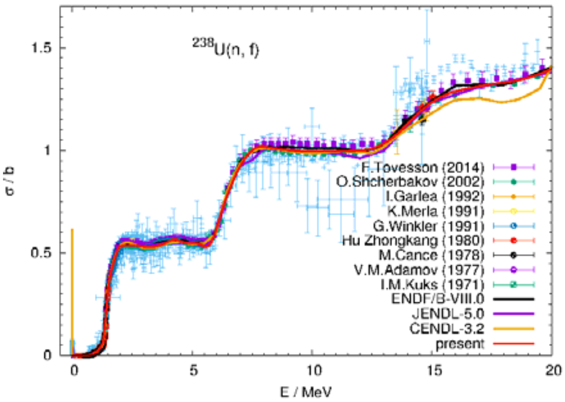

Fig. 2. Evaluated ^{238}U(n,f) cross section

The simultaneous evaluation technology is also applied in the ^{238}U(n, γ) cross section evaluation. Three types of measurements, ^{238}U(n, γ) cross section, ratio of ^{238}U (n, γ)/^{235}U(n, f), and ratio of ^{238}U(n, γ)/^{238}U(n, f), are analyzed back-to-back. The basis for evaluating these experimental data mainly includes experimental methods, neutron sources, detectors, uncertainty processing, and other experimental measurement information. Under the guidance of integral benchmark results, the evaluated (n, γ) cross section has been adjusted several times. The final curve is presented in Fig. 3.

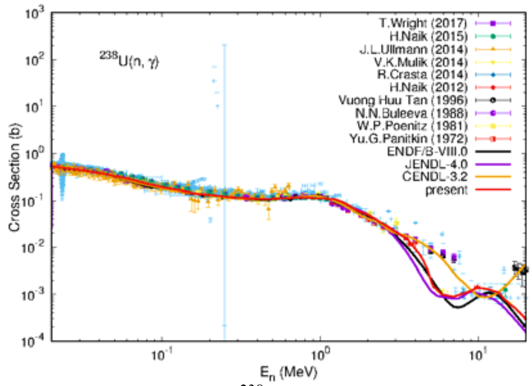

Fig. 3. Evaluated ^{238}U(n, γ) cross section

The average number of prompt fission neutrons (PR, NU) has a significant impact on criticality calculations. In EXFOR 30 sets measurements covered 1955-2015 over 240 points have been collected, and they are totally different. In order to better provide the location of the evaluation data center value, measurement elements such as the neutron source unipotency, neutron flux calibration method, and detector efficiency in the experiment are considered to evaluate the experimental data. Fig. 4 shows the focus recommended data in marked symbols, and the evaluated curve compared with all experimental and evaluated data. Our results are very close to evaluations form ENDF/B-VIII.0.

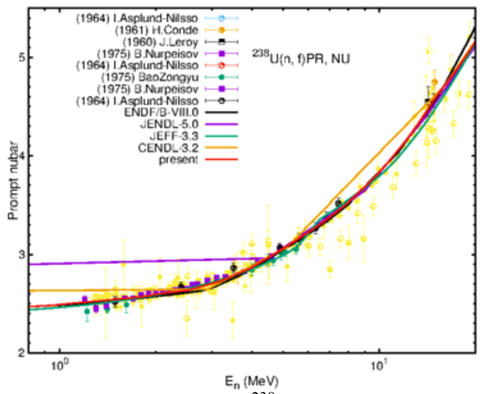

Fig. 4. Evaluated ^{238}U(n,f) PR, NU

In the same way, the measured average number of delayed fission neutrons (DL, NU) is recommended, as shown in Fig. 5, and the present evaluation is based on these data and CENDL-3.2 evaluation. DL is much smaller in quantity than PR.

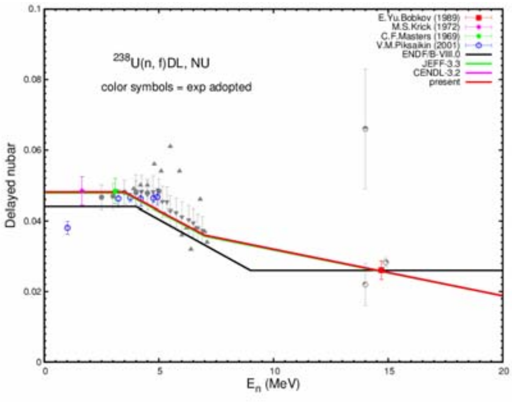

Fig. 5. Evaluated ^{238}U(n,f) DL, NU

Measurements of total average number of fission neutrons are limited and do not covers the energy range of 0.1-20MeV. Measurement data from J.Voignier (1968) and E.Barnard (1965) are recommended to guide evaluation. We also referred to evaluations form other libraries and the normalization of prompt and delayed fission neutrons. Fig. 6 shows the present curve.

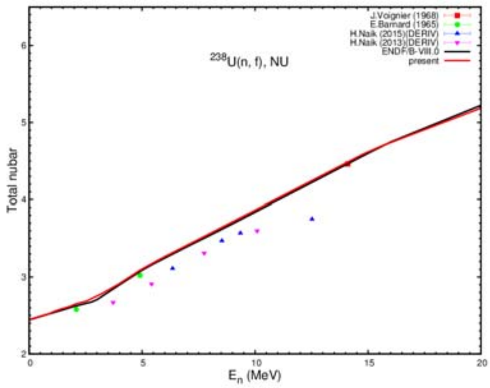

Fig. 6. Evaluated ^{238}U(n,f) , NU

28 subentries, 191 points covered 1956-2017 measured ^{238}U(n,2n) cross sections are collected and analyzed. Although all these measurements were carried out using activation method, they are almost different as shown in Fig. 7. According to experimental information such as monochromaticity of neutron source, Background processing, neutron flux calibration method, detector resolution, and uncertainty processing, special focusing on the resolution ability of detectors, the marked measurements are recommended. The present evaluated ^{238}U(n,2n) cross section is obtained by fitting these data.

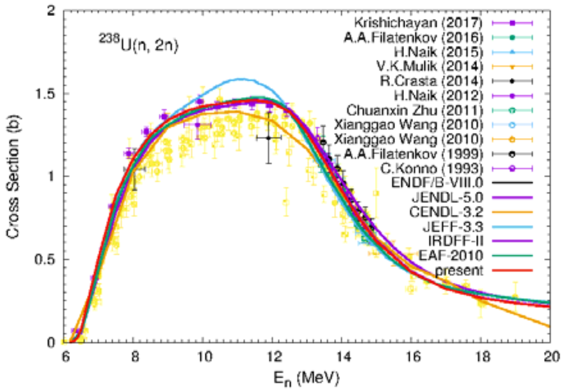

Fig. 7. Evaluated ^{238}U(n,2n) cross section

There are 8 subentries and 31 points of experimental data for ^{238}U(n,3n) cross section. They were also carried out using activation method. Similar evaluation methods have reached conclusions that measurements from Xianggao Wang (2013) are recommended, and our results are based on these data and calculated results to be mentioned below. Fig.8 presents the evaluated (n,3n) cross section.

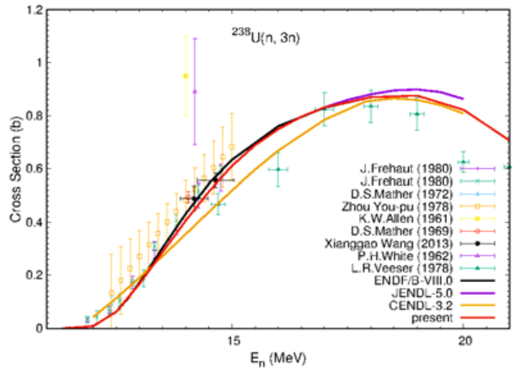

Fig. 8. Evaluated ^{238}U(n,3n) cross section

2.2 Calculated results

Based on the guidance and constraints of above evaluations, calculations using the FUNF fission nuclear reaction theoretical model program [6] are carried out for n+^{238}U reactions. The theoretical basis of the FUNF program includes the spherical optical model, the unified Hauser-Feshbach, and the exciton model related to angular momentum parity. Due to the introduction of an improved pick-up mechanism, the calculation of complex particle pre equilibrium emission has been improved. Because of the strict consideration of nuclear recoil effect in all reaction processes, FUNF can ensure energy balance. The FUNF program can calculate the complete set of neutron nuclear data for incident energy from the upper boundary of the resonance region to the 20MeV energy region, including the cross sections of all reaction channels, the angular distribution and energy spectrum of emitted neutrons, the double differential cross sections of various emitted particles, and gamma photon generation data: multiplicity, cross sections, angular distribution and energy spectrum, etc.

Optical model potential parameters form Han Yinlu (2006) [7] were adopted in the whole calculation.

Fig. 9 shows the calculated ^{238}U(n,el) cross section comparing with existing experimental and evaluated data from ENDF/B-VIII.0, JENDL-5.0, CENDL-3.2, etc.. Their consistency indicates that our optical model potential parameters are reasonable.

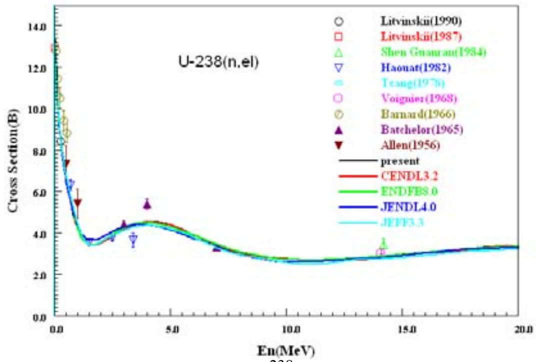

Fig. 9. Calculated ^{238}U(n,el) cross section

Fig. 10 shows the calculated elastic angular distribution at 1.1, 3, 7, and 14 MeV comparing with experimental and evaluated data. All these calculations are basically consistent but disagree in details. More discussion both for evaluation and experimental data should be carried out.

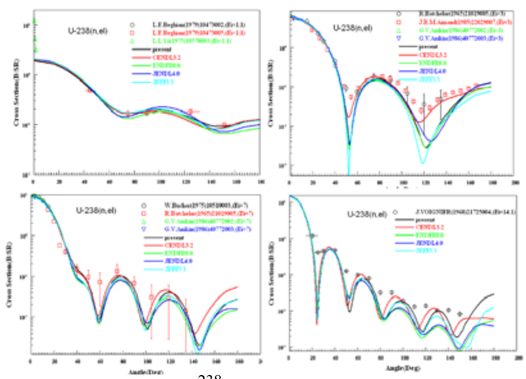

Fig. 10. Calculated ^{238}U(n,el) angular distribution

Fig. 11 gives the calculated ^{238}U(n,inl) cross section comparing with other data. The trends of curves are consistent, but there are differences in the amount of data. This divergence will affect the double differential cross section.

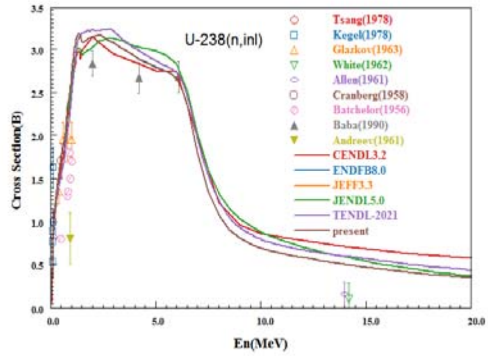

Fig. 11. Calculated ^{238}U(n,inl) cross section

The comparisons of the calculated results and the existing evaluations the cross sections for the first, second, third and fourth excited states are shown in Fig. 12. Similar to Fig. 11., the data divergence will also affect the double differential cross section.

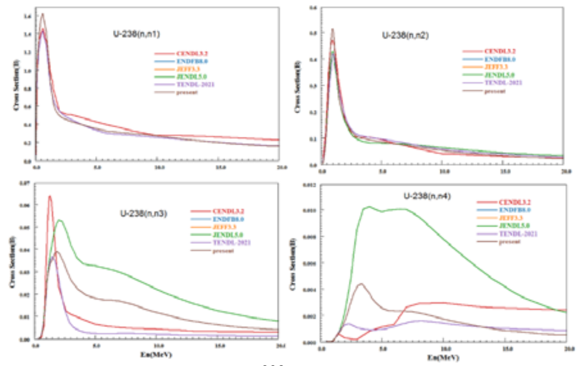

Fig. 12. Calculated ^{238}U(n,n$_1$-n$_4$) cross section

Fig. 13 shows the calculated neutron emission spectra at 14.05 MeV comparing with existing data. The trends of curves are consistent, but disagree in details. The evaluated elastic scattering peaks are perfectly consistent but higher than experimental data, perhaps due to improper widening selection. The distributions of discrete levels are mostly different. Theoretical calculation for inelastic distributions requires some improvement.

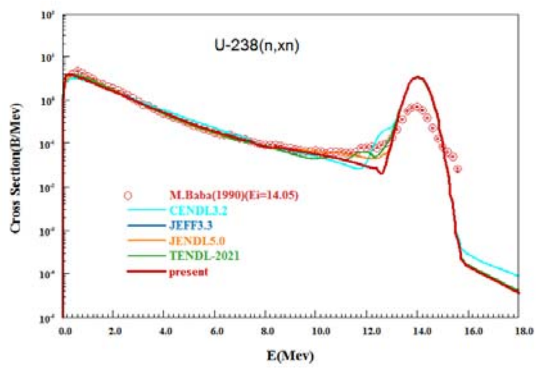

Fig. 13. Calculated ^{238}U(n,xn) energy spectra

Same situation can be seen in double differential cross section at 14.05 MeV described in Fig. 14. The curve shapes are correct, but some details need to improve.

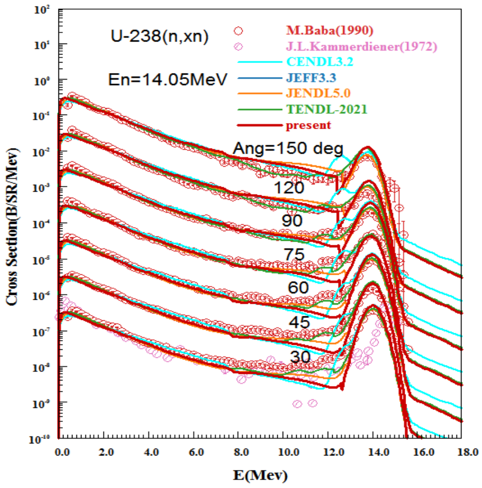

Fig. 14. Calculated ^{238}U(n,xn) double differential distributions

2.3 Calculated Covariance

The correlation of the main 11 reactions is calculated for n+^{238}U reaction, as shown in Fig. 15. Diagonal elements are all equal to 1, indicating the self-correlation of each energy point. The value of the non-diagonal element is between -1 and 1, indicating the correlation between any two energy points of any two cross-sections.

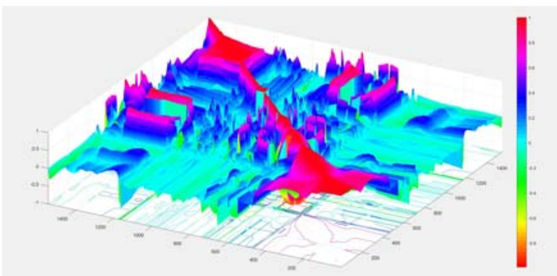

Fig. 15. Calculated covariance for n+^{238}U reactions

2.4 Results of Integral Benchmark

Referring to the Lawrence Livermore pulse sphere benchmark experiment [8], integral benchmark tests have been performed for ^{238}U neutron data by using the Monte Carlo code JMCT [9].

Fig. 16 and 17 show the comparison of test results with the 0.8mfp and 2.8mfp thickness samples. The parameters of the sample ball, such as thickness, flight path, detector and threhold energy are marked in the figures. It can be seen that significant improvement has been done in data quality through adjustments.

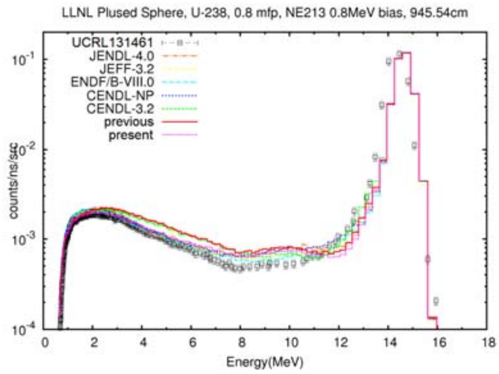

Fig. 16. 0.8 mfp pulse sphere benchmark experiment

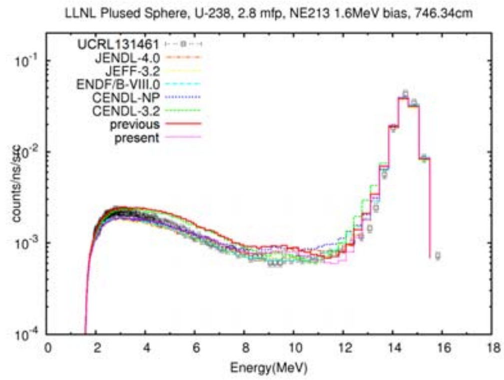

Fig. 17. 2.8 mfp pulse sphere benchmark experiment

Fig. 18 shows the comparison of the criticality benchmark test results based on the ICSBEP [10] LCT benchmarks among ENDF/B-VIII.0, previous and present revision. Based on the same data set other than ^{238}U both previous and present revision evaluations show better performance than ENDF/B-VIII.0 in the LCT system.

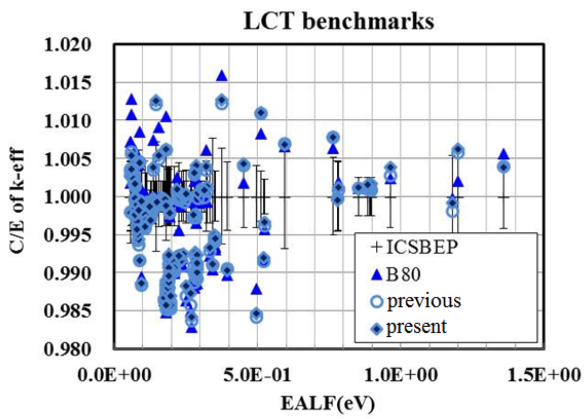

Fig. 18. Comparison of C/E of k_{eff} for LCT system

3. Conclusions

According experimental measurement elements such as method, purpose, neutron beam quality, detector resolution ability, and uncertainty analysis etc., important reactions, such as average number of fission neutrons, (n,tot), (n, γ), (n,f), (n,2n) and (n,3n) cross sections are evaluated for neutron induced ^{238}U reactions. The whole set of neutron data, the cross sections of all reaction channels, the angular distribution and energy spectrum of emitted neutrons, the double differential cross sections of various emitted particles, etc., is calculated by using theoretical model program FUNF, with covariance. Under the guidance of integral benchmark testing, the inelastic cross section and radiation capture cross section in the fast energy region have been evaluated interatively. The benchmark results for the LCT system have been improved.

There are some details such as theoretical calculation for inelastic distributions should be improved, and this work is still in progress.

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