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NUCLEAR DATA REPORT FOR THE EMEANSS PROJECT

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Nuclear Data report for the eMEANSS project

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1 INTRODUCTION

An EPSRC grant entitled Enhanced Methodologies for Advanced Nuclear System Safety (eMEANSS) is a joint UK-India Civil Nuclear Collaboration with a remit to assess the impact of data uncertainties within the nuclear industry. As part of this project work package 1.4 states the project will:

“Identify a set of isotopes and neutron energies for which nuclear data uncertainty should be reduced. This will be used as a pointer to a planned future Round VI Indo UK project dedicated specifically to ‘nuclear data’.”

Initial discussions were held between Dr Anurag Gupta, Professor William Nuttall and Professor Geoff Parks in Cambridge on 23 November 2023. It was resolved that the focus should initially avoid actinide materials and that neutron energies of interest would only be thermal or epithermal.

The compilation of a list of candidate isotopes was developed and this report aims to give an overview of the state of the nuclear data of these isotopes.

1.1 ENERGY RANGE OF INTEREST

The stated energy range of interest for this work is thermal and epithermal. There are no fixed definitions of neutron energy ranges with different authors quoting different boundaries. The aim of choosing thermal and epithermal was to avoid fast neutron energies and therefore this study will include cross sections for neutron energies between 1 meV and 100 keV, which includes neutrons often labelled “slow” or “intermediate".

1.2 REACTIONS CROSS SECTIONS

A reaction cross section is essentially the probability of an interaction occurring between and incident particle and a target nucleus. In our case the incident particle is neutron which can vary in energy over a wide range. Reaction cross sections are typically defined as a reaction rate, R, (measured) divided by the number of incident particles per unit time, I, and the number of target nuclei per unit area, N. As such the unit for cross section, σ, is area per nucleus [1].
A typical radius, r, of a nucleus is 6 fm, resulting in the geometric area, $\pi.r^2$, of approximately 100 fm^2, which is the definition of 1 barn (b) the typical unit for reporting reaction cross sections.
There are many different types of reaction cross section that can be reported. The total reaction cross section, labelled (n,tot) in databases, is the probability (per nucleus) of any neutron reaction occurring on a target nucleus and is typically measured via attenuation/transmission experiments. These reactions are dependent on the energy of the incident neutron and total cross sections are sums of those for all the possible reaction mechanisms. There are many reaction mechanisms possible when a neutron impinging a target and they are strongly energy dependant. Neutron induced reaction cross sections up to 100 keV are dominated by two reaction mechanisms, elastic scattering and neutron capture. It is also possible to induce inelastic scattering reactions towards the top of the energy range of interest.
The reaction cross sections discussed in this report are integral, i.e. integrated over angle and energy of the reaction product, it does not include differential or double-differential reaction cross sections.

1.2.1 Elastic scattering

Elastic scattering are reactions in which the projectile and target are unchanged, and the kinetic energy of the system is conserved, i.e. no energy is transferred into excited states of the reaction products. This means kinetic energy is the same before and after the reaction in the centre-of-mass frame of reference. In the laboratory frame of reference this is not the case as some energy has been transferred to the previous stationary target nucleus.

1.2.2 Neutron capture

Neutron capture involves the incident projectile neutron being captured in the target nucleus and forming a compound system which is in an excited state. This excitation energy is lost typically through emitting 1 or more gamma rays. The resulting nucleus may be unstable and subject to radioactive decay.

1.2.3 Inelastic scattering

Inelastic scattering are reactions in which the projectile and target are unchanged but the kinetic energy of the system is not conserved, i.e. energy is transferred into excited states of the reaction products. This means the inelastic scattering reactions can only proceed above lowest lying excited state in the target nucleus, as below this energy there is no excited state available to populate.

1.3 NUCLEAR DATA

For the nuclear data and evaluations included in this report the data was retrieved using JANIS-4.0 provided by the Nuclear Energy Agency (NEA). JANIS (Java-based nuclear information software) is a display program designed to facilitate the visualisation and manipulation of nuclear data. Its objective is to allow the user of nuclear data to access numerical values and graphical representations without prior knowledge of the storage format. It offers maximum flexibility for the comparison of different nuclear data sets. JANIS includes experimental data in the EXFOR library and many evaluated nuclear data libraries [2].

1.3.1 EXFOR

The EXFOR library contains an extensive compilation of experimental nuclear reaction data. Neutron reactions have been compiled systematically since the discovery of the neutron, while charged particle and photon reactions have been covered less extensively [3].

1.3.2 BROND-3.1

Russian evaluated neutron data library, 2016. The library is in ENDF-6 format and contains data for 372 files for isotopes from hydrogen to curium and the incident neutron energies from the thermal one up to 20 MeV. The library provides reaction cross sections but not standard deviations [4].

1.3.3 CENDL-3.1

The Chinese Evaluated Nuclear Data Library, released in June 2020 via the China Nuclear Data Coordination Network (CNDCN). The library contains neutron-induced data up to 20 MeV for 272 nuclides materials from 1-H-1 to 98-Cf-249. The library provides reaction cross sections but not standard deviations [5].

1.3.4 ENDF/B-VIII.0

The US evaluated nuclear data library released in February 2018. The library is divided into 14 sublibraries, 1 of which is the incident neutron library, which has data for 557 nuclides from 0-n-1 to 100-Fm-255 from 10^{-5} eV to 10’s or 100’s MeV [6].

1.3.5 FENDL-3.1

The Fusion Evaluated Nuclear Data Library (FENDL) is a comprehensive and validated collection of nuclear cross section data coordinated by the International Atomic Energy Agency (IAEA) Nuclear Data Section (NDS) [7].

1.3.6 JEFF-3.2

The Joint Evaluated Fission and Fusion File is an evaluated library produced via an international collaboration of Data Bank member countries co-ordinated by the JEFF Scientific Co-ordination Group, under the auspices of the NEA Data Bank. The JEFF-3.2 general purpose library has been released on March 5, 2014 and contains incident neutron data for 472 nuclides or elements from 1-H-1 to 100-Fm-255 [8].

1.3.7 JENDL-4.0

Japanese Evaluated Neutron Data Library, released in 2010. The library is in ENDF-6 format and contains data for 406 materials from 1-H-1 to 100-Fm-255 [9].

1.3.8 RUSFOND-2010

Russian File of Evaluated Neutron Data, released in 2010. The library is in ENDF-6 format and contains data for 686 materials from 1-H-1 to 100-Fm-257 [10].

1.3.9 TENDL

TENDL [11] is a nuclear data library which provides, in ENDF format, the output of the TALYS [12] nuclear model code system for direct use in both basic physics and applications. The TENDL library is based on both default and adjusted TALYS calculations and is complemented by data from other sources whenever required, e.g. in the resolved resonance region.

1.3.10 EAF-2010

The European Activation File (EAF) is an extensive data library prepared for the European Activation System (EASY). The EAF-2010 activation-transmutation neutron nuclear data library includes 816 target isotopes for neutron energy ranging from 10-5 eV to 60 MeV. Parts of the original EAF-2010 in EAF format library has been translated into ENDF-6 format [13].

2 NUCLEAR DATA OF INTEREST

2.1 SILICON-28

Silicon has three stable isotopes with mass numbers 28, 29 and 30. The most abundant isotope is 28Si with approximately 92 % of natural silicon being 28Si. An important material for new nuclear reactors will be silicon-carbide as it can withstand high temperatures and is chemically stable, reducing the risk of hydrogen generation. As such this material will feature in future accident tolerant claddings for nuclear fuel in thermal reactors. Silicon-carbide is also a component of high-density fuels for advanced proliferation-resistant research reactors operating with HALEU fuel.

Figure 1 shows the relevant cross sections across the energy range of interest. The dominant cross section is elastic scattering which comprises the majority of the total across the whole range.

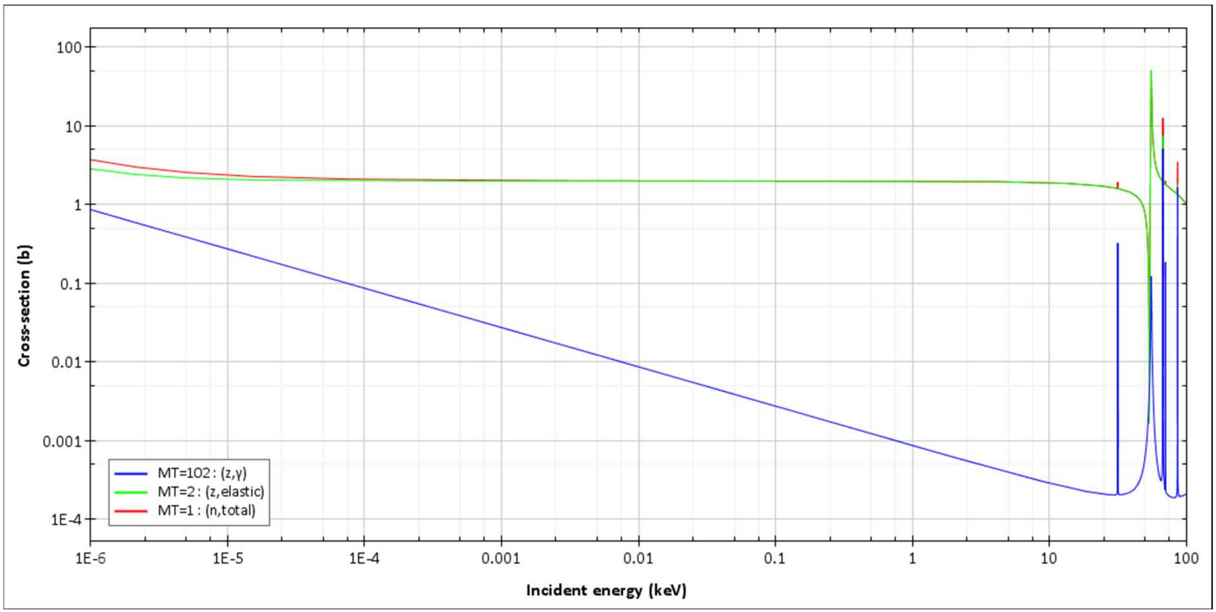

Figure 1: Evaluated cross sections relevant to the energy range of interest from ENDF/B-VIII.0 for ^{28}Si

There are two data sets that fall within the energy range of interest for the neutron induced total reaction channel, (n,tot), Y. A. Alexandrov et al (1997)[14] and S. F. Mughabghab (2006)[15]. The experiments published by Y. A. Alexandrov were transmission measurements using a time-of-flight spectrometer (GNEIS) and linear accelerator in St Petersburg. The data covers a range from approximately 1 eV to 100 eV with small uncertainties of less than 1 % (average uncertainty 0.25 %). These uncertainties only include statistical uncertainties.

The S. F. Mughabghab EXFOR entry is referenced to the “Atlas of neutron resonances resonance parameters and thermal cross sections Z=1-100” and will appear several times in this report. The publication is an extensive list of detailed individual resonance parameters for each nucleus, thermal cross sections and average resonance parameters. The EXFOR entry notes the method of producing these data as ‘evaluation’, but it is an evaluation of a limited set of data, measured thermal cross sections and resonance parameters, unlike evaluations such as ENDF/B which cover the full range of energies and make use of nuclear models. EXFOR states “The experimental results for nuclei between H and Fm were critically surveyed, renormalized and resonance parameters were deduced. Cross sections and resonance integrals were given where available, otherwise they were calculated using the resonance parameter data."

Evaluated data libraries for the (n,tot) reaction are in good agreement across the range of interest. The TENDL-2019 evaluation diverges from the other libraries above ~300 eV. All evaluations shown are in good agreement (within uncertainties) with the data of S. F. Mughabghab but agree less well with the data of Y. A. Alexandrov, not reproducing the shape or magnitude of; the data of Alexandrov is up to 5% higher than the evaluations. The evaluations reproduce the structure seen within the measured cross section at higher energies, between 1 and 20 MeV, which gives confidence to the lower energy region. The uncertainty provided by the libraries are typically small (if they are provided). For example the stated standard deviation in the (n,tot) cross section for the JEFF-3.3 library is < 0.5 % at 25.3 meV (thermal). See Figure 2.

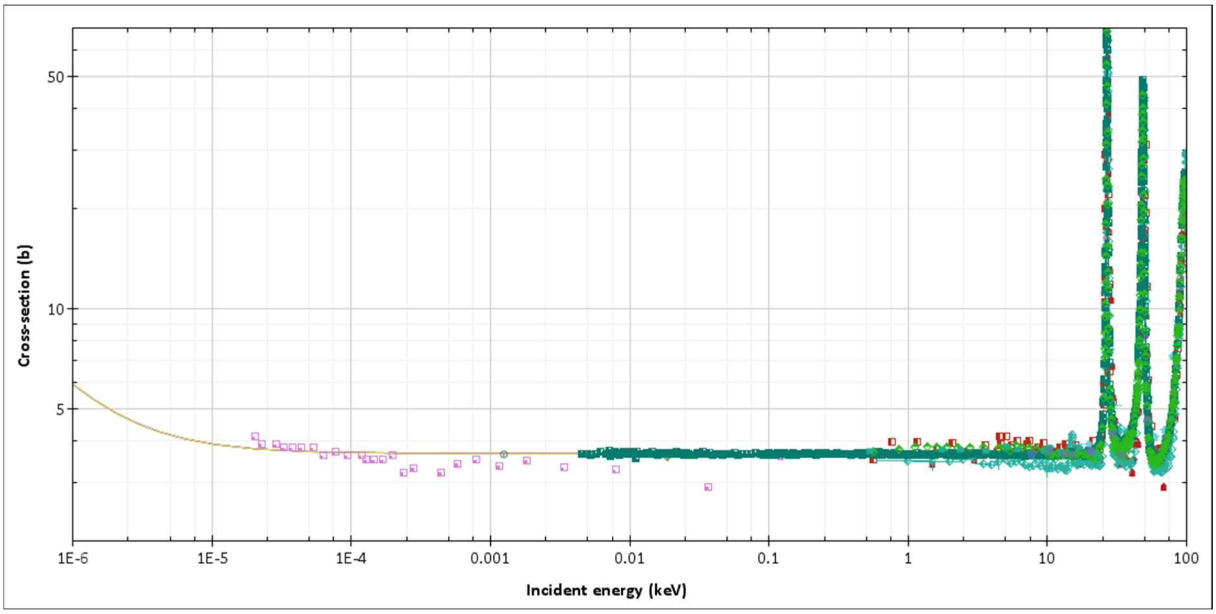

Figure 2: EXFOR data for the total reaction cross section (points) and evaluated cross sections (lines) relevant to the energy range of interest for ^{28}Si

For the elastic scattering reaction, there is only data from S. F. Mughabghab within the energy range of interest; there 5 experiments (of 1 or 2 data points each) in the MeV energy range. Again, the evaluated data libraries for the (n,el) reaction are in good agreement across the range of interest. The TENDL-2019 evaluation diverges from the other libraries above ~350 eV. All evaluations shown are in good agreement (within uncertainties) with the data of S. F. Mughabghab. The evaluations also agree with the other data sets in the MeV region. See Figure 3.

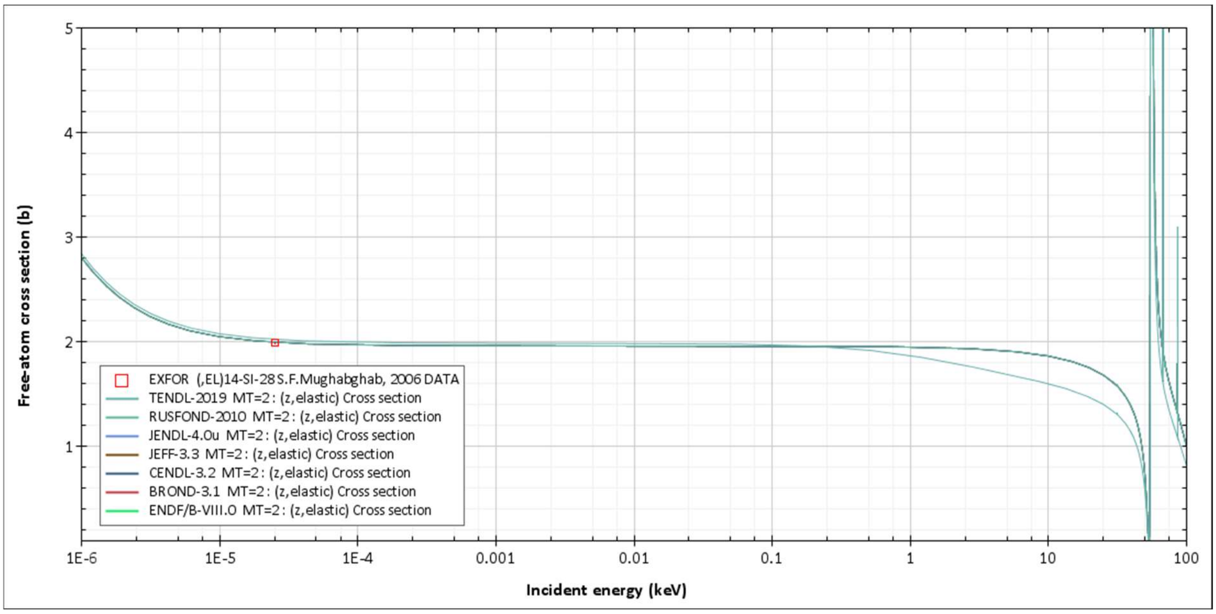

Figure 3: EXFOR data for the elastic scattering reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{28}Si

For the neutron capture reaction cross section on 28Si there are 3 data sets in the energy range of interest. These are B. J. Allen (1973)[16], K. H. Guber (2002)[17] and S. F. Mughabghab (2006)[15]. The two experimental data sets use data from the ORELA electron linac facility at Oak ridge utilising time-of-flight techniques, the work by Allen et al. also includes experimental data from a Van de Graaff facility in Lucas Heights, Australia. The neutron capture cross sections data is presented with large energy ranges for each data point, presumably related to the timing resolution of the detectors used at the time-of-flight facility. There are no uncertainties in the cross section for the Guber data and uncertainties of 10% for the Allen data. See Figure 4.

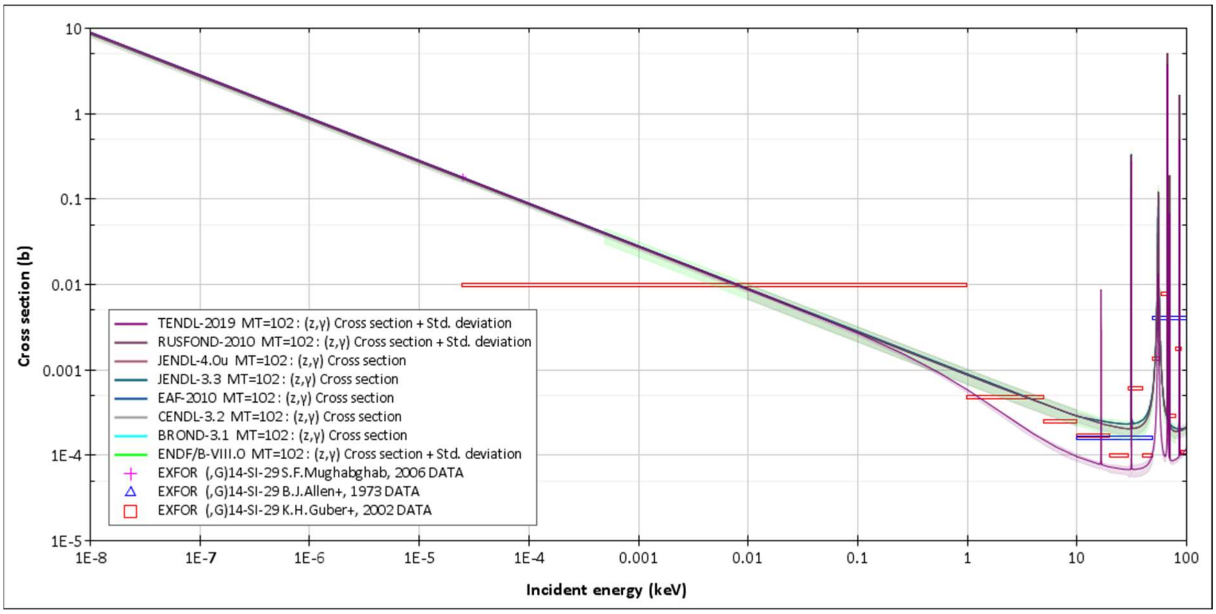

Figure 4: EXFOR data for the neutron capture reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{28}Si

2.2 CARBON-12

Carbon is the other main element in Silicon-Carbide which will be utilised in accident tolerant fuel cladding for advanced thermal reactor systems and HALEU fuel. Carbon (graphite) is also well known as a moderator in thermal reactors and is still used in the AGR fleet of reactors in the UK. There is an interest in knowing more about carbon in epithermal (reduced moderation) reactors and in high temperature reactors. Carbon-12 is the dominant stable isotope of carbon with approximately 99% natural abundance.

Figure 5 shows the relevant cross sections across the energy range of interest. The dominant cross section is elastic scattering which comprises the majority of the total across the whole range.

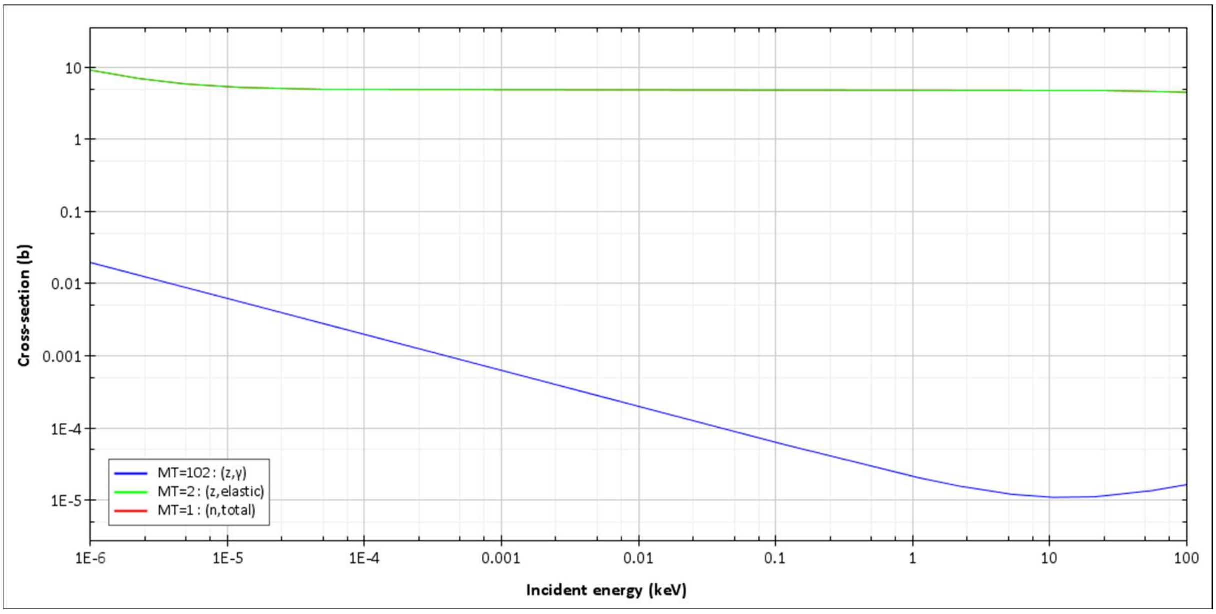

Figure 5: Evaluated cross sections relevant to the energy range of interest from ENDF/B-VIII.0 for ^{12}C

There are a large number of experimental data sets in the neutron induced total reaction cross section for 12C, with over 70 entries in the EXFOR data base. The nuclear data evaluations agree well across the energy range of interest with a ~0.2 % difference between the evaluations at 25.3 meV. This is smaller than the given uncertainty, i.e. the standard deviation on the ENDF/B-VIII.0 evaluation is ~0.5 %. However, below thermal energy there is significant divergence of the evaluations from the experimental data. See Figure 6.

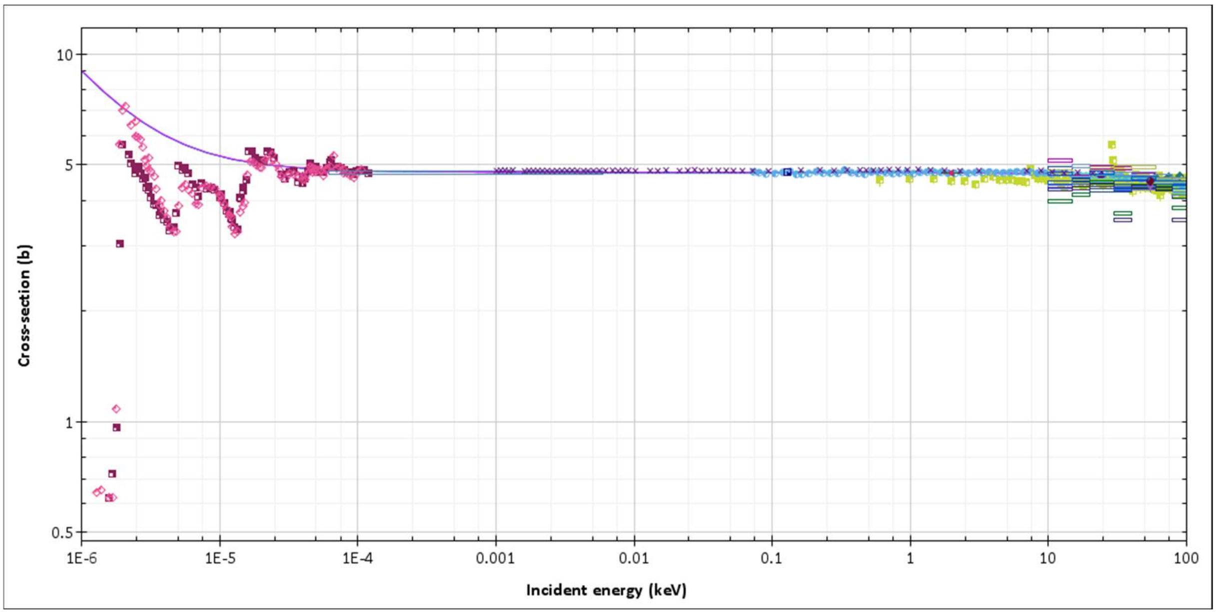

Figure 6: EXFOR data for the total reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{12}C

There are fewer data for the elastic scattering cross section on 12C, with only three entries in the EXFOR database, one of which is the same reference of S. F. Mughabghab discussed previously. The two experimental data sets utilise neutron beams from fission reactors. W.Triftshaeuser (1965)[18] has data at 33.9 and 61.1 eV with small uncertainties of ~0.04 %. V.P.Vertebnyj (1970)[19] has data at 25.3 meV with uncertainties of ~2 %. Within this uncertainty it agrees with S. F. Mughabghab at 25.3 meV. All evaluations agree well with each other across the energy range. The evaluations also agree well with the data W.Triftshaeuser, but not with the experimental data at 25.3 meV. For example, the ENDF/B-VIII.0 evaluation is ~4.3 % higher than the EXFOR entry of S. F. Mughabghab. This difference is significantly larger than the uncertainty on either the EXFOR entry or the evaluation; the standard deviation of the ENDF/B-VIII.0 evaluation is 0.7 % and the uncertainty of S. F. Mughabghab is ~0.04 %. See Figure 7.

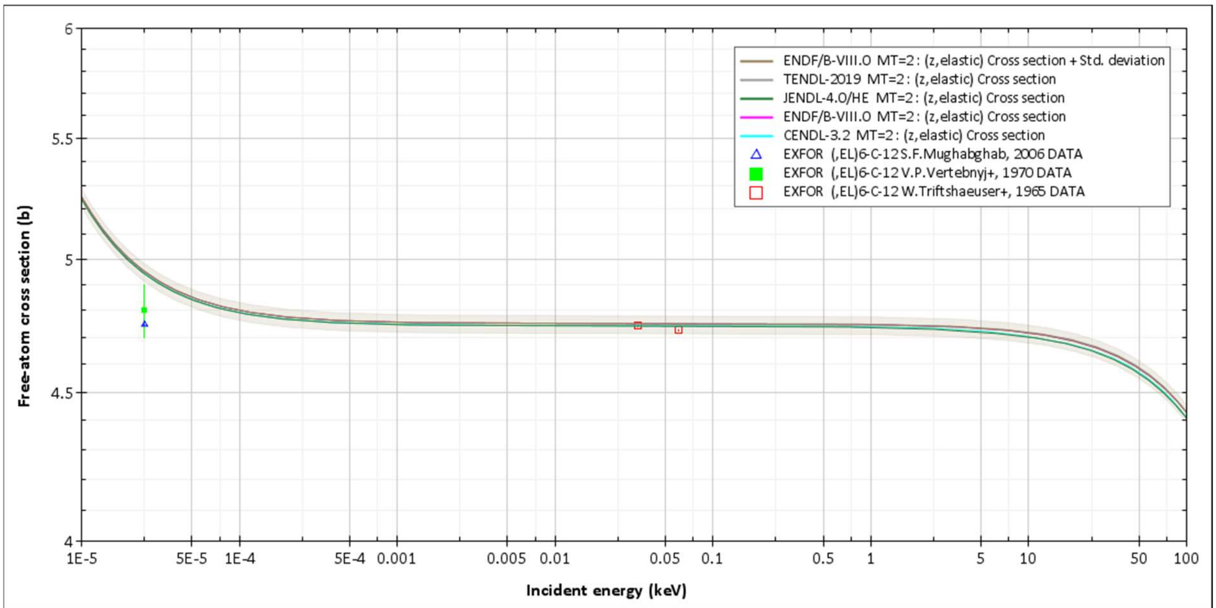

Figure 7: EXFOR data for the elastic scattering reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{12}C

The neutron capture cross section on 12C has 4 entries in EXFOR: S. F. Mughabghab and R. B. Firestone (2016)[20] at thermal neutron energy; and Y. Nagai (1991)[21] and T. Ohsaki (1994)[22] with data in the 10-200 keV region. The R. B. Firestone data was taken using both guided thermal and cold neutron beams at the 10-MW Budapest Reactor and measuring neutron capture γ-ray spectra using Compton supressed HPGe detectors. The data of Y. Nagai and T. Ohsaki were produced using the 3.2 MV Pelletron at the Tokyo Institute of Technology to produce a 30 keV Maxwellian (of astrophysical importance) neutron pulsed field with measurements done using the time-of-flight technique using various scintillators. The evaluations for this reaction agree broadly well across the energy range of interest with some caveats. There are two groups of evaluations which both agree with the data in the keV region. However, one group seems to be normalised to the S. F. Mughabghab thermal datum (CENDL-2.3, EAF-2010), and the other to the R. B. Firestone datum (ENDF/B-VIII.0, JENDL-4.0, TENDL-2019). This difference is ~15% at thermal energies, between the highest and lowest (ENDF/B-VIII.0 and CENDL-3.2) evaluations, which is much larger than the uncertainties in the 2 data points. There is another divergence between the evaluations at ~5 keV where the CENDL-3.2 evaluation reduces by ~ 1 order of magnitude and does not reproduce the data in the keV region; all other evaluations reproduce the data in the keV region. See Figure 8 and Figure 9.

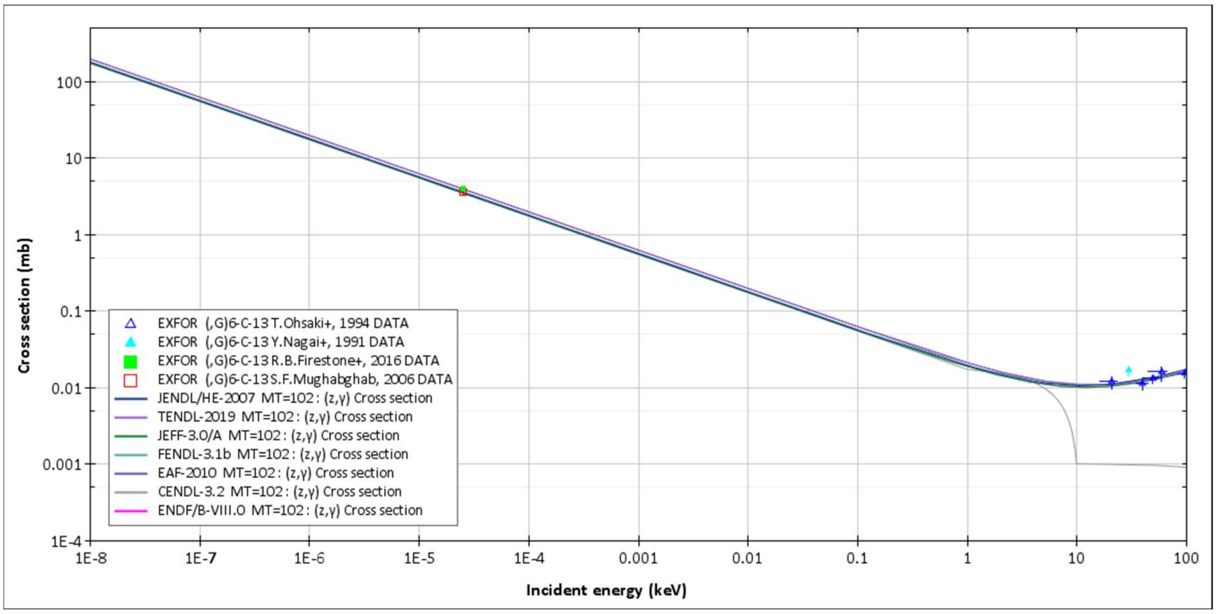

Figure 8: EXFOR data for the neutron capture reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{12}C

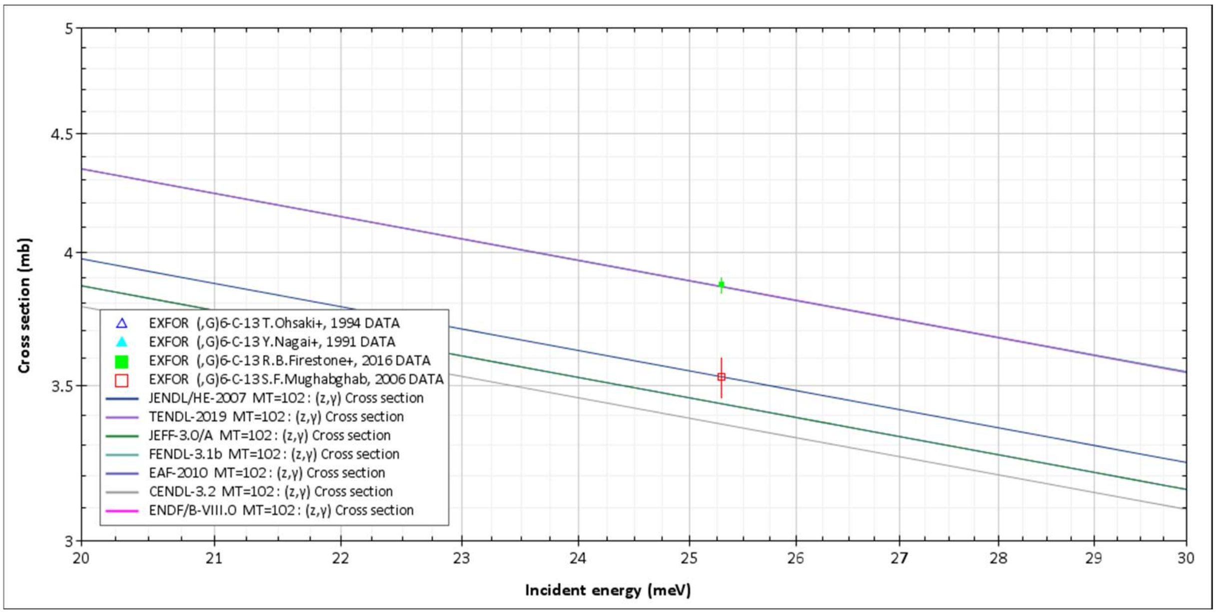

Figure 9: EXFOR data for the neutron capture reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{12}C, zoomed on thermal neutron energy

2.3 ZIRCONIUM-91 AND 92

Zirconium has 5 stable isotopes, with the most abundant being 90Zr at approximately 51 %. Zirconium-91 and -92 are less abundant at approximately 11 % and 17 % respectively. Zirconium alloys (Zircaloy) are key components in in the nuclear power industry, particularly in nuclear fuel cladding and structural components.

2.3.1 Zirconium-91

Figure 10 shows the relevant cross sections across the energy range of interest. The dominant cross section is elastic scattering which comprises the majority of the total across the whole range. However, at the low end of the energy range the neutron capture increases as a percentage of the total amounting to ~35 % of the total at 1 meV.

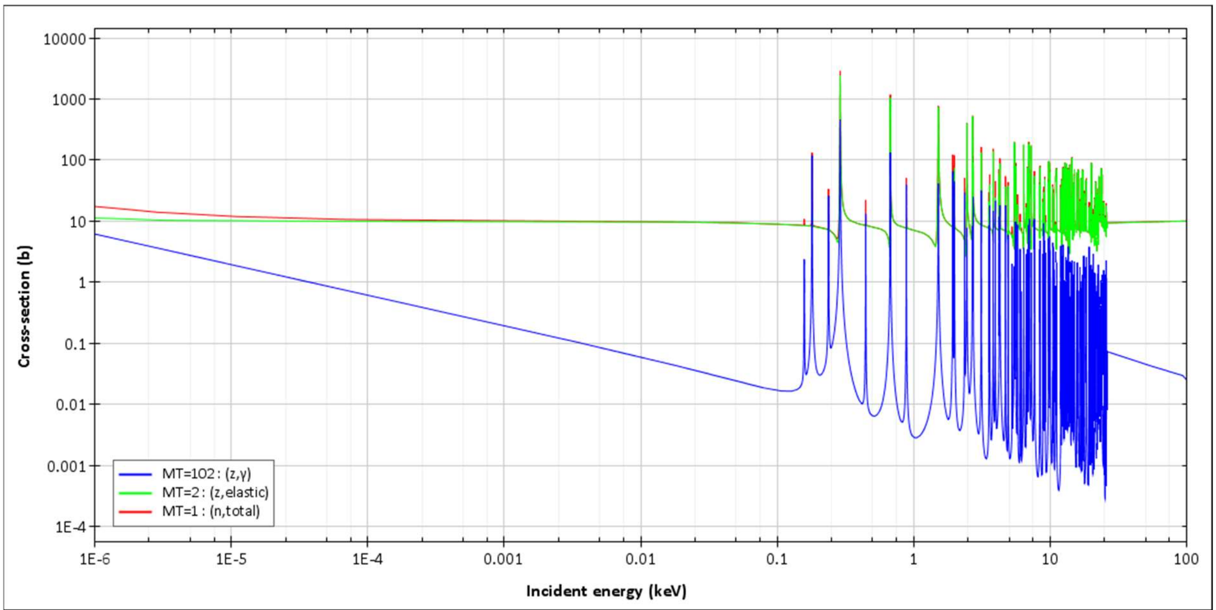

Figure 10: Evaluated cross sections relevant to the energy range of interest from ENDF/B-VIII.0 for ^{91}Zr

The (n,tot) reaction cross section for 91Zr has 5 entries in the EXFOR database and the experimental data ranges from 0.05 keV to above 100 keV, there are no data at thermal neutron energy. The evaluations reproduce the resonance structure as seen by Musgrove (1977)[23]. However, only the TENDL-2019 evaluation reproduces the magnitude of the resonance region, with the other evaluations being ~25 % higher than the data. The spread of the evaluations at thermal energies is large with a standard deviation of 8.65 %. See Figure 11.

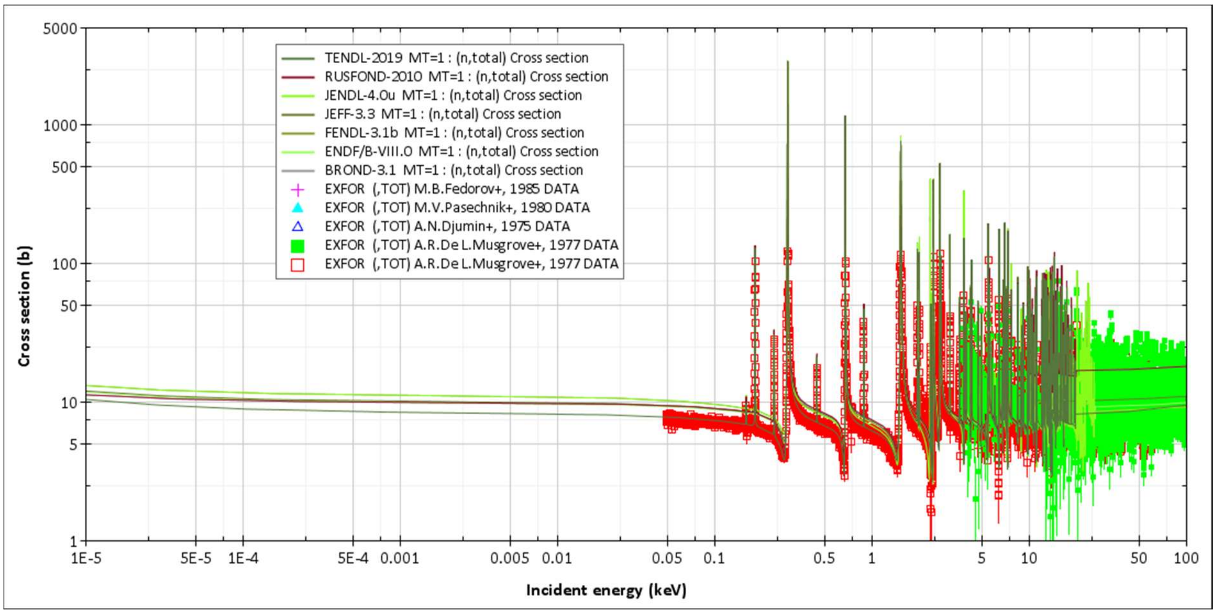

Figure 11: EXFOR data for the total reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{91}Zr

There is only one entry in the EXFOR database for the elastic scatter of neutrons on 91Zr, that of Mughabghab at thermal neutron energy. The data agrees with CENDL-3.2, JENDL-4.0 and FENDL-3.1b within uncertainties. The standard deviation of the evaluated cross section at thermal neutron energy is 8.94%. If the TENDL-2019 evaluation is excluded the standard deviation is 5.61 %. The TENDL-2019 value is ~25 % lower than the mean of the other evaluations. See Figure 12.

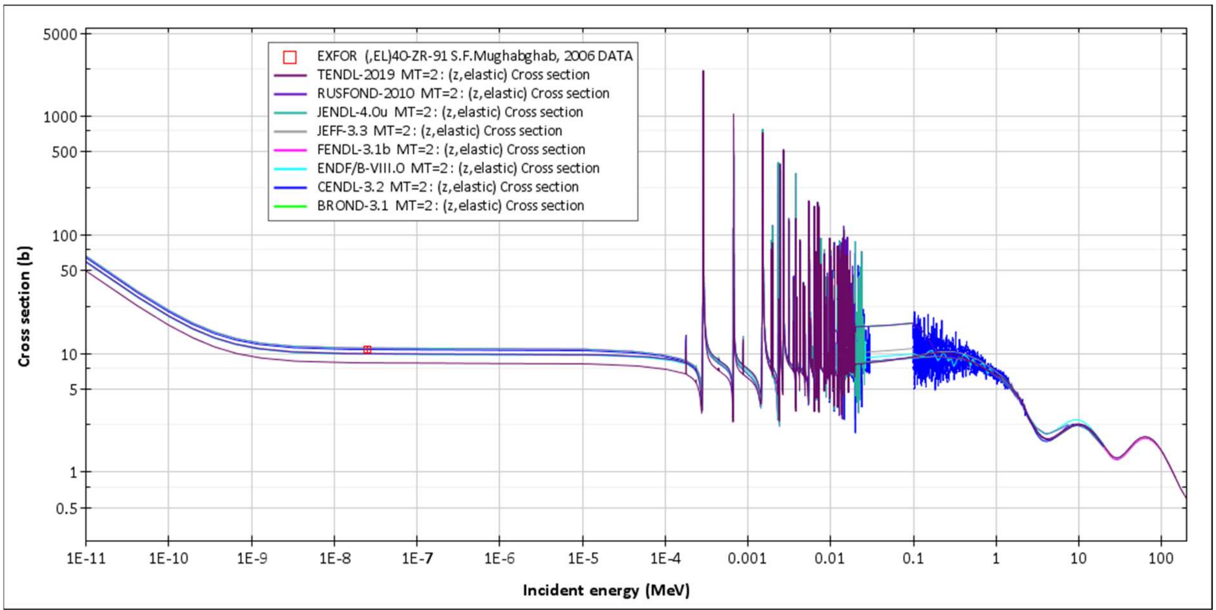

Figure 12: EXFOR data for the elastic scattering reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{91}Zr

There are 8 data entries for neutron capture reactions on 91Zr, with most data above 0.01 keV neutron energy, and only 1 value at thermal energy (Mughabghab). The evaluated libraries agree well in the resonance region. However, the structure of the resonance peaks is not reproduced in the experimental data, its seems to be averaged out over the entire region. At thermal energies the data agrees well with the evaluations BROND-3.1 and RUSFOND-2010. The remaining evaluated libraries are ~40-55% higher than the data. See Figure 13.

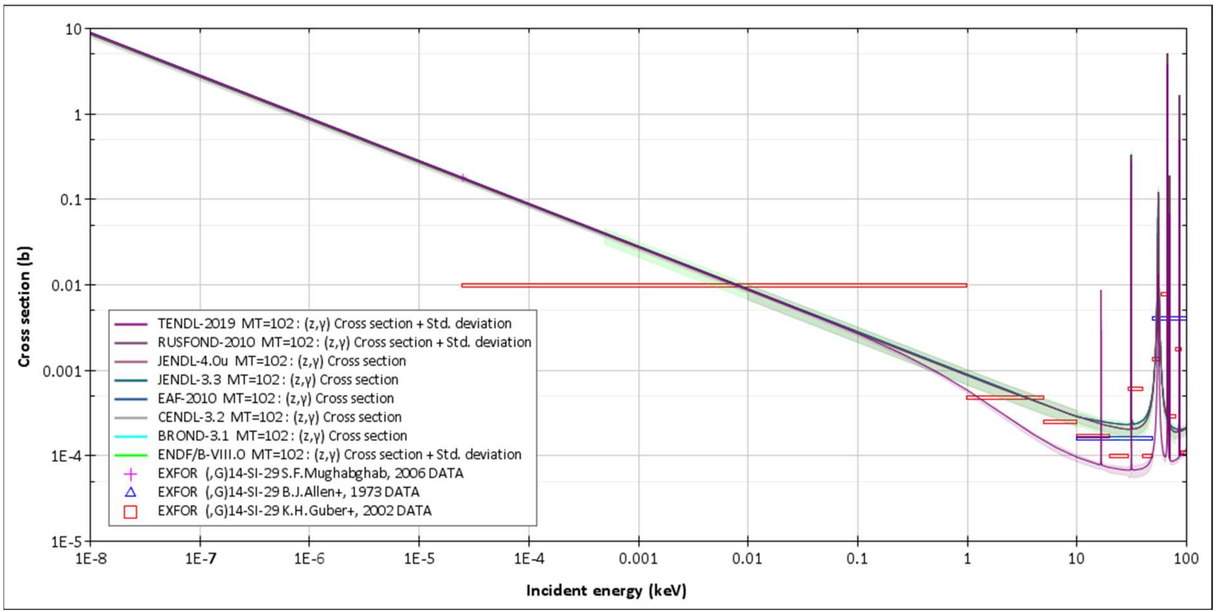

Figure 13: EXFOR data for the neutron capture reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{91}Zr

The lowest lying excited state in 91Zr is above 100 keV and as such there is now inelastic scattering reaction channel in the energy range of interest.

2.3.2 Zirconium-92

Figure 14 shows the relevant cross sections across the energy range of interest. The dominant cross section is elastic scattering which comprises the majority of the total across the whole range. However, at the low end of the energy range neutron capture is ~13 % of the total at 1 meV.

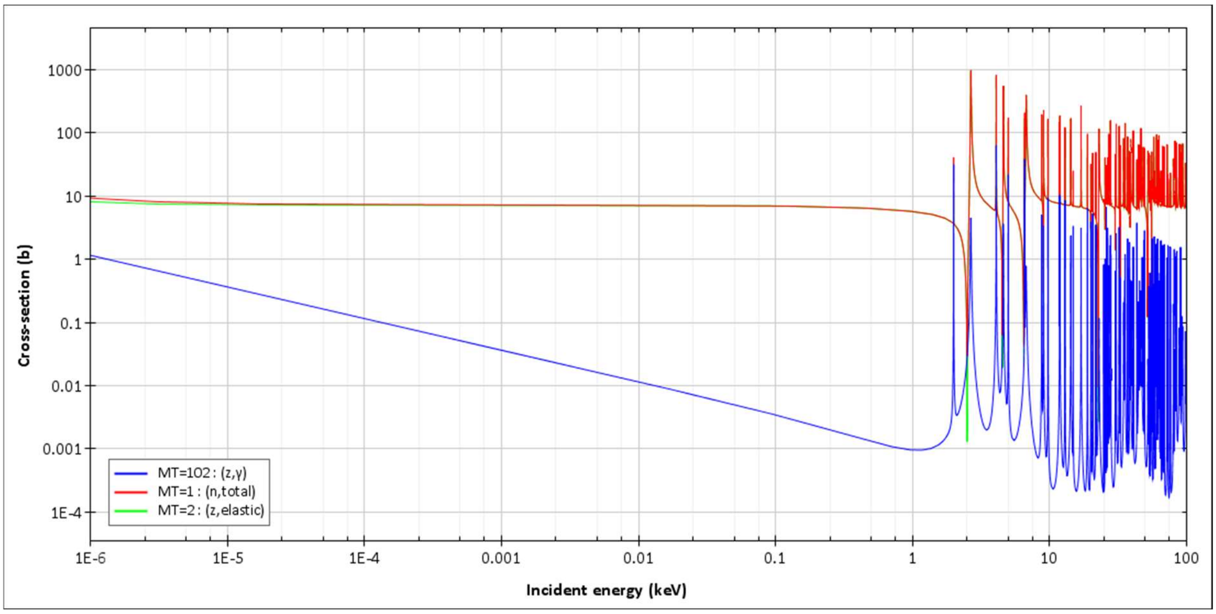

Figure 14: Evaluated cross sections relevant to the energy range of interest from ENDF/B-VIII.0 for ^{92}Zr

The (n,tot) reaction cross section for 92Zr has 6 data sets in the EXFOR database with all data above 1 keV, there are no data at thermal neutron energy. The evaluated cross sections reproduce the data in magnitude, but not in detail as the experimental data does not show resonances with the same height or width of peaks. See Figure 15.

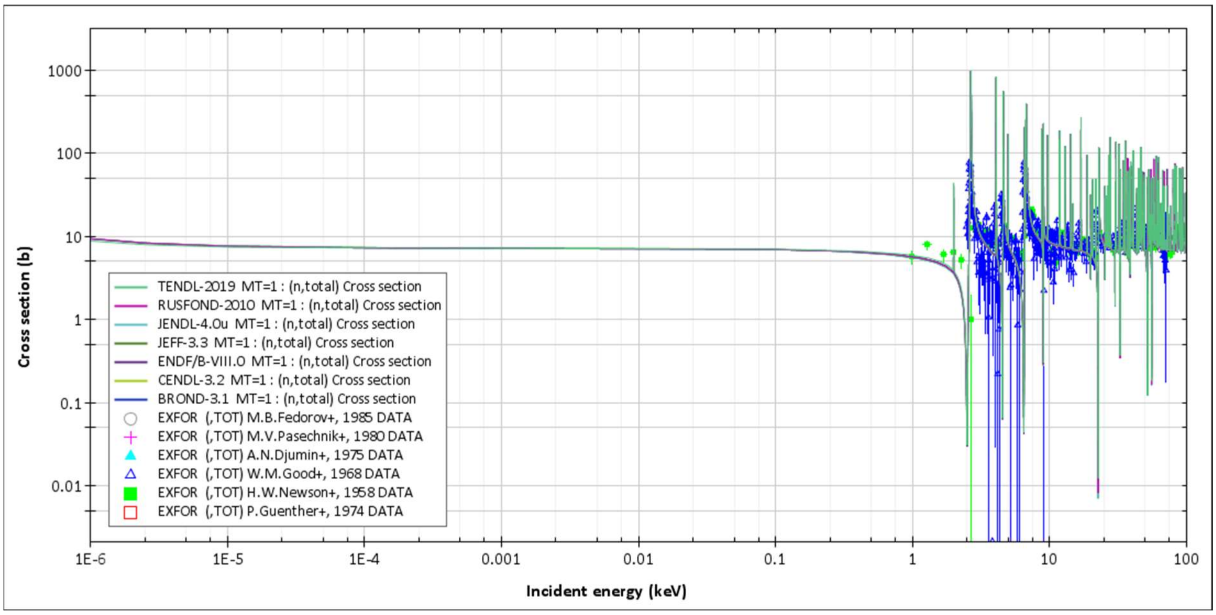

Figure 15: EXFOR data for the total reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{92}Zr

Similar to 91Zr, there is only one entry in the EXFOR database for the elastic scatter of neutrons on 92Zr, that of Mughabghab at thermal neutron energy. All evaluated cross section, with the possible exception of TENDL below about 0.5 keV, agree well with each other across the whole energy range of interest and also with the datum of Mughabghab within uncertainties. See Figure 16.

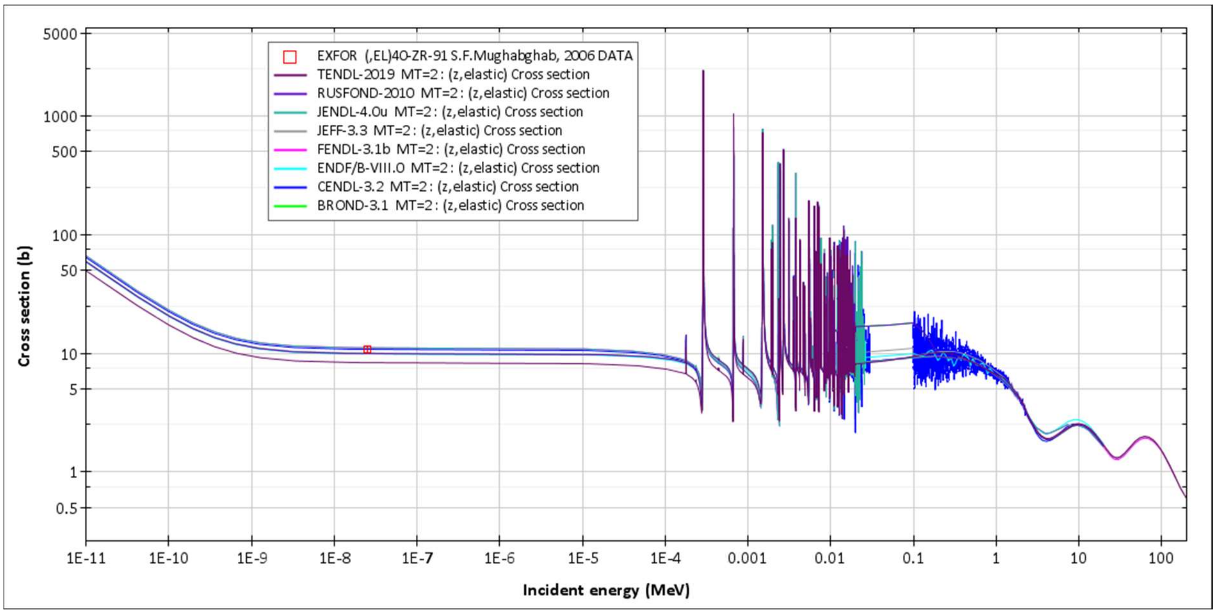

Figure 16: EXFOR data for the elastic scattering reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{92}Zr

There are 3 data sets for neutron capture reactions on 92Zr, with two data sets above 1 keV neutron energy, and only 1 datum at thermal energy (Mughabghab). The evaluated libraries agree well in the resonance region. However, the is resonance peak structure is not reproduced in the experimental data, as each data point covers a large energy range. At thermal energies the data agrees well within uncertainties with all the evaluations other than TENDL-2019, which is ~50% lower than the EXFOR entry from Mughabghab. See Figure 17.

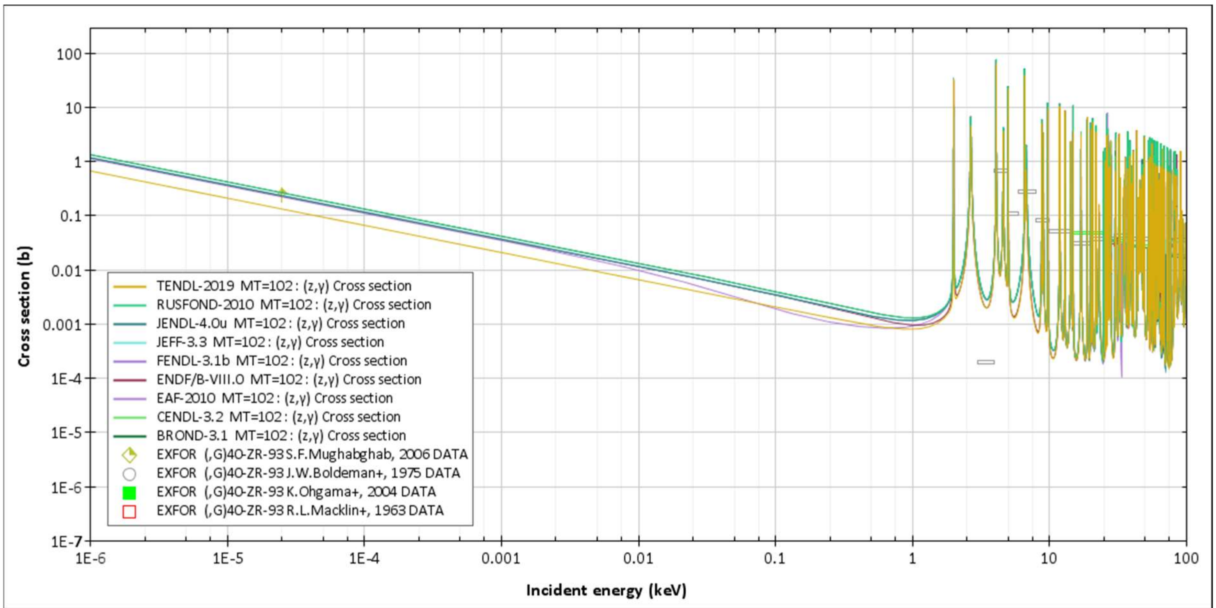

Figure 17: EXFOR data for the neutron capture reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{92}Zr

The lowest lying excited state in 92Zr is above 100 keV and as such there is now inelastic scattering reaction channel in the energy range of interest.

2.4 FLOURINE-19

Fluorine is monoisotopic, the only stable is isotope is Flourine-19. Fluorine is a potential component of coolants in molten salt reactors (MSR), for example a FLiBe coolant. Fluorine is also relevant to MSR designs in which the fuel takes a solid form (heterogeneous) or where the fuel is itself part of the molten salt (homogeneous).

Figure 18 shows the relevant cross sections across the energy range of interest. The dominant cross section is elastic scattering which comprises the majority of the total across the whole range.

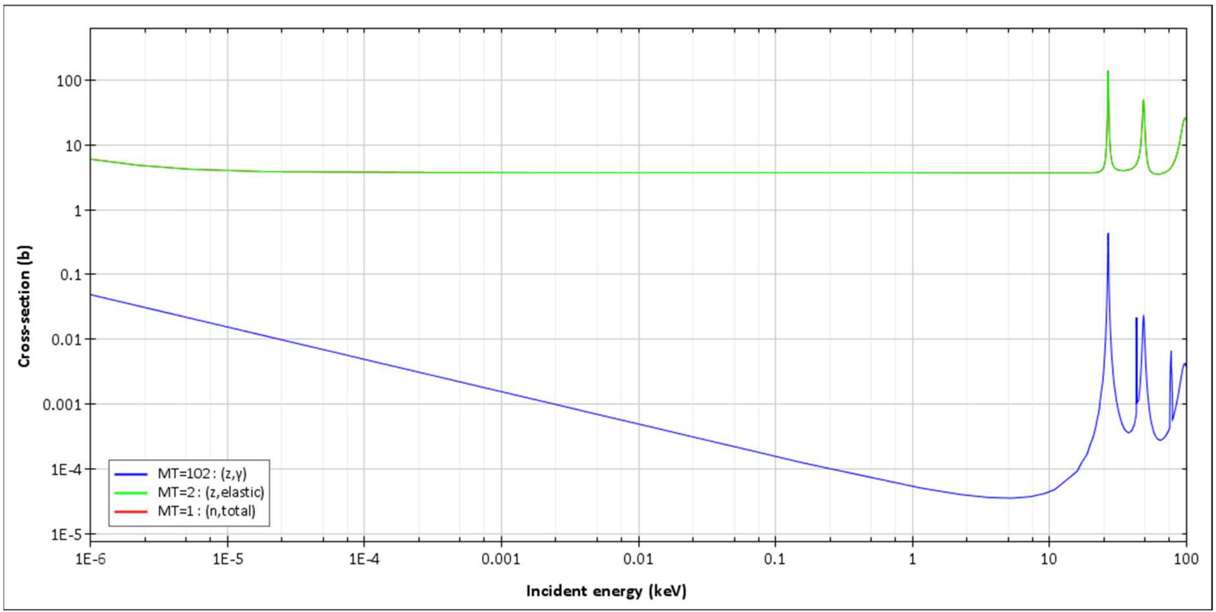

Figure 18: Evaluated cross sections relevant to the energy range of interest from ENDF/B-VIII.0 for ^{19}F

There are a large number of experimental data in the neutron induced total reaction cross section for 19F, with over 40 entries in the EXFOR data base. The nuclear data evaluations agree well across the energy range of interest with a standard deviation ~0.02 % between the evaluations at 25.3 meV. This is smaller than the given uncertainty, i.e. the standard deviation on the ENDF/B-VIII.0 evaluation at thermal neutron energy is ~1.5 %. See Figure 19.

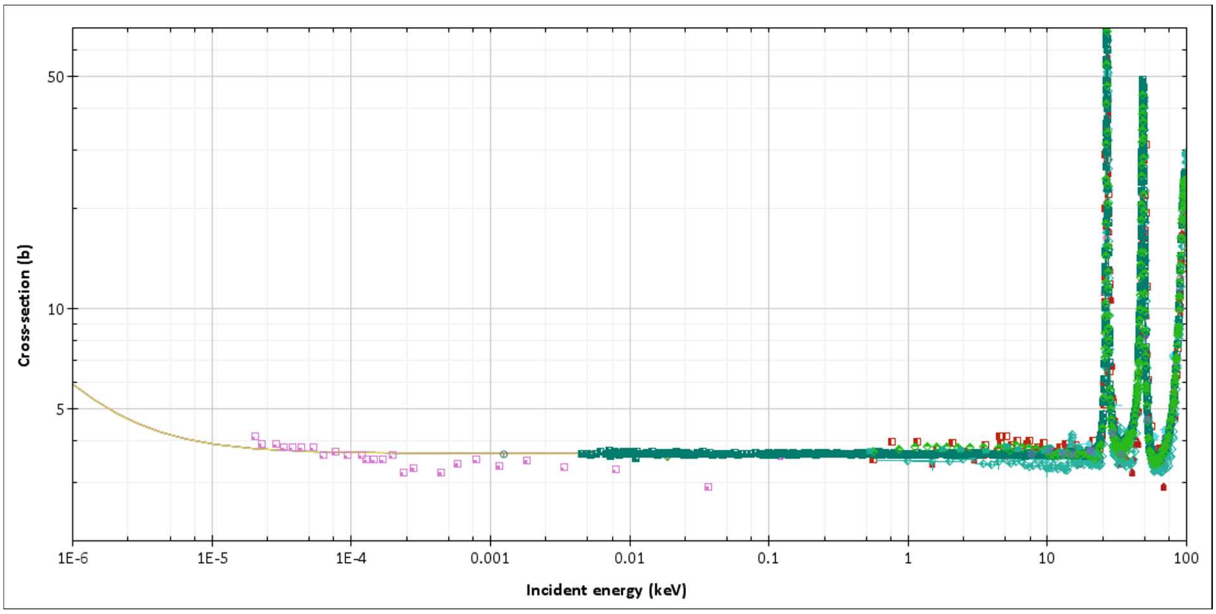

Figure 19: EXFOR data for the total reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{19}F

There are no experimental data in the EXFOR library for the elastic scattering reaction on 19F that can be compared to the evaluated data libraries, i.e. the experimental data is not integrated over angle or the neutron energy is a dummy incident projectile energy spectrum, converted from a different energy. There is a datum from S. F. Mughabghab that can be compared to evaluations. The evaluated nuclear data libraries agree well across the whole energy range of interest, with a standard deviation of 0.02% at thermal neutron energy. However, the evaluations do not agree with the value of Mughabghab, which is ~2.7 % lower than the mean of the evaluations. See Figure 20.

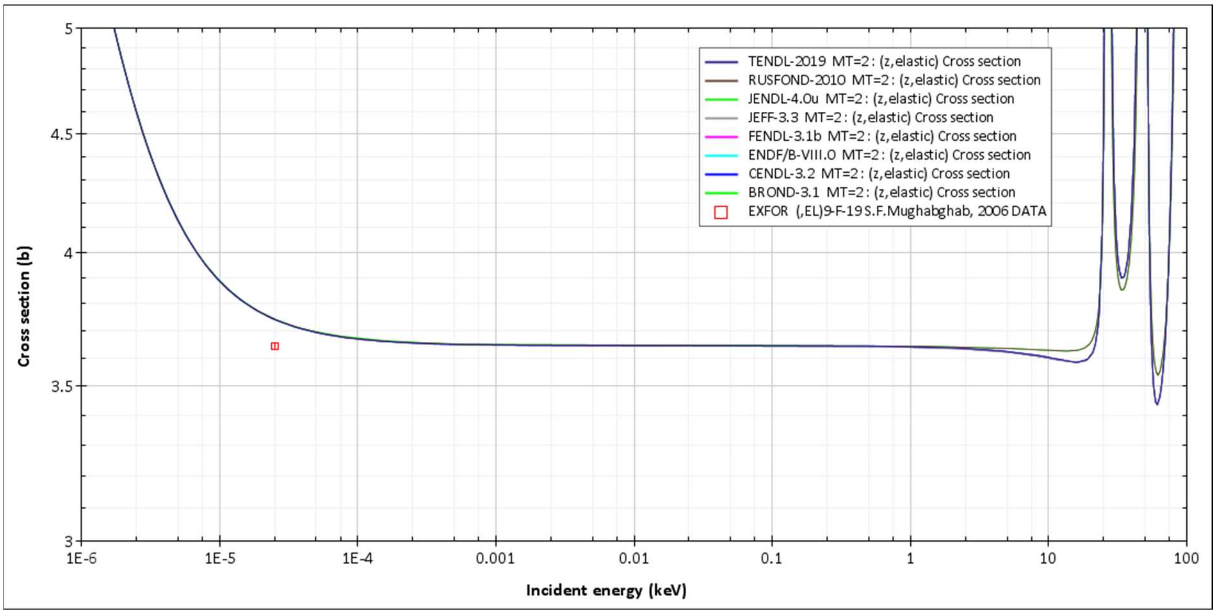

Figure 20: EXFOR data for the elastic scattering reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{19}F

There are 8 data entries for the neutron capture reaction channel for 19F, with most data above 10 keV neutron energy, and 2 data sets at or near thermal energy. The evaluated libraries agree well up to ~1 keV. At thermal energies the libraries agree well with a standard deviation of ~0.04%, excluding the EAF-2010 evaluation which is ~0.7% lower than the other evaluations. Above 1 keV the experimental data do not show the resonance structure as strongly as visible in the evaluated libraries. See Figure 21 and Figure 22.

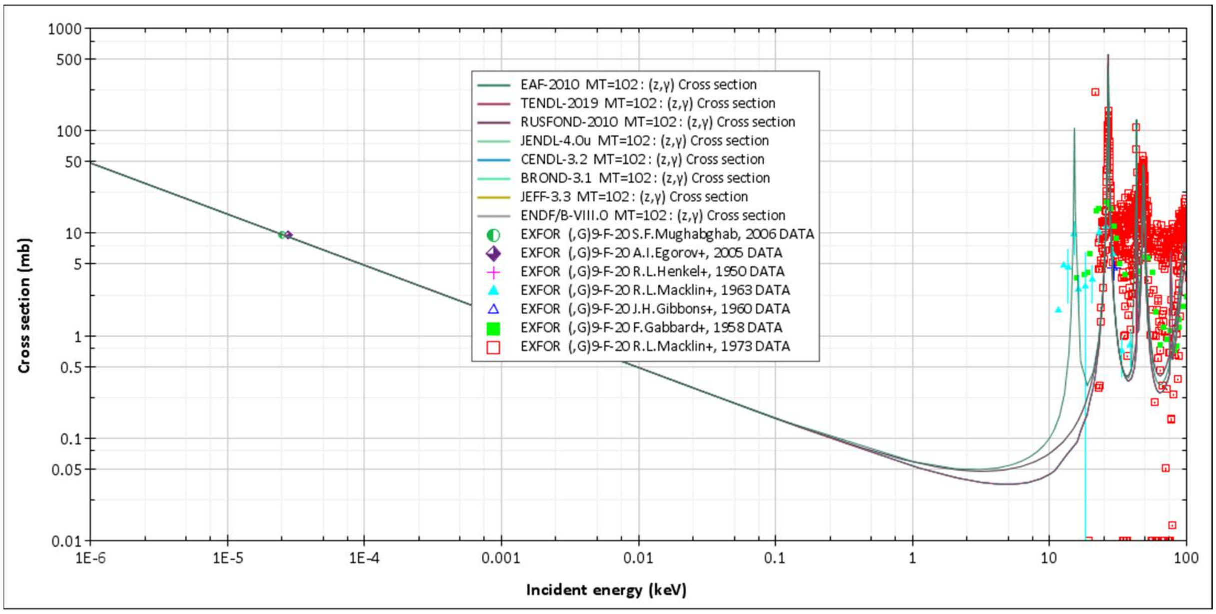

Figure 21: EXFOR data for the neutron capture reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{19}F

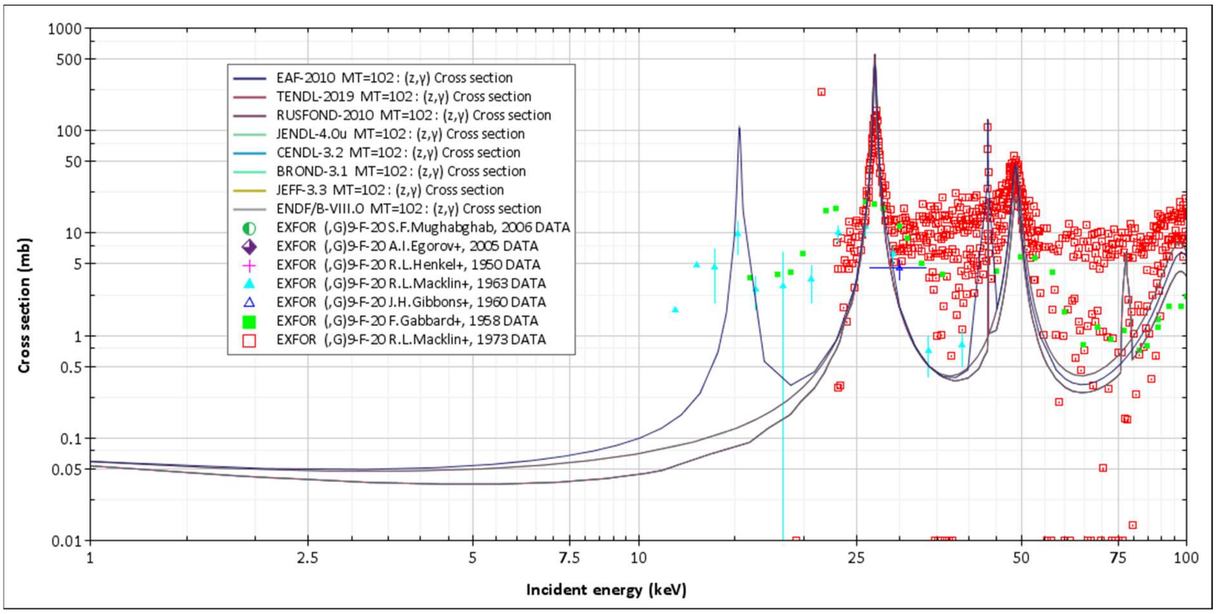

Figure 22: EXFOR data for the neutron capture reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{19}F, zoomed on the region 1 to 100 keV

The lowest lying excited state in 19F is above 100 keV and as such there is now inelastic scattering reaction channel in the energy range of interest.

2.5 NIOBIUM-93

Niobium is monoisotopic, the only stable is isotope is Niobium-93. Niobium is an impurity (at ~1%) in Zircaloy and it has a larger absorption cross-section than zirconium isotopes. This means that this small impurity is relevant to the performance of nuclear fuel cladding in thermal and epithermal reactors. During neutron capture reactions 93Nb is transmuted into 94Nb with a 20,000-year half-life, which is potentially problematic for nuclear waste. Separately niobium is a possible component of future advanced fuels.

Figure 23 shows the relevant cross sections across the energy range of interest. The dominant cross section is elastic scattering which comprises the majority of the total across the whole range. However, at the low end of the energy range neutron capture is ~44 % of the total at 1 meV.

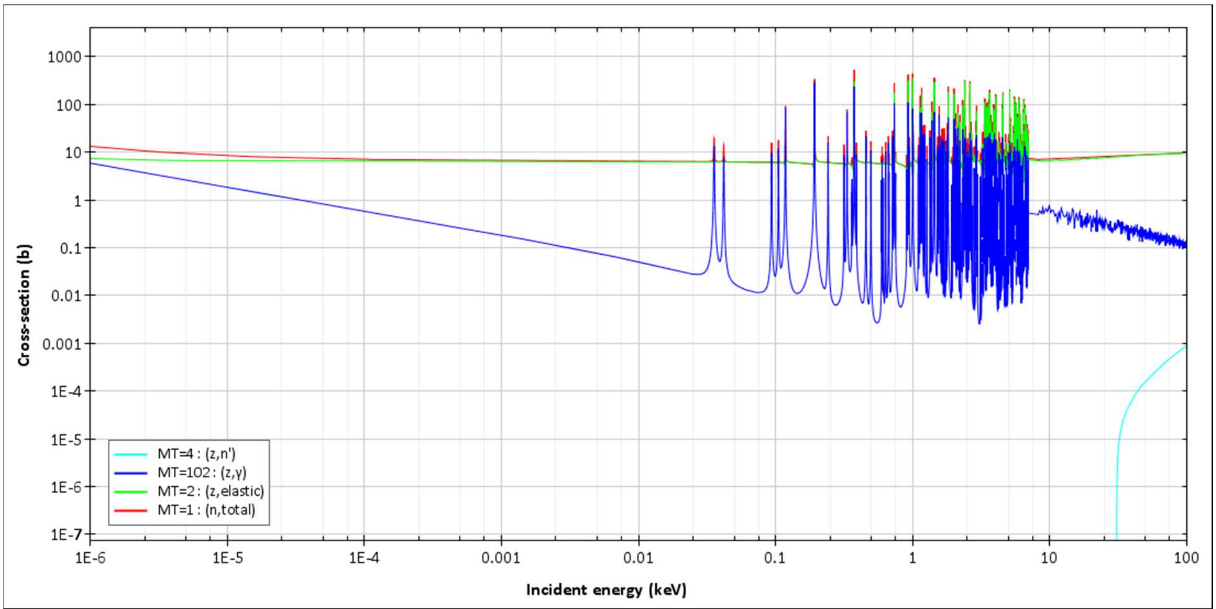

Figure 23: Evaluated cross sections relevant to the energy range of interest from ENDF/B-VIII.0 for ^{93}Nb

There are a large number of experimental data in the neutron induced total reaction cross section for 93Nb, with over 40 entries in the EXFOR database. The experimental data and evaluations agree across the energy range and the resonance region in the data is well reproduced in the evaluations. At lower energy, below ~100 eV, there is a significant spread in the data and the evaluations do not reproduce the shape of the cross section seen in the experimental data. At thermal energy the difference between the highest and lowest experimental data points is ~35%. See Figure 24.

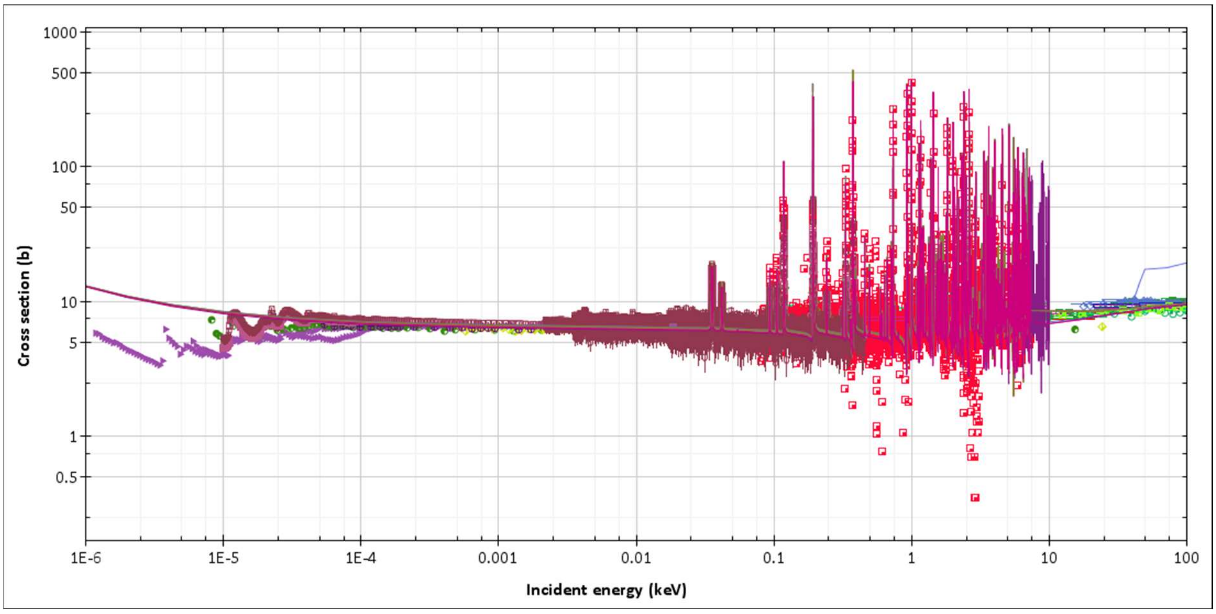

Figure 24: EXFOR data for the total reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{93}Nb

There are 3 data entries for EXFOR in the energy range of interest for the neutron induced elastic scattering reaction: S. F. Mughabghab, and C. G. Shull (1950)[24] at thermal neutron energy and A. B. Popov (1982)[25] above ~2 keV. The data of A. B. Popov agrees well with the CENDL-3.2, FENDL-3.1b ,JENDL-4.0, RUSFOND-2010, but not with the other evaluations. Above 10 keV the largest difference between the evaluations is ~27 %. The two thermal data points agree within uncertainties with each other and the evaluations. See Figure 25.

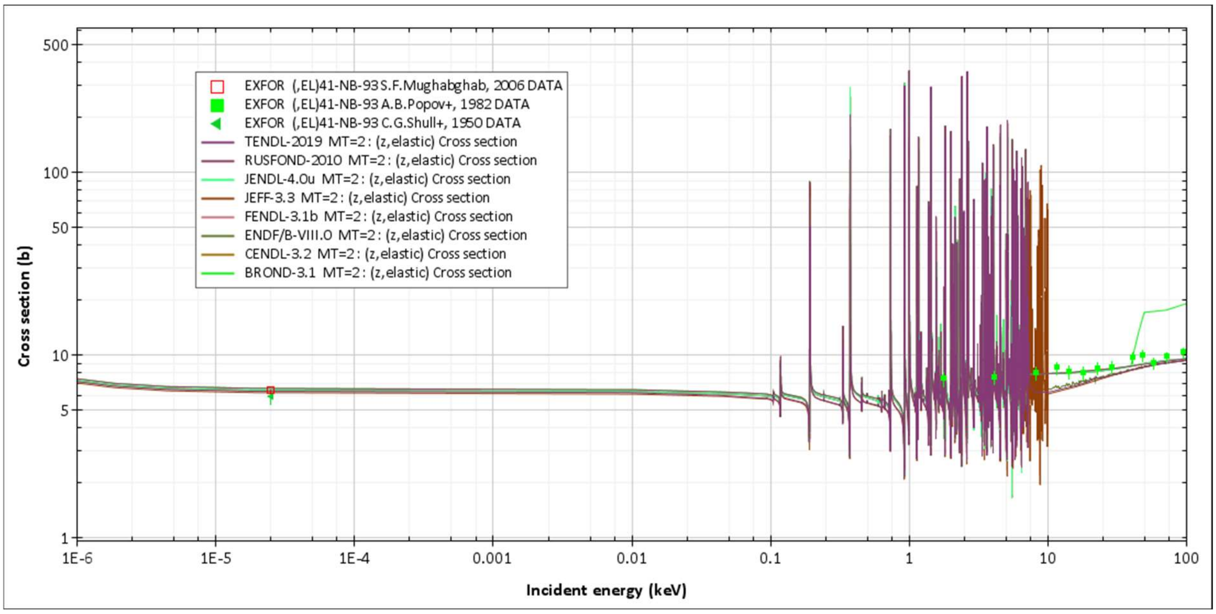

Figure 25: EXFOR data for the elastic scattering reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{93}Nb

There are 31 data entries for neutron capture reactions on 93Nb, with most data above 10 keV neutron energy, and 4 data sets at or near thermal energy. The evaluated libraries agree well above ~10 keV. Between ~4 eV and 10 keV there is strong resonance structure in the evaluated cross sections. Some of this is reproduced in the experimental data, but its largely averaged out above 0.5 keV. At thermal energies 3 of the 4 data sets agree well with each other and the evaluations. The fourth data set of S. Endo (2022)[26] is lower than the others (~20 %). However, this is recent publication and not included in the evaluated cross sections. See Figure 26.

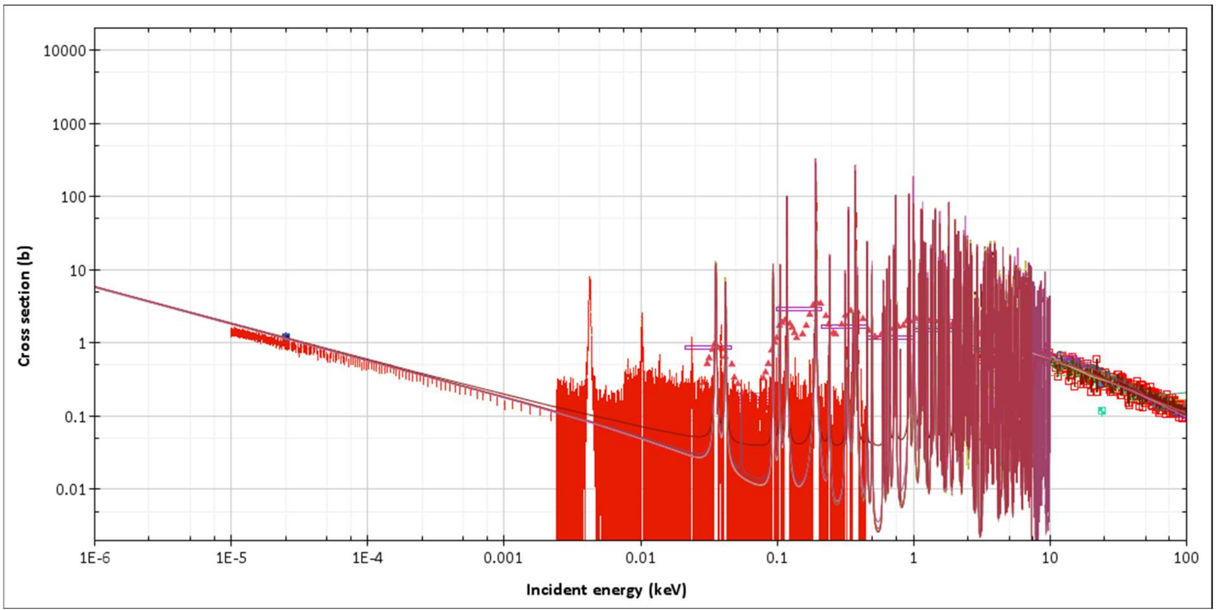

Figure 26: EXFOR data for the neutron capture reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{93}Nb

The lowest lying excited state in 93Nb is at ~30 keV which means inelastic scattering reactions are possible within the energy range. There are 11 entries in the EXFOR database for this reaction, but the incident neutron energy range for the data sets is 400 keV to 20 MeV, i.e. above the range of interest. The evaluations agree well with each other and are small compared to the other reaction mechanisms at this energy, i.e. ~10,000 times less than (n,tot) at 100 keV. The 30 keV excited state in 93Nb is isomeric and has a half life of 16.12 years. See Figure 27.

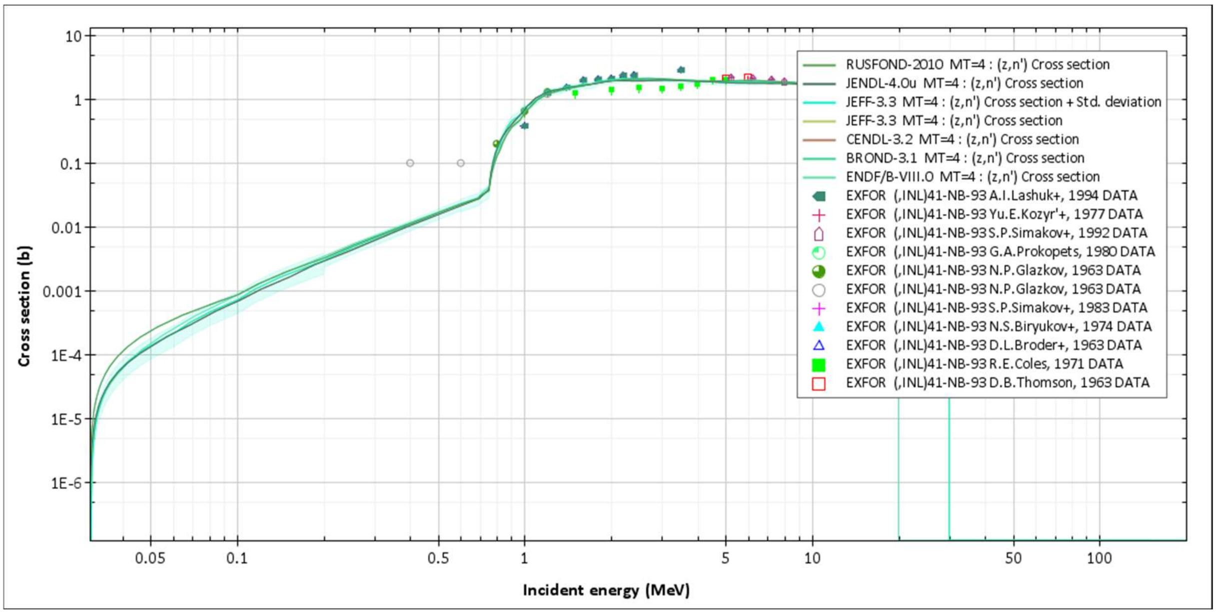

Figure 27: EXFOR data for the inelastic scattering reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{92}Nb

2.6 XENON-135

There are 9 stable isotopes of xenon. Xenon-135 is unstable and only has a 9.168 h half life. Xenon-135 is a gaseous fission fragment and has a very large neutron capture cross section, and as such it is a well-known neutron poison.

Figure 28 shows the relevant cross sections across the energy range of interest. The dominant cross section at low energy is the neutron capture reaction, which is very high at ~2.7×10^6 b at thermal energy. At this energy the elastic scattering cross section is also very large at ~3×10^5 b. At ~1.5 eV the elastic scattering becomes larger than neutron capture. At 100 keV the elastic scatter cross section is dominant and ~180 times larger than the neutron capture reaction.

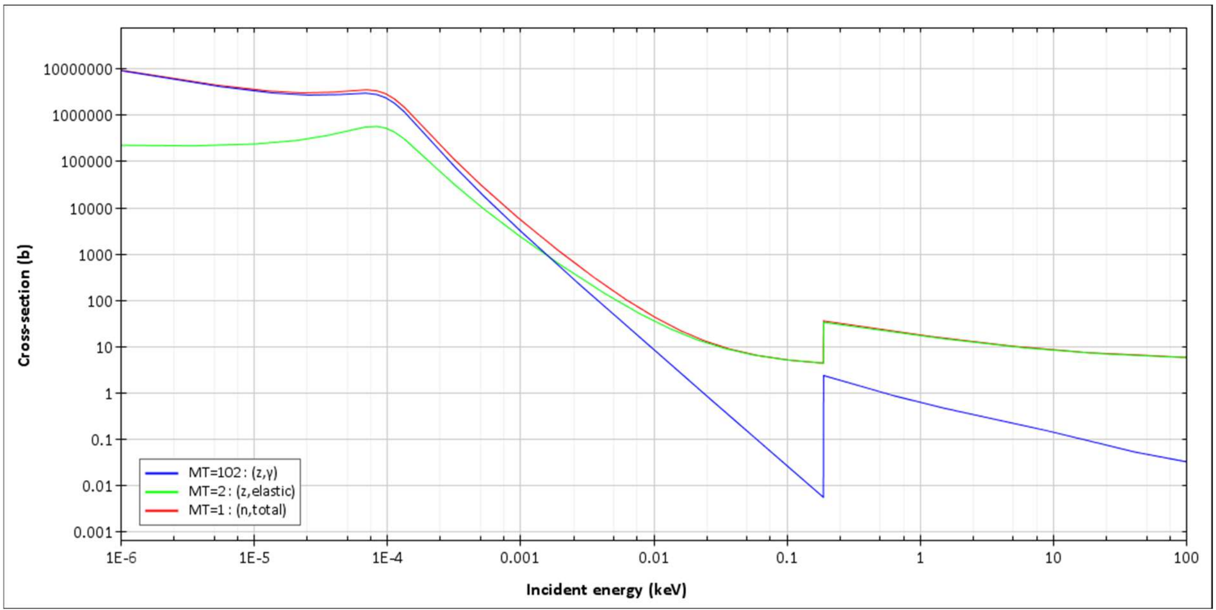

Figure 28: Evaluated cross sections relevant to the energy range of interest from ENDF/B-VIII.0 for ^{135}Xe

There is one measurement of the total neutron cross section on 135Xe. The measurement, by Smith (1959)[27] was performed at Oak Ridge National Laboratory. A mechanical time-of-flight chopper was used to select neutrons in the energy range from 10 meV to ~325 meV. The 135Xe gas used in this experiment was first collected from a reactor. The evaluated data libraries agree well with the experimental data and with each other up to ~10 eV. The resonance region is approximated by all evaluated cross sections (seen as a discontinuity in the cross section between 0.1 and 1 keV, depending on the evaluation) other than TENDL-2019. See Figure 29.

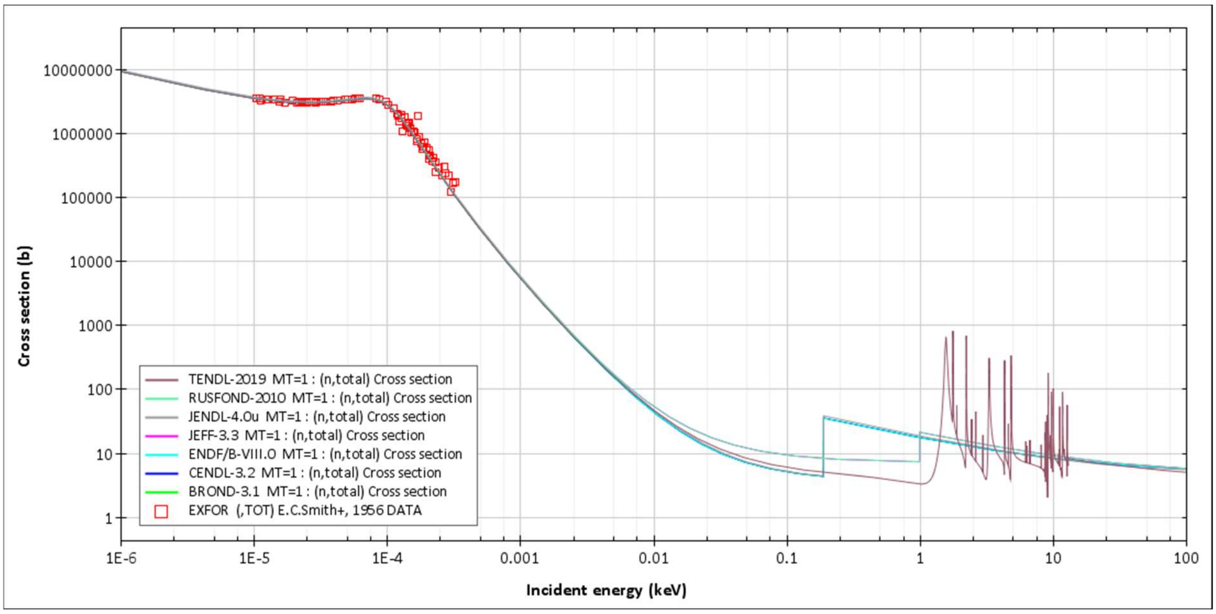

Figure 29: EXFOR data for the total reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{135}Xe

There are no entries in the EXFOR data base for elastic scattering reactions on 135Xe. The evaluated data libraries agree well across the range up to ~10 eV, other than JENDL-4.0 which is ~10% at thermal neutron energy. Similarly to the total cross section for this isotope, the resonance region is approximated by all evaluated cross other than TENDL-2019 and there are discontinuities in the evaluated cross sections. See Figure 30.

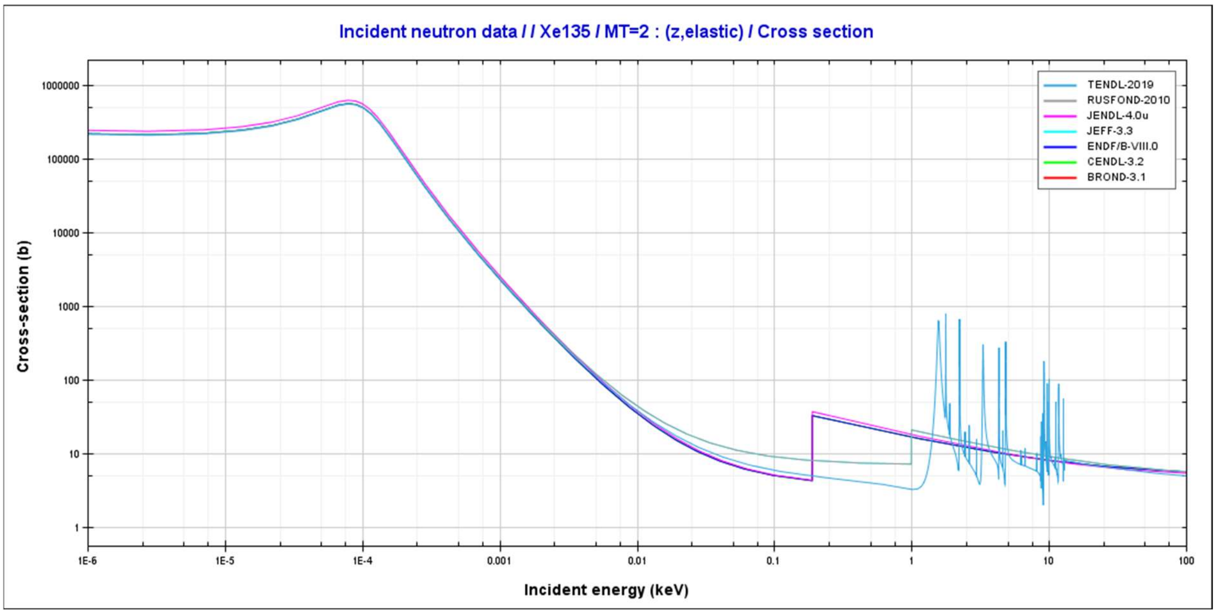

Figure 30: EXFOR data for the elastic scattering reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{135}Xe

There is one entry in EXFOR for neutron capture reactions on 135Xe, that of Mughabghab. All evaluated cross sections agree with this datum within uncertainties, except JENDL-4.0, which is ~ 4% larger than the mean of the other evaluations. At higher energies, in the keV region the resonance region is approximated by all evaluated cross sections, other than TENDL-2019, and there are discontinuities in the evaluated cross sections. See Figure 31.

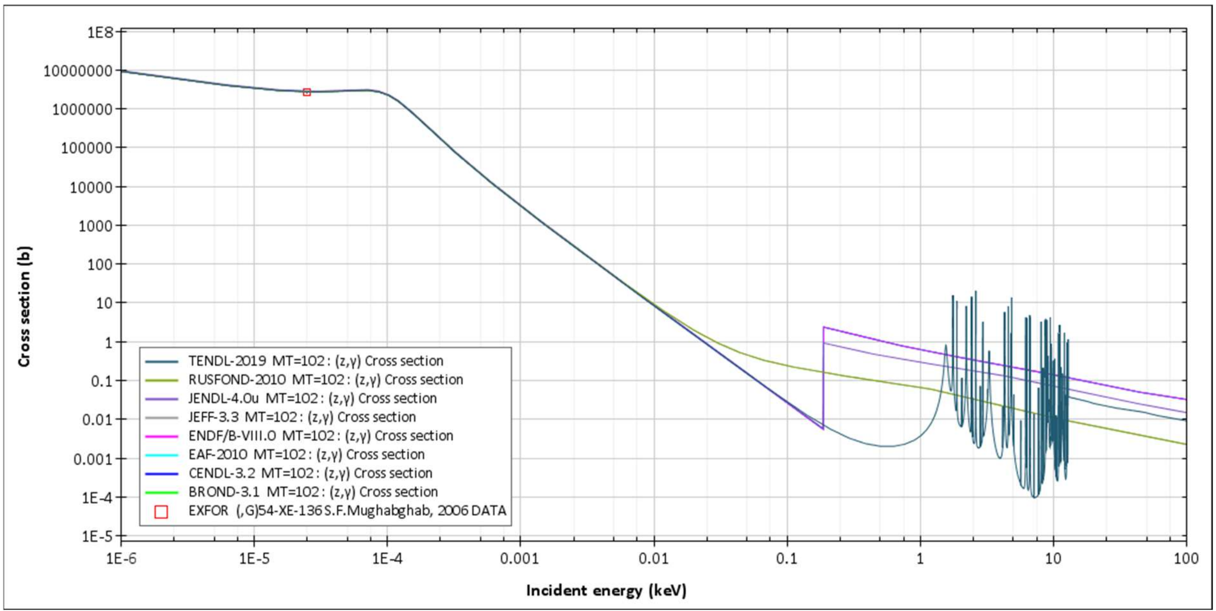

Figure 31: EXFOR data for the neutron capture reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{135}Xe

The lowest lying excited state in 135Xe is above 100 keV and as such there is now inelastic scattering reaction channel in the energy range of interest.

2.7 SAMARIUM-149

There are 8 stable isotopes of Samarium, one of which is Sm-149 with a natural abundance of 13.8 %. Samarium-149 is a fission product in thermal fission and has a large neutron capture cross section, as such it is an important ‘zero power neutron poison’.

Figure 32 shows the relevant cross sections across the energy range of interest. The dominant cross section is neutron capture which comprises the majority of the total, at thermal energy where the neutron capture cross section is ~220 time larger than elastic scattering. At ~0.1 keV, neutron capture is approximately equal to elastic scattering, and by 100 keV elastic scattering is dominant, being ~12 times larger than neutron capture. At 100 keV inelastic scattering is ~15 times less than elastic, comprising ~5 % of the total cross section. See Figure 32.

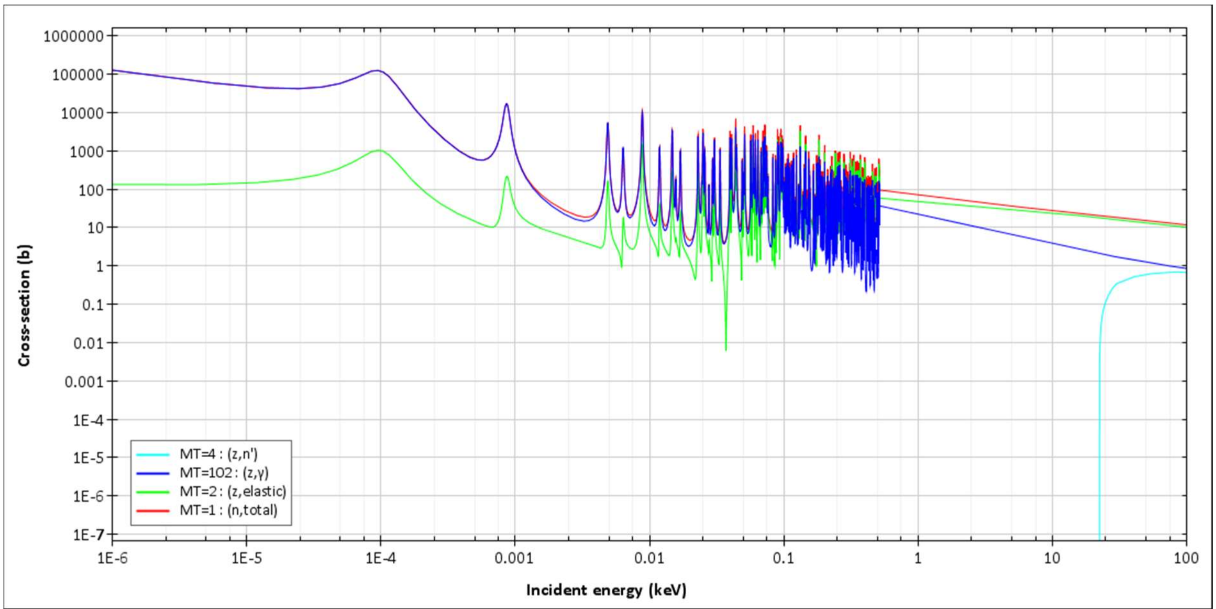

Figure 32: Evaluated cross sections relevant to the energy range of interest from ENDF/B-VIII.0 for ^{149}Sm

There are 6 data sets for the total neutron cross section for 149Sm in the EXFOR database. 5 of these cover the energy range from ~1 meV to 5 eV. The other data set covers the range from 10 to 100 keV. The evaluations agree with the data across the range, with some discrepancies for the resonances at 0.85 and 4.9 eV. See Figure 33.

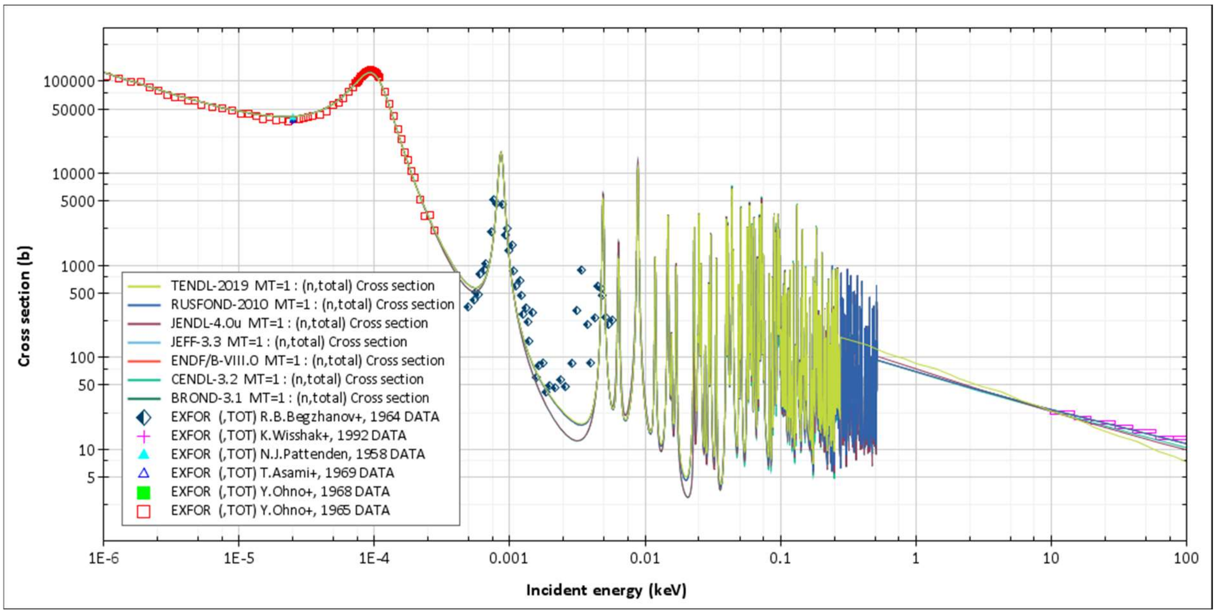

Figure 33: EXFOR data for the total reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{149}Sm

There is only 1 entry in the EXFOR database for elastic scattering on 149Sm, that of Mughabghab at thermal energy. The evaluations agree at thermal energy, with a standard deviation of 2%. The data of Mughabghab is lower than the mean of the evaluations by ~2%. The energy of resonance peaks agree between the evaluations, but the CENDL-3.2 and JENDL-4.0 libraries show a lower magnitude between the resonances by up to a factor of 10. See Figure 34.

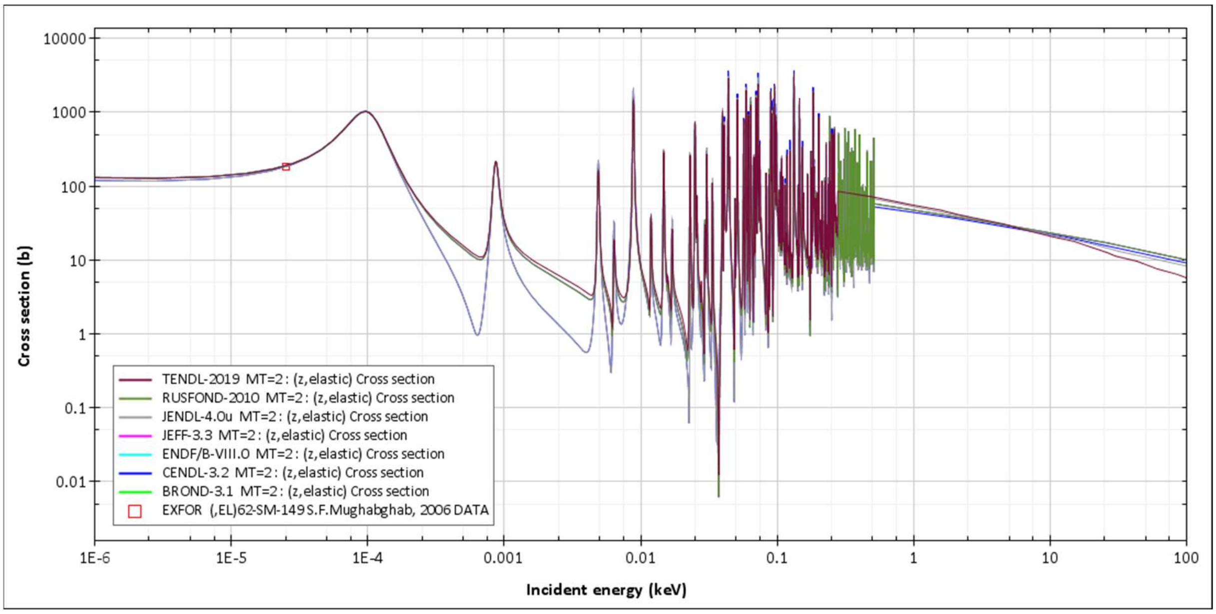

Figure 34: EXFOR data for the elastic scattering reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{149}Sm

There are 10 data sets for the neutron capture reaction on 149Sm, with all except 3 data sets in the energy region above 1 keV. The three data entries at thermal neutron energy, of Mughabghab, Pattenden (1958)[28] and Aitken (1961)[29], agree with each other (within uncertainties) and with the evaluations. In the keV region the data are discrepant, with two distinct trends, one group being ~70% larger than other at 20 keV. The evaluations align with the lower group of data (other than TENDL-2019), which includes more recent data (Wisshak (1992)[30] and Diamet (1999)[31]) than the higher group (Mizumoto (1979)[32] and Kononov (1977)[33]). See Figure 35 and Figure 36.

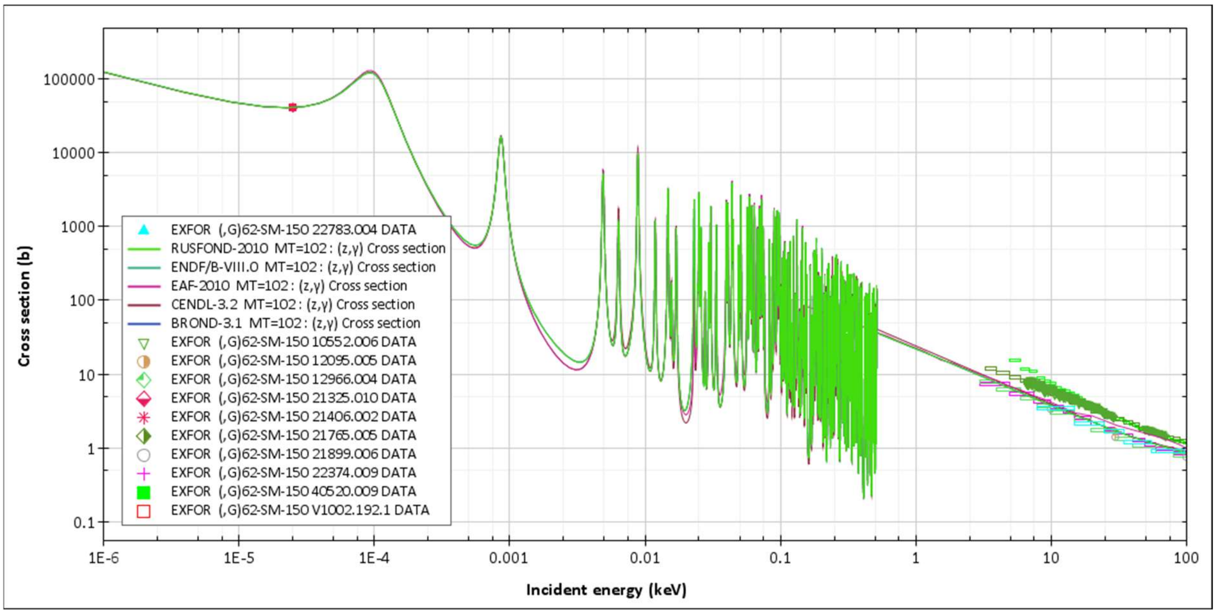

Figure 35: EXFOR data for the neutron capture reaction cross section and evaluated cross sections relevant to the energy range of interest forfor ^{149}Sm

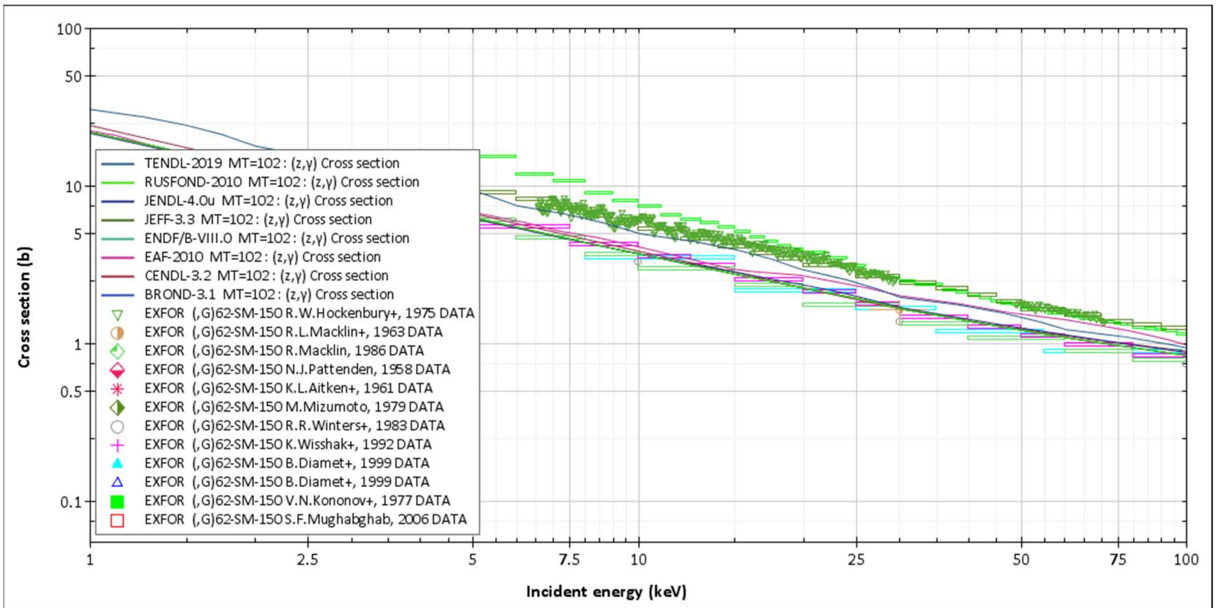

Figure 36: EXFOR data for the neutron capture reaction cross section and evaluated cross sections relevant to the energy range of interest forfor ^{149}Sm, zoomed on the keV energy region

The lowest lying excited state in 149Sm is at ~22 keV, therefore, inelastic scattering reactions are possible within the energy range. There are no entries in the EXFOR database for this reaction. There are discrepancies between the evaluations across the energy range of interest. For example, at 30 keV the smallest evaluation is ~3 times smaller than the largest. See Figure 37. There are no isomeric states in 149Sm, so an activation experiment with subsequent decay measurement is not possible.

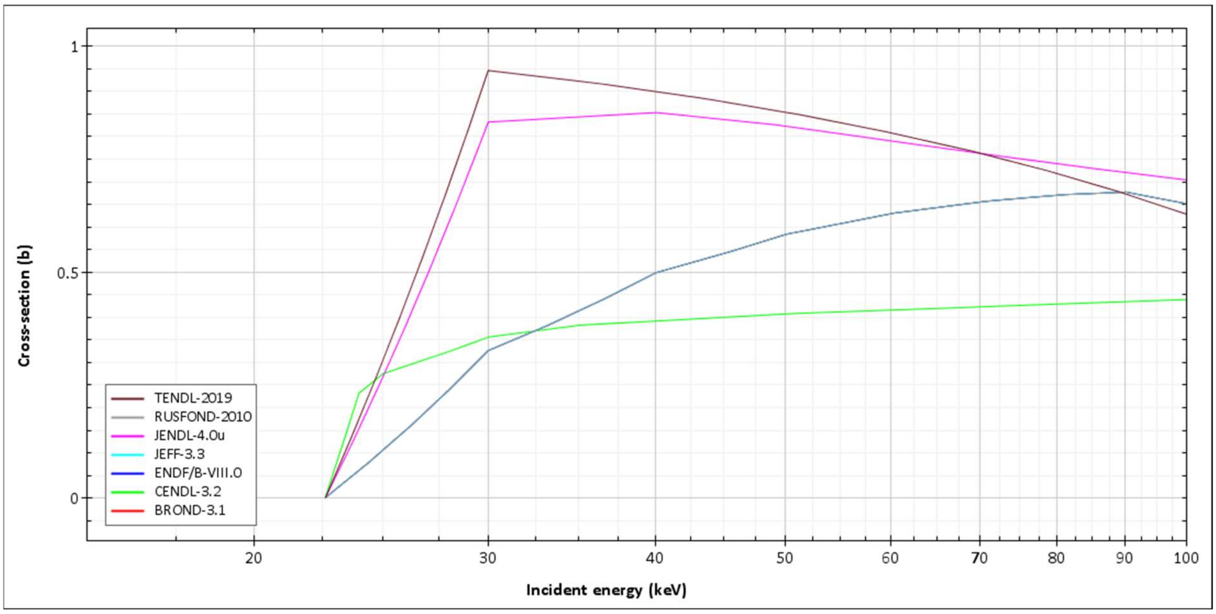

Figure 37: Evaluated inelastic scattering reaction cross sections relevant to the energy range of interest for ^{149}Sm

2.8 CAESIUM-133

Caesium-133 is monoisotopic, it is the only stable naturally occurring isotope of caesium. Caesium ratios can be used in reactor physics calibration calculations to determine the degree of reactor fuel burn-up and the age of a fuel rod. As a consequence, any error in its assumed cross-sections could lead to erroneous reactor physics analysis.

Figure 38 shows the relevant cross sections across the energy range of interest. The dominant cross section is neutron capture which comprises the majority of the total, at thermal energy the neutron capture cross section is ~7 times larger than elastic scattering. At ~0.1 keV, neutron capture is approximately equal to elastic scattering, and by 100 keV elastic scattering is dominant, being ~19 times larger than neutron capture. At 100 keV inelastic scattering is small and ~50 times less than elastic, comprising ~2 % of the total cross section.

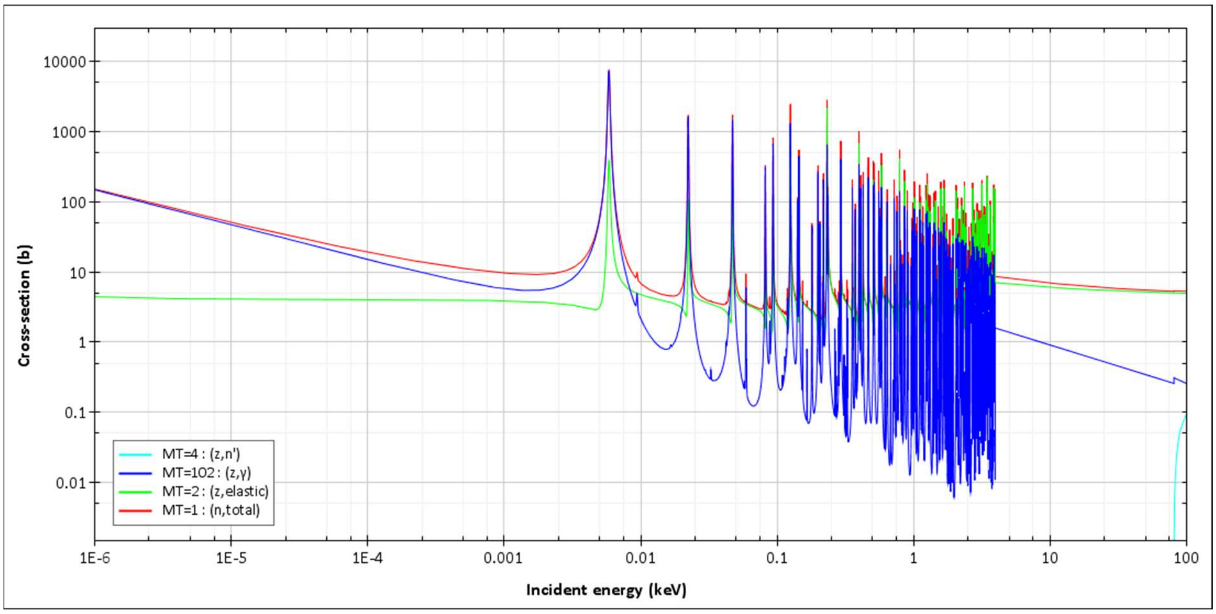

Figure 38: Evaluated cross sections relevant to the energy range of interest from ENDF/B-VIII.0 for ^{133}Cs

There are 7 data sets for the total reaction cross section on 133Cs. The energy range of the data sets is from approximately thermal up to ~10 keV. Data in the region of 10 eV to 5 keV (Harvey (1955)[34] and Garg (1965)[35] have a large scatter, but it appears the evaluations are lower than the mean of the data. TENDL-2019 fits the data through this region better than the other evaluations but does not reproduce the data below 0.5 eV (Hickman (1965)[36] and Brazos (1966)[37]), which the other evaluations do. See Figure 39.

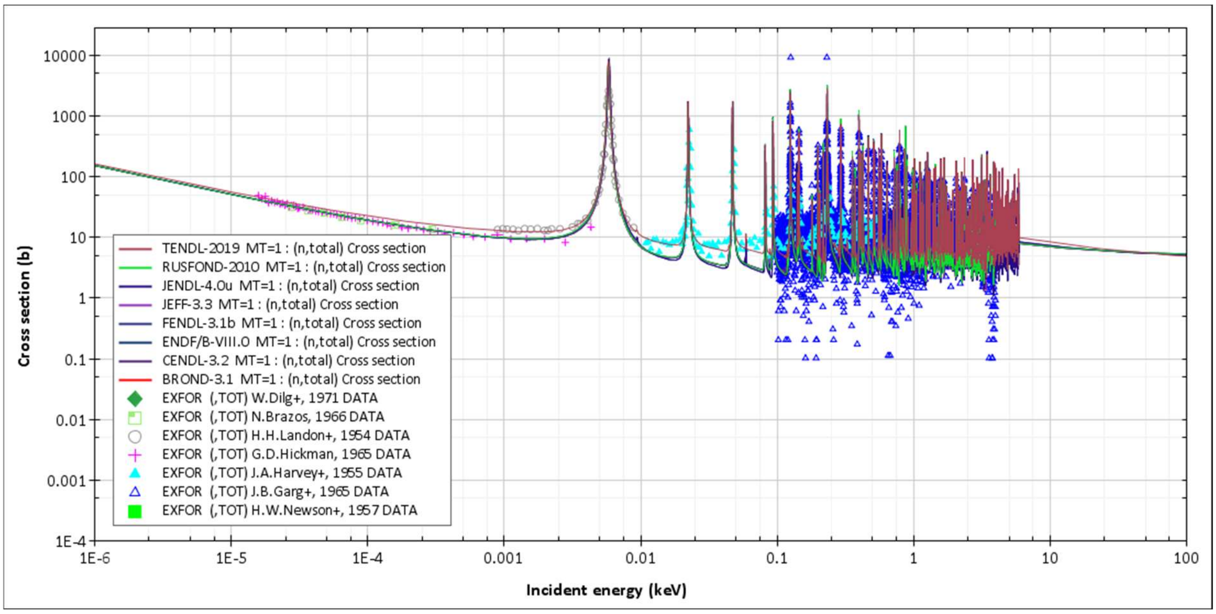

Figure 39: EXFOR data for the total reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{133}Cs

There are 2 EXFOR entries for elastic scattering on 133Cs, both at thermal neutron energy, one of Mughabghab and the other Shull (1950)[24]. The data do not agree with each other, the data of Shull is ~79% larger than Mughabghab, which is much larger than the uncertainties on the data. Most of the evaluations agree with the Mughabghab data, other than TENDL-2019 which agrees with the data of Shull. The discrepancy between TENDL-2019 and the other evaluations continues through the resonance region to the end of the energy range of interest. See Figure 40.

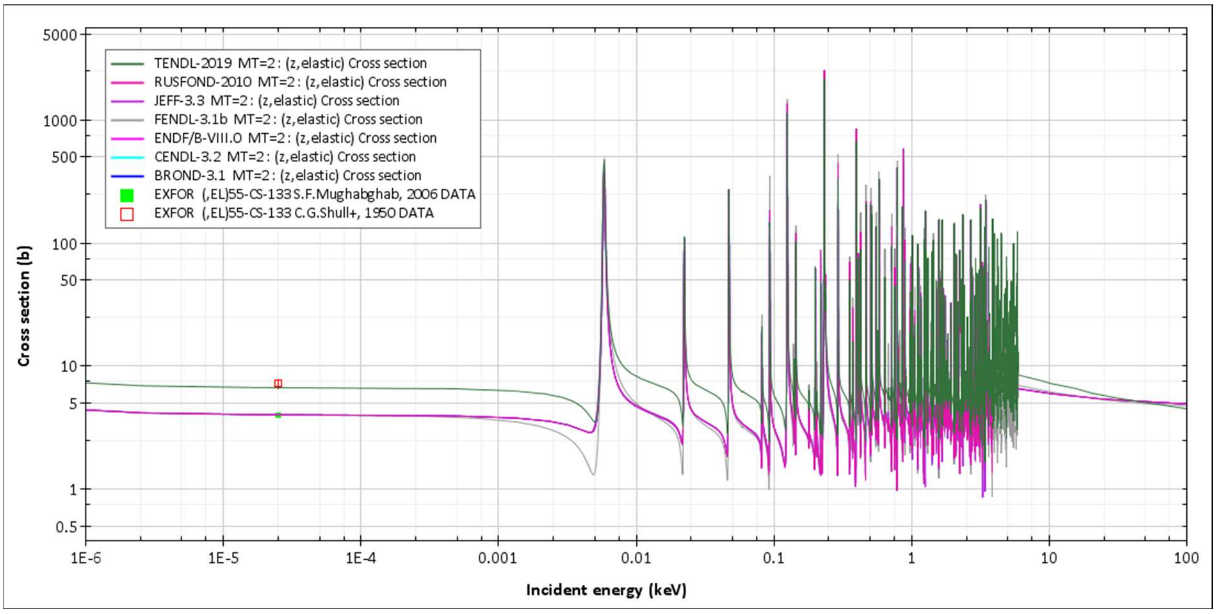

Figure 40: EXFOR data for the elastic scattering reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{133}Cs

There are 20 data sets for the neutron capture cross section on 133Cs. There is generally good agreement across the energy range, with some discrepancies in the resonance region, and 1 data set (D.Kompe (1966)[38]) higher than the others in the keV region. The evaluated cross sections are consistent across the energy range of interest and agree well with the data. See Figure 41.

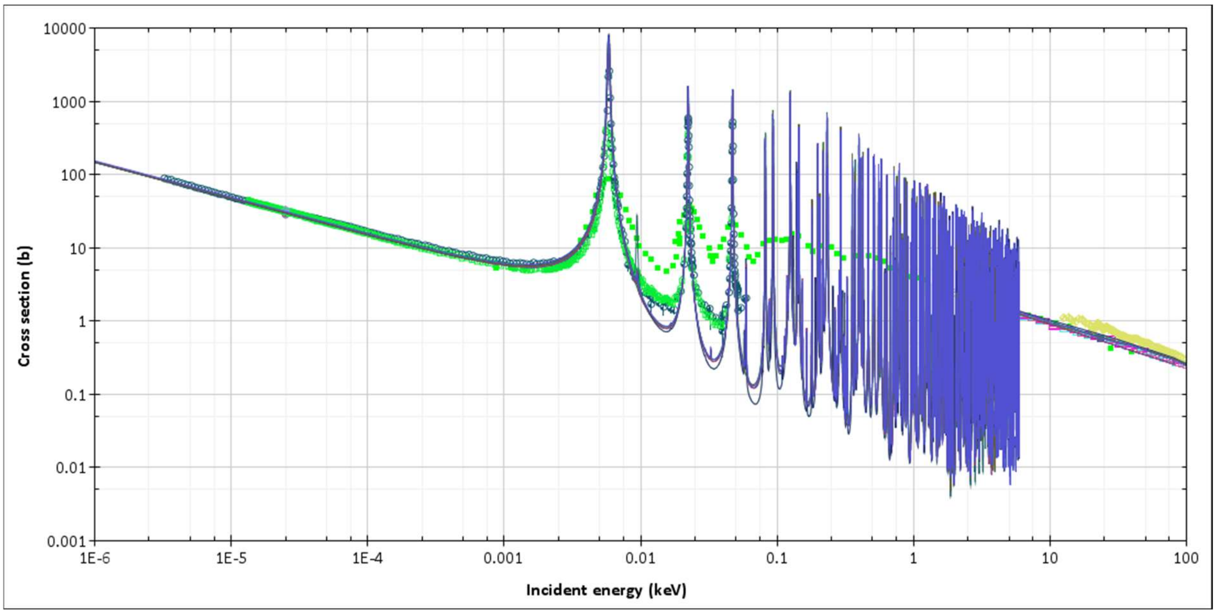

Figure 41: EXFOR data for the neutron capture reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{133}Cs

The lowest lying excited state in 133Cs is at ~81 keV, therefore, inelastic scattering reactions are possible within the energy range. There are no entries in the EXFOR database for this reaction. There are discrepancies between the evaluations across the energy range of interest. For example, at 90 keV the smallest evaluation is ~2 times smaller than the largest. There are no isomeric states in 133Cs, so an activation experiment with subsequent decay measurement is not possible. See Figure 42.

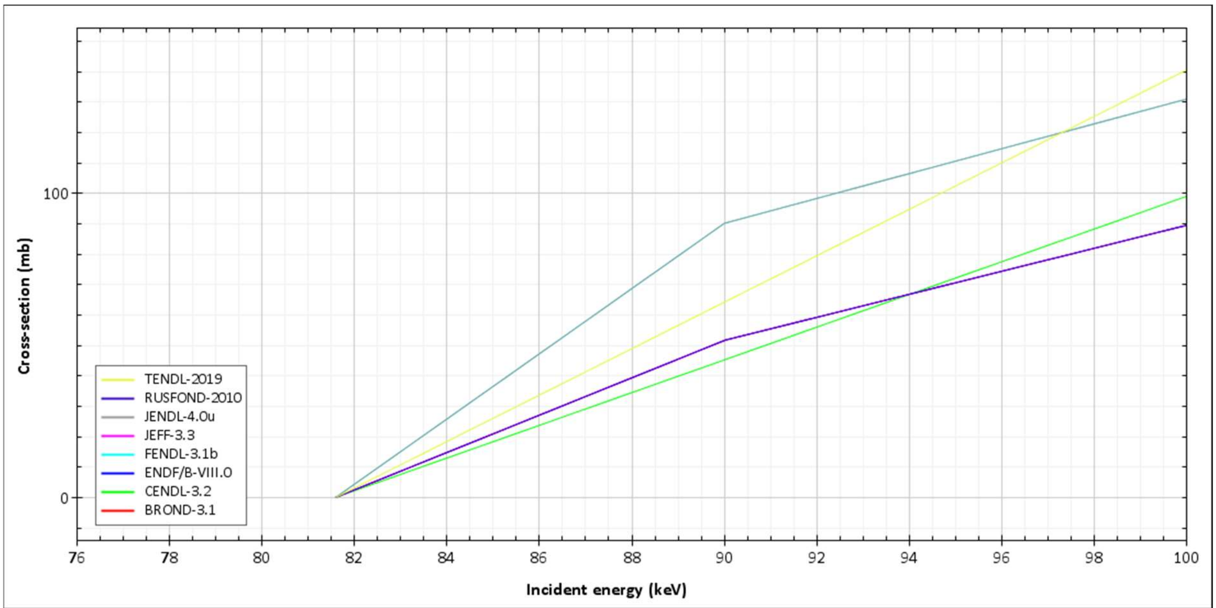

Figure 42: Evaluated inelastic scattering reaction cross sections relevant to the energy range of interest for ^{133}Cs

2.9 NEODYMIUM-148

There is 7 naturally occurring isotopes of neodymium, with the most abundant being 142Nd with an abundance of ~27 %. Neodymium-148 has an abundance of 5.8%. Neodymium-148 is produced following fission and its precursors in a fission product decay chain are all non-volatile and Nd-148 itself is locked in the fuel matrix. As such, its concentration can give a good measure of nuclear fuel burnup.

Figure 43 shows the relevant cross sections across the energy range of interest. At very low energies the larger cross section is neutron capture which comprises the majority of the total. However, at thermal energy the elastic scattering cross section is larger than neutron capture by a factor of ~1.7. Elastic scattering is then dominant for the remainer of the energy range. At 100 keV the elastic scatter cross section is ~100 times larger. See Figure 43.

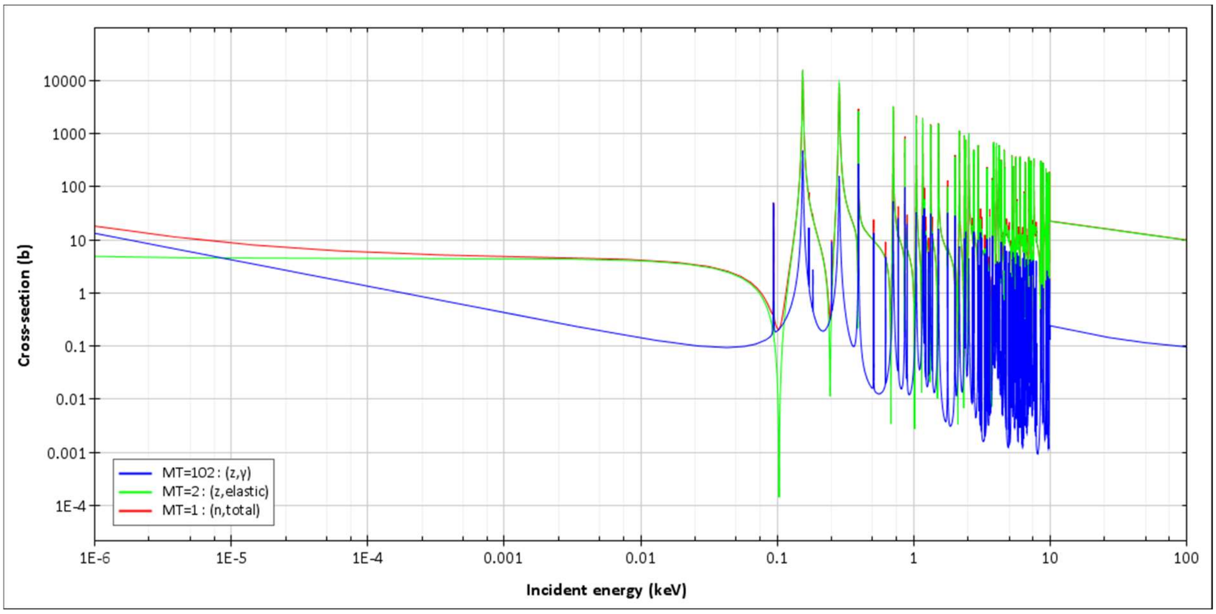

Figure 43: Evaluated cross sections relevant to the energy range of interest from ENDF/B-VIII.0 for ^{148}Nd

There are 2 data sets for the total reaction cross section on 148Nd in the EXFOR database. The data of Tellier (1971)[39] covers an energy range of ~40 eV to 10 keV and was taken at the 60 MeV Saclay Linear Accelerator using time-of-flight techniques and the transmission method. The data of Wisshak (1997)[40] covers the keV energy range up to the energy of interest in this work and utilised the 3.75 MV Van de Graaff accelerator at the Karlsruhe Institute of Technology, also using time-of-flight techniques and the transmission method. There is no data at thermal neutron energy. The evaluated cross sections agree well with the data across the energy range of interest with small variations across the resonance region. Some of the experimental data is not reproduced by the evaluations with resonance peaks missing, particularly below 0.1 keV. Above 10 keV the evaluations agree with the data Wisshak, with the exception of TENDL-2019, in-which the cross section is low by ~50% compared with the other evaluated cross sections. At thermal neutron energy the evaluations have a standard deviation of ~2 %. See Figure 44.

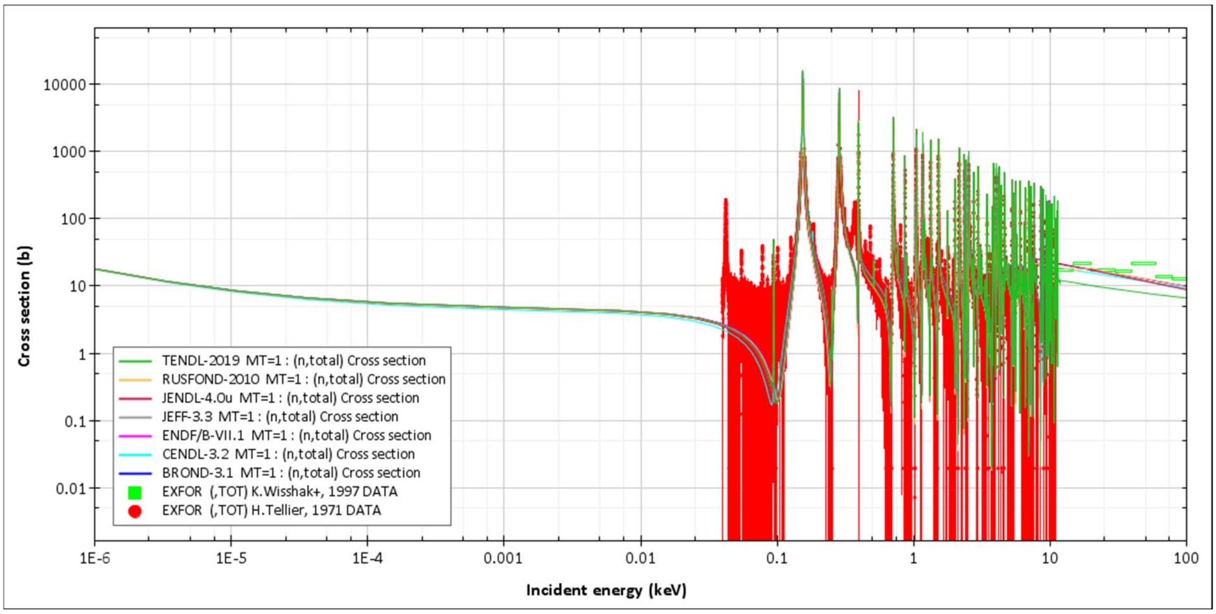

Figure 44: EXFOR data for the total reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{148}Nd

There are 2 entries in the EXFOR database for elastic scattering reaction cross section on 148Nd. The data of Vertebnyj (1973)[41] covers the range of 20 meV to 10 eV and used the WWR-M thermal reactor in Kyiv with a mechanical chopper and time-of-flight techniques. The other entry is that of Mughabghab at thermal energy. The evaluated cross sections agree across the energy range although small differences in the magnitude of peaks and valleys occur in the resonance region. At thermal neutron energy the data of Vertebnyj is 7.5 % lower than that of Mughabghab, although they agree within uncertainties. The evaluations seem to have been normalised to the Mughabghab data, other than CENDL-3.2 which aligns with the data of Vertebnyj. At thermal neutron energy the standard deviation of the evaluations is ~3.2 %, or 1.6 % excluding CENDL-3.2. Similar to the total cross section, above 10 keV the evaluations agree with each other, with the exception of TENDL-2019, which is low by ~50% compared with the other evaluations. See Figure 45.

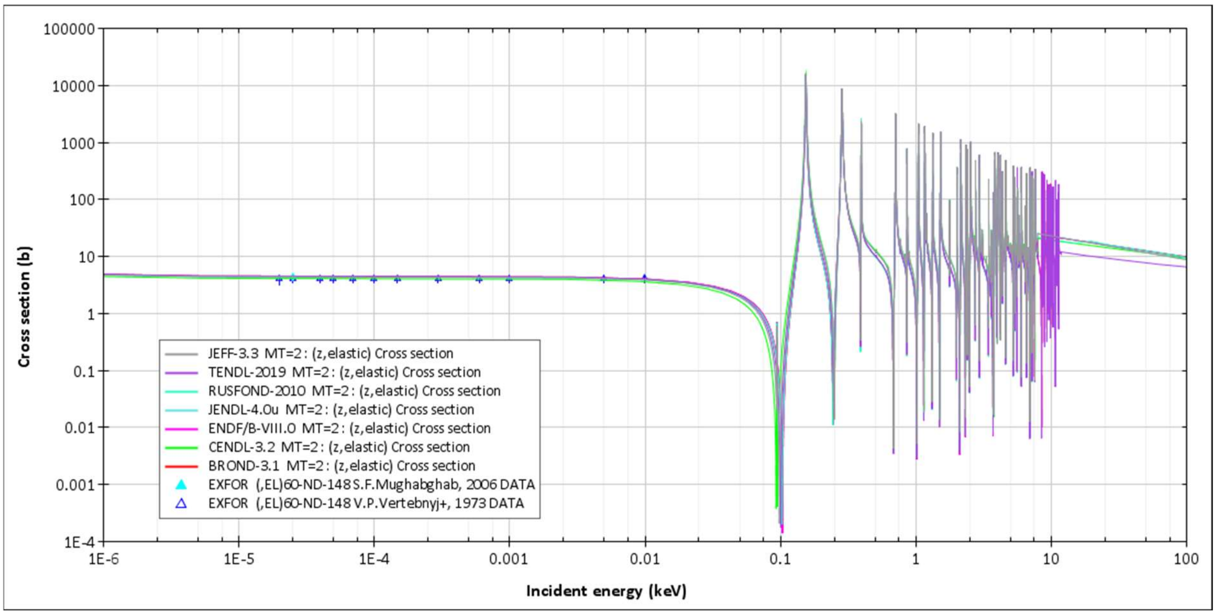

Figure 45: EXFOR data for the elastic scattering reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{148}Nd

There are 11 data sets for the neutron capture reaction on 148Nd, with 7 in the keV energy range and 4 at thermal neutron energy. The standard deviation of the thermal data is 3.8 %, which is comparable to the uncertainties on each data point. However, the evaluations (other than EAF-2010) appear to have been fitted to the Mughabghab data, which is the data with the highest value of the cross section. This means the data with the lowest value for the cross section (Corte (1988)[42]) is 9 % lower than the evaluations. The data sets in the keV region follow the same trend but are of different magnitude. For example, there are several data sets at ~25 keV, the largest value is ~270 % more than the lowest. The evaluations all follow the trend of the data, but also have varying magnitudes in the keV region. The standard deviation of the evaluations at 25 keV is ~12 %. See Figure 46.

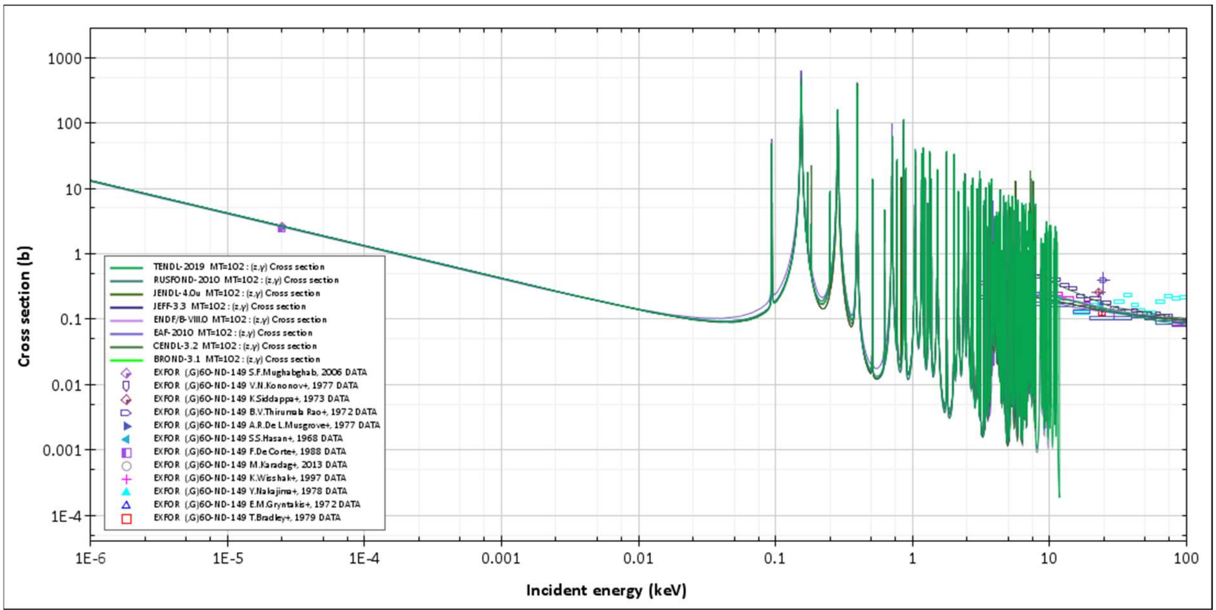

Figure 46: EXFOR data for the neutron capture reaction cross section and evaluated cross sections relevant to the energy range of interest for ^{148}Nd

The lowest lying excited state in 148Nd is above 100 keV and as such there is now inelastic scattering reaction channel in the energy range of interest.

3 CONCLUSIONS

In view of dearth of experimental data, cross section evaluations are largely based on nuclear models, with normalisation to data, often at thermal energy. The evaluations considered here tended to agree with each other over much of the energy range for most of the isotopes, which makes it a little surprising when there is disagreement over part of an energy region.

TENDL at times disagrees with the average of the other evaluations.

Determining the reasons for such disagreements would involve a detailed examination of the nuclear models used, a task requiring a significant level of understanding of nuclear models for calculating cross sections.

The influence of the measured data on the evaluations is highlighted in Figure 9 and Figure 40 where evaluations appear to have been normalised to two different thermal cross section values resulting in differences between the evaluations that extend to higher energies.

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