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Verification & validation of processes for Fe, Cr, W, Ta, V, Mn

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Abstract

This report summarizes the work and results obtained for the F4E-GRT-168.01 grant, under the task 6.1. Comparisons between the TENDL-2011 and EAF-2010 libraries are presented for the Fe, Cr, W, Ta, V and Mn isotopes and their cross sections.

Reviewers	
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Validation and Verification on the Eurofer constituents for TENDL-2011

Under a contract for Fusion for Energy,
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Contents

Glossary

autonorming Action from the TALYS system to automatically import a given cross section. The sum rules are also used to obtain a consistent sum of cross sections.

AutoTalys Shell script used as a driver for TALYS and the other nuclear data software.

EAF European Activation File (EAF) prepared for the European Activation System (EASY).

ENDF-6 Format of the nuclear data as used in nuclear data libraries.

ENDF/B-VII.1 American evaluated nuclear data library, version 7.1.

EXFOR Experimental Nuclear Reaction Data database.

JEFF Joint Evaluated Fission and Fusion File,collaboration between NEA Data Bank member countries.

MF Part of the nuclear data library containing a given type of nuclear data (such as cross sections).

MT Subpart of the nuclear data library containing a given reaction channel.

TAFIS Software for the calculation of fission yields and neutron emission during the fission process developed at NRG.

TALYS Software for the simulation of nuclear reactions developed at NRG.

TALYS system Software package including TALYS to produce the TENDL libraries.

TANES Software for the calculation of fission neutron spectra developed at NRG.

TARES Software for the calculation of the resonance parameters developed at NRG.

TASMAN Software for the variation of nuclear parameters, developed at NRG.

TEFAL Software to format the nuclear data into ENDF-6 libraries developed at NRG.

TENDL TALYS Evaluated Nuclear Data Library.

Summary

This report summarizes the work and results obtained for the F4E-GRT-168.01 grant, under the task 6.1. Comparisons between the TENDL-2011 and EAF-2010 libraries are presented for the Fe, Cr, W, Ta, V and Mn isotopes and their cross sections.

The following main results for the comparison of the libraries were found:

1. Cross sections for 16 isotopes (Eurofer constituents) were compared between TENDL-2011 and EAF-2010 (^{54,56,57,58}Fe, ^{50,52,53,54}Cr, ^{180,182,183,184,186}W, ^{181}Ta, ^{51}V and ^{55}Mn),
2. Two types of results can be observed
   - in the case of "*autonormed*" (automated import) cross sections, the comparison between TENDL-2011 and EAF-2010 shows a very good agreement,
   - in the case of original TALYS calculations, the comparison between TENDL-2011 and EAF-2010 shows expected differences.

1 Description of the task

The present work is part of the F4E-GRT-168.01 grant, under task 6.1, defined as:

6. Improvement of cross-section data libraries (JEFF, EAF and TENDL):

   6.1 Development of consistent TALYS model based activation-transmutation and transport TENDL neutron sub-libraries. Verification and validation of the processes and data streams.

   6.2 Post processing of photonuclear libraries and thermal scattering tables for Monte Carlo applications

The objective is to generate a consistent TENDL based general purpose/activation sub-library for Fe, Cr, W, Mn Ta, V, Mn (major Eurofer constituents) and demonstrate/prove consistency of the produced data with EAF data for activation and JEFF data for neutron transport.
This report represents the deliverable on the verification and validation (V&V) analysis.

2 Tools and Methods

2.1 The TALYS system

A detailed publication presenting the complete system to produce random nuclear data (called the "TALYS system") can be found in Ref. [1]. A short summary will be presented here. All random nuclear data files used for this work are produced with the TALYS software package, which for the present application contains 7 different codes. A flowchart for the entire system is presented in Fig. 1, which shows that by looping over the entire process of basic nuclear physics, data file production, data file processing and applied calculations, a natural statistical approach towards uncertainty propagation can be obtained. The following 7 codes and scripts are essential in this procedure:

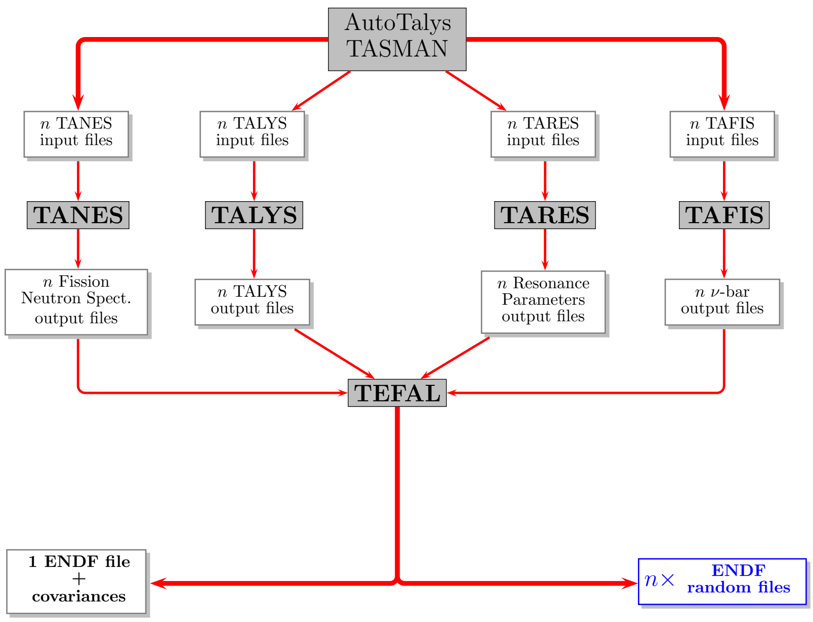

Figure 1: Flow chart of the TALYS system, involving the 7 different codes and scripts to produce random nuclear data.

- TALYS
  The nuclear reaction code TALYS has been extensively described in many publications (see Refs. [1, 2]). It simulates reactions that involve neutrons, gamma-rays. . . from thermal to 200 MeV energy range. With a single run, cross-sections, energy spectra, angular distributions. . . for all open channels over the whole incident energy range are predicted. The nuclear reaction models are driven by a restricted set of parameters, such as optical model, level density, photon strength and fission parameters, which can all be varied in a

TALYS input file. All information that is required in a nuclear data file, above the resonance range, is provided by TALYS.

- TASMAN
  TASMAN is a computer code for the production of covariance data using results of the nuclear model code TALYS, and for automatic optimization of the TALYS results with respect to experimental data. The essential idea is to assume that each nuclear model (i.e. TALYS input) parameter has its own uncertainty, where for the moment the uncertainty distribution is assumed to have a Gaussian shape. Running TALYS many times, whereby each time all elements of the parameter vector are *randomly* sampled from a normal distribution with a specific width for each parameter, provides all needed statistical information to produce a full covariance matrix. The basic objective behind the construction of TASMAN is to facilitate all this.
  TASMAN is using central value parameters, as well as a probability distribution function. The central values were chosen to globally obtain the best fit to experimental cross sections and angular distributions (see for instance Ref. [3]). The uncertainties on parameters (or widths of the distributions) are also obtained by comparison with experimental data, directly taken from the EXFOR database [4]. The distribution can then be chosen between, equiprobable, Normal or other. In principle, with the least information available (no measurement, no theoretical information), the equiprobable probability distribution is chosen. Otherwise, the Normal distribution is considered.

  An important quantity to obtain rapid statistical convergence in the Monte Carlo process is the selection of random numbers. Several tests were performed using pseudo-random numbers, quasi-random numbers (Sobol sequence), Latin Hypercube random numbers or Centroidal Voronoi Tessellations random numbers. As the considered dimension (number of parameters for a TALYS calculation) is rather high (from 50 to 80), not all random number generators perform as required (covering as fast as possible the full parameter space, without repeating very similar configurations and avoiding correlations). For the time being, the random data files are produced using the Sobol quasi-random number generator.

- TEFAL
  TEFAL is a computer code for the translation of the nuclear reaction results of TALYS, and data from other sources if TALYS is not adequate, into ENDF-6 formatted nuclear data libraries. The basic objective behind the construction of TEFAL is to create nuclear data files without error-prone human interference. Hence, the idea is to run TALYS for a projectile-target combination and a range of incident energies, and to obtain a ready to use

nuclear data library from the TEFAL code through processing of the TALYS results, possibly in combination with experimental data or data from existing data libraries. This procedure is completely automated, so that the chance of human errors is minimized.

- TARES
  This is a code to generate resonance information in the ENDF-6 format, including covariance information. It makes use of resonance parameter databases such as the EXFOR database [4], resonance parameters from other libraries (ENDF/B-VII.0 [5]) or compilations (Ref. [6]). ENDF-6 procedures can be selected, for different R-matrix approximations, such as the Multi-level Breit Wigner or Reich Moore formalism. The covariance information is stored either in the "regular" covariance format or in the compact format.

- The TANES program
  TANES is a simple program to calculate fission neutron spectrum based on the Los Alamos model. The original Madland-Nix or Los Alamos model for the calculation of prompt fission neutrons characteristics (spectra and multiplicity) has been implemented in a stand-alone module. The TANES code is using this stand-alone module, combined with parameter uncertainties (on the total kinetic energy, released energy and multi-chance fission probabilities) to reproduce and randomize the fission neutron spectrum. The output of this program is the central and random values for the fission neutron spectra at different incident energies (MF5) and their covariances (MF35).

- The TAFIS program
  TAFIS is used to calculate fission yields, prompt neutron emission from fission and other necessary fission quantities (kinetic energy of the fission products, kinetic energy of the prompt and delayed fission neutrons, total energy released by prompt and delayed gamma rays). For fission yields, it is using the systematics of fission-product yields from A.C. Wahl, combined with *ad hoc* uncertainties. It calculates the independent and cumulative fission yields at any incident energy up to 200 MeV and for different incident particles (spontaneous, neutrons, protons, deuterons, *etc*). Empirical equations representing systematics of fission-product yields are derived from experimental data. The systematics give some insight into nuclear-structure effects on yields, and the equations allow estimation of yields from fission of any nuclide ($Z = 90$ to 98 and $A = 230$ to 252). The output of this program is a fission yield file with uncertainties, prompt neutron emission files for central and random values (MF1 MT452), a list of central and random fission quantities (MF1 MT458) and prompt neutron covariances (MF31).

- AutoTalys
  AutoTalys is a script which takes care of the communication between all software and packages described above and runs the complete sequence of codes, if necessary for the whole nuclide chart. Many options regarding TALYS and all other codes can be set, and it makes the library production straightforward.

2.2 Autonorming

The *autonorming* capability of the TALYS system is a key functionality in this project. It was first tested in TENDL-2009 and was thereafter further developed and improved. The principle is rather simple: if a cross section is better evaluated in another library, it should be possible to "import" it for the TENDL evaluations, without manual interventions, and following a few rules:

- read the original cross section with its energy grid,
- import it in the TENDL evaluation (replacing the existing TALYS cross section),
- expand or simply adjust the energy grid to match the TENDL lower and higher limits,
- respect the sum rules (modifying one or more of the total, elastic and non elastic cross sections),
- keep the possibility to obtain random cross sections for the TMC uncertainty propagation.

In practice, this functionality needs care to be properly implemented. In this work, it is extensively used to reproduce cross sections from the EAF-2010 library. Even if this method can be applied to any cross sections, independently of the values of the original TALYS cross sections, it is better to *autonorm* cross sections which are already close to the imported ones. In order to minimize the modifications to other channels because of the sum rule, the cross section to be replaced should first be adjusted to values which are in agreement to the imported ones. This can be achieved by adjusting the TALYS parameters so that the right cross section values are obtained. The prior agreement between the two sets of cross sections does not need to be perfect, but small differences (less than 5 %) assures that the modifications to other channels (such as elastic), or to related quantities (such as angular distributions, particle emissions) do not jeopardize physical consistency.

2.3 The TENDL libraries

2.3.1 Generalities

Many well recognized and respected nuclear data libraries exist, as for instance (and to cite only one) the US ENDF/B-VII.0 and VII.1 libraries [5, 7].

As nuclear data are relevant for different kind of applications, all countries with a large nuclear industry possess their own team(s) of nuclear data evaluators to answer their special needs. From a common historical background, these research groups share the same experimental databases and nuclear reaction theories, and have a restricted number of codes/programs to produce the so-called *evaluated files*. Also as an heritage of historical segregation, nuclear data specialists are often not the same persons as the application specialists. They are separated by buildings, language, education, and sometimes countries (in short they do not share the same culture). A common practice in the community is to let nuclear data evaluators do the best possible job by using model codes and judging differential and integral measurements, manually adjusting parameters, submit the results to users of the application teams, wait for feedback (which generally comes years later) and do again the best possible job based on comments from the user groups. This looping procedure has started 50 years ago and is still today in operation.

This approach, even if highly questionable, has produced evaluations which are used worldwide, approved by safety authorities and nuclear industries, and finally used in simulation codes for reactor design and safety assessment. For instance, the JEFF-3.1.1 nuclear data library [8] was produced following the previous scheme, including "*incremental approaches*" (meaning minimal changes, targeted to improve a number of reference calculations, from one library version to another), and is now the reference library for the French nuclear authorities, operator and designers.

There are nevertheless a few inconveniences related to this method of work, especially in a world with higher constraints on safety, efficiency and cost-effectiveness. The *incremental approach*, used to improve a series of benchmarks, advocates minimal changes to nuclear quantities such as cross sections. It allows to find the closest best solution in the multi-dimensional nuclear data space, but there is no guarantee that this local best solution is the absolute best solution. It is in principle possible to choose a different set of nuclear data (far from a solution given by an incremental approach), and to have a better agreement with the same series of benchmarks. Due to the large turn around time of data library creation, adoption and validation, it can be argued that in the European community, the recent adoption of JEFF-3.1.1 by various nuclear industries gives to nuclear data evaluators (usually called the JEFF community) time to look for a better solution and deviate from the *incremental approach*. Another drawback of this approach is that nuclear data are considered as input for a specific, well validated and fixed reactor code "*A*" designed a few decades ago. By incrementally adjusting the inputs, the combination "new inputs and code A" is improving its performances compared to "previous inputs and code A". The changes in nuclear data can nevertheless be seen as correction factors for imperfections of this code. It does not automatically imply that the combination "new inputs and code B" will perform better than "previous inputs and code B".

Additionally, in an economy where quality-assurance, reproducibility or traceability are so widely spread, it seems unrealistic to manually modify nuclear data files (as usually done by nuclear data evaluators), to separate data producers and users, and to rely on a worldwide unique stream of thoughts (the same question can probably be asked to safety authorities). Data libraries are becoming more alike as a result of file exchanges, unity of processing codes and conservatism. As a consequence of a knowledgeable nuclear scientists retiring, a lot of manually produced evaluations are kept in libraries (without real a understanding of their contents). But, as a consequence of a knowledgeable nuclear scientists not retiring, methods from the middle of the last century are kept alive and artificially maintained.

In an effort to impose an unconventional approach, a new method of nuclear data evaluation has been recently proposed [9]. Nuclear data evaluation can be performed much more efficiently if more disciplined working methods are adopted. Basically it means that the ENDF-6 data file should not be touched manually, and is rather seen as a helpful by-product of an evaluation process. Figs. 2 summarizes the approach. Once the nuclear model code and ENDF-6 formatting code used in the evaluation process are well verified and validated, the 3 left boxes contain the essential information that produces a nuclear data file. All relevant experimental data for the nucleus under consideration should be readily available, as well as a file with deduced resonance parameters (and uncertainties). An input file for the nuclear model code with parameters (and uncertainties) adjusted to reproduce the available experimental data produces a complete set of nuclear reaction results. Finally, a formatting code produces the ENDF-6 data file, which is driven by a script that performs any additional actions such as copy-paste from existing data libraries or, if necessary, scientifically dubious adjustments for the sake of good performance of the data file in applications. As Fig. 2 suggests, this could be done for all nuclides and the system would consist of "blind" evaluations for isotopes which are either relatively unimportant or have no experimental data available, and very detailed evaluations with fine tuned model parameters, direct inclusion of certain sets of experimental data, etc. for the important and/or well-measured nuclides. The central message is that the data library can be automatically produced from its components, and that the knowledge of the data evaluator can be preserved in a much more compact way than in an entire ENDF-6 data file.

This new approach should not be confused with "quick and dirty" or "blind automated" nuclear data production, it should rather be called “systematic evaluation”. What this approach guarantees is that all information emerging from large efforts invested in single nuclide evaluation will remain at our disposal forever: reproducibility of the evaluation process is essential, while a bare undocumented ENDF-6 file, produced by a retired evaluator, usually does not give a lot of insight. In Ref. [9] we already showed one possible reward of this approach: exact uncertainty propagation using Monte Carlo nuclear data file production and validation. In this document we deliver another one: complete nuclear data libraries including covariance data for almost the entire nuclide chart, and all projectiles.

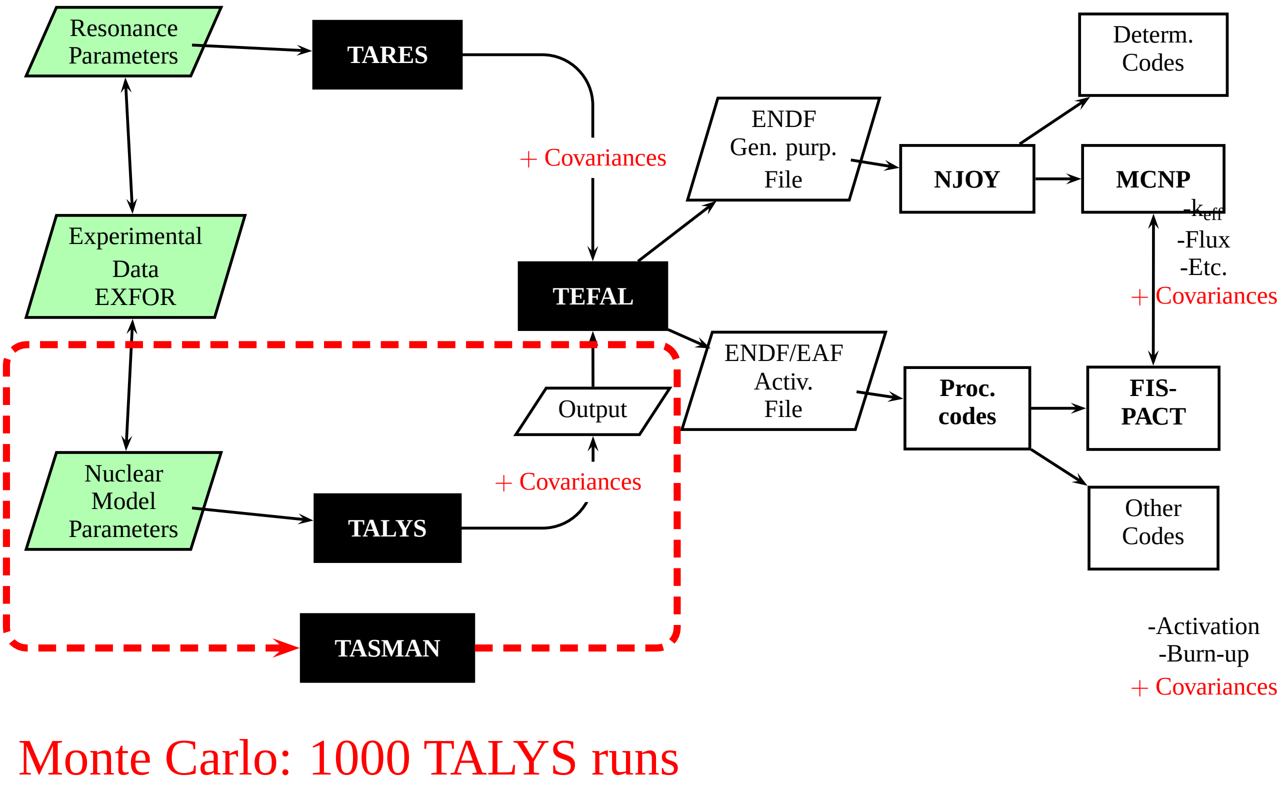

Figure 2: Flowchart of automated, reproducible evaluation process used for the production of TENDL-2008 to 2013.

The TENDL concept is based on principles which have been embraced by many other industries long ago: quality, automation, reproducibility, completeness and consistency. It relies on the robust nuclear model code TALYS [1] and on the two simple ideas that any information used to create an evaluation is kept "*forever*" to be re-used as necessary, and that manual intervention *during* the library production is strictly forbidden. The spin-offs of such a new method are multiple (see Fig. 3): complete nuclear data libraries (TENDL) on an unprecedent scale [10, 11, 12, 13], including covariance production, exact (Monte Carlo) uncertainty propagation [9], *etc.* It is even possible to "clone" an existing library (*e.g.* the entire ENDF/B-VII.1 or EAF-2010 [14] libraries and start further development from that point, such as filling all missing sections using TALYS, addition of covariance data, *etc.*

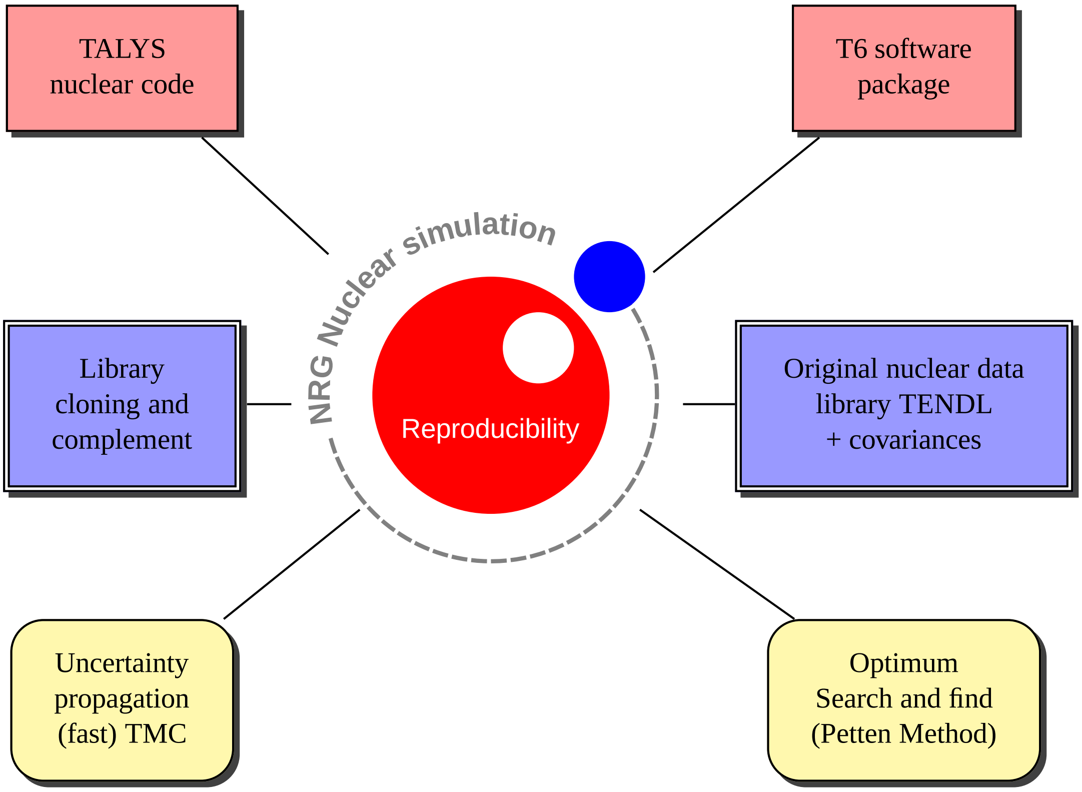

Figure 3: Presentation of the possible outcomes based on the TALYS system.

2.3.2 TENDL-2011 and the EAF-2010 library

EAF-2010 differs from other libraries in the sense that not all major channels are explicitly given. The total and elastic cross sections are not provided.

In this work, some of the EAF-2010 cross sections are imported following the *autonorm* procedure. It was not the goal of TENDL-2011 to entirely reproduce EAF-2010, therefore not all EAF-2010 cross sections have been *autonormed*. In total, 23 channels are *autonormed* in TENDL-2011 to the EAF-2010 library:

- ^{56}Fe(n,p)
- ^{52}Cr(n,2n), (n,p), (n,t)
- ^{180}W(n,3n)
- ^{182}W(n,2n)
- ^{183}W(n,p)

- ^{184}W(n,p) (n,n'p)
- ^{185}W(n,p) (n,n'p) (n,α), (n,2n)m_1
- ^{181}Ta(n,p)
- ^{51}V(n,n'α), (n,p), (n,t)
- ^{55}Mn(n,2n), (n,γ), (n,p), (n,t), (n,h), (n, α)

The other cross sections are not the same as in EAF-2010. In the following, details about each nucleus are given. Complete comparison by means of plots of cross sections and ratios of cross sections can be found in the appendix A to F.

3 Results

In the following, the TENDL-2011 evaluations for the constituents of Eurofer will be compared with the cross sections coming from the EAF-2010 library. These elements are Fe, Cr, W, Ta, V and Mn. As the TENDL libraries are produced, cross sections can come from TALYS calculations, or from other libraries (the process of importing cross sections from other libraries is called "*autonorm*" in the TENDL vocabulary.
It should be noticed that the EAF evaluations do not include all channels: the (n,tot), (n,el) and (n,inl) are not given.

3.1 Fe

Iron has four natural isotopes (^{54}Fe, ^{56}Fe, ^{57}Fe and ^{58}Fe). In the TENDL libraries, only one channel is imported from EAF-2010: ^{56}Fe(n,p). The other channels are either original TALYS calculations, or imported from the ENDF/B-VII.1 library [5, 7] or from the JENDL-4.0 library [15].

3.1.1 ^{54}Fe

The ^{54}Fe evaluations from TENDL-2011 to TENDL-2013 do not refer to EAF-2010 by the means of *autonorm* procedure. Therefore, the cross sections included in TENDL-2011 (and other TENDL libraries) are different compared to the ones in the EAF-2010 library. Comparisons of the EAF-2010 and TENDL-2011 libraries can be found in appendix A page 35.
In order to demonstrate the capabilities of the TALYS system, an additional evaluation was prepared with *autonorms* to the major cross sections of ^{54}Fe from EAF-2010. The following channels were considered up to 20 MeV: (n,n'α), (n,n'p), (n,2np), (n,γ), (n,p), (n,d), (n,h).
Examples of the comparisons between a few cross sections are presented in Fig. 4.
It can be seen on Fig. 4 that the procedure of *autonorming* to EAF-2010 cross sections is providing good results, different than the TENDL-2011 cross sections (as presented in Appendix A).

3.1.2 ^{56}Fe

The ^{56}Fe evaluation from TENDL-2011 is using EAF-2010 for only one channel, the (n,p) reaction. The other cross sections are either coming from TALYS or from other libraries. Comparisons between the EAF-2010 and TENDL-2011 cross sections can be found in

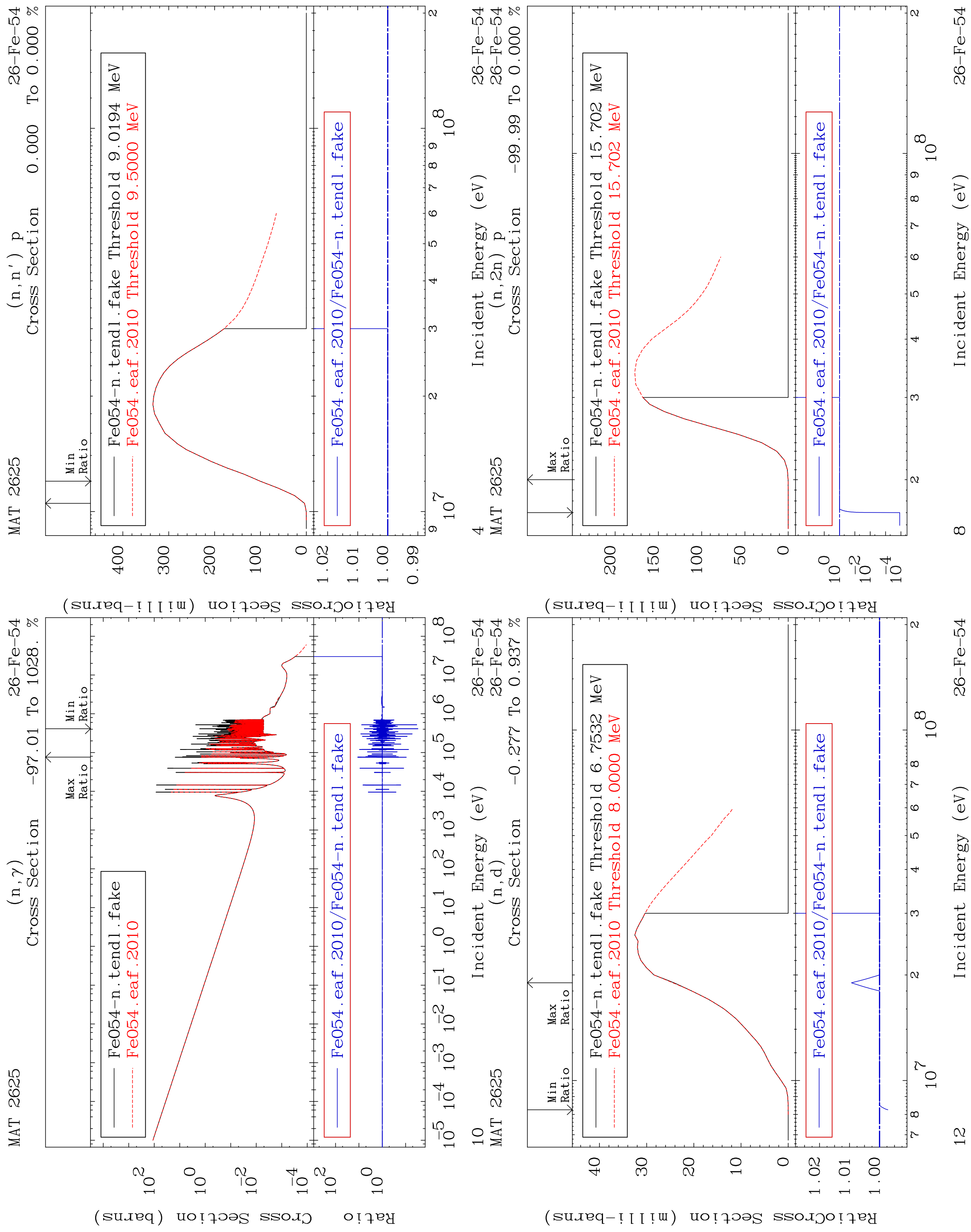

Figure 4: Autonormed ^{54}Fe cross sections to EAF-2010 for a few channels.

Appendix A, page 37. The (n,p) cross sections are identical in EAF-2010 and TENDL-2011 libraries, showing the good performance of the *autonorming* procedure.

Similarly to ^{54}Fe, an additional ENDF-6 file was produced with all cross sections *autonormed* to EAF-2010 for ^{56}Fe. Examples are presented in Fig 5.

Again, the procedure leads to cross sections which are in perfect agreement. It should be noticed that the (n,tot) cross section can not be identical, since the (n,tot) and (n,el) cross sections are not given in the EAF-2010 evaluation.

3.1.3 ^{57}Fe

In the TENDL libraries, ^{57}Fe cross sections either come from TALYS calculations or *autonormed* to the ENDF/B-VII.1 library. Therefore, the cross sections are different from those of EAF-2010. Comparisons between the EAF-2010 and TENDL-2011 cross sections can be found in Appendix A, page 39.

As in the case of the two other Fe isotopes, the performances of the *autonorm* procedure are demonstrated in Fig. 6 where an ENDF-6 evaluation was produced to reproduce the EAF-2010 cross sections.

Again, the results present a very good agreement between the two libraries, in the fast neutron range. For the capture cross section, the resonance range differs between EAF and the result of the TALYS evaluation since no resonance parameters are given in the EAF evaluations, whereas the TALYS ENDF file is using the MF-2 representation (resonance parameters).

3.1.4 ^{58}Fe

In the TENDL libraries, ^{58}Fe cross sections either come from TALYS calculations or *autonormed* to the JENDL library. As for ^{57}Fe, the cross sections are different from those of EAF-2010. Comparisons between the EAF-2010 and TENDL-2011 cross sections can be found in Appendix A, page 41.

As for the other iron isotopes, an additional ENDF file was produced, *autonormed* to EAF-2010. The results are not presented here as they are similar to the other Fe isotopes.

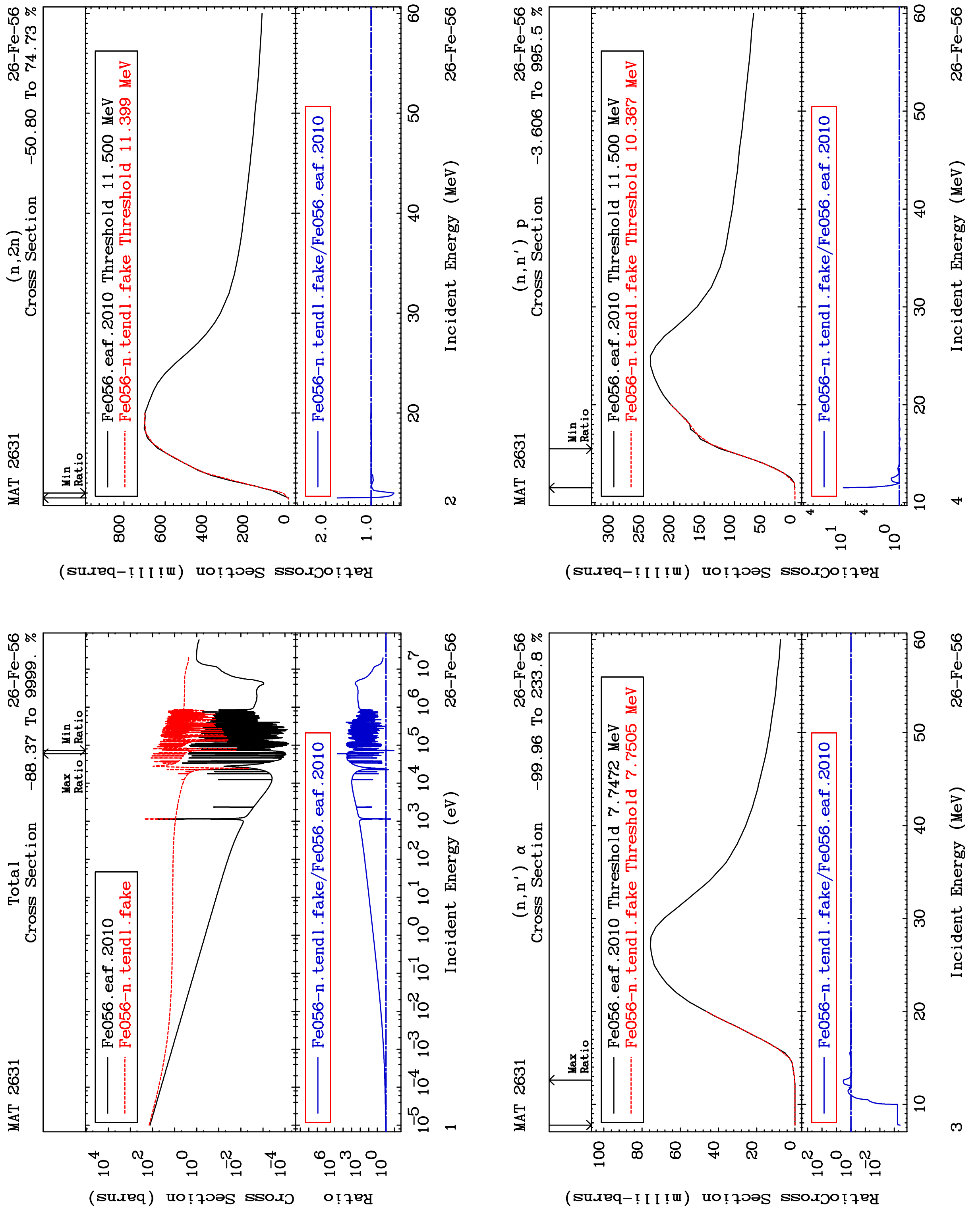

Figure 5: Autonormed ^{56}Fe cross sections to EAF-2010 for a few channels.

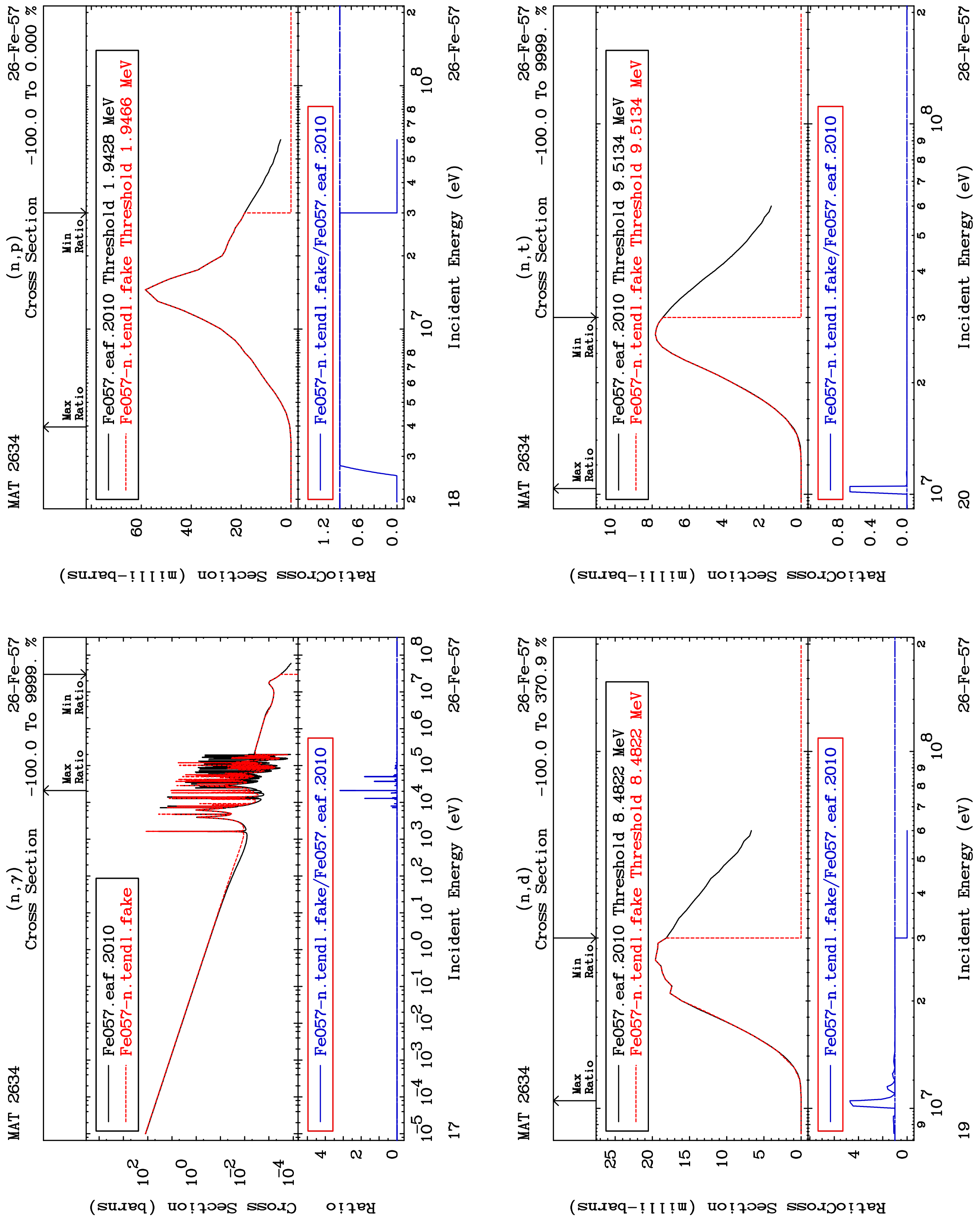

Figure 6: Autonormed ^{57}Fe cross sections to EAF-2010 for a few channels.

3.2 Cr

Chromium has four stable isotopes (^{50}Cr, ^{52}Cr, ^{53}Cr and ^{54}Cr) and the EAF library also includes two short-lived isotopes (^{48}Cr and ^{51}Cr). In the TENDL libraries, one isotope is *autonormed* to the EAF cross sections: ^{52}Cr for the (n,2n), (n,t) and (n,p) channels.

3.2.1 ^{50}Cr

In the TENDL libraries, ^{50}Cr cross sections either come from TALYS calculations or *autonormed* to the ENDF/B-VII.0 or ENDF/B-VII.1 libraries. The cross sections are therefore different than those of EAF-2010. Comparisons between the EAF-2010 and TENDL-2011 cross sections can be found in Appendix B, page 43.

3.2.2 ^{52}Cr

For ^{52}Cr cross sections, 3 reactions are *autonormed* to EAF-2010: (n,2n), (n,p) and (n,t). The comparison for all channels are presented in Appendix B, page 46.
The cross sections which are similar to EAF-2010 are additionally presented in Fig. 7. As seen in Fig. 7, the agreement between both libraries is very good for the *autonormed* channels.

3.2.3 ^{53}Cr

In the TENDL libraries, ^{53}Cr cross sections either come from TALYS calculations or *autonormed* to the ENDF/B-VII.0 or ENDF/B-VII.1 libraries. The cross sections are therefore different than those of EAF-2010. Comparisons between the EAF-2010 and TENDL-2011 cross sections can be found in Appendix B, page 47.

3.2.4 ^{54}Cr

In the TENDL libraries, ^{54}Cr cross sections either come from TALYS calculations or *autonormed* to the ENDF/B-VII.0 or ENDF/B-VII.1 libraries. The cross sections are therefore different than those of EAF-2010. Comparisons between the EAF-2010 and TENDL-2011 cross sections can be found in Appendix B, page 49.

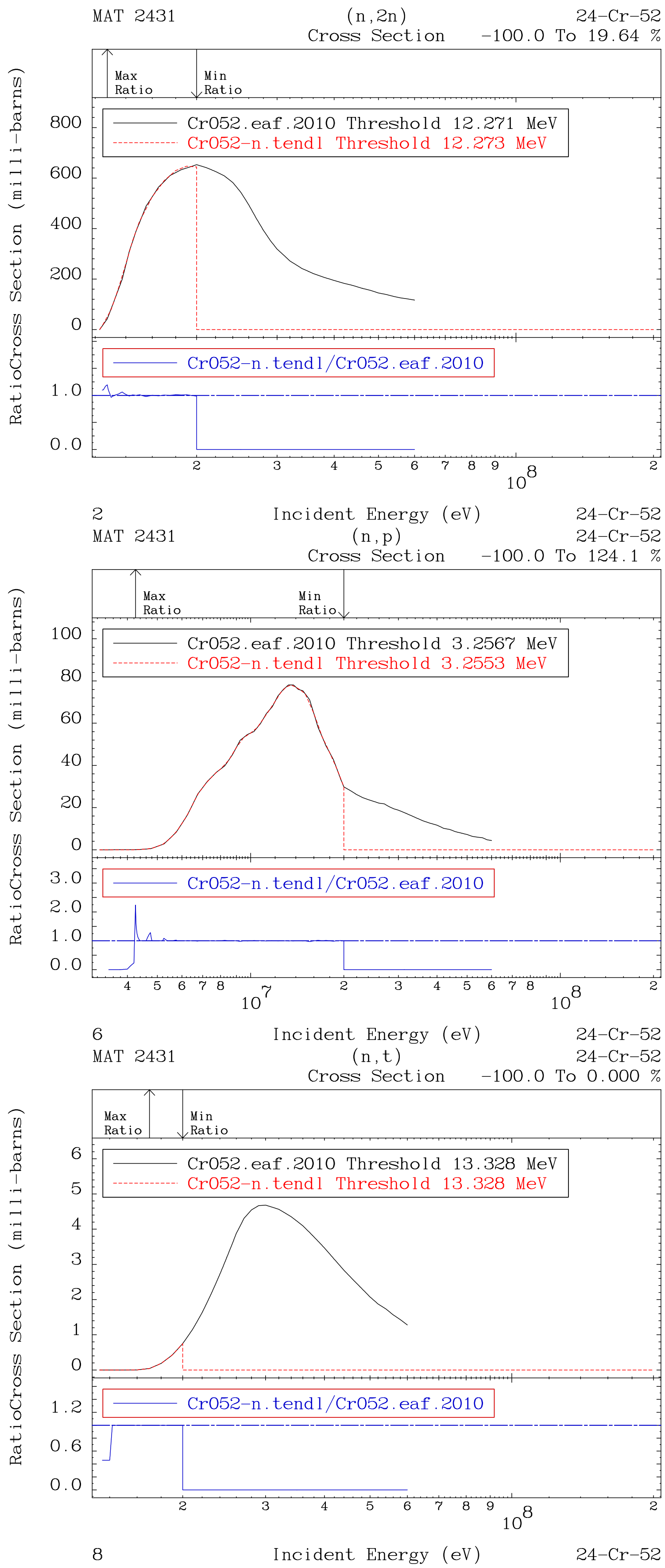

Figure 7: Autonormed ^{52}Cr cross sections to EAF-2010 for a few channels.

3.3 W

Tungsten has five stable isotopes (^{180}W, ^{182}W, ^{183}W, ^{184}W and ^{186}W). The EAF-2010 contains ten W isotopes, from ^{178}W to ^{188}W. Each isotope evaluations in TENDL-2011 is using a few cross sections from EAF-2010, as presented in the next subsections.

3.3.1 ^{180}W

In the TENDL-2011 library, the (n,3n) cross section of ^{180}W comes from EAF-2010. The other reactions directly come from TALYS. The comparison for all channels are presented in Appendix C, page 51.

The (n,3n) *autonormed* channel is presented in Fig. 8.

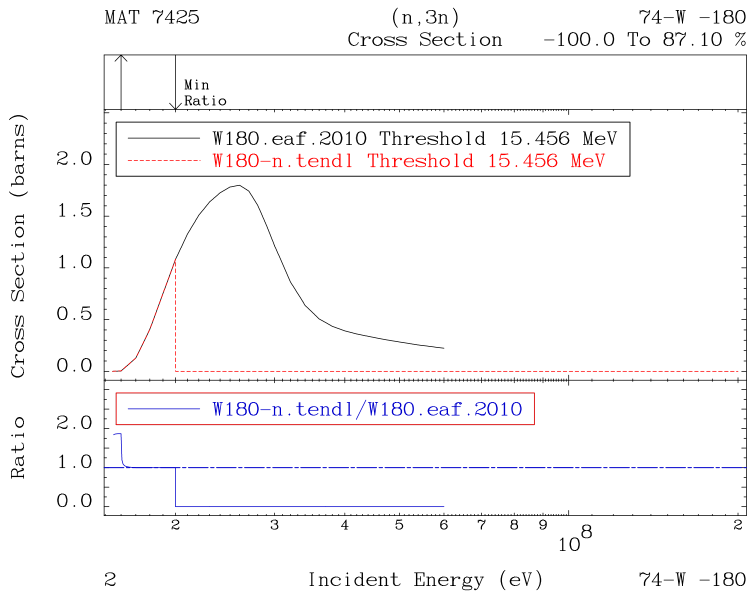

Figure 8: Autonormed ^{180}W(n,3n) cross section to EAF-2010.

3.3.2 ^{182}W

In the TENDL-2011 library, the (n,2n) cross section of ^{182}W comes from EAF-2010. The other reactions directly come from TALYS. The comparison for all channels are presented in Appendix C, page 52.

The (n,2n) *autonormed* channel is presented in Fig. 9. As for the previous cases, the *autonorm* functionality provides cross sections which are in good agreement with the reference.

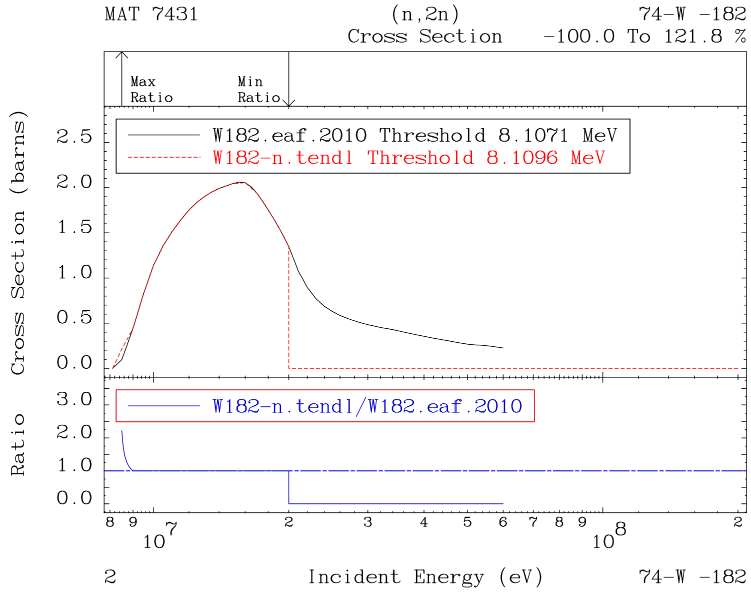

Figure 9: Autonormed ^{182}W(n,2n) cross section to EAF-2010.

3.3.3 ^{183}W

In the TENDL-2011 library, the (n,p) cross section of ^{183}W comes from EAF-2010. The other reactions directly come from TALYS. The comparison for all channels are presented in Appendix C, page 53.

The (n,p) *autonormed* channel is presented in Fig. 10.

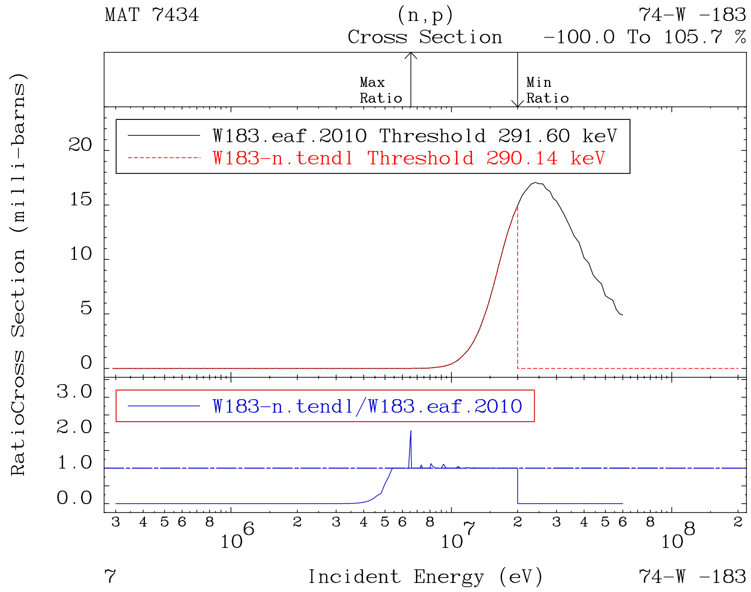

Figure 10: Autonormed ^{183}W(n,p) cross section to EAF-2010.

3.3.4 ^{184}W

In the TENDL-2011 library, the (n,p) and (n,n'p) cross sections of ^{184}W come from EAF-2010. The other reactions directly come from TALYS. The comparison for all channels are presented in Appendix C, page 54.

The (n,p) and (n,n'p) *autonormed* channels are presented in Fig. 11.

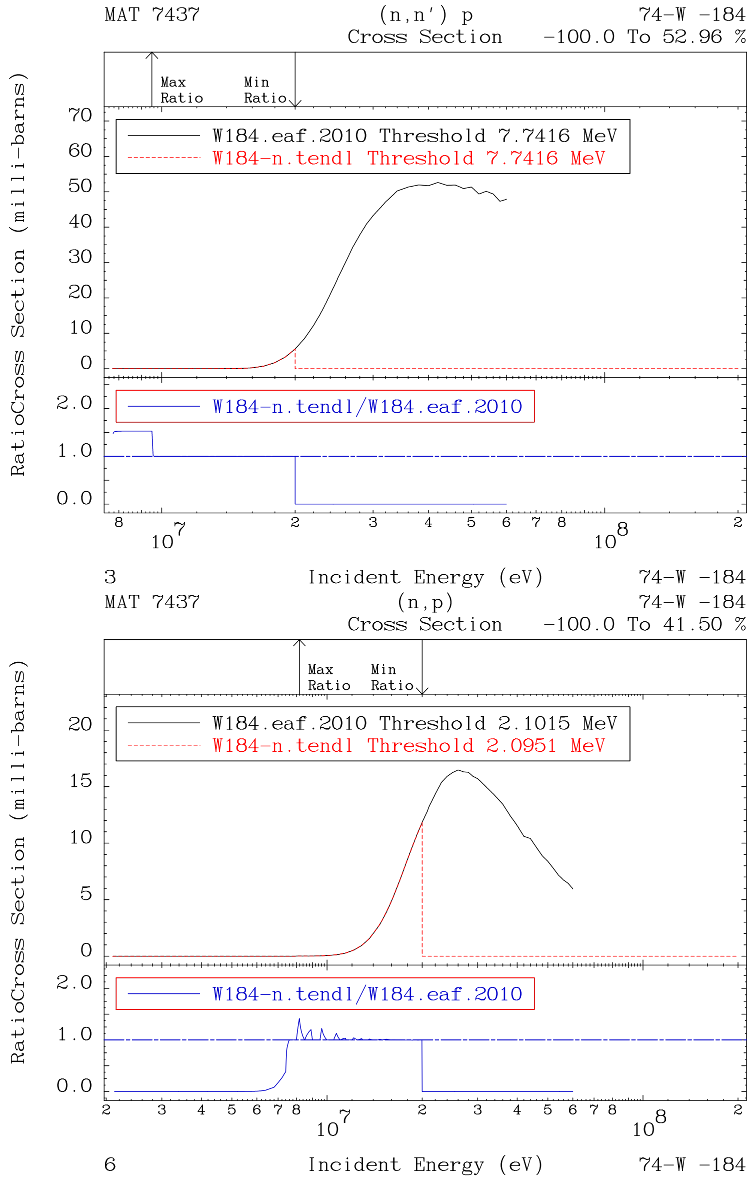

Figure 11: Autonormed ^{184}W(n,p) and (n,n'p) cross sections to EAF-2010.

3.3.5 ^{186}W

In the TENDL-2011 library, the (n,p), (n,n'p), (n,α) and (n,2n)m_1 cross sections of ^{186}W come from EAF-2010. The other reactions directly come from TALYS. The comparison for all channels are presented in Appendix C, page 55.

The *autonormed* channels are presented in Fig. 12.

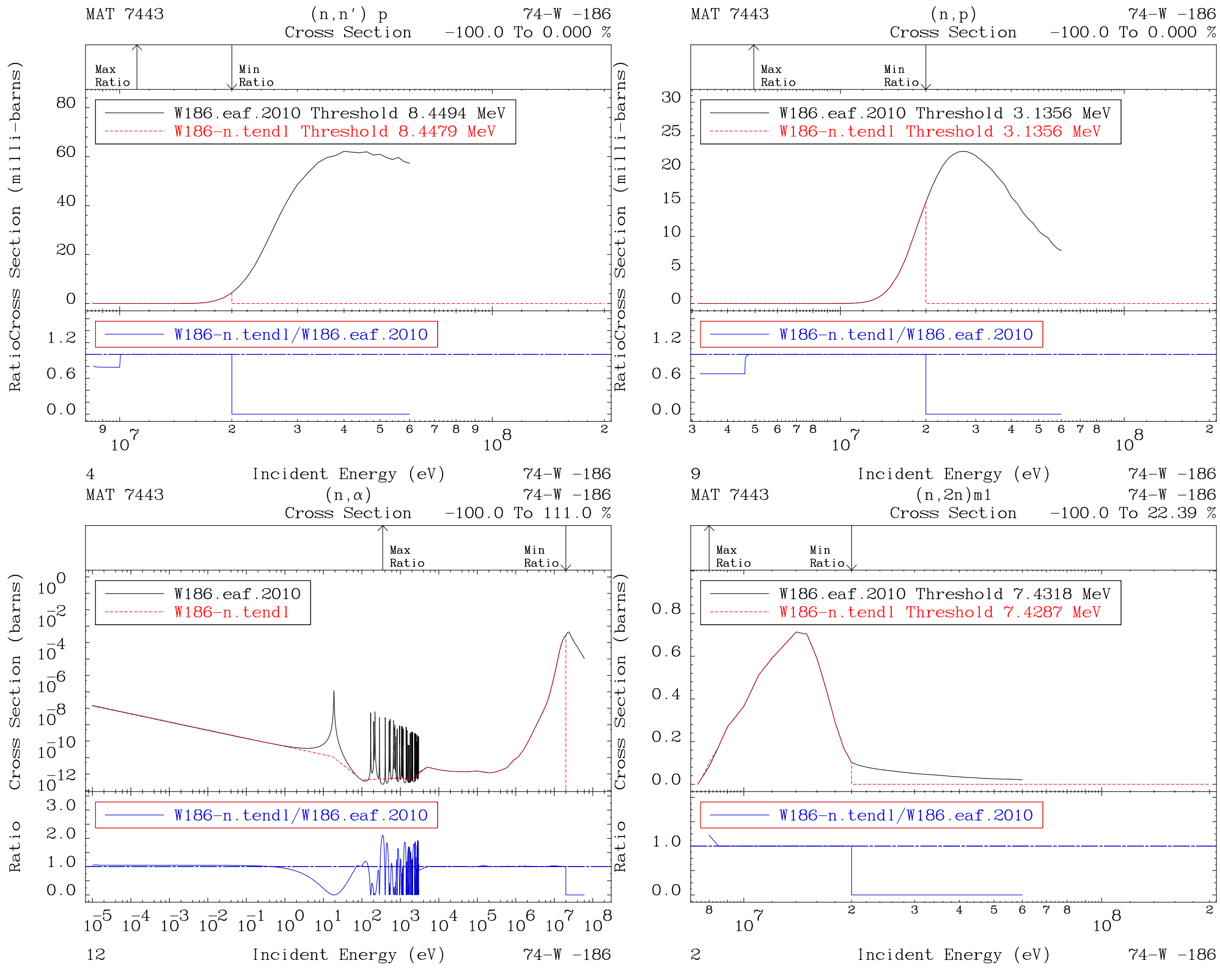

Figure 12: Autonormed ^{186}W cross sections to EAF-2010.

3.4 ^{181}Ta

Tungsten has two stable isotopes (^{180}Ta and ^{181}Ta). The EAF-2010 contains ten Ta isotopes, from ^{175}Ta to ^{184}Ta. Only the ^{181}Ta evaluation in TENDL-2011 is using cross sections from EAF-2010. The other Ta isotopes in TENDL-2011 are not *autonormed* to EAF-2010 and will not be presented here.

In the TENDL-2011 library, only the (n,p) channel from EAF-2010 is used for ^{181}Ta. The other cross sections come from original TALYS calculations. The *autonormed* (n,p) channel is presented in Fig. 13. The comparison for all channels are presented in Appendix D, page 57.

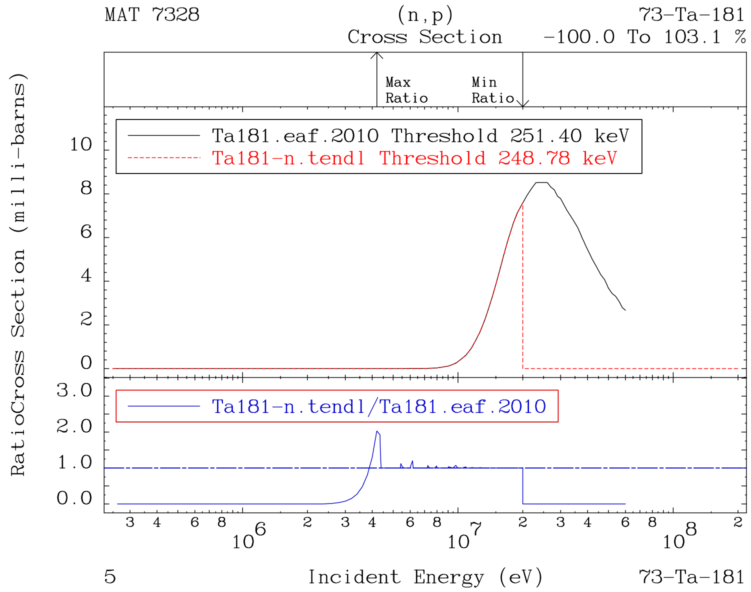

Figure 13: Autonormed ^{181}Ta cross section to EAF-2010.

3.5 ^{51}V

Vanadium has two stable isotopes (^{50}V and ^{51}V). The EAF-2010 contains four V isotopes, but in TENDL-2011, only cross sections of ^{51}V are *autonormed* to EAF-2010. The other V isotopes in TENDL-2011 are from original TALYS calculations and will not be presented here. The comparison for all channels are presented in Appendix E, page 59. The *autonormed* channels are presented in Fig. 14.

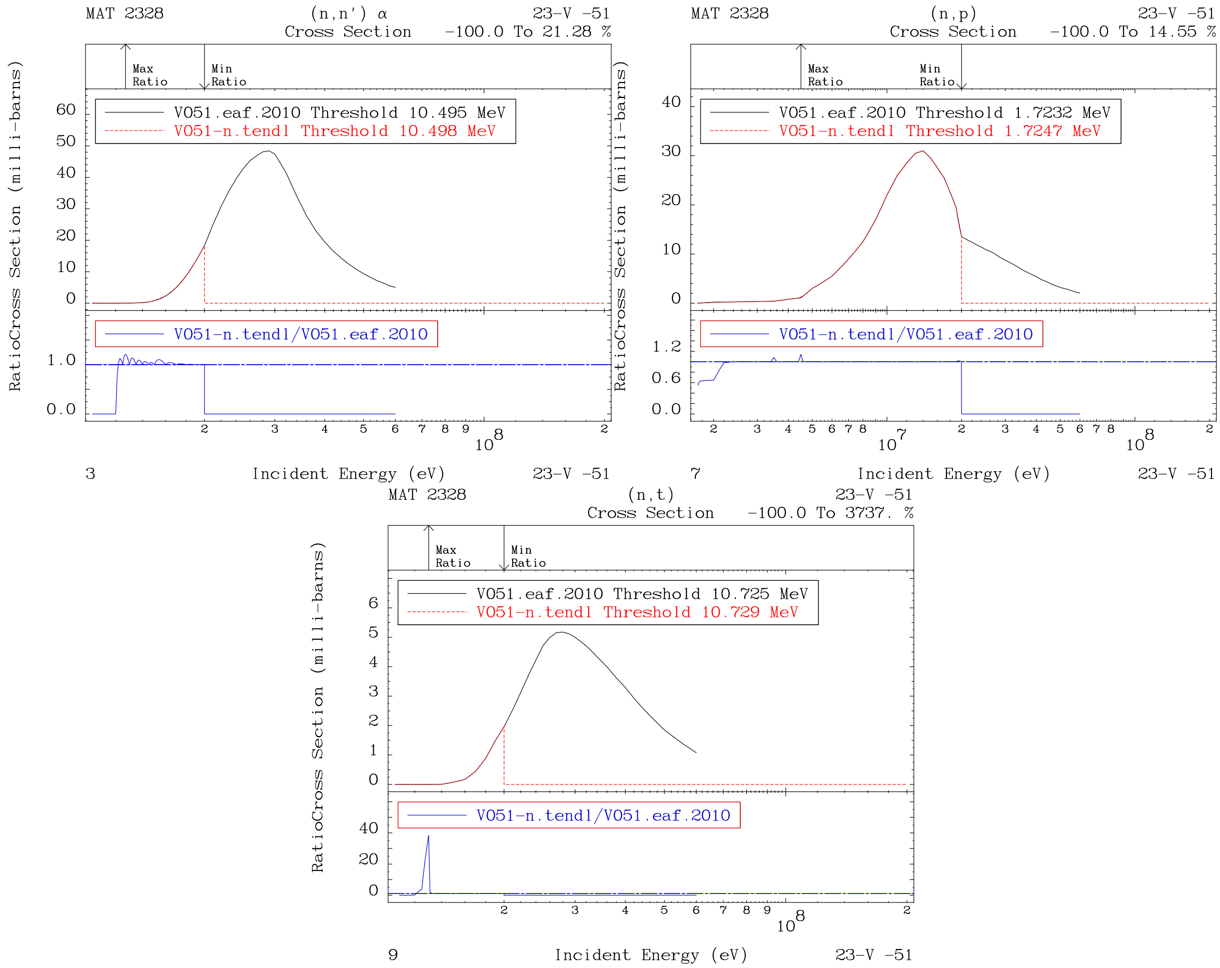

Figure 14: Autonormed ^{51}V cross sections to EAF-2010.

3.6 ^{55}Mn

Manganese has only one stable isotope (^{55}Mn). The EAF-2010 contains four Mn isotopes, only cross sections of ^{55}Mn from EAF-2010 are used in TENDL-2011. The comparison for all channels are presented in Appendix F, page 62. The *autonormed* channels are presented in Fig. 15.

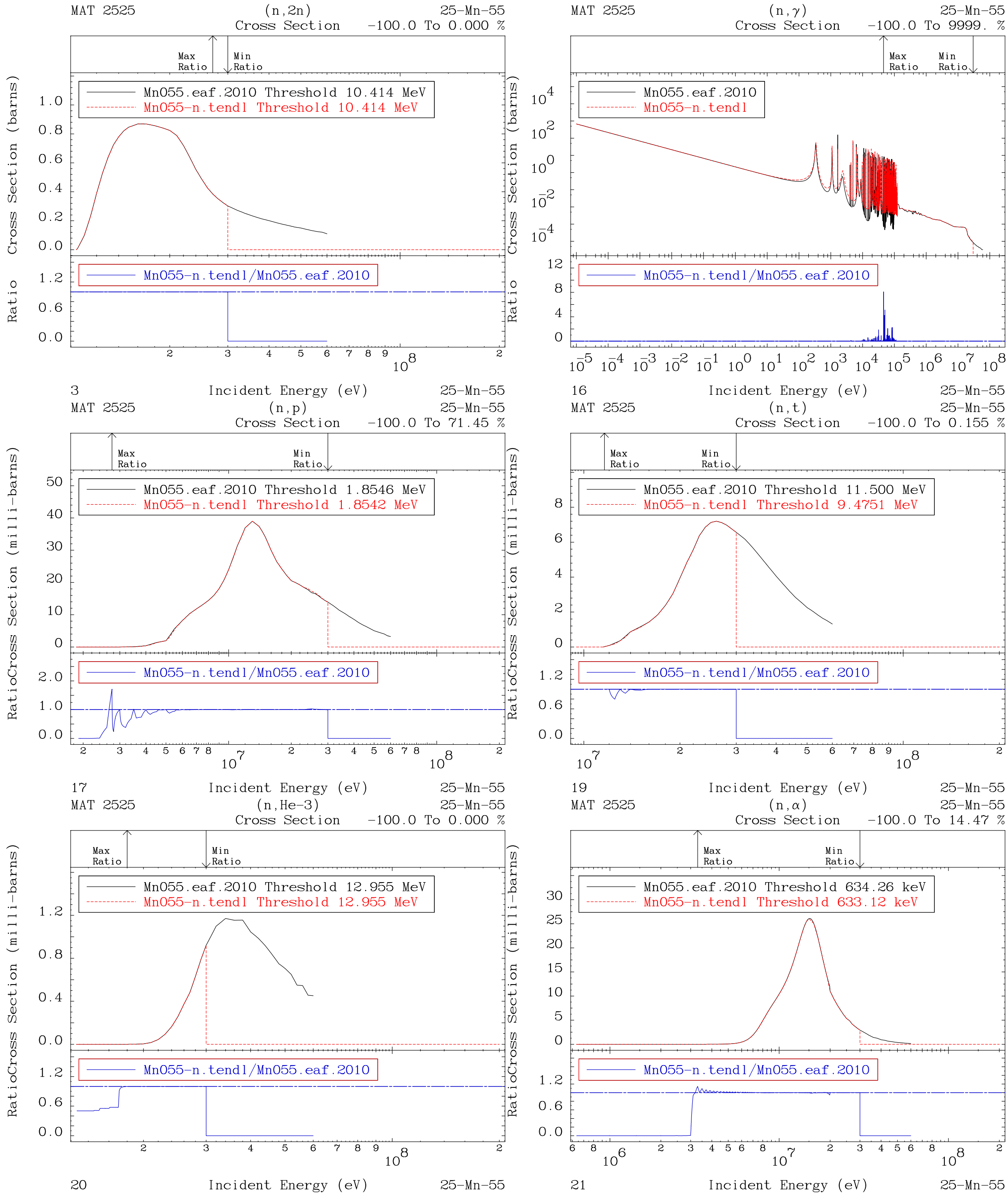

Figure 15: Autonormed ^{55}Mn cross sections to EAF-2010.

4 Conclusion

The validation and verification of modeling capabilities for TENDL-2011 on the 16 isotopes of the Eurofer consistuents are presented in this report. The V& V is performed by means of comparison between the TENDL-2011 and EAF-2010 libraries. For each of the isotopes, the cross sections are compared (plots of cross sections and ratios). The following main results for the comparison of the libraries were found:

1. Cross sections for 16 isotopes (Eurofer constituents) were compared between TENDL-2011 and EAF-2010 (^{54,56,57,58}Fe, ^{50,52,53,54}Cr, ^{180,182,183,184,186}W, ^{181}Ta, ^{51}V and ^{55}Mn),
2. Two types of results can be observed
   - in the case of "*autonormed*" (automated import) cross sections, the comparison between TENDL-2011 and EAF-2010 shows a very good agreement,
   - in the case of original TALYS calculations, the comparison between TENDL-2011 and EAF-2010 shows expected differences.

In the TENDL-2011 library, not all cross sections were *autonormed* (automatic import) to the ones of EAF-2010; for the 23 cross sections *autonormed* to EAF-2010, the agreement is very good, proving the capabilities of such method. The produced ENDF-6 files follow all the ENDF format rule and can be used as any other ENDF file for transport calculations.

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Appendix A: Fe EAF-2010/TENDL-2011

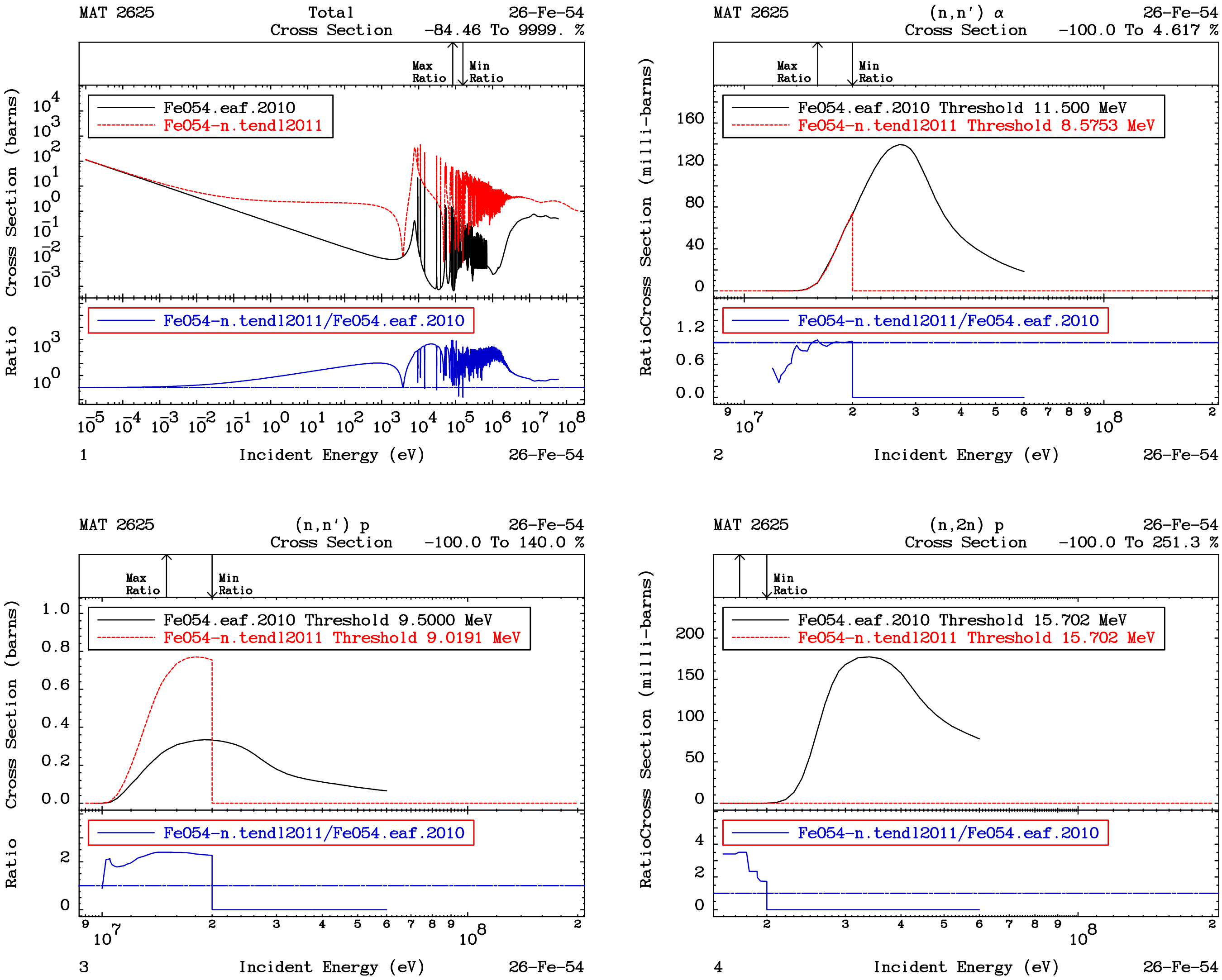

Figure 16: Cross sections and ratios for ^{54}Fe between TENDL-2011 and EAF-2010

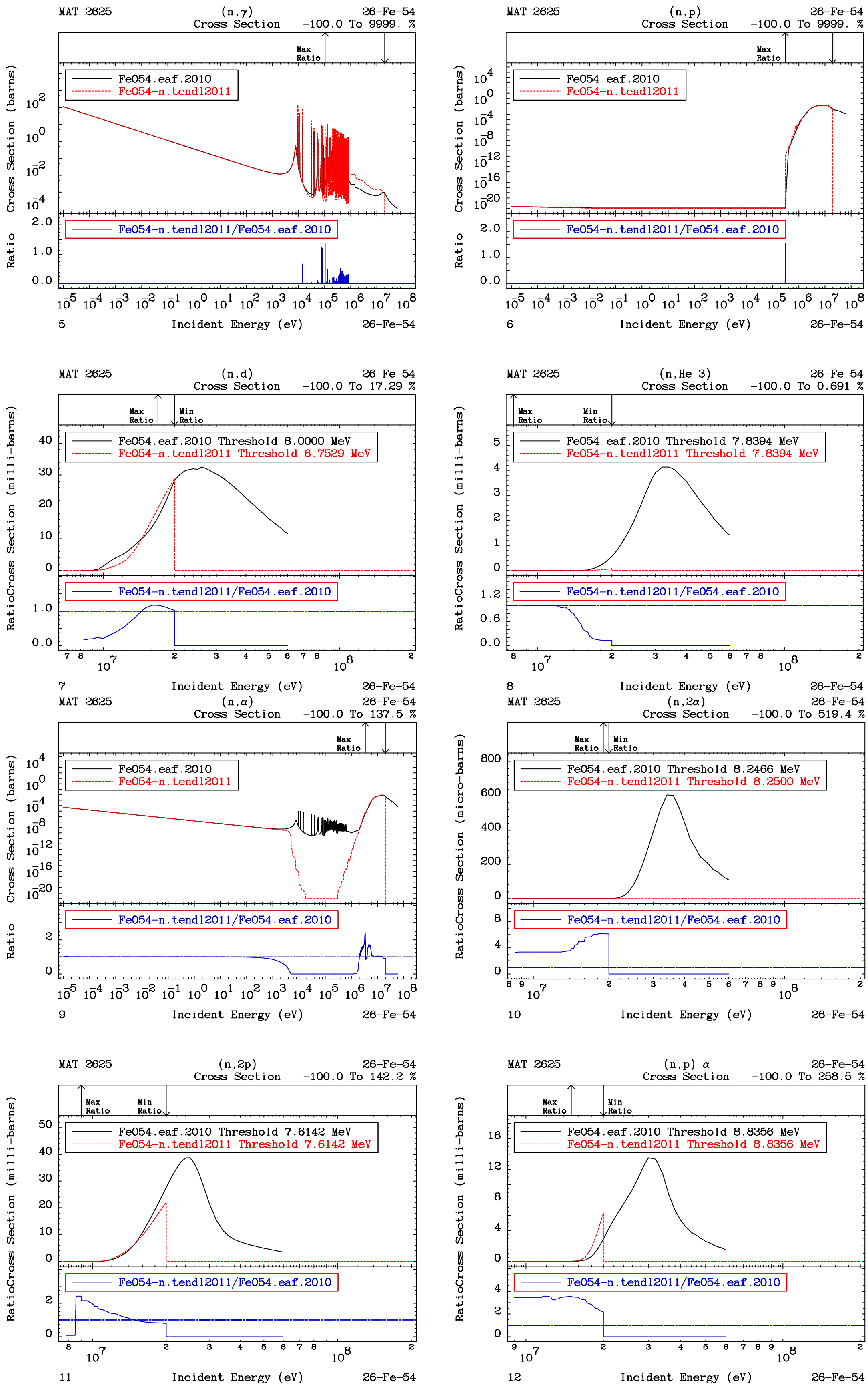

Figure 17: Cross sections and ratios for ^{54}Fe between TENDL-2011 and EAF-2010

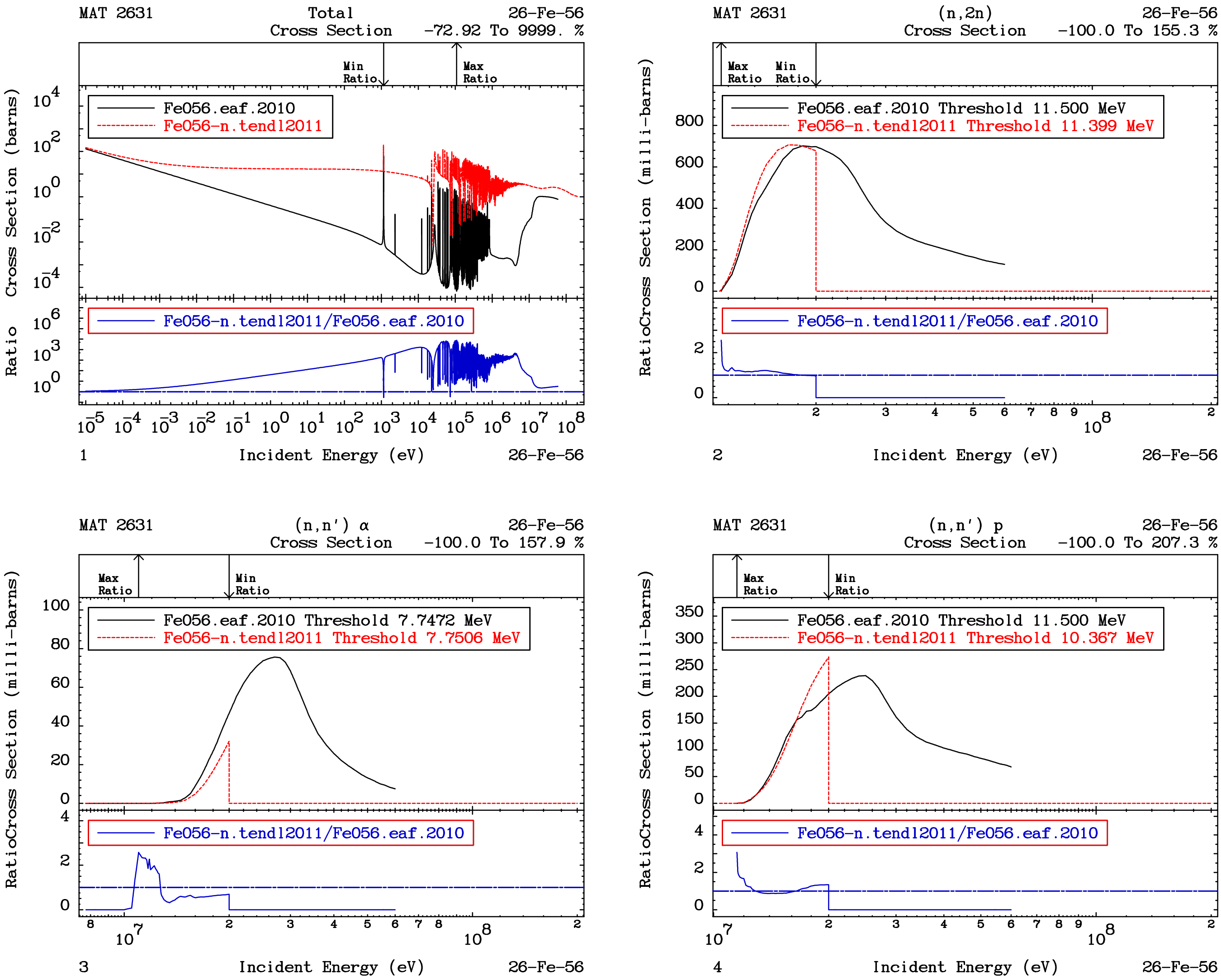

Figure 18: Cross sections and ratios for ^{56}Fe between TENDL-2011 and EAF-2010

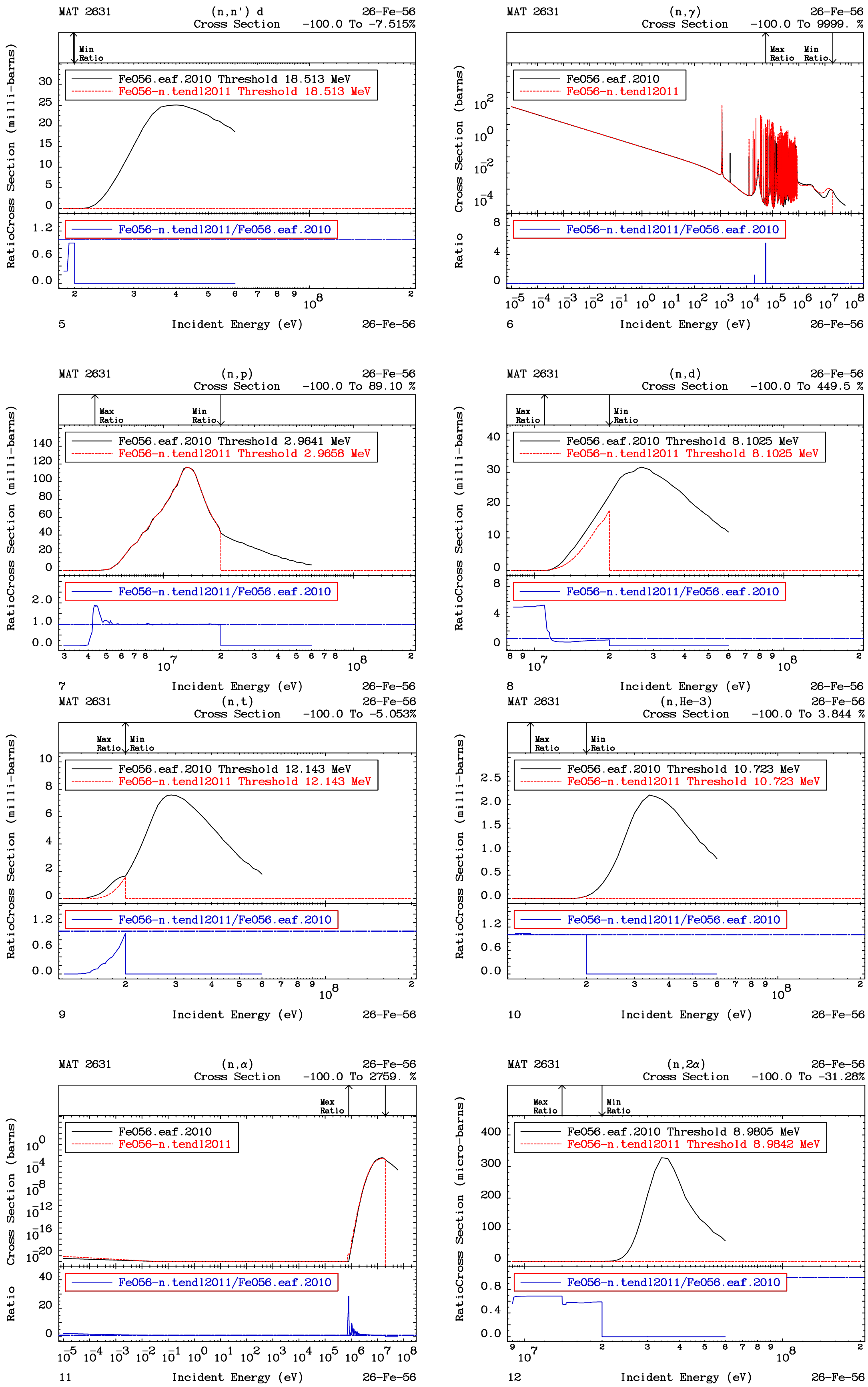

Figure 19: Cross sections and ratios for ^{56}Fe between TENDL-2011 and EAF-2010

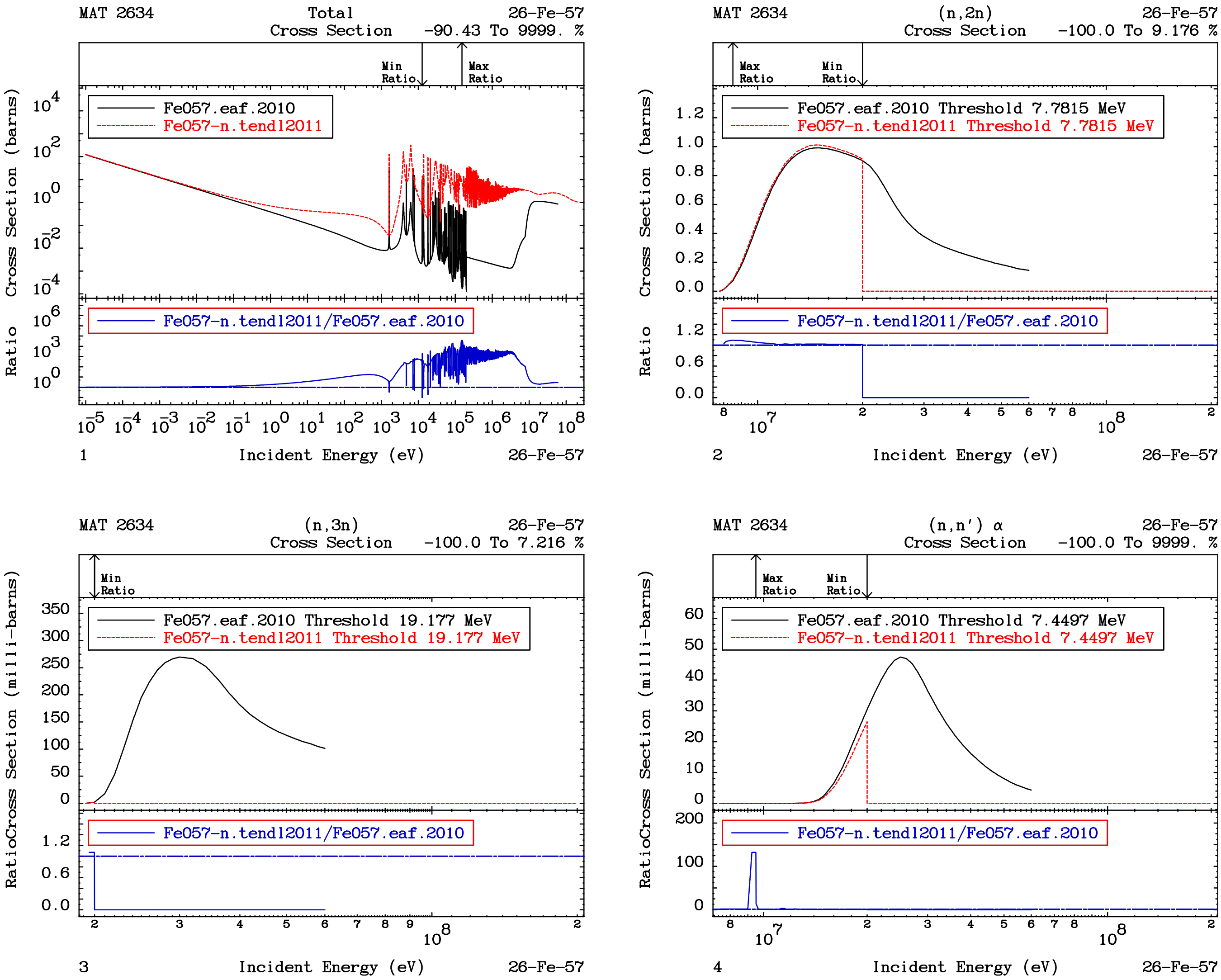

Figure 20: Cross sections and ratios for ^{57}Fe between TENDL-2011 and EAF-2010

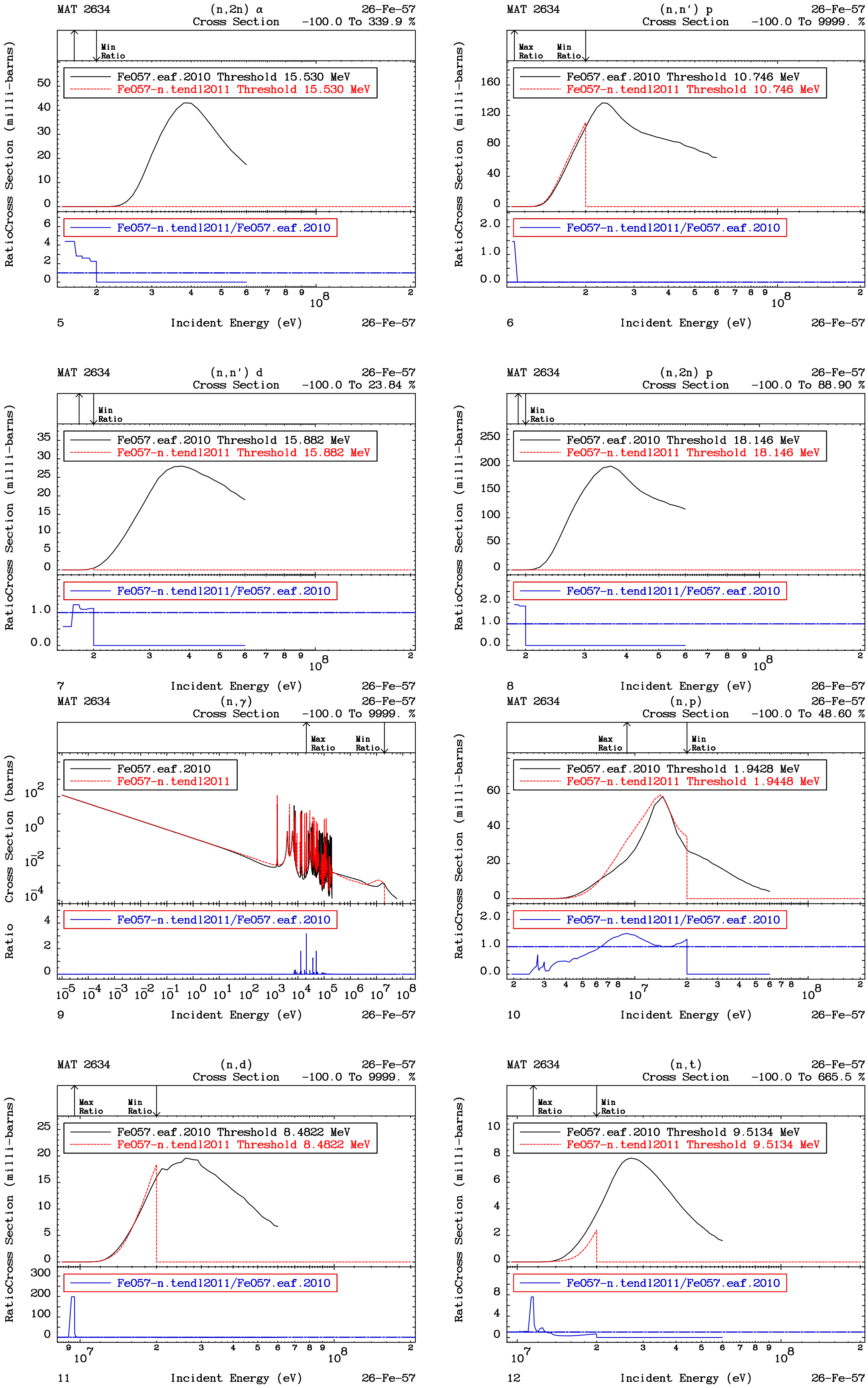

Figure 21: Cross sections and ratios for ^{57}Fe between TENDL-2011 and EAF-2010

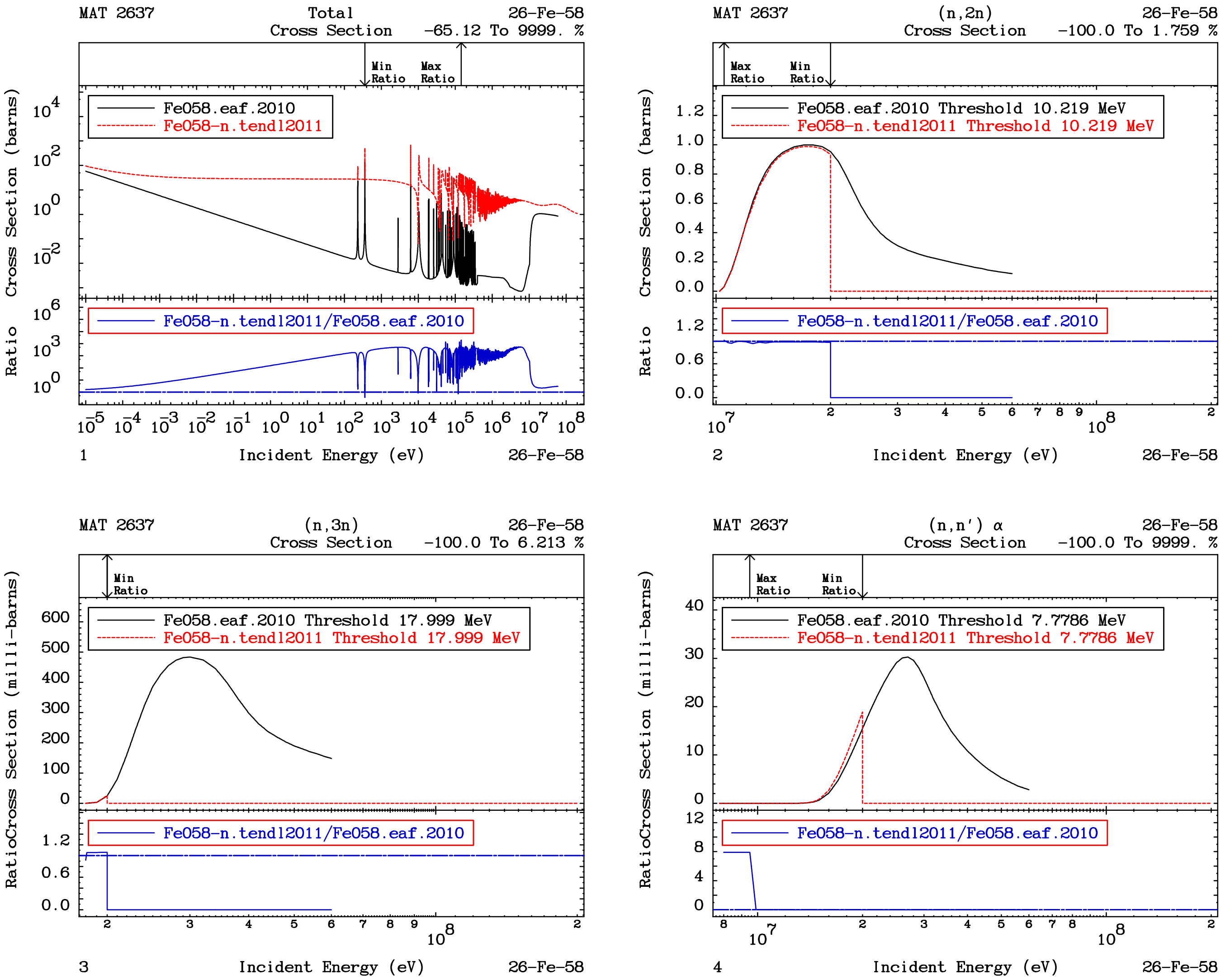

Figure 22: Cross sections and ratios for ^{58}Fe between TENDL-2011 and EAF-2010

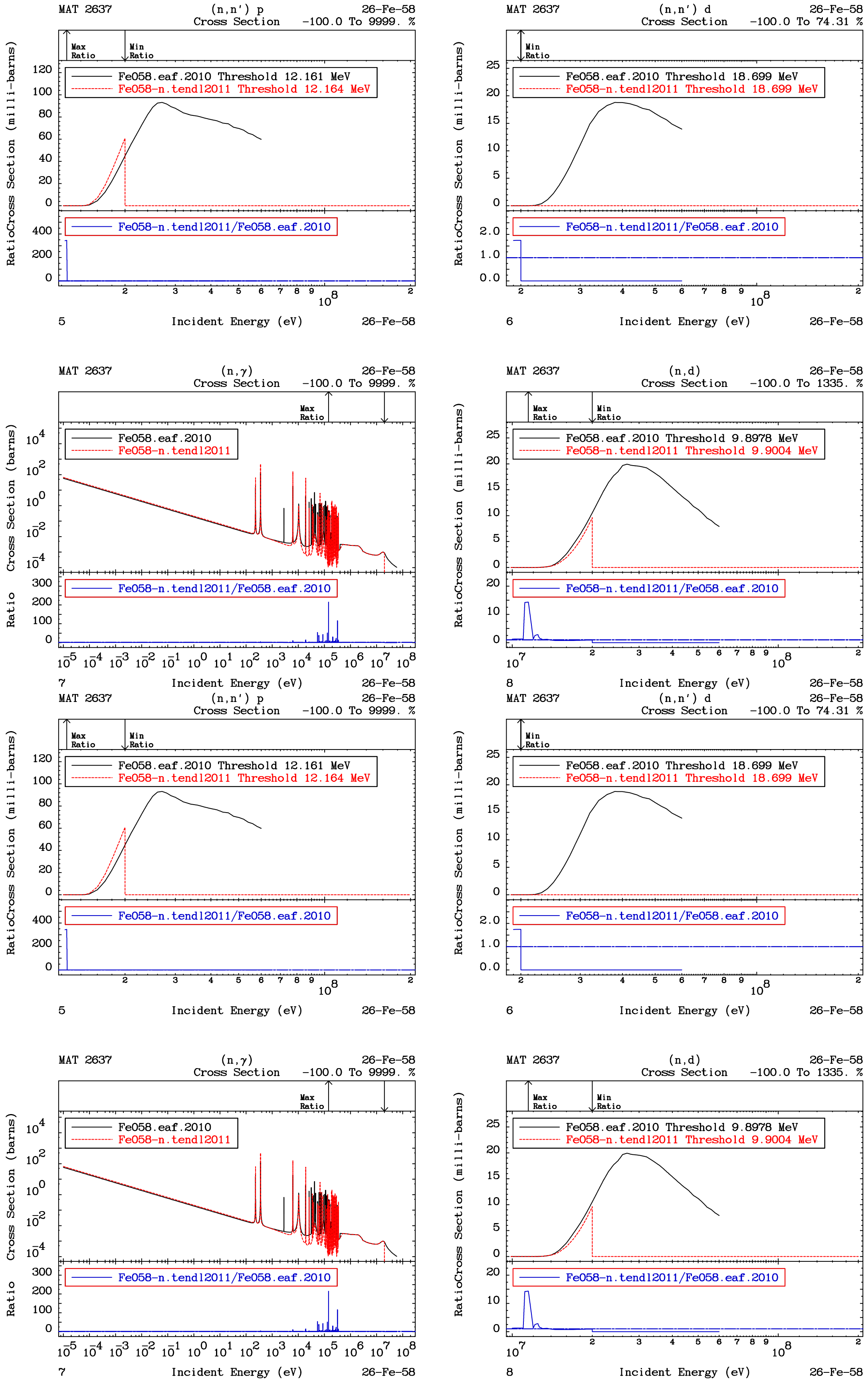

Figure 23: Cross sections and ratios for ^{58}Fe between TENDL-2011 and EAF-2010

Appendix B: Cr EAF-2010/TENDL-2011

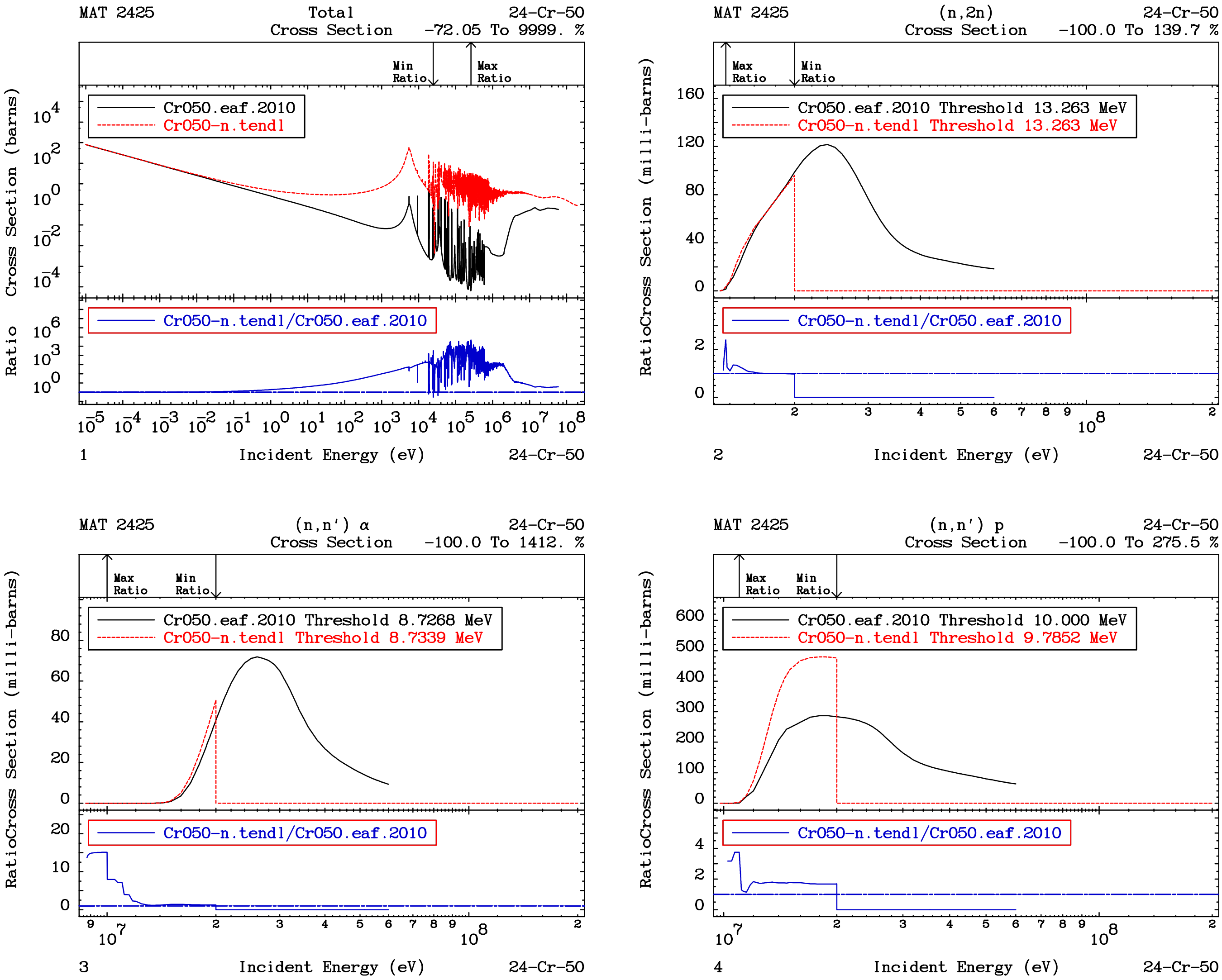

Figure 24: Cross sections and ratios for ^{50}Cr between TENDL-2011 and EAF-2010

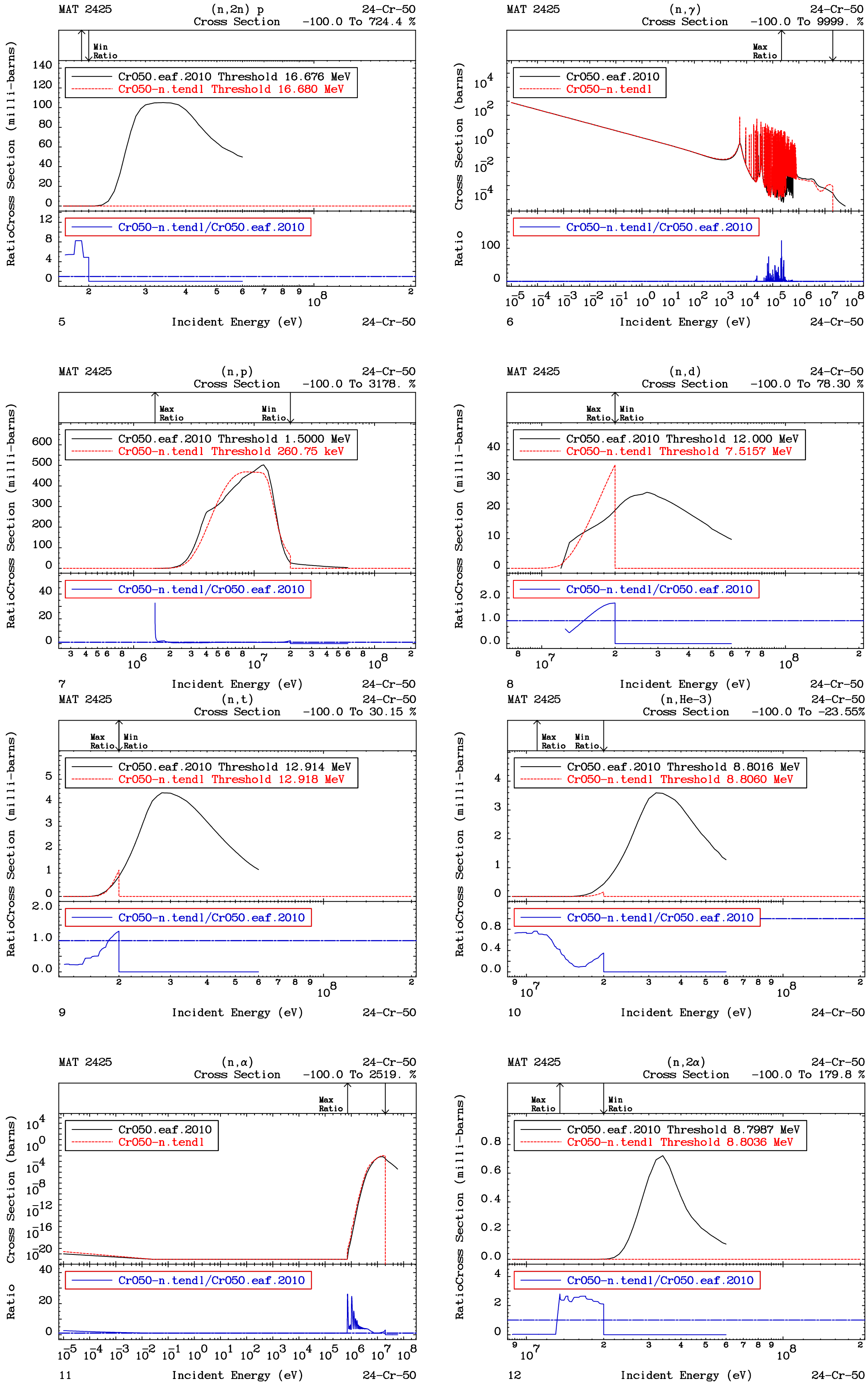

Figure 25: Cross sections and ratios for ^{50}Cr between TENDL-2011 and EAF-2010

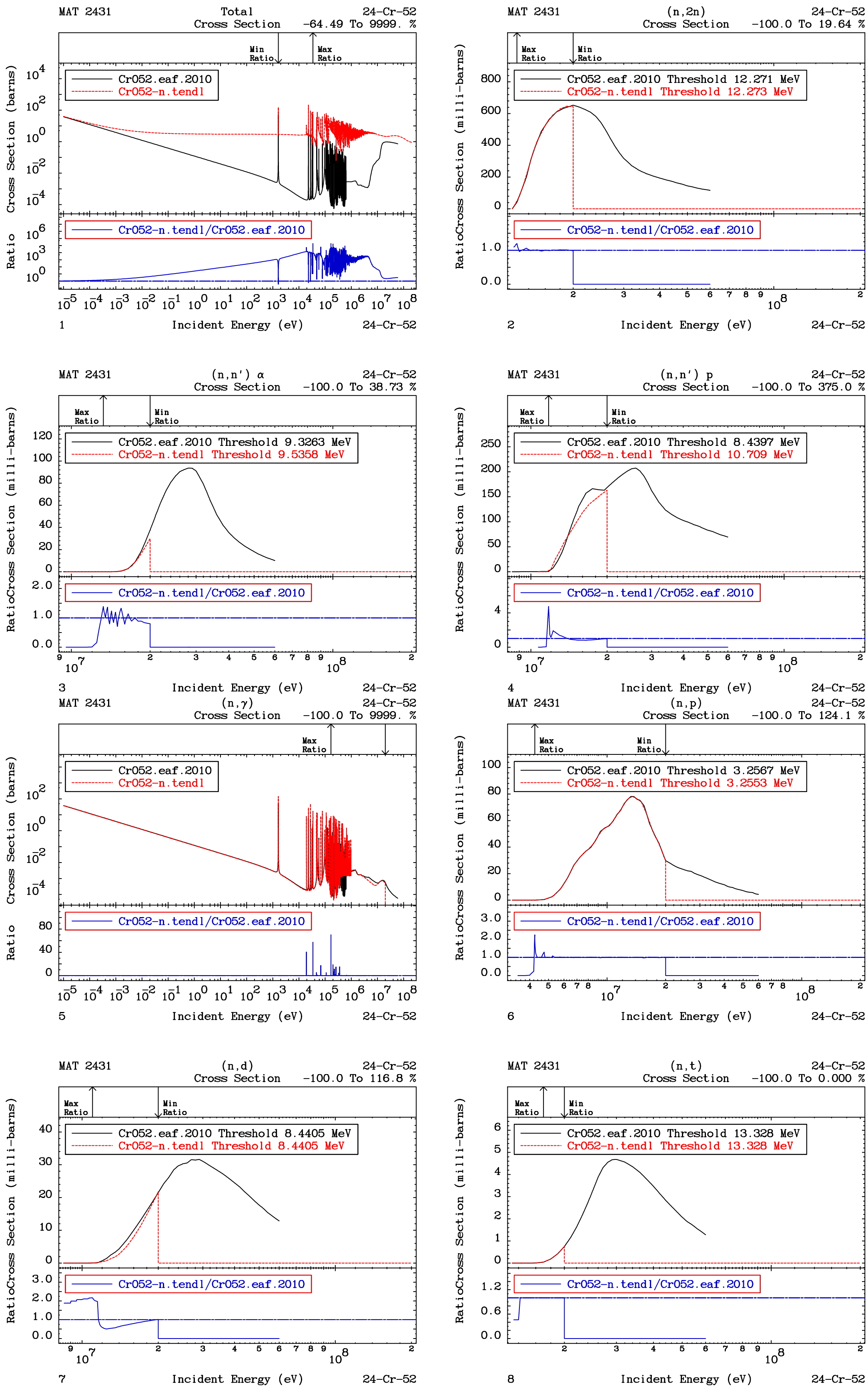

Figure 26: Cross sections and ratios for ^{52}Cr between TENDL-2011 and EAF-2010

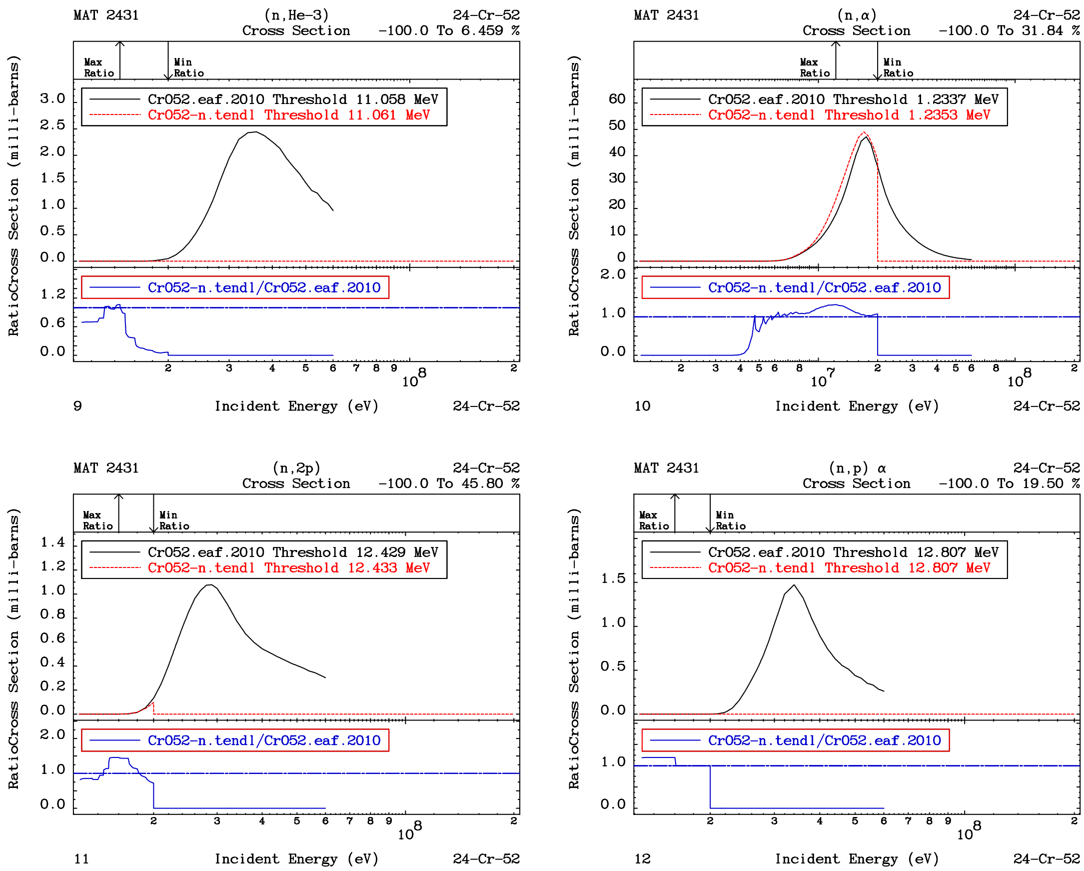

Figure 27: Cross sections and ratios for ^{52}Cr between TENDL-2011 and EAF-2010

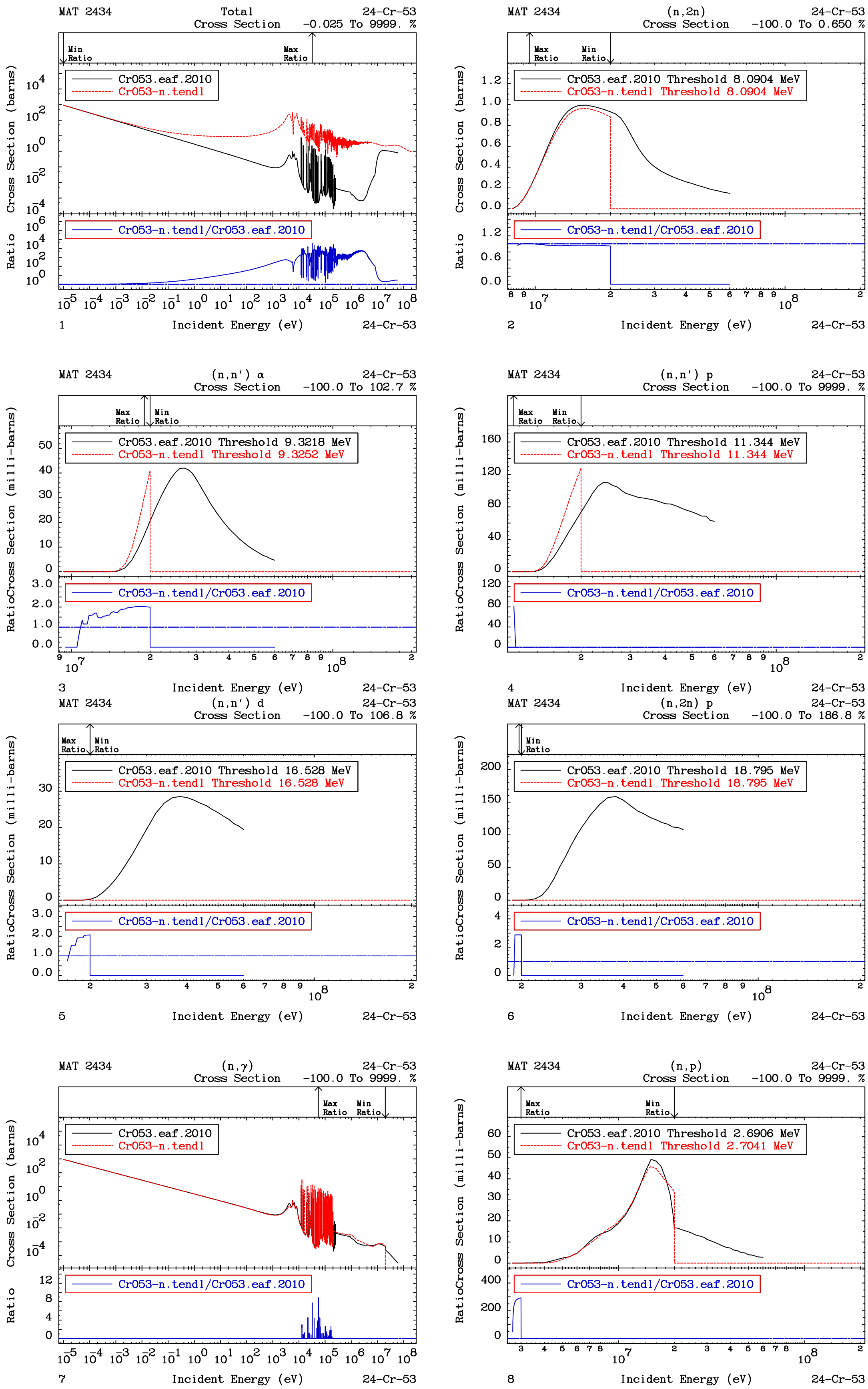

Figure 28: Cross sections and ratios for ^{53}Cr between TENDL-2011 and EAF-2010

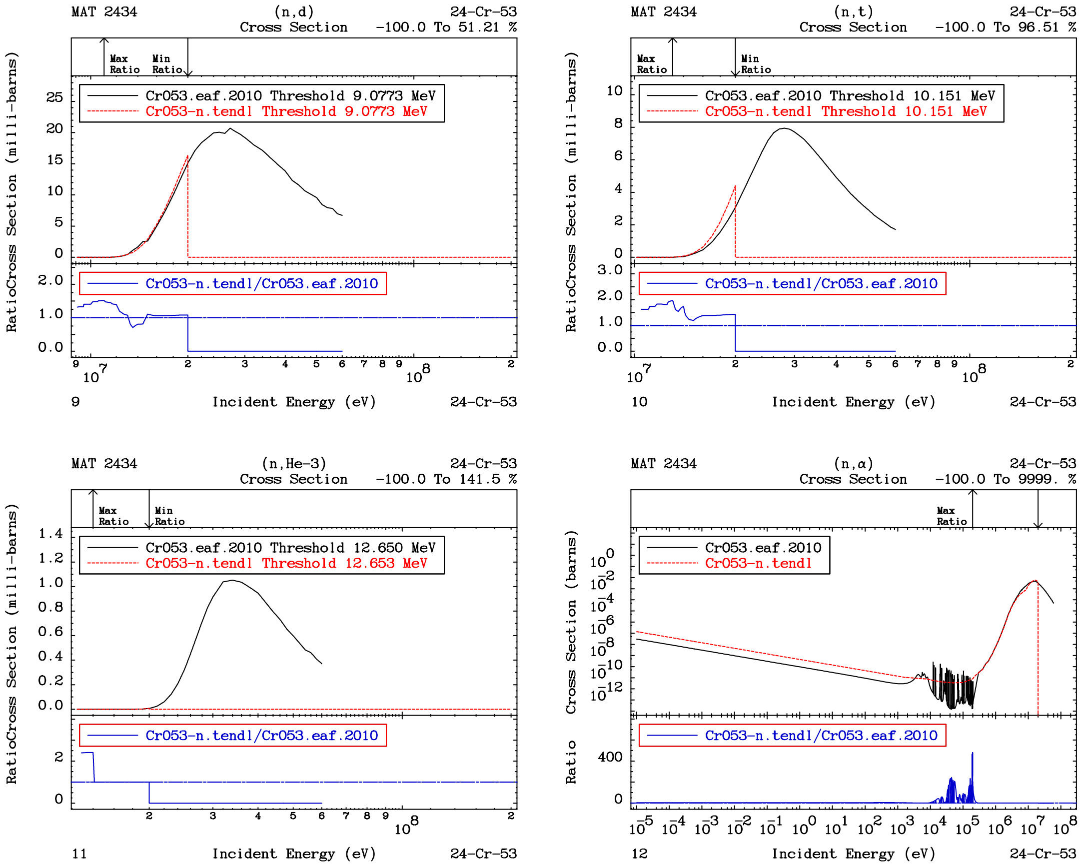

Figure 29: Cross sections and ratios for ^{53}Cr between TENDL-2011 and EAF-2010

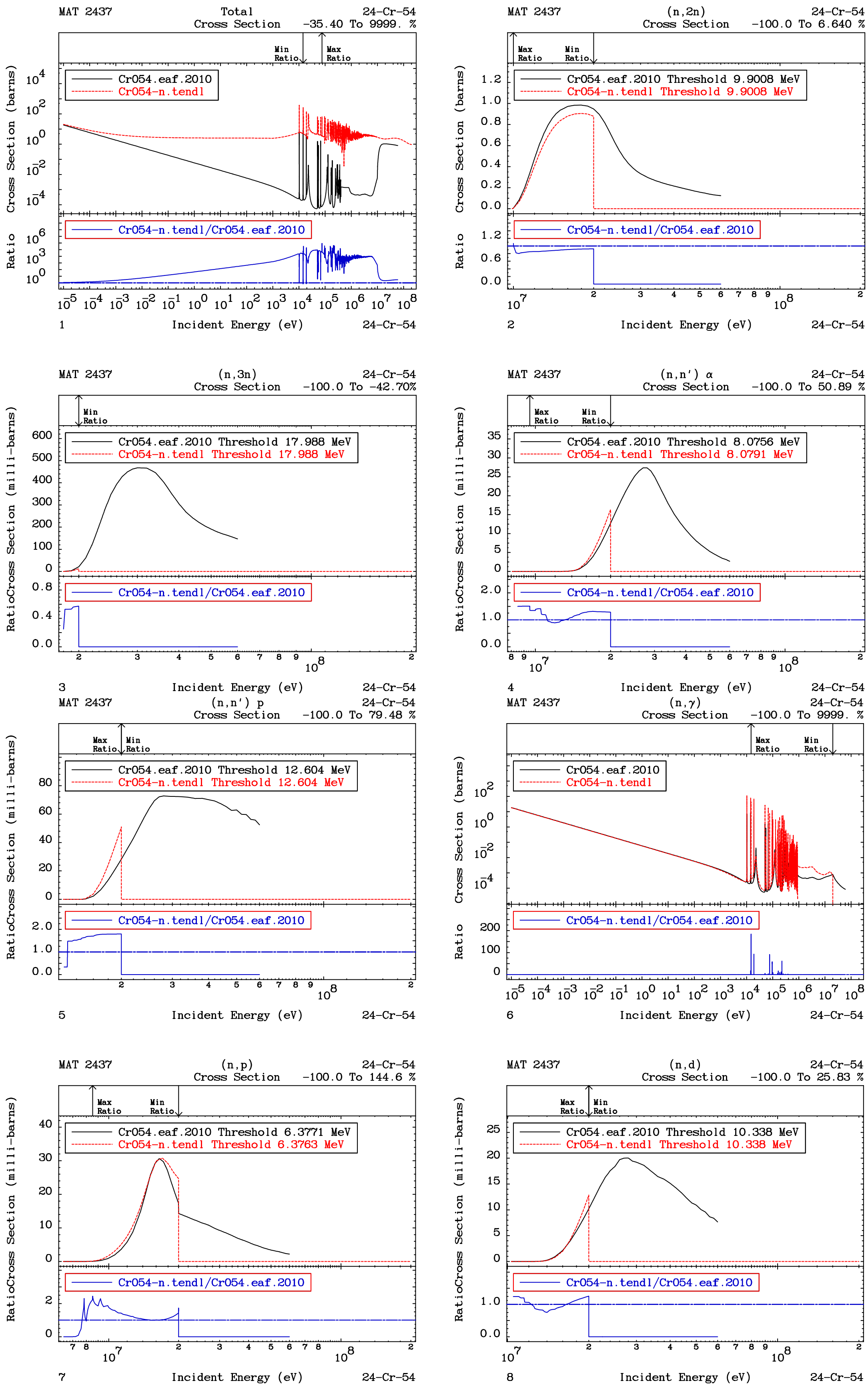

Figure 30: Cross sections and ratios for ^{54}Cr between TENDL-2011 and EAF-2010

Appendix C: W EAF-2010/TENDL-2011

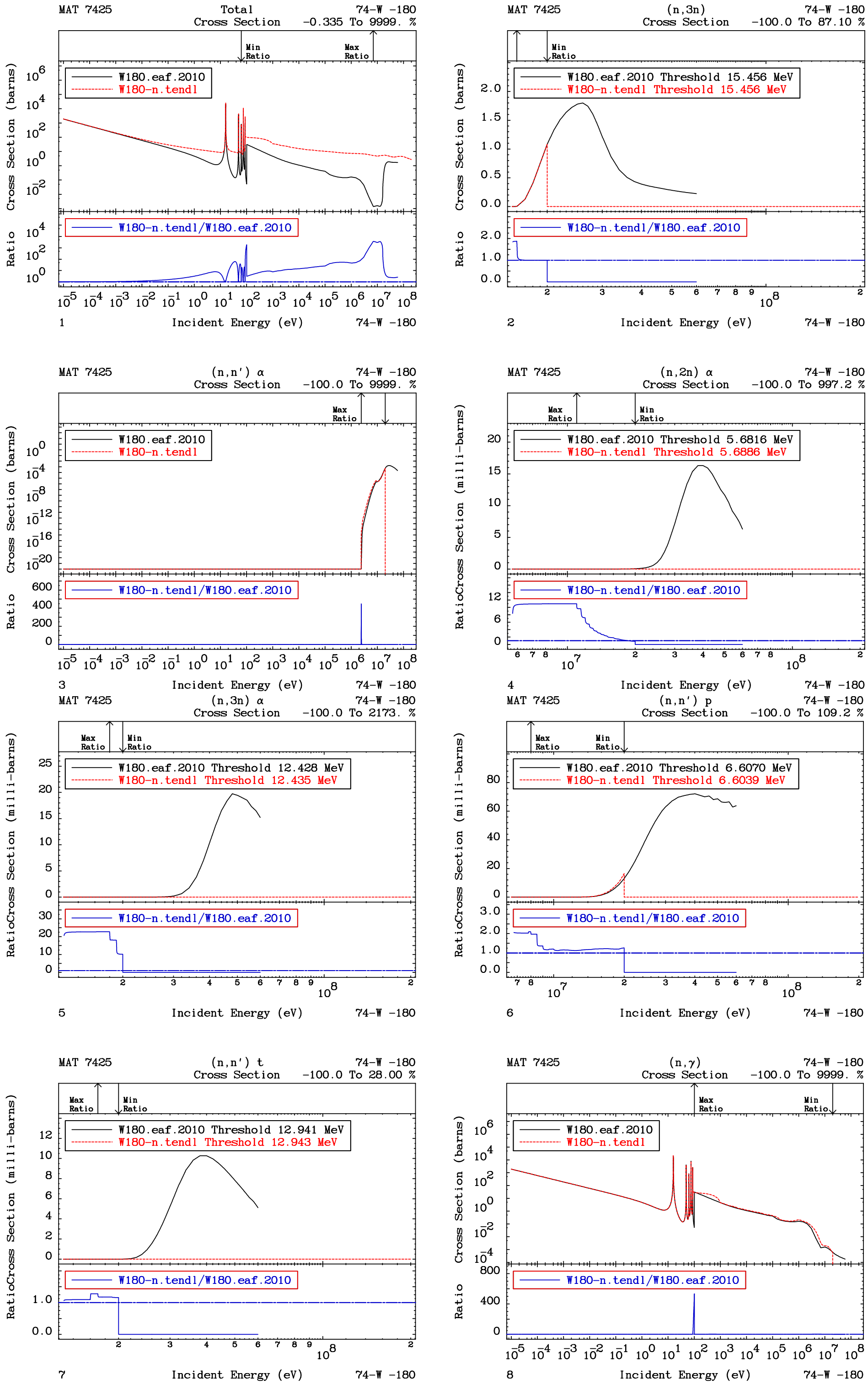

Figure 31: Cross sections and ratios for ^{180}W between TENDL-2011 and EAF-2010

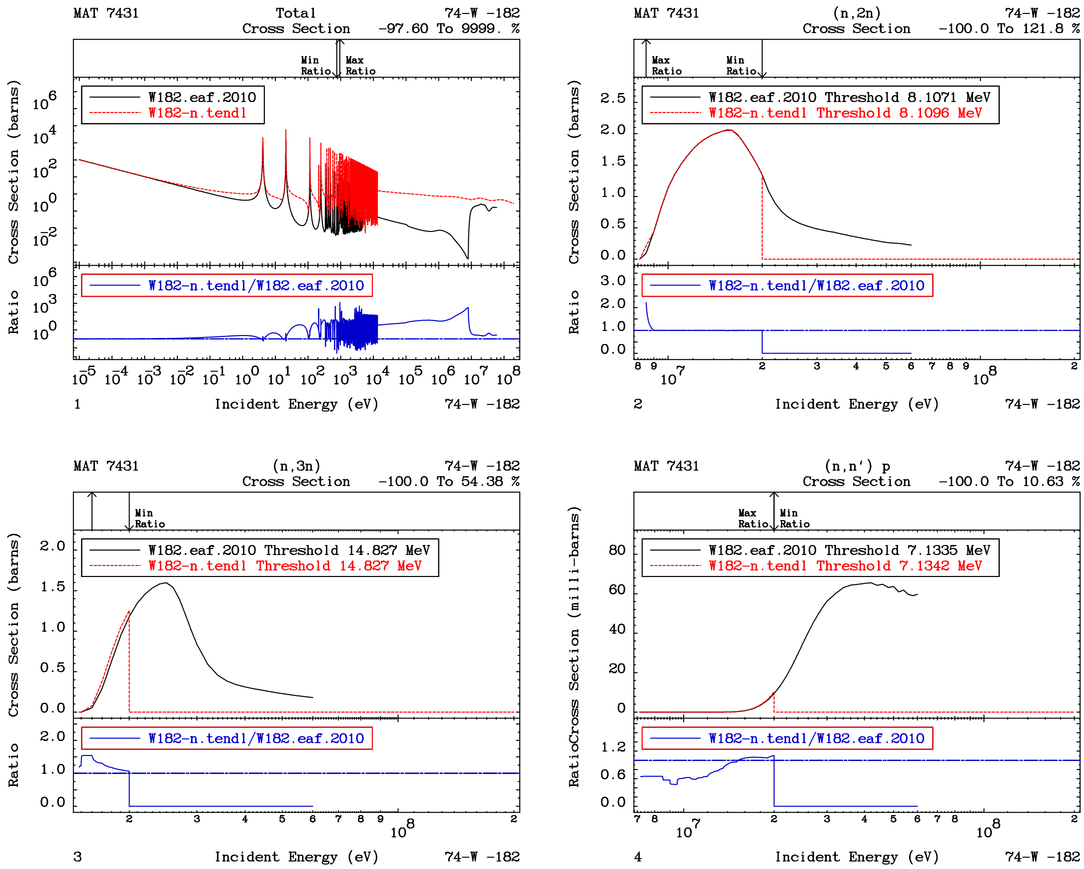

Figure 32: Cross sections and ratios for ^{182}W between TENDL-2011 and EAF-2010

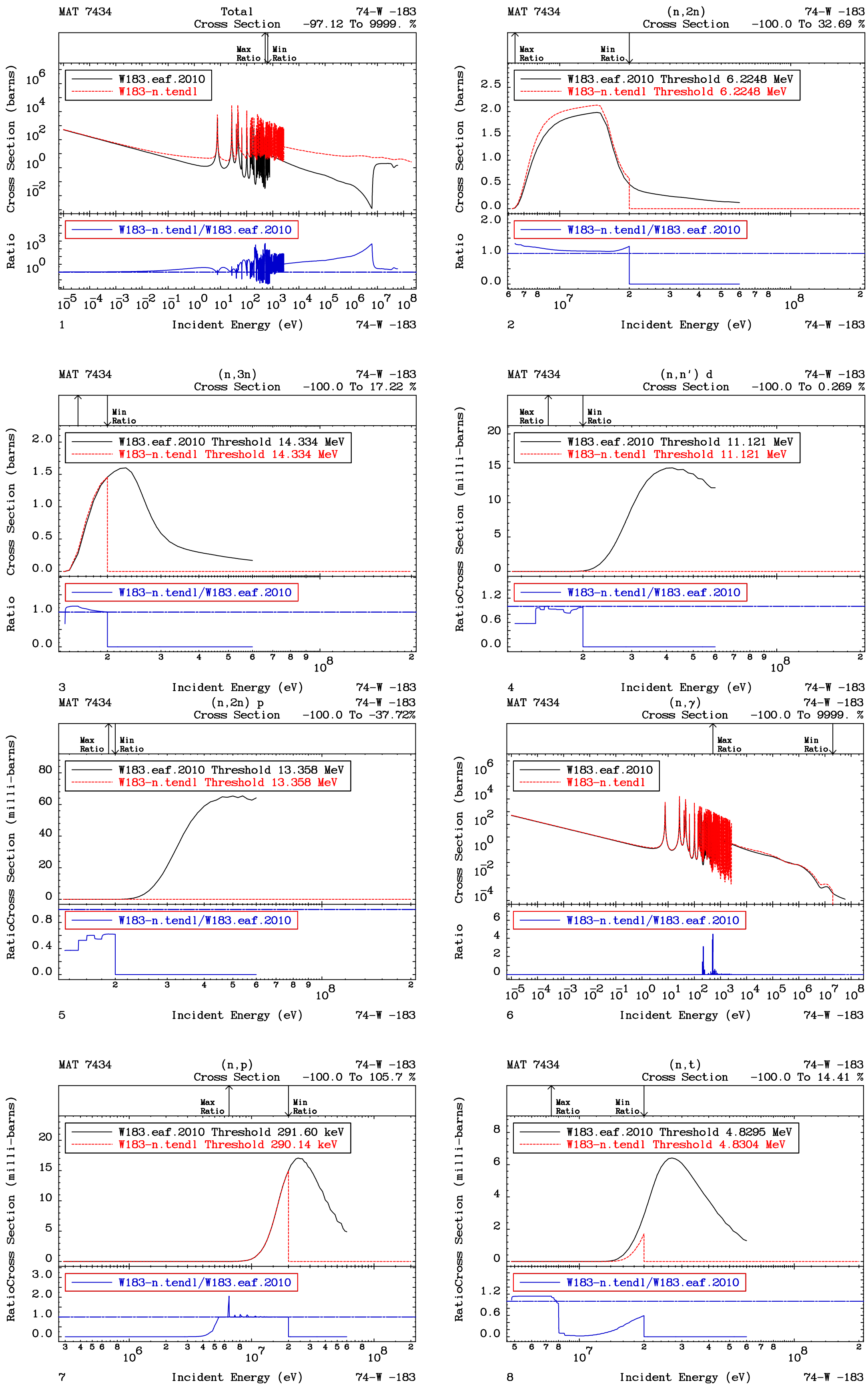

Figure 33: Cross sections and ratios for ^{183}W between TENDL-2011 and EAF-2010

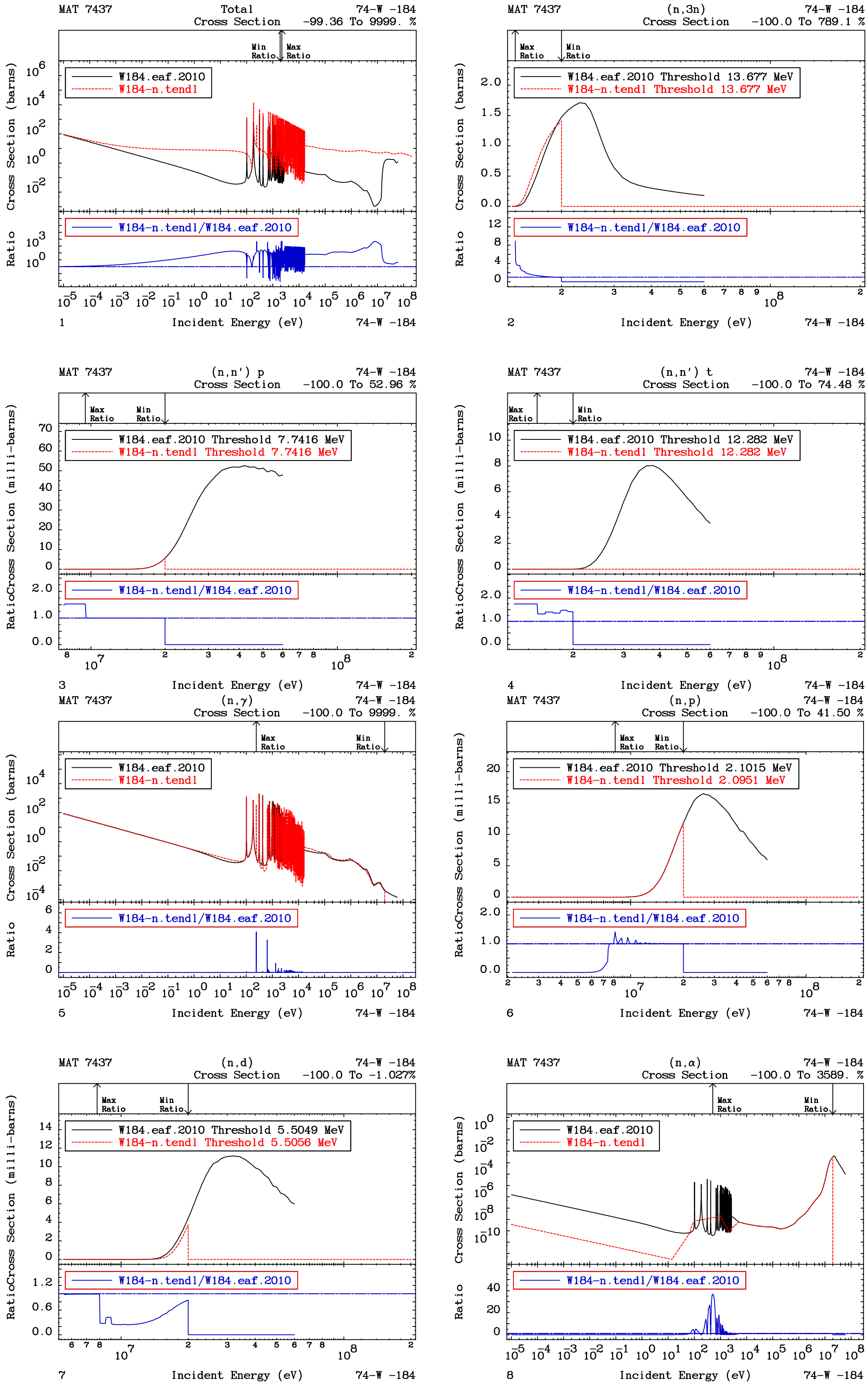

Figure 34: Cross sections and ratios for ^{184}W between TENDL-2011 and EAF-2010

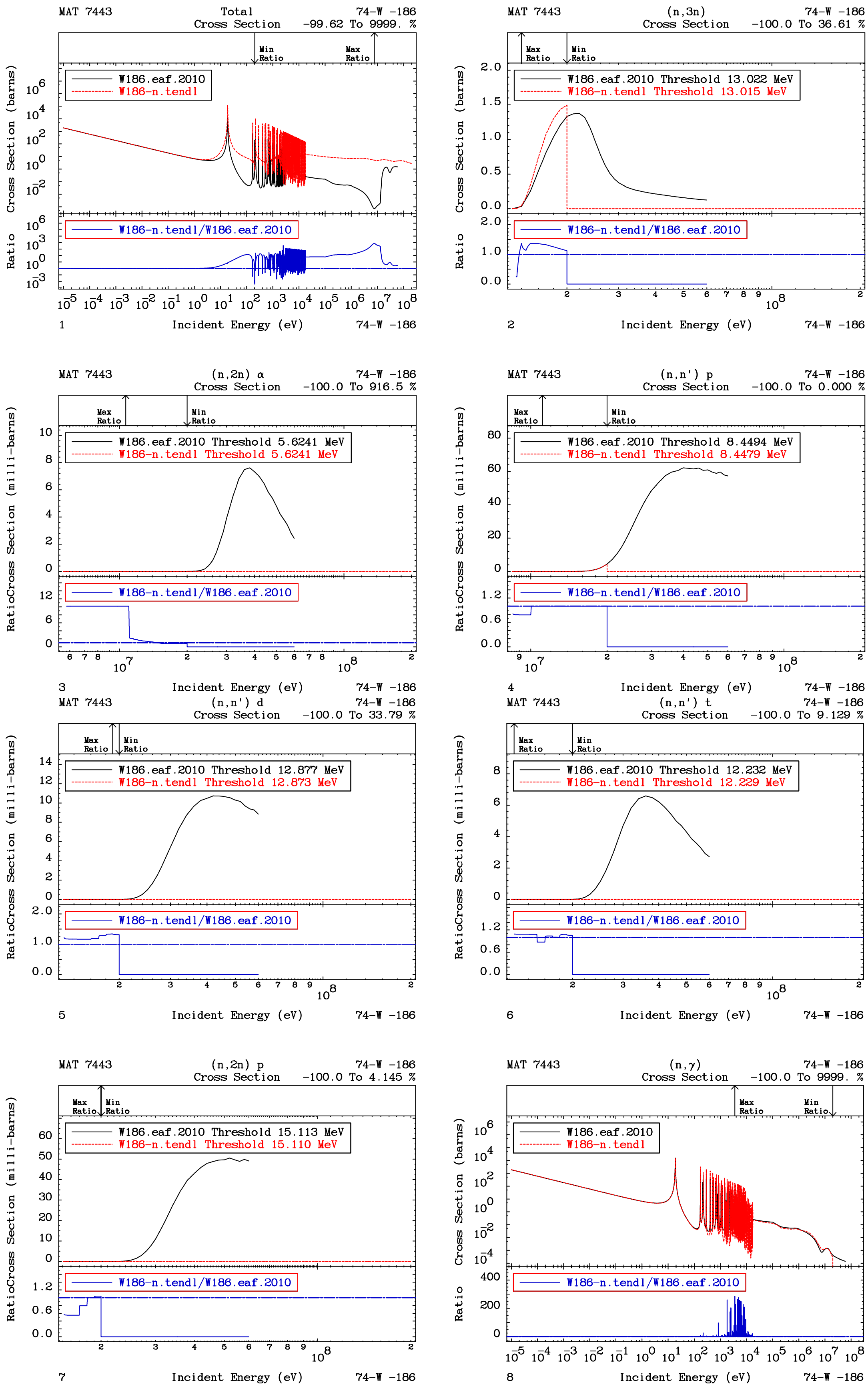

Figure 35: Cross sections and ratios for ^{186}W between TENDL-2011 and EAF-2010

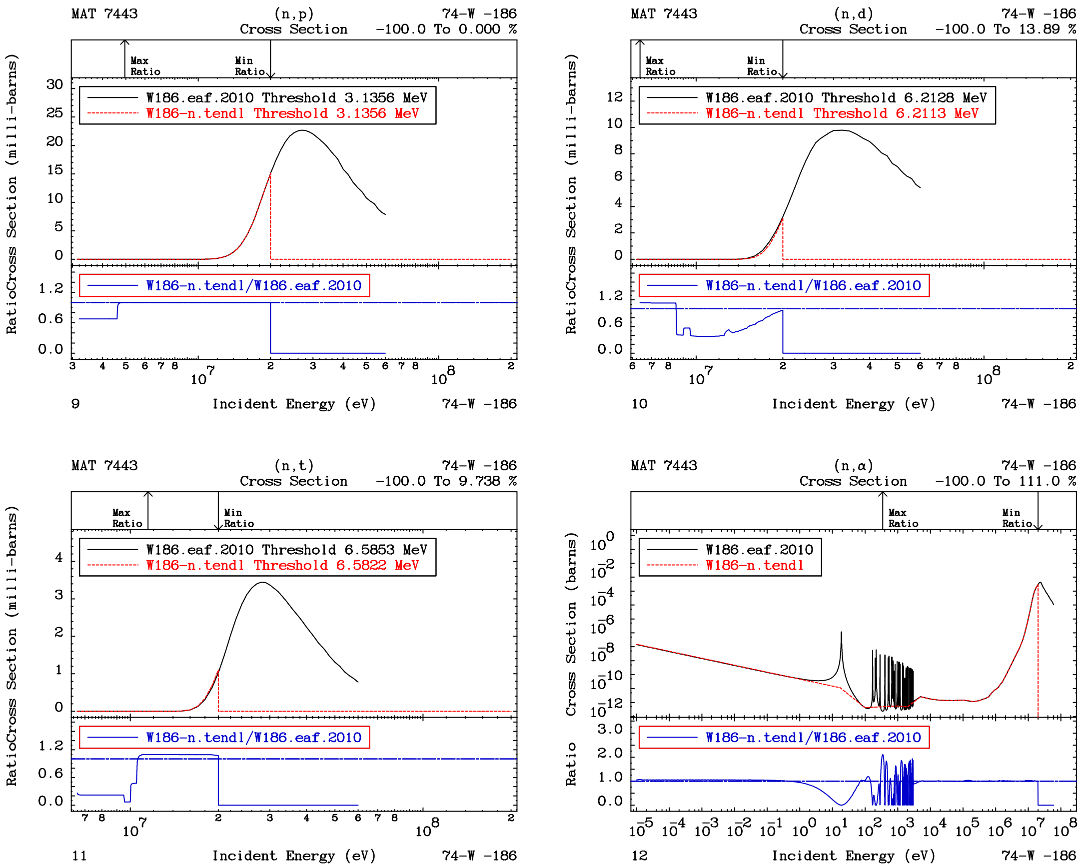

Figure 36: Cross sections and ratios for ^{186}W between TENDL-2011 and EAF-2010

Appendix D: Ta EAF-2010/TENDL-2011

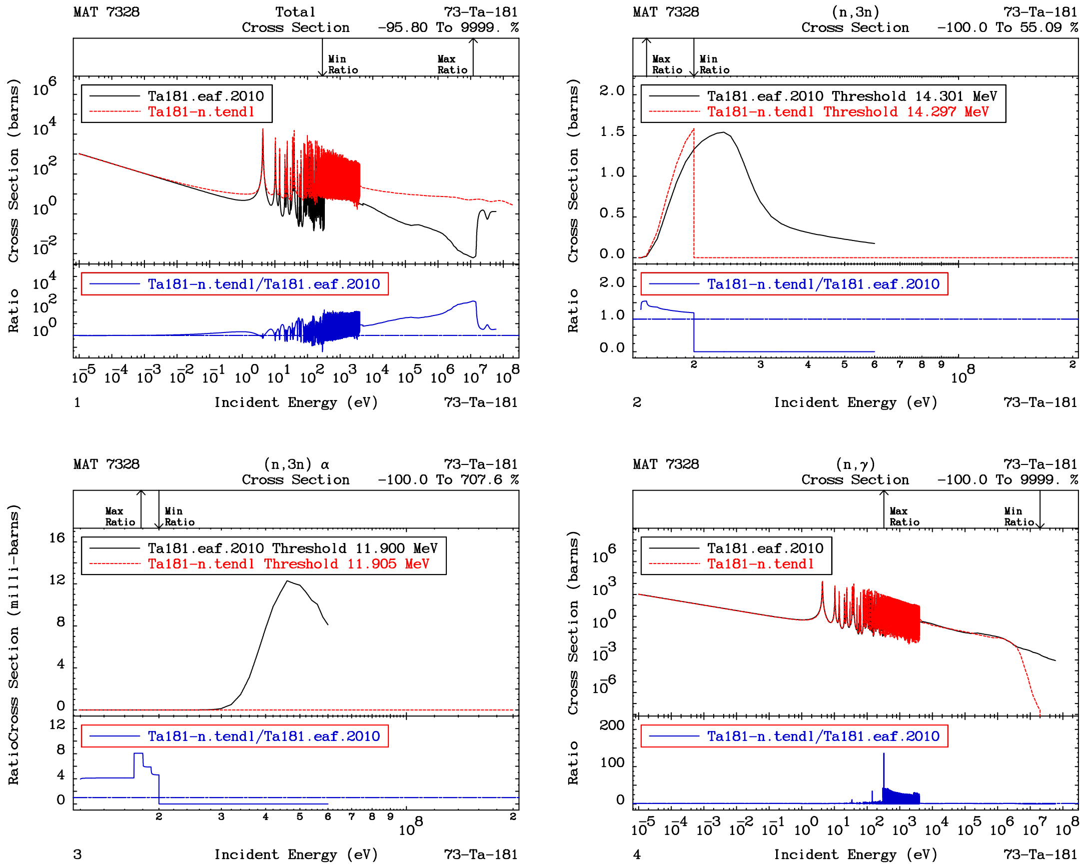

Figure 37: Cross sections and ratios for ^{181}Ta between TENDL-2011 and EAF-2010

Appendix E: V EAF-2010/TENDL-2011

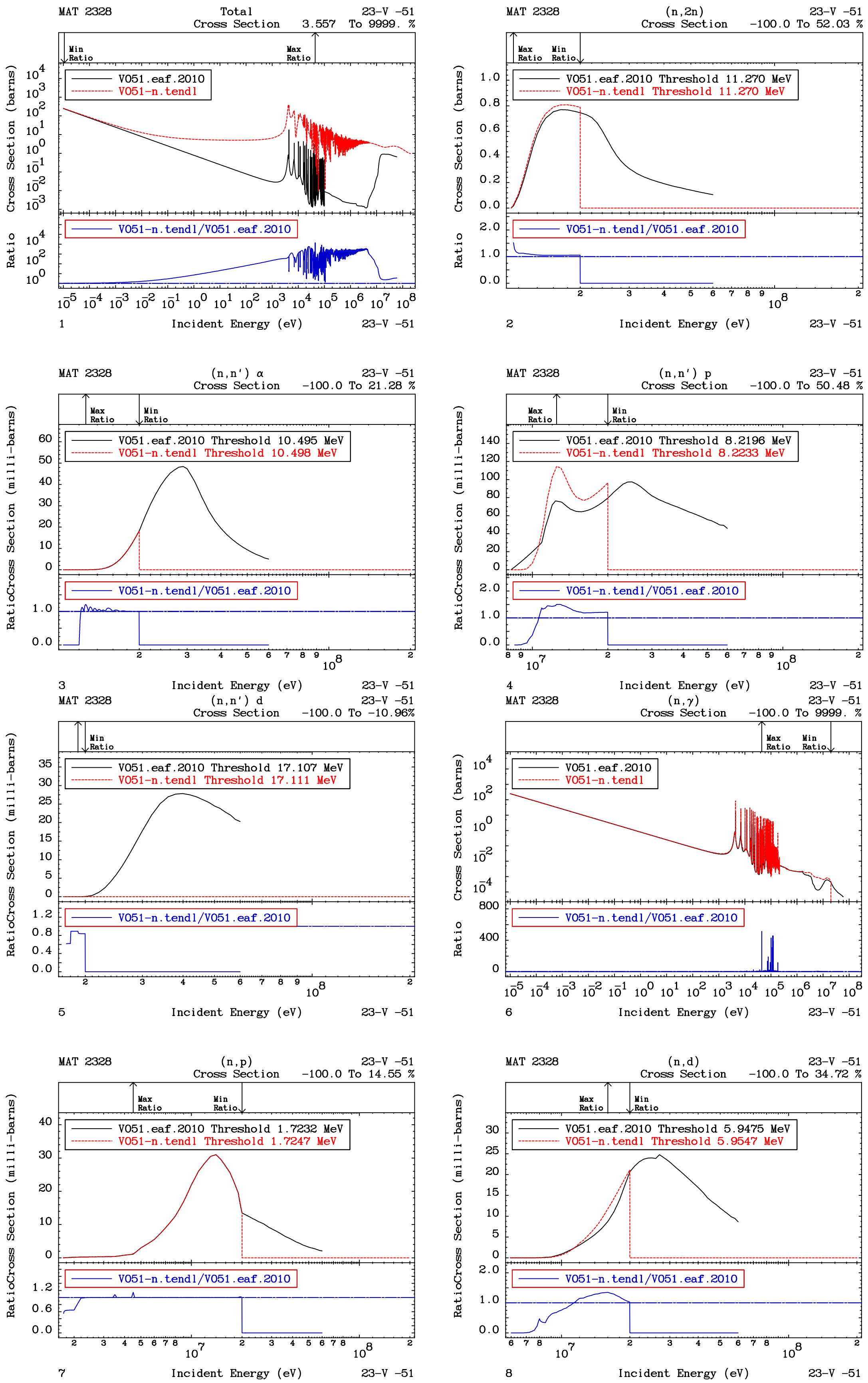

Figure 38: Cross sections and ratios for ^{51}V between TENDL-2011 and EAF-2010

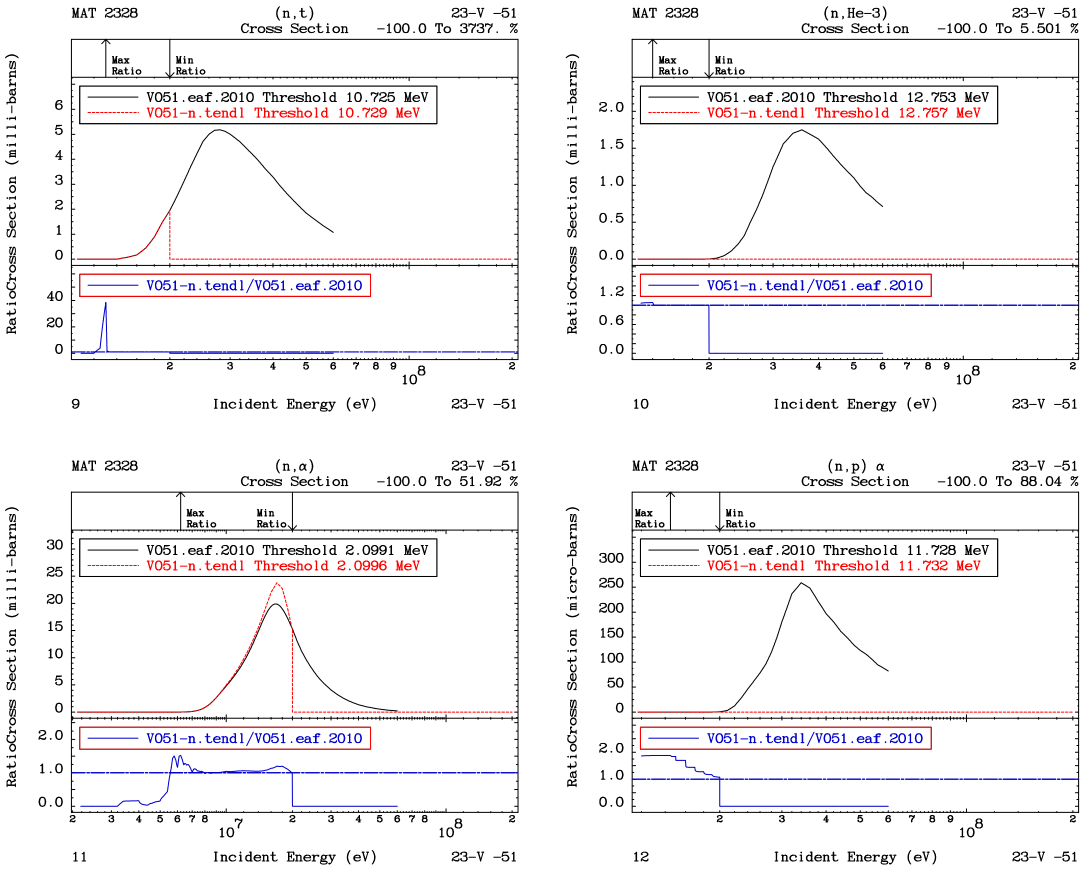

Figure 39: Cross sections and ratios for ^{51}V between TENDL-2011 and EAF-2010

Appendix F: Mn EAF-2010/TENDL-2011

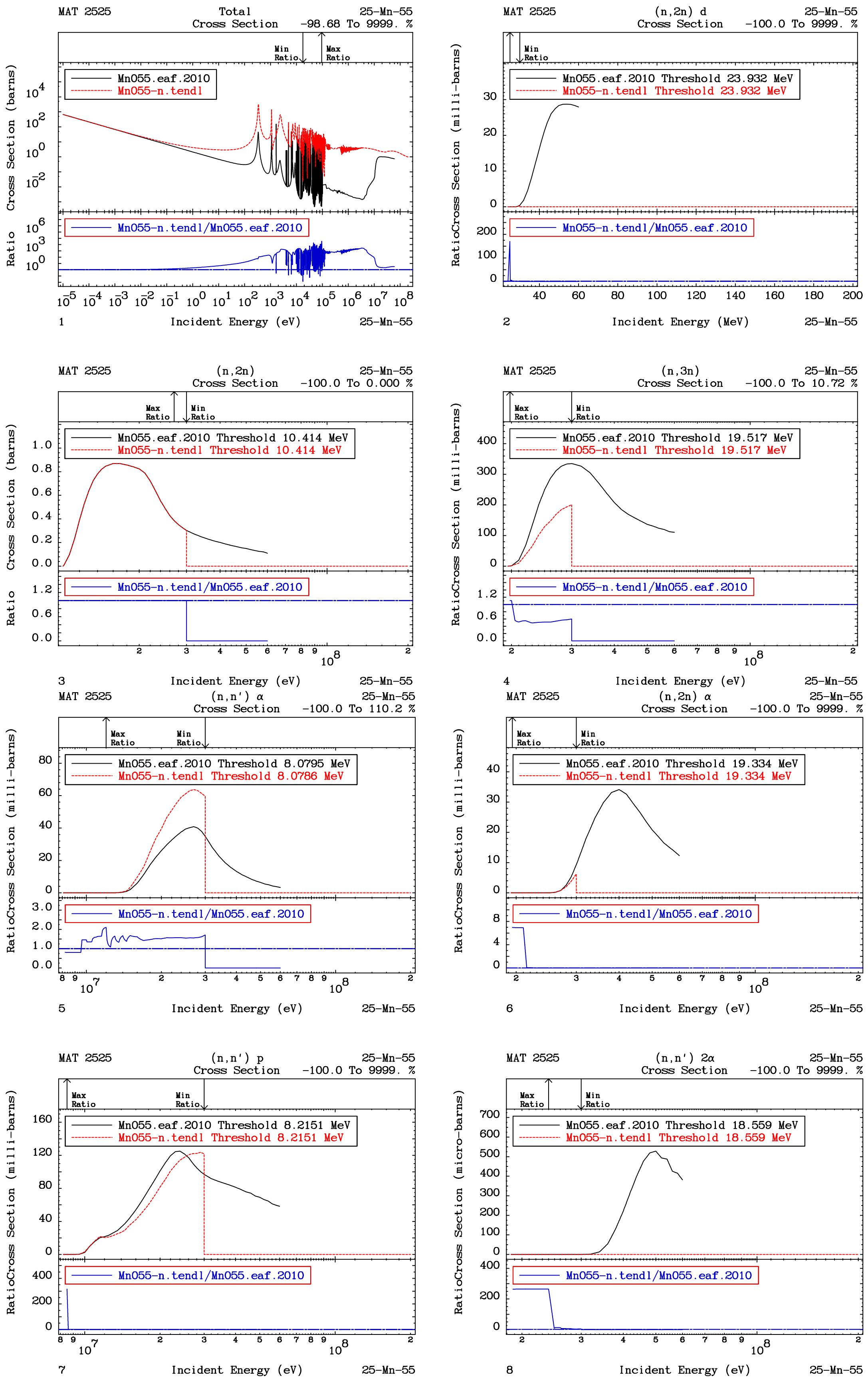

Figure 40: Cross sections and ratios for ^{55}Mn between TENDL-2011 and EAF-2010

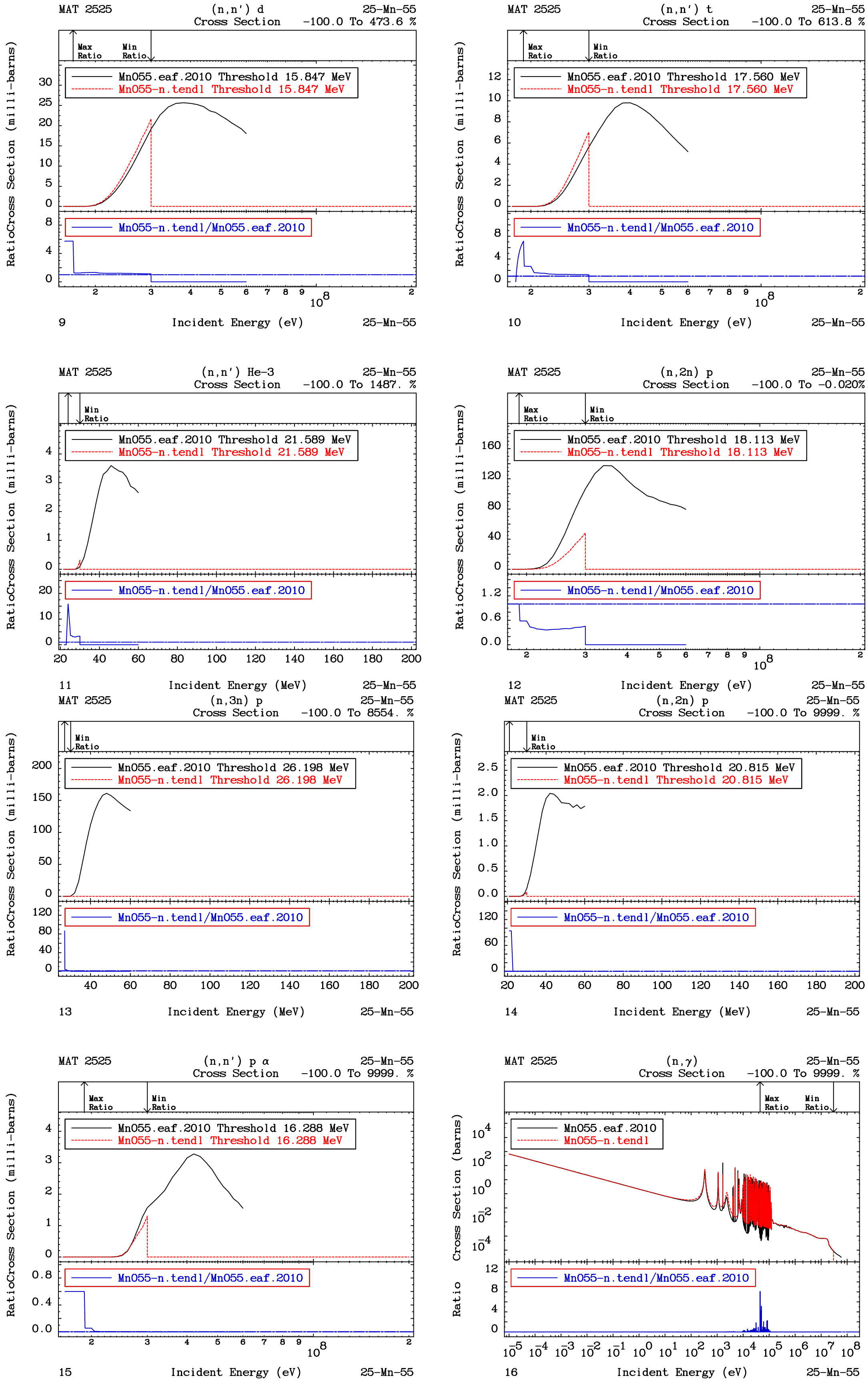

Figure 41: Cross sections and ratios for ^{55}Mn between TENDL-2011 and EAF-2010

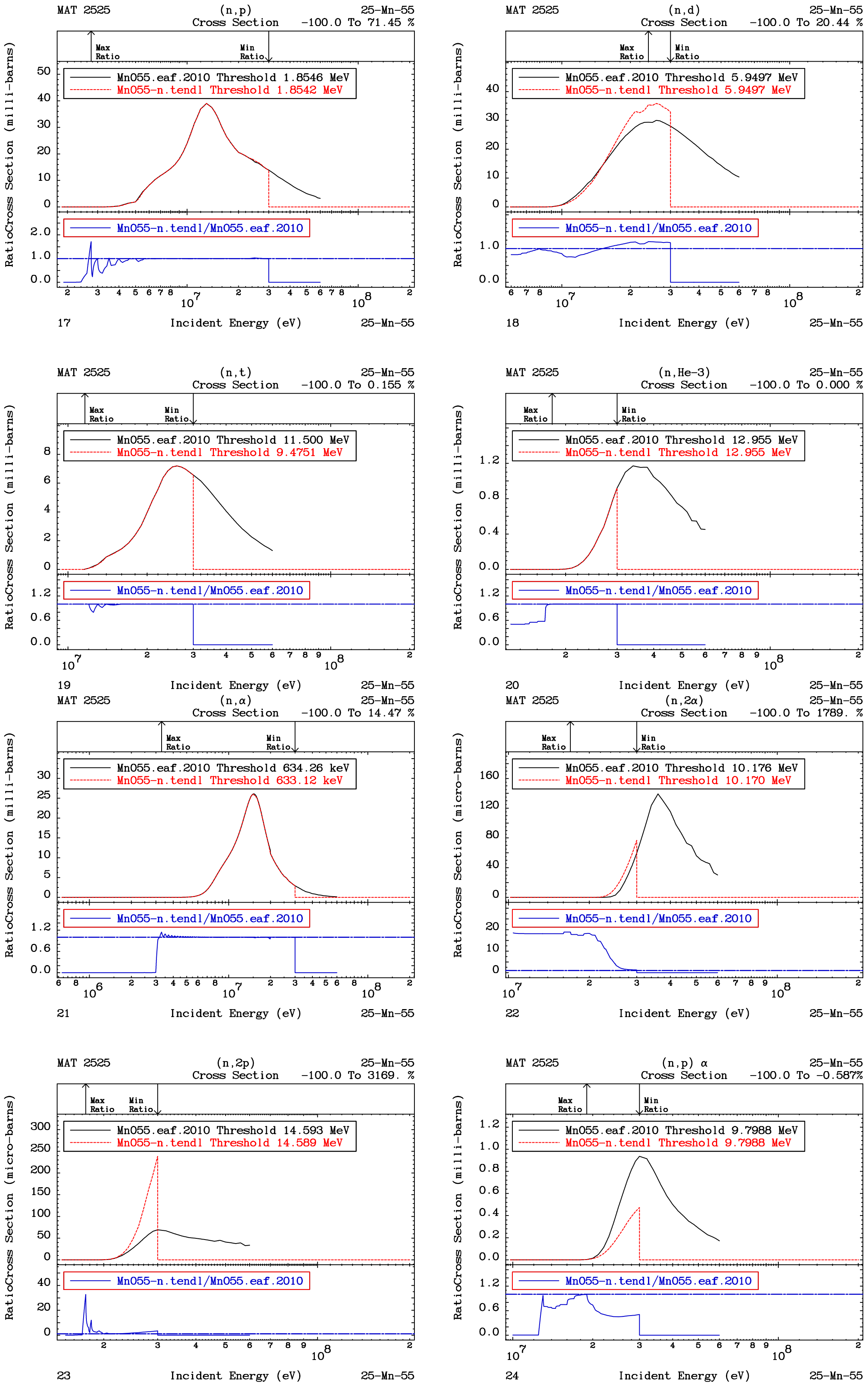

Figure 42: Cross sections and ratios for ^{55}Mn between TENDL-2011 and EAF-2010

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