LAWRENCE LIVERMORE NATIONAL LABORATORY

LLNL-TR-784548

Data Evaluation of Actinide Cross Sections: 237Np and 239Np

R. D. Hoffman, E. Jurgenson, M. A. Descalle, I. Thompson, J. Burke

July 31, 2019

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Data Evaluation of Actinide Cross Sections: ^{237}Np and ^{239}Np

R.D. Hoffman, E. Jurgenson, M.-A. Descalle, I. Thompson, J. Burke

July 31, 2019

LLNL-TR-784548

This work was funded by the Office of Defense Nuclear Nonproliferation Research and Development within the U.S. Department of Energy's National Nuclear Security Administration by Lawrence Livermore National Laboratory under Contract No DE-AC52-07NA27344.

Table of Contents

Introduction

A new evaluation of the ENDL cross section set for Neptunium (Z=93) is developed using the TALYS statistical model cross section code. The primary goal of this effort is to produce an evaluation that attempts to match as closely as possible fission cross sections developed through surrogate reaction techniques on actinide targets ^{237}Np and ^{239}Np. Additional experimental data on the long-lived ^{237}Np target including (n,g), (n,2n), (n,total), and (n,elastic) is also considered. This evaluation effort and the processing needed to render its results into data libraries is a necessary step in making the efforts of nuclear experimentalists useful to the broad community of researchers engaged in simulations of nuclear fusion for basic and applied science. Another aspect, verification and validation against various AGEX experiments, is also presented. The end-product is an updated library that includes the latest measurements of key fission cross sections for comparison against those measured via traditional techniques.

All the steps in the evaluation, processing, validation and verification, and library release are described in the following sections. For completeness, the appendices contain all the parameters used in the TALYS evaluation for the ^{237}Np and ^{239}Np cross sections.

Current Evaluations

The current LLNL ENDL evaluations for Neptunium include neutron induced cross sections on target nuclei with mass numbers 234 < A < 239. They are based on the evaluation efforts of Iwamoto and Nakagawa (JENDL/AC-2008 [1]) who developed them using the CCONE statistical model code. First appearing in ENDL2009.0, an updated evaluation (JENDL-4.0) that only affected cross sections on ^{237}Np was performed by the same group in 2010 and was adopted in ENDL2011.2 [2]. That evaluation has been replaced by a 2010 LANL effort [3] that took into account recent results from the Godiva, Flattop-28, and Big-10 critical assemblies. We compare our effort to the JENDL/AC-2008 evaluation.

The cross sections in the ENDL evaluations include the total neutron cross section (n,tot), the elastic and inelastic scattering (n,n) cross sections, the (n,2n), (n,3n), and (n,4n) cross sections, the total fission cross section (n,f), the neutron capture cross section (n,g), and inelastic scattering to discrete states (n,n'g). The TALYS evaluation will produce all of these for Np target nuclei 237 and 239. Plots of cross sections in the ENDL2009.3 vs. ENDL2011.2 libraries are provided in Figures 1-3.

Experimental and Evaluated Data

Multiple direct measurements of the ^{237}Np fission cross section are available, many are presented as ratios to the well measured cross sections ^{232}Th and ^{235}U. Two recent efforts [5-6] provide summaries of recent experimental methods done since the JENDL/AC-2008 evaluation.

In Figure 4 we show the JENDL evaluated ^{237}Np(n,f) cross section vs. select experimental data from the NNDC EXFOR site (version 2019-07-19). The JENDL evaluation seems to have been fit to the time of flight data from Shcherbakov [8]. A more recent effort by Diakaki [9] agrees with it for neutron energies > 1 MeV. Our ^{237}Np evaluation is based on the new surrogate (n,f) cross section data from Bausina et al. [7] that starts at 10 MeV and is about 5-10% higher than the JENDL evaluation.

Several other reaction channels have been directly measured on the ^{237}Np target. We will only exhibit a few from the EXFOR database that were clearly used in the JENDL evaluation. EXFOR data on ^{238}Np and ^{239}Np is limited to (n,f) cross sections [10,11] and thermal capture cross sections [12]. Our ^{239}Np evaluation will be based on the fission cross section of Czeszumska et al. [11].

Evaluation Method

We used the TALYS-1.8 statistical model code [13] to develop cross sections for neutrons incident on ^{237}Np and ^{239}Np. TALYS is an NRG/CEA-developed software code which combines nuclear models for direct, compound, pre-equilibrium and fission reactions. In the following, we describe the models and parameters utilized to produce the evaluations, which we will refer to as 'ENDL2009.3-ex15'.

Any neutron cross section evaluation effort requires choosing an optical potential model. We adopted the one by Soukhovitskii et al. [13] which was designed for use in the actinide region and has been successfully employed in recent LLNL evaluations of Pu and Am cross sections [15,16].

The structure database in TALYS had to be supplemented with information defining which discrete energy levels to include in our coupled channel calculations to produce the compound-formation cross sections for neutrons impinging on the (deformed) ^{237}Np, ^{238}Np, and ^{239}Np target nuclei. From these the requisite neutron transmission coefficients are developed for use in Hauser-Feshbach calculations for the production and all decay channels from the relevant compound nuclear states. We adopted the coupled level rotational schemes defined in the JENDL AC-2008 evaluation for all Np targets with 234 < A < 239. We also adopted deformation parameters $\beta_2 = 0.213$ and $\beta_4 = 0.066$. Table 1 shows a summary of these states for the ^{237}Np, ^{238}Np, and ^{239}Np targets.

Table 1. Rotational states employed in the coupled-channel calculations.

Rotational States	^{237}Np		^{238}Np		^{239}Np	
	Level J^π	E_x (MeV)	**Level J^π**	E_{ex} (MeV)	**Level J^π**	E_{ex} (MeV)
g.s.	(0) 5/2+	0.0000	(0) 2+	0.0000	(0) 5/2+	0.0000
2	(1) 7/2+	0.0332	(1) 3+	0.0267	(1) 7/2+	0.0311
3	(3) 9/2+	0.0759	(2) 4+	0.0623	(2) 9/2+	0.0712
4	(5) 11/2+	0.1299	(4) 5+	0.1062	(5) 11/2+	0.1225
5	(7) 13/2+	0.1915	(7) 6+	0.1617	(7) 13/2+	0.1800

The convergence of the coupled-channel calculation with respect to the number of included rotational states was tested for the case of the ^{237}Np. We found that the inclusion of 9 rotational states (in the ground state band) did not substantially change the results for the total cross section, particularly in the energy region below 5 MeV. We did keep 9 coupled levels in ^{237}Np but only five in the other nuclei.

Hauser Feshbach statistical model calculations

Fission, gamma, and neutron decay channels were included in all calculations. For neutrons incident on ^{237}Np we tested the inclusion of charged particles in the exit channel and found less than 1% difference in the calculated (n,tot), (n,inel), (n,f), (n,3n), (n,2n), and (n,g) cross sections.

The neutron-transmission coefficients were taken from the coupled-channel optical model calculations, with the level scheme of the targets shown in Table 1. Preequilibrium emission, which takes place after the first stage of the reaction but long before statistical equilibrium of the compound nucleus is attained, has been computed within the two-component exciton model of Koning and Duijvestijn [15].

Level Densities

We used the constant temperature model of Gilbert and Cameron [18] with the energy dependent level density parameterization of Iljinov [19] and vibrational and rotational collective enhancement. The fitted level density parameters needed for the ^{237}Np+n calculations (on the ground states and two fission barriers) are summarized in Table 2. Shown are the level density parameter at the neutron separation energy, $a(S_n)$, the asymptotic level density parameter $a(asym)$, the pairing energy, $Pair$, the shell correction energy, δ_W, temperature of the Gilbert-Cameron formula, T, 'back-shift' energy, E_0, and matching energy E_M. The damping parameters for the shell corrections were 0.07407, 0.07417, and 0.07664 for ^{238}Np, ^{237}Np, and ^{236}Np, respectively.

Table 2. Ground state and barrier level density parameters.

Nuclide	$a(S_n)$ (MeV^{-1})	$a(asym)$ (MeV^{-1})	Pair (MeV)	δ_W (MeV)	T (MeV)	E_0 (MeV)	E_M (MeV)
^{238}Np GS	33.32396	29.27574	0.0000	2.27197	0.37329	-1.06954	2.79081
^{238}Np B1	33.32396	29.27574	0.0000	2.21589	0.42821	-2.47064	3.08700
^{238}Np B2	33.32396	29.27574	0.0000	1.51465	0.40519	-2.36510	3.40590
^{237}Np GS	27.43487	23.92342	0.7795	2.43490	0.44252	-1.22075	4.91457
^{237}Np B1	27.43487	23.92342	0.7795	1.62327	0.43712	-1.32610	5.24392
^{237}Np B2	27.43487	23.92342	0.7795	1.62327	0.44494	-0.85437	4.57852
^{236}Np GS	15.46388	13.65825	0.0000	2.13178	0.34730	-1.10041	2.20939
^{236}Np B1	15.46388	13.65825	0.0000	1.50000	0.34730	-1.03535	2.06481
^{236}Np B2	15.46388	13.65825	0.0000	0.60000	0.34730	-1.15572	1.83895

Fission Barriers

For the fission channel, we used the model based on the transition state hypothesis of Bohr and assumed double-humped fission barriers. The effective transmission coefficients for the double-humped barriers were computed starting from the Hill-Wheeler expression for the probability of tunneling through each barrier of height B_i and width $\hbar\omega_i$ $(i = 1,2)$. The fitted fission barrier parameters for ^{235}Np, ^{236}Np, ^{237}Np, ^{238}Np, and ^{239}Np are shown in Table 3. Above the fission barriers we assumed continuum states.

Table 3. Fission barrier parameters.

Nuclide	B_1 (MeV)	$\hbar\omega_1$ (MeV)	B_2 (MeV)	$\hbar\omega_2$ (MeV)
^{239}Np	3.750	0.800	5.200	0.600
^{238}Np	5.579	0.460	6.023	0.3774
^{237}Np	3.050	1.000	5.320	0.500
^{236}Np	6.000	0.600	5.832	0.400
^{235}Np	4.900	1.000	3.600	0.600

Gamma-ray Strength Functions

For the gamma-ray strength functions we adopted the generalized Lorentzian form of Kopecky and Uhl [20] to describe E1 transitions, while for all other transition types used the Brink-Axel standard Lorentzian form [21]. The total radiative width (Γ_γ) and the strength (σ), energy (E) and width (Γ) of the adopted gamma-ray strength functions for ^{238}Np, ^{239}Np, and ^{240}Np are shown in Table 4, 5 and 6, respectively.

Table 4. Gamma-ray strength functions for ^{240}Np.

Multipole	σ (mb)	E (MeV)	Γ (mb)
E1	718.234	13.284	3.635
M1	1.138	6.598	4.000
E2	0.612	10.138	3.230
M2	0.001	6.598	4.000
Γ_γ (eV)	0.030		

Table 5. Gamma-ray strength functions for ^{239}Np.

Multipole	σ (mb)	E (MeV)	Γ (mb)
E1	715.022	13.297	3.642
M1	1.131	6.607	4.000
E2	0.611	10.152	3.242
M2	0.001	6.607	4.000
Γ_γ (eV)	0.030		

Table 6. Gamma-ray strength functions for ^{238}Np.

Multipole	σ (mb)	E (MeV)	Γ (mb)
E1	711.797	13.310	3.649
M1	1.124	6.616	4.000
E2	0.610	10.166	3.254
M2	0.001	6.616	4.000
Γ_γ (eV)	0.041		

For other parameters not reported in the tables above, we adopted the TALYS-1.8 default values. The TALYS input files and complete lists of model parameters are provided in Appendix 1.

Results from the data evaluation for ^{237}Np and ^{239}Np

Figure 5 shows the evaluated fission ^{237}Np cross section compared to the JENDL evaluation and the experimental data of Shcherbakov [8]. In this work obtaining reasonable agreement with the high energy data of Bausina between 10 and 18 MeV was the primary consideration, which we achieved with some success. No choice of parameters in the TALYS code were found that could improve the agreement of the calculation and data above 18 MeV. Agreement with the magnitude of first chance fission peak near 2 MeV was also a priority, as well as maintaining rough agreement with the low (< 0.1 MeV) energy cross section from the JENDL evaluation (lower figure). The onset and peak of second chance fission between 6 and 10 MeV was sacrificed to obtain these outcomes.

Figure 6 shows the TALYS evaluated ^{237}Np neutron capture cross sections vs. experimental data and the JENDL evaluation. We achieved very good agreement with the experimental data of Buleeva [22] between 0.1 and 1.0 MeV. At lower energies the TALYS evaluation agrees the JENDL evaluation that lies between the data from Kobayashi [23] and Esch [24]. We consider this an acceptable result.

Figure 7 shows the TALYS evaluated ^{237}Np(n,2n) cross sections vs. experimental data and the JENDL evaluation. Although the TALYS evaluation is roughly 10% higher than the JENDL evaluation, it is within experimental uncertainty at 14 MeV, which we consider a success. An attempt to normalize the (n,2n) cross section via an adjustment of the overall optical model strength considered by the pre-equilibrium model did not produce a satisfactory result.

Figure 8 shows the TALYS evaluated ^{237}Np (n,total) and (n,elastic) cross sections vs. experimental data and the JENDL evaluation. Both evaluations are in agreement with each other and, for (n,tot) with E> 1.0 MeV, experimental data.

Figure 9 shows the evaluated ^{239}Np fission cross section compared to the JENDL evaluation and the derived surrogate data of Czeszumska[11] and Desai[25]. As with ^{237}Np(n,f) we required agreement with the surrogate data in the high energy range between 8 and 18 MeV and still retain reasonable agreement at low energy. No combination of TALYS parameters was able to reproduce an evaluation that matched the structure in the first chance fission peak.

Figure 10 shows a comparison between select cross sections for neutrons incident on ^{237}Np and ^{239}Np targets developed in the new (TALYS) evaluation vs. ENDL2009.3 (JENDL). Most are similar with the exception of the fission and inelastic scattering cross sections (a change in the one necessitated a change in the other), with some minor differences in the (n,g) cross sections at high energy and the (n,2n) and (n,3n) cross sections (also at high energy). The ^{237}Np(n,3n)^{235}Np appears to have a problem. The new cross section starts at the wrong reaction threshold indicating an error in the TALYS atomic mass database or with the level density parameterization for ^{235}Np. All the others are fairly similar.

Processing

The evaluations as provided by the evaluator are in the form of output files from TALYS runs, for the several target nuclei reacting with incident neutrons. The evaluator has found the parameters of Hauser-Feshbach calculations that match the cross sections for neutrons from about ~0.1 to 20 MeV. For each neutron incident energy, files are provided for the cross sections and angular distributions of outgoing neutrons and gamma rays when residual nuclei are in specific final states. As well, cross sections and exit energy distributions are provided for exit neutrons and gammas for the remaining processes when the residual nuclear states are unspecified.

These files are read into the code GEFT (Get ENDL From TALYS), that was written at LLNL by Neil Summers and subsequently developed by Eric Jurgenson. This is a python code that reads the TALYS output, stores it using FUDGE data structures as developed at LLNL, and writes out ENDL-format files for use by applications at LLNL. These files can also be translated into ENDF format for use by the international data community, and into GNDS format for use by the very recently developed GIDI processing methods at LLNL.

The data from the TALYS output, however, is not fully sufficient for application use, and has to be supplemented by further information for low-energy reactions, and for specifying the products of fission reactions. Low-energy reactions of neutrons (below about 1 to 10 keV) are dominated by resonances, and these have to be specifically measured by time-of-flight neutron experiments. Similarly, the products of fission processes (prompt neutron multiplicities, prompt neutron energy distributions, total fission energy production, fission product distributions) were not fitted by the evaluator. In the present work for Np isotopes, the resonance data and fission product data were adopted unchanged from the previous evaluations in the ENDL2009.3 library (sourced from JENDL and subsequently ENDF/B-VII). For ^{237}Np the resonances were included from 0-1 keV, corresponding to the lower extent of the new evaluation and the previous point of splicing evident in the existing data. For ^{239}Np no existing resonance data was available and the low energy was included at a cut of .1 eV determined by the low extent of the new evaluation, the same as in previous evaluations.

Finally, we developed ENDL files using our evaluations for ^{237}Np and ^{239}Np. In order for these evaluations to be tested, we must supplement cross sections for these two targets with those of other Np nuclei in critical assemblies and other applications. We constructed a new library, ENDL2009.3-ex15, by substituting the newly evaluated ENDL files for ^{237}Np and ^{239}Np targets into an ENDL2009.3 library (our current official standard). This combination was then processed for deterministic and Monte Carlo simulations using the multigroup codes NDFGEN and MCFGEN, respectively. These also process cross sections that have been broadened by Maxwellian distributions to a range of temperatures suitable for applications. The new evaluations were then tested by comparing results from the 'ex15' evaluations with those from the ENDL2009.3 library. The new experimental release is hosted in the standard Livermore nuclear data space on Livermore Computing machines with a path:
/usr/gapps/data/nuclear/development/ENDL2009/endl2009.3-ex15.

Np Evaluations Verification and Validation

The new evaluations for ^{237}Np and ^{239}Np were processed and merged in ENDL2009.3-ex15v2/mcf, the legacy Monte Carlo library file. They were then tested using the Nuclear Data Group Automated Verification and Validation test suite [26][22]. The verification step consists of a 'Broomstick' test and the validation step relies on comparison to criticality benchmarks and reaction ratio benchmark data [27]. Mercury simulations were run on Livermore Computing (LC) systems for these two Neptunium isotopes [28][29]. Results for the new Np evaluations in ENDL2009.3-ex15v2 were compared to those obtained with ENDL2009.3 and ENDF/B-VIII.0, two officially released cross section libraries. The sources of the ^{237}Np and ^{239}Np evaluations in these libraries are summarized in Table 7 [30].

The 'Broomstick' model consists of a thin cylinder of material made of a single isotope of density 1.0 g/cm^3. The cylinder is 10^5 cm long with a radius of 10^{-5} cm, long enough to be considered semi-infinite so that all incident neutrons interact once in the material, and thin enough to ensure once-scattered and secondary particles escape without interactions. A monoenergetic pencil beam of thermal, 1 or 14 MeV neutrons is directed along the cylinder axis. Currently, available tallies include the number of reactions per reaction type within the cylinder and leakage spectra as a function of energy or angular emission.

Normalized summed cross-section contributions derived from broomstick simulations at these three energies are plotted in figure 11. Overall, the new ^{237}Np evaluation is close to the ENDL2009.3 evaluation and the new ^{239}Np evaluation is very similar to evaluations in ENDL2009.3 and ENDF/B-VIII.0.

In the thermal range, ^{237}Np evaluations in the ENDL libraries showed an increase in (n, el) and a smaller contribution from the (n, g) channel compared to ENDF/B-VIII.0. At 1 MeV, ^{237}Np contributions from the (n, n') channels were greater than ENDL2009.3 and smaller than ENDF/B-VIII.0. At 14 MeV, the ^{237}Np evaluation showed lower contributions from the (n, n') and$(n, 3n)$ channel compared to ENDL2009.3 and from the $(n, 3n)$ channel compared to ENDF/B_VIII.0.

The angular and energy distributions of outgoing neutrons after a single interaction simulated with the ENDL2009.3-ex15v2, ENDL2009.3 and ENDF/b-VIII.0 cross section libraries are shown in Figure 12 to 15. These are typical examples of V&V results that can provide feedback on specific evaluations and highlights differences in these leakage distributions. Results for the new ^{237}Np evaluation show a smaller (n,n') and smaller (n,3n) cross-sections at 14 MeV.

Table 7. Sources of ^{237}Np, ^{239}Np evaluations in nuclear data libraries simulations

	ENDF/B-VIII.0	ENDL2009.3	ENDL2009.3-ex15v2
^{237}Np	ENDF/B-VII.1	JENDL-AC-2008	New (Hoffman)
^{239}Np	JENDL-4.0	JENDL-AC-2008	New (Hoffman)

The ^{237}Np evaluation described in this report was validated against integral criticality and activation benchmark experiments.[27] SPEC-MET-FAST-008-001, SPEC-MET-FAST-011-001 and SPEC-MET-FAST-014-001 are critical assemblies from the International Criticality Safety Benchmark Evaluation Project (ICSBEP) with a core made of a Neptunium-237 sphere surrounded by shells of highly enriched uranium (HEU). SPEC-MET-FAST-008-001 is bare, a.k.a it is not surrounded by a reflector material, while the other assemblies are encased in a reflector made of polyethylene (SPEC-MET-FAST-011-001) and low-carbon steel (SPEC-MET-FAST-014-001). These experiments were simulated with Mercury, LLNL particle transport Monte Carlo code for the three nuclear data libraries shown in table 7. Simulated and benchmark k effective are compared in table 8. The k effective of SPEC-MET-FAST-011-001 is within 1 sigma of the benchmark and those of SPEC-MET-FAST-008-001 and SPEC-MET-FAST-014-001 are within 2σ.

For the activation experiments, ^{237}Np foils were irradiated at the center of fast critical assemblies to determine reaction rates for ^{237}Np(n,f) and ^{237}Np(n,γ). The published data and simulated results are given in terms of reaction ratios, where the reaction rate of interest is normalized by the reaction rate for ^{235}U(n,f). ^{237}Np reaction ratios from Mercury simulations (C) are compared to benchmark experiments (E) and C/E are presented in Table 9. Mercury results for the ENDF/B.VIII.0 ^{237}Np evaluation are consistent with published MCNP results for ENDF/B.VII.1 and for ENDF/B.VIII.0 shown in the first column of Table 9 [31][32]. C/E for the two ENDL evaluations are essentially the same and they are lower than those for ENDF. Finally, the C/E for the (n, γ) reaction in FUND-IPPE-FR-MULT-RRR-001 is improved by 11.4%.

Table 8. Simulated k effective of ICSBEP critical assembly benchmark experiments with ^{237}Np spherical cores surrounded by shells of reflectors. Mercury simulation statistical error is < 1e-4.

ICSBEP Case ID	Reflector	Benchmark	ENDF/B-VIII.0	ENDL2009.3	ENDL2009.3-ex15v2
SPEC-MET-FAST-008-001	None	1.0026 ± 0.0034	0.9977	0.9989	0.9978
SPEC-MET-FAST-011-001	Polyethylene	1.0017 ± 0.0029	N/A	1.0041	1.0029
SPEC-METFAST-014-001	Low-Carbon steel	1.0001 ± 0.0039	0.9950	0.9954	0.9943

Table 9. C/E for ^{237}Np (n,f) and ^{237}Np(n,f) reaction ratios in benchmark critical assemblies. Mercury calculations were run with ENDF/B-VIII.0, ENDL2009.3, and ENDL2009.3-ex15v2. MCNP results were reported in ref [31]and [32].

Reaction Ratio	**ICSBEP Case ID**	**ENDF/B-VIII.0^a & *VII.1^b* MCNP**	**ENDF/B-VIII.0 Mercury**	**ENDL2009.3 Mercury**	**ENDL2009.3-ex15v2 Mercury**
^{237}Np(n,f)/ ^{235}U(n,f)	HEU-MET-FAST-001 (Godiva)	*0.977^a*	0.977	0.969	0.969
	HEU-MET-FAST-028 (Flattop)	*0.991^a*	0.990	0.984	0.984
	PU-MET-FAST-001 (Jezebel)	*0.993^a*	0.993	0.982	0.982
	IEU-MET-FAST-007 (Bigten)	N/A	0.982	0.960	0.960
	FUND-IPPE-FR-MULT-RRR-001	1.055^b	N/A	1.049	1.049
^{237}Np(n,γ/ ^{235}U(n,f)	FUND-IPPE-FR-MULT-RRR-001	1.253^b	N/A	1.110	1.110

Conclusion

We have performed a new data evaluation of ^{237}Np and ^{239}Np cross sections using newly obtained fission cross section data. The new evaluations in ENDL2009.3-ex15v2 include the nuclear cross sections for (n,γ), (n,n'), $(n,2n)$, $(n,3n)$, (n,f) and all their associated distributions. The evaluations were then translated into ENDL format using GEFT, and processed into accessible libraries for Monte Carlo and Deterministic simulation codes WITH MCFGEN and NDFGEN, respectively. The ENDL2009.3-ex15v2/mcf Monte Carlo library was then used for a simulation on a "broomstick" example to verify the integrity of the library and check the functionality of the results. The ENDL2009.3-ex15v2/mcf library has now been released as an "experimental" version for internal access. All results have been documented within this report, through the associated references and the appendices at the end of this report.

References

[1] O. Iwamoto et al., JENDL Actinoid File 2008, J. Nucl. Sci. Technol., **46**(5), 510-528 (2009).
[2] K. Shibata et al., JENDL-4.0, J. Nucl. Sci. Technol., **48**(1), 1-30 (2011).
[3] Holloway, Kahler, Chadwick, 4-22-10 – LANL evaluation – **need ref**
[4] F. Tovesson and T.S. Hill, Phys. Rev. C, **75**, 034610 (2007).
[5] C. Paradela et al., Phys. Rev. C, **82**, 034601 (2010).
[6] Lapenas et al., in Neutron Spec. Meas. By Activation, Riga. **15**, 63 (1975).
[7] M.S. Bausina et al., Nucl. Instrum. Methods Phys. Res. **B267**, 1899 (2009).
[8] O. Shchebbakov et al., J. Nucl. Sci. Technol. Suppl., **2**, 230 (2002).
[9] M. Diakiki et al., Physical Review C **93**, 034614 (2016)
[10] H.C. Britt and J.B. Wilhelmy, Nucl. Sci. & Eng. **72**, 222 (1979)
[11] A. Czeszumska et al., Phys. Rec. C, **87**, 034613 (2013).
[12] S. F. Mughabghab, *Atlas of Neutron Resonances: Resonance Parameters and Thermal Cross Sections Z=1-100*, 5th Edition, Elsevier (2006).
[13] A.J. Koning and D. Rochman, Nuclear Data Sheets **113**, 2841 (2012).
[14] E. Sh Soukhovitskii, S. Chiba, J.-Y. Lee, O. Iwamoto and T. Fukahori, J. Phys. G: Nucl. Part. Phys. **30**, 905 (2004).
[15] S. Quaglioni et. al., LLNL-TR-739697 (2017).
[16] E. Ormand et al. LLNL-TR-763689 (2018).
[17] J. Koning and M.C. Duijvestijn, Nucl. Phys. A **744**, 15 (2004).
[18] A. Gilbert and A.G.W. Cameron, Can. J. Phys. **43**, 1446 (1965).
[19] Iljinov, A.S. et al, Nucl. Phys. **A543**, 517 (1992).
[20] J. Kopecky, M. Uhl and R.E. Chrien, Phys. Rev. C **47**, 312 (1993).
[21] D.M. Brink, Nucl. Phys. 4, 215 (1957); P. Axel, Phys. Rev. **126**, 671 (1962).
[22] N. N. Buleeva et al., Soviet Atomic Energy, **65**(5), 920 (1988).
[23] K. Kobayashi et al., J. Nucl. Sci. Technol. **39**(2), 111 (2002).
[24] E.-I. Esch et al., Physical Review C **77**, 034309 (2008).
[25] V. V. Desai et al., Physical Review C 88, 014613 (2013).
[26] P. Vranas et a., LLNL-SM-733021 (2017)
[27] International Criticality Safety Benchmark Evaluation Project (ISCBEP), International Handbook of Evaluated Criticality Safety Benchmark Experiments, NEA/NSC/DOC/(95)03, September 2011 Edition [CD-ROM], Nuclear Energy Agency (2011).
[28] "Mercury web site," accessed: 2017-09-22. [Online]. Available: https://wci.llnl.gov/simulation/computer-codes/mercury
[29] P. S. Brantley et al., Mercury User Guide: Version d.8, LLNL-SM-560687, Lawrence Livermore National Laboratory (2012).
[30] I.J. Thompson, et al., Technical report, LLNL-TR-741270 (2017).
[31] D.A. Brown, et al., Nucl. Data Sheets, **148**, 1 (2018).
[32] A.C. Kahler, et al., Nucl. Data Sheets, **112**, 2997 (2011)

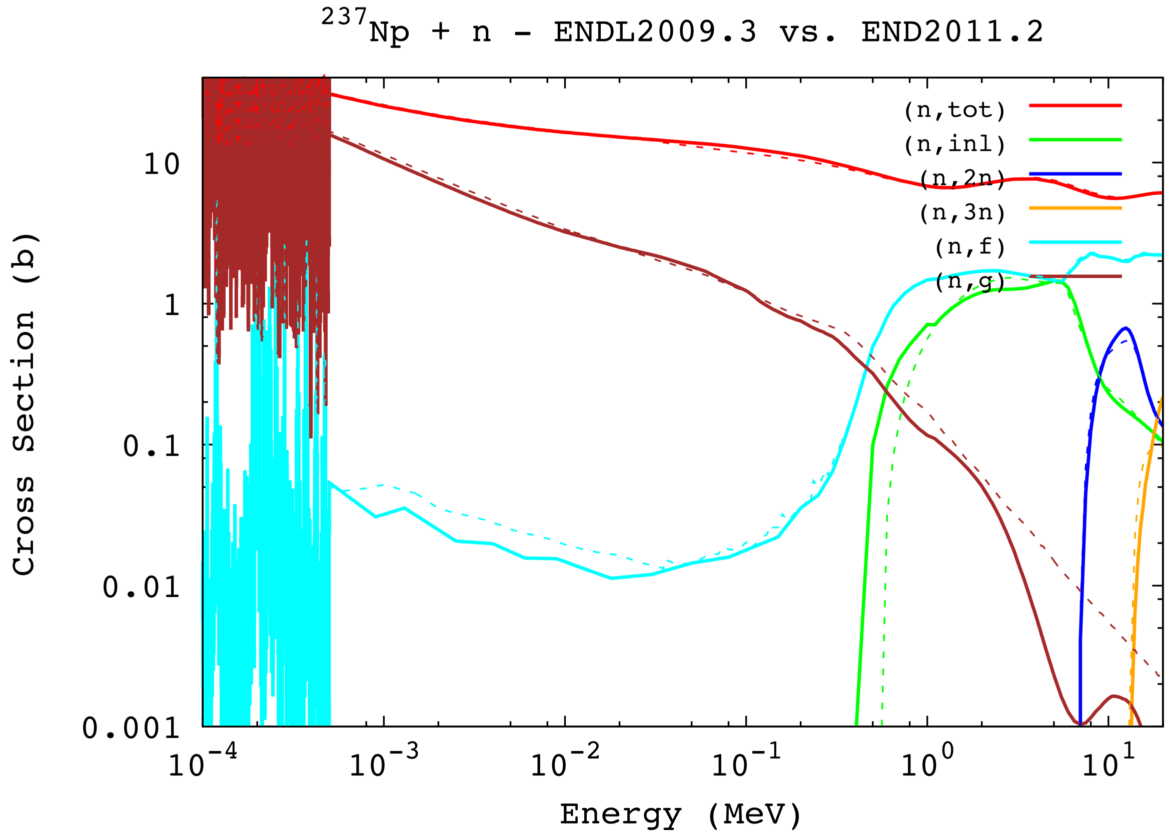


Figure 1. Evaluated ENDL cross sections on target ^{237}Np. Solid (dashed) curves denote cross sections in the LLNL ENDL2009.3 (2011.2) evaluated libraries. The most recent effort by Young et al. affected the ^{237}Np(n,f) cross section at low energies (<1 MeV) due to the sub-threshold measurements of Toveson and Hill [4]. Also effected is the inelastic and especially the ^{237}Np(n,g) capture cross section at higher energies.

The (n,f) and (n,g) cross sections in the resonance region (E_n < 5.e-3 MeV) only exist for this target nucleus in all of the Neptunium ENDL evaluations.

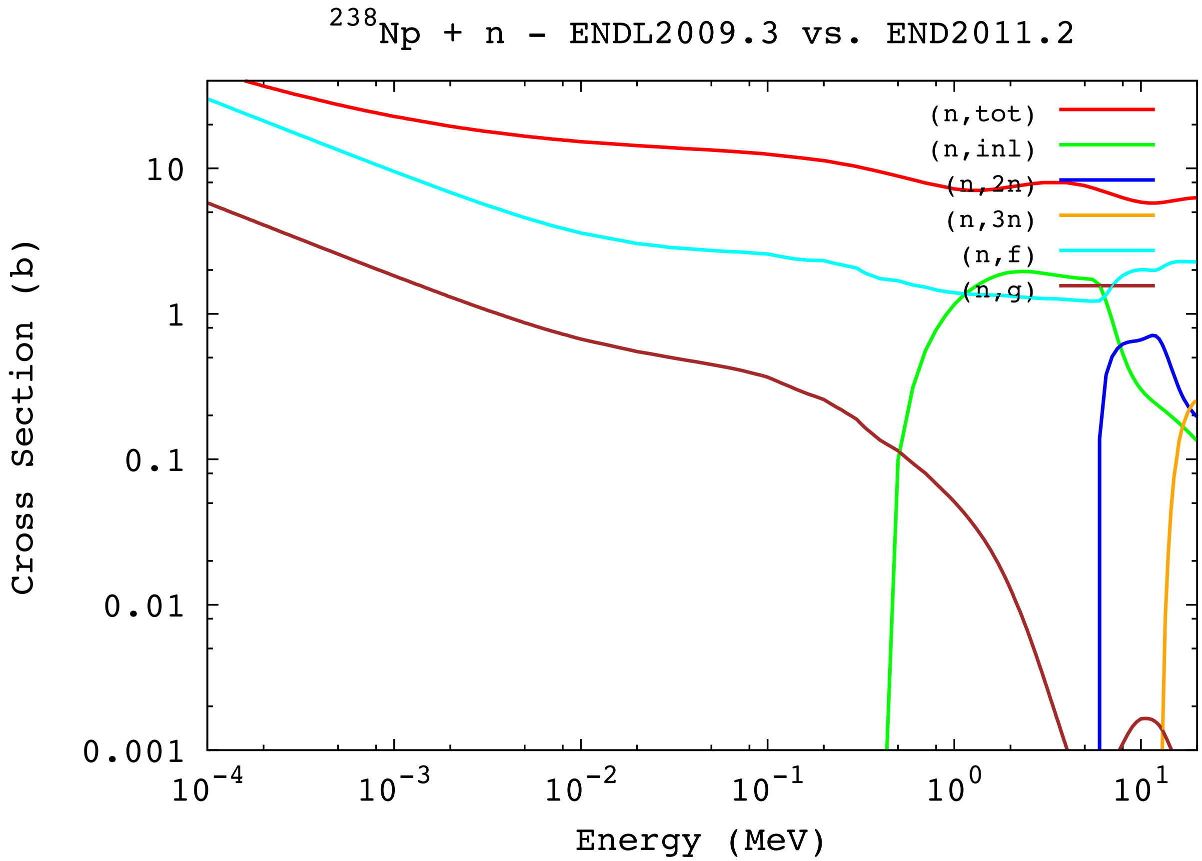


Figure 2. Evaluated ENDL cross sections on target ^{238}Np. Solid (dashed) curves denote cross sections in the LLNL ENDL2009.3 (2011.2) evaluated libraries (identical in both).

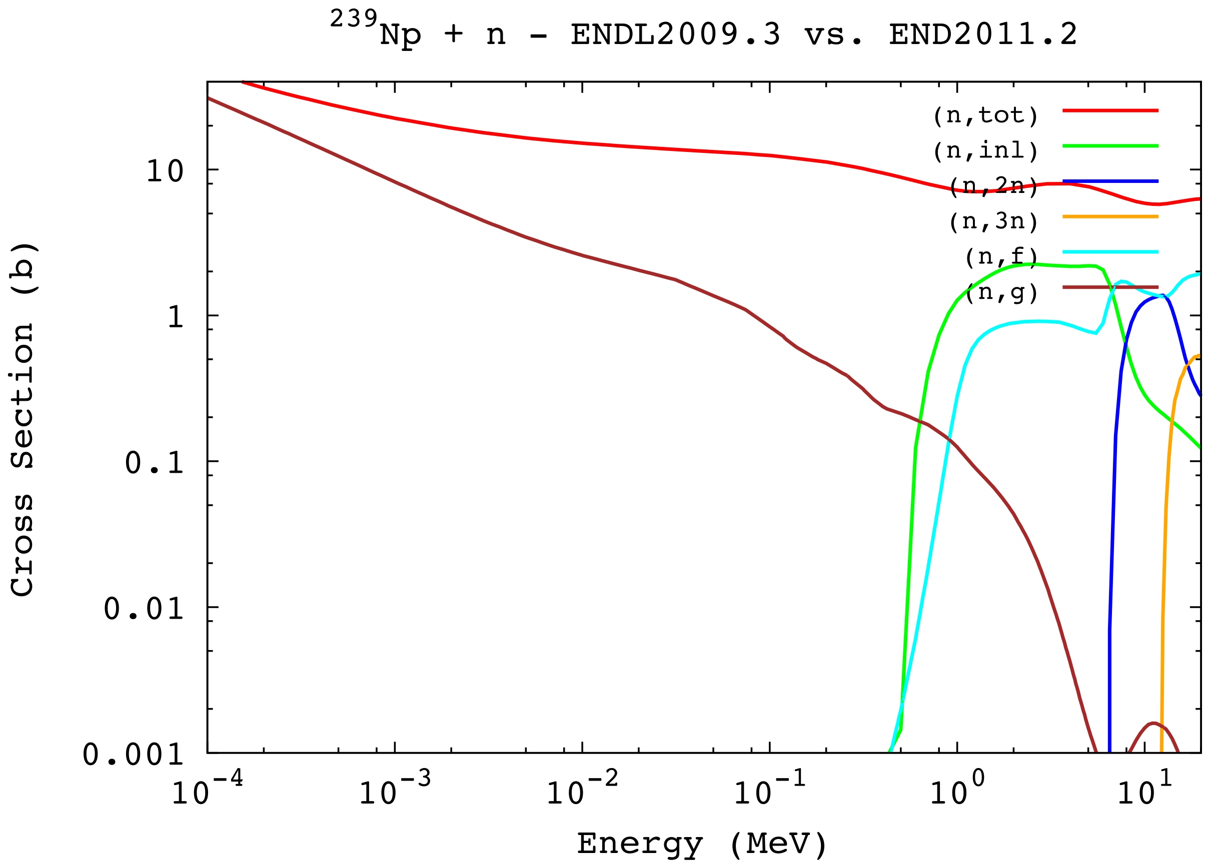


Figure 3. Evaluated ENDL cross sections on target ^{239}Np. Solid (dashed) curves denote cross sections in the LLNL ENDL2009.3 (2011.2) evaluated libraries (identical in both).

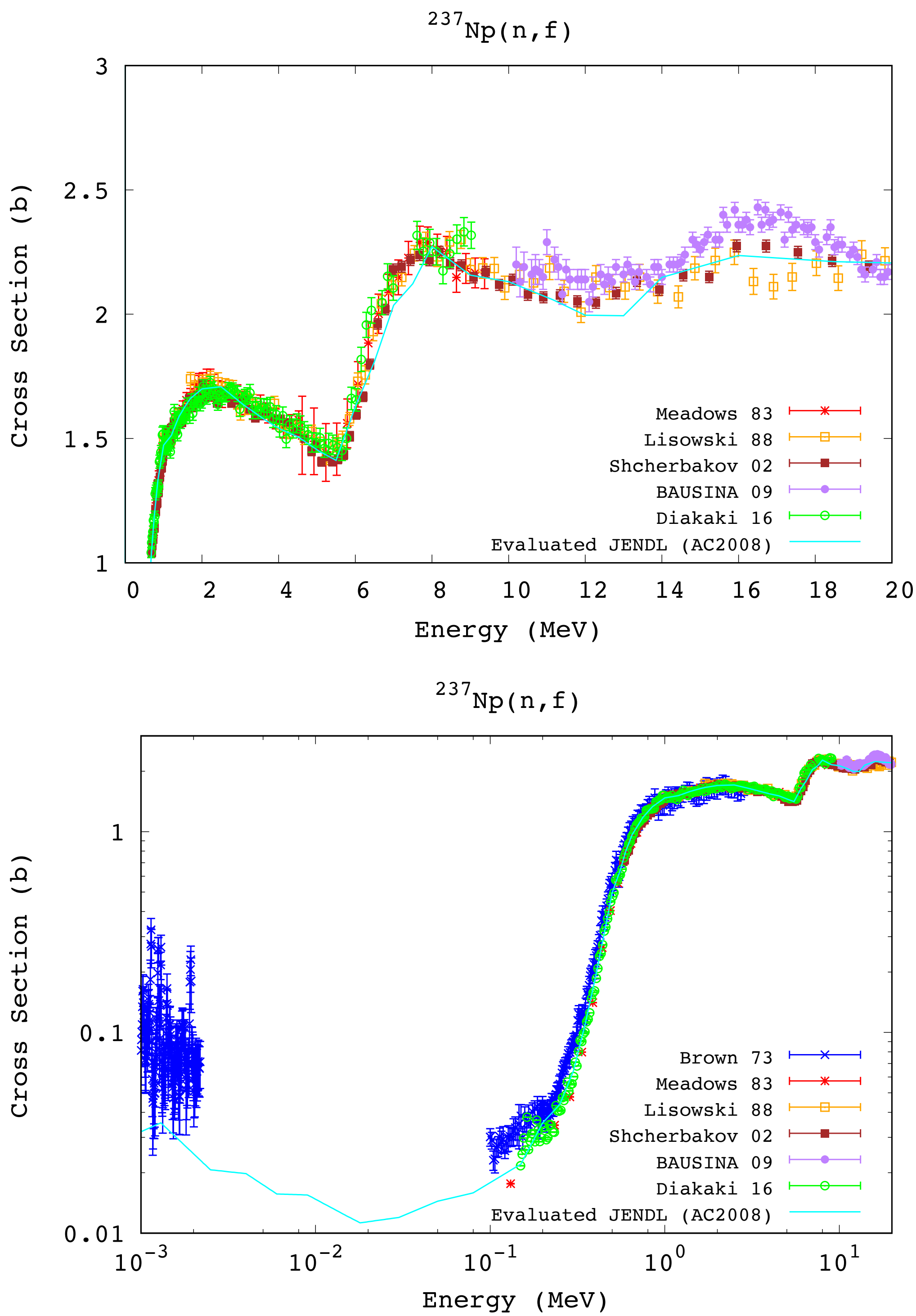


Figure 4. The JENDL ^{237}Np fission cross section as a function of incident neutron energy vs. experimental data from NNDC.

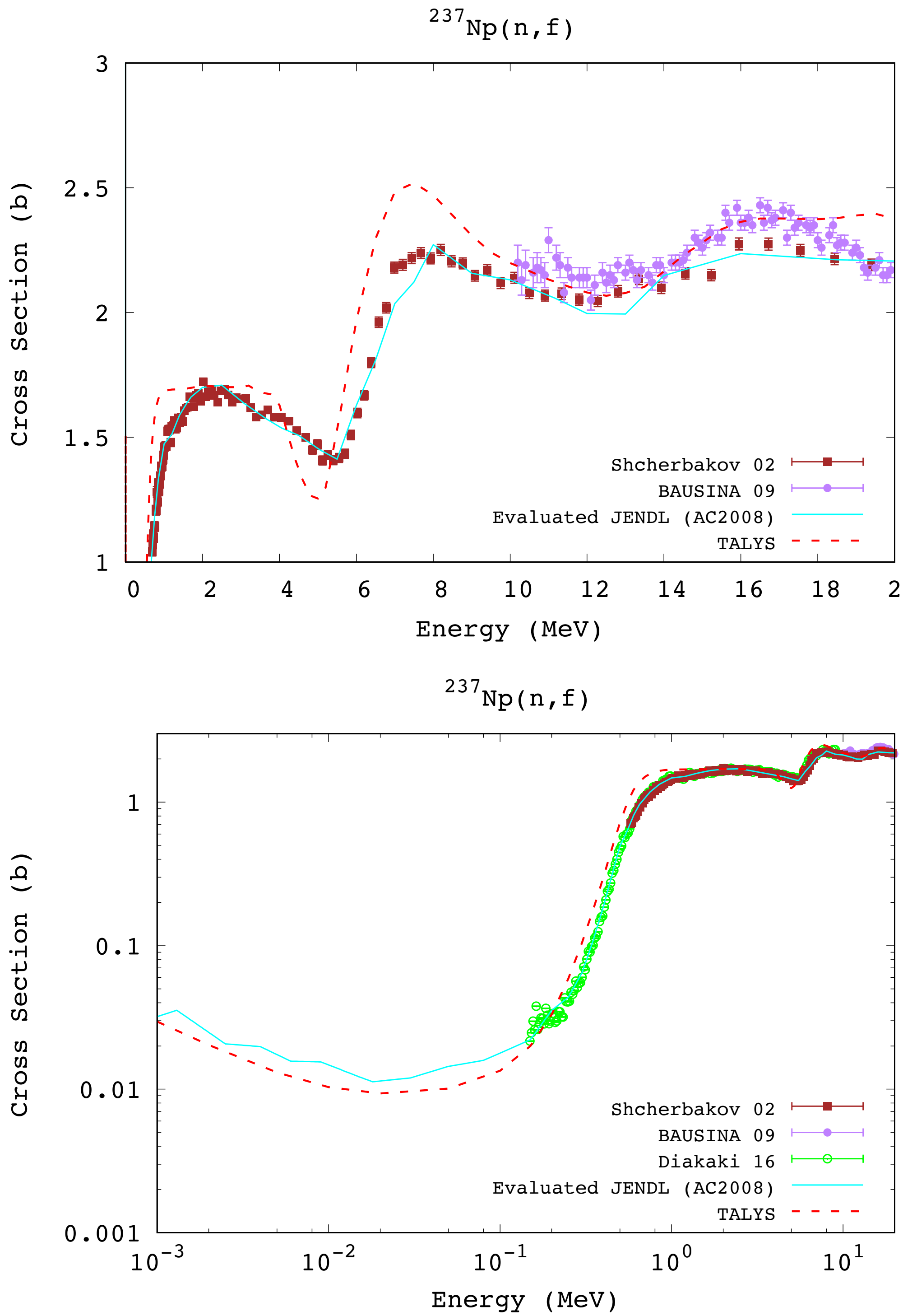


Figure 5. The TALYS evaluation of 237Np(n,f) vs. select EXFOR experimental data and the JENDL evaluation. The new data to be fit (starting at 10 MeV) is from Bausina 2009.

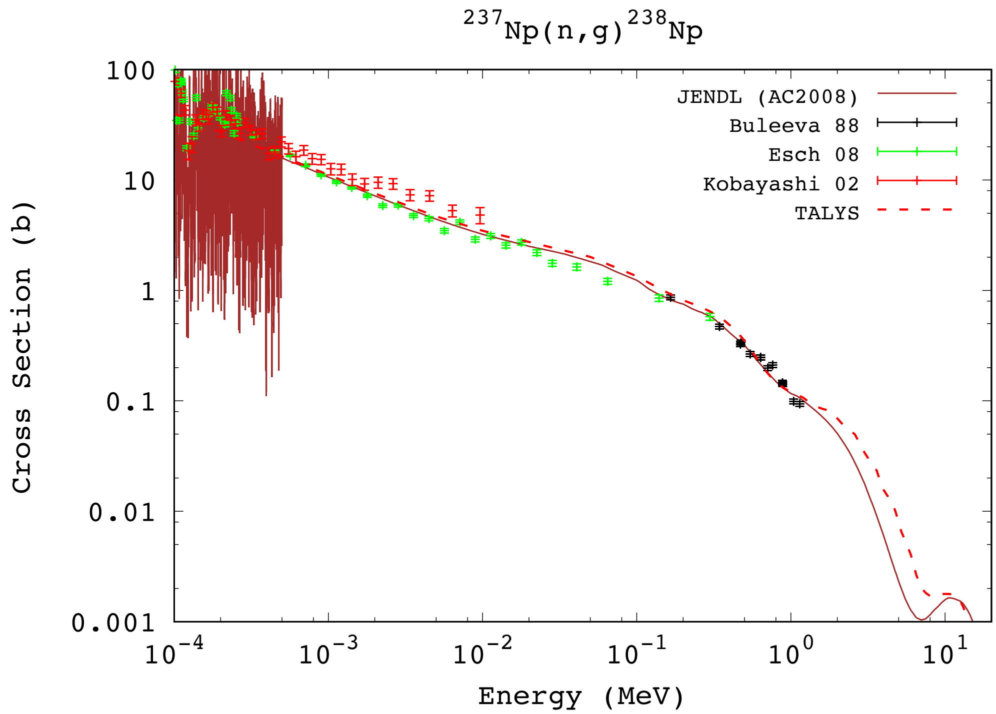


Figure 6. TALYS ^{237}Np(n,g)^{238}Np neutron capture cross section vs. select EXFOR experimental data and the JENDL evaluation. Between 0.1 and 1.0 MeV very good agreement with Buleeva 88 was obtained using the gamma-ray input quantities from the JENDL evaluation.

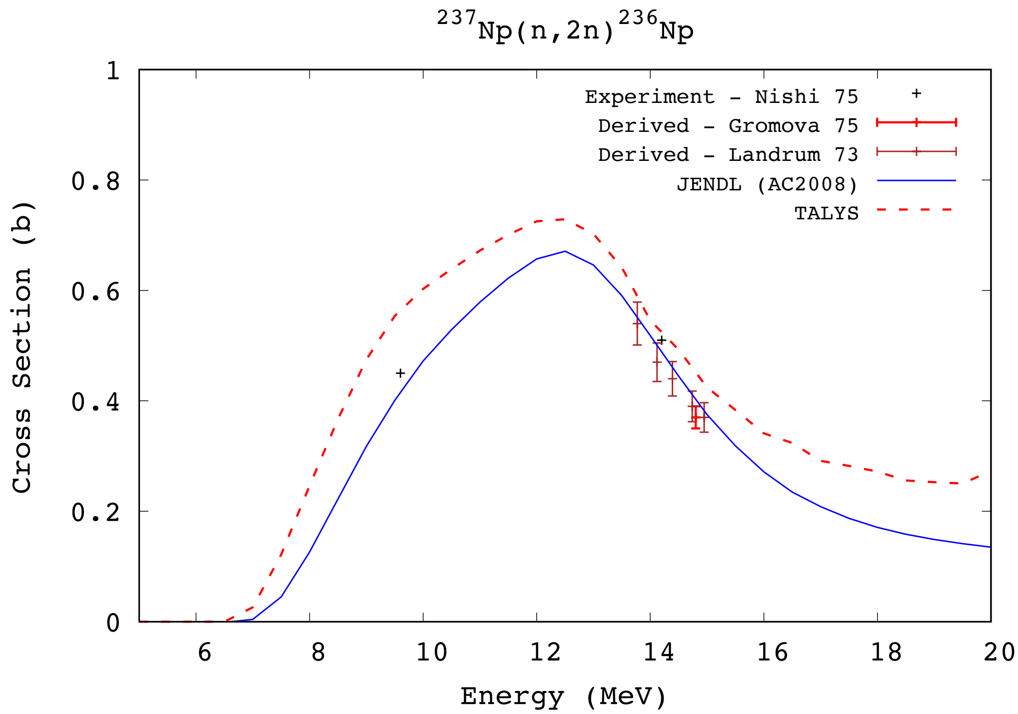


Figure 7. TALYS ^{237}Np(n,2n)^{236}Np cross section vs. experimental data and the JENDL evaluation. The TALYS evaluation at 14 MeV is within experimental uncertainty.

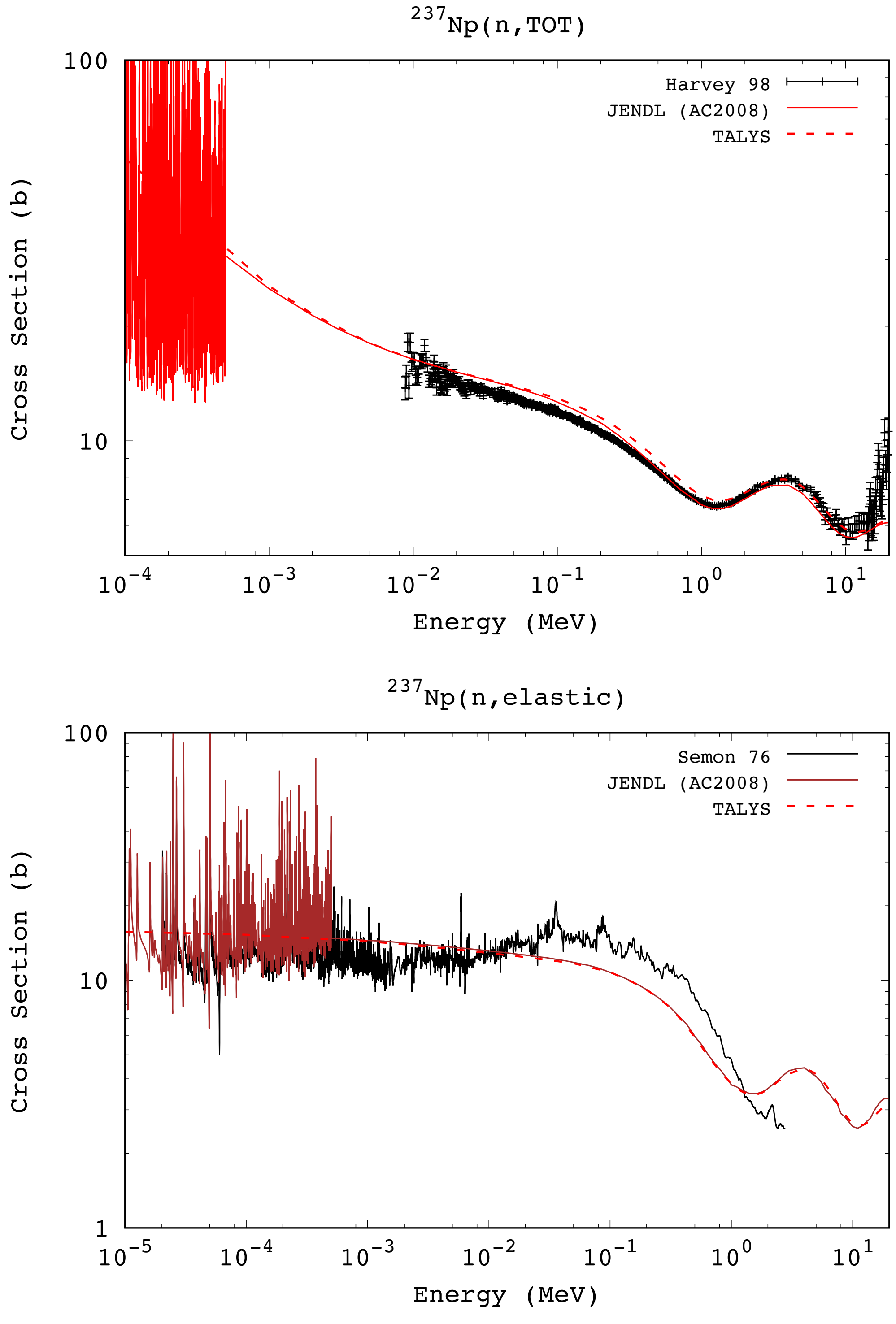
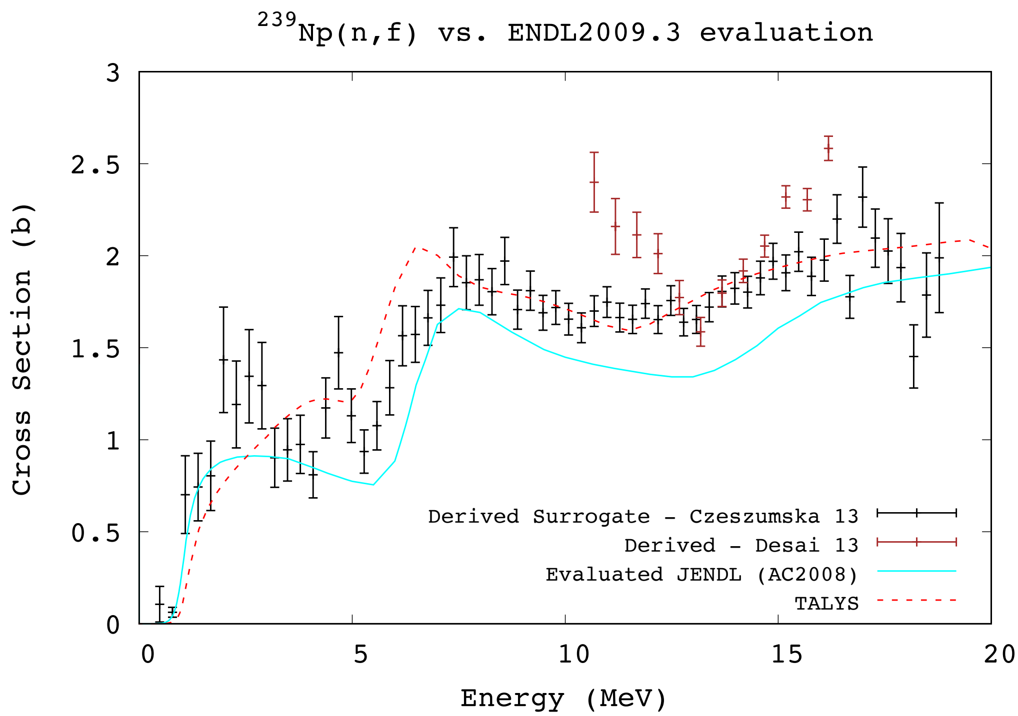


Figure 8. TALYS (n,total) and (n,elastic) cross sections vs. experimental data and the JENDL evaluation. The two evaluations are in good agreement with each other and, for the total cross section above 1 MeV, with experimental data.



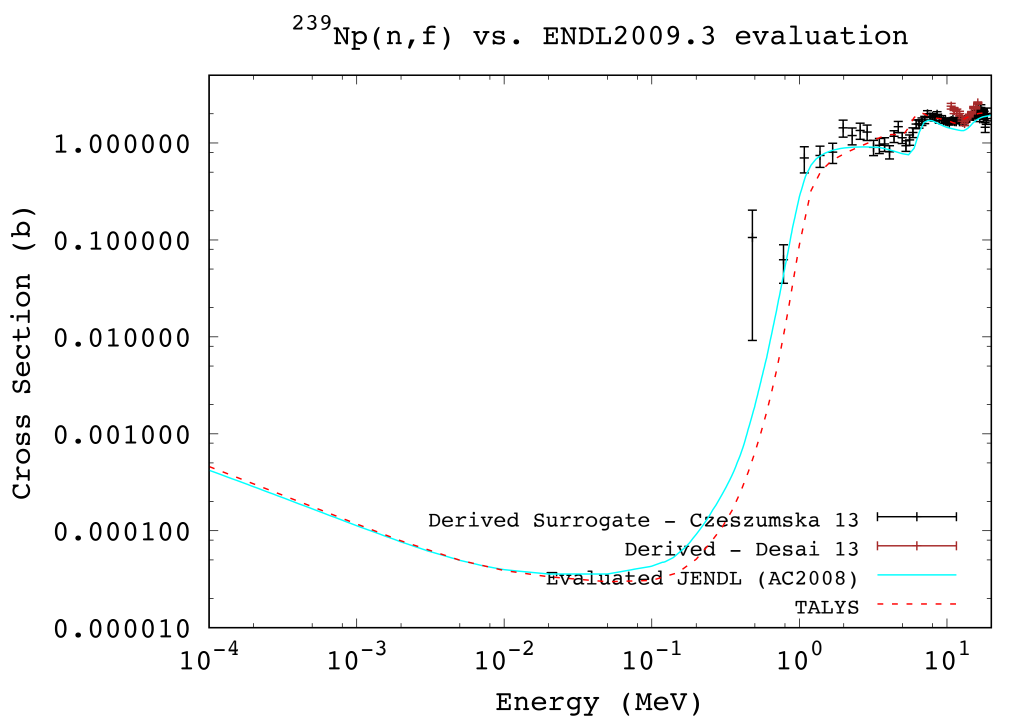
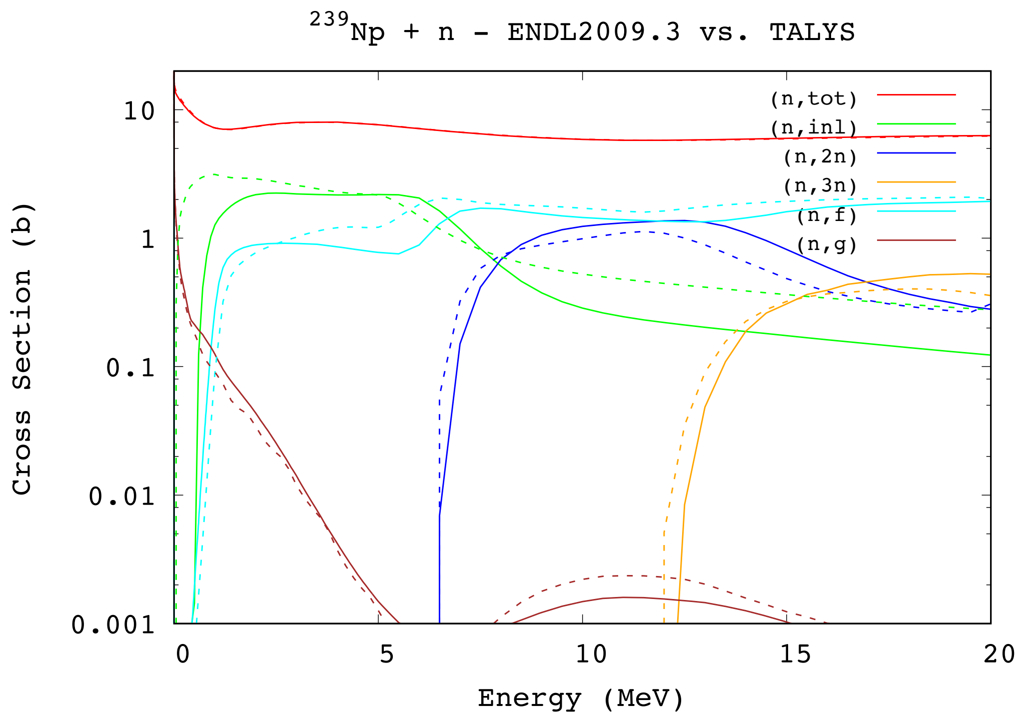


Figure 9. The JENDL and TALYS evaluations for ^{239}Np(n,f) are shown vs. select derived surrogate data. Both high and low energy evaluations are shown.



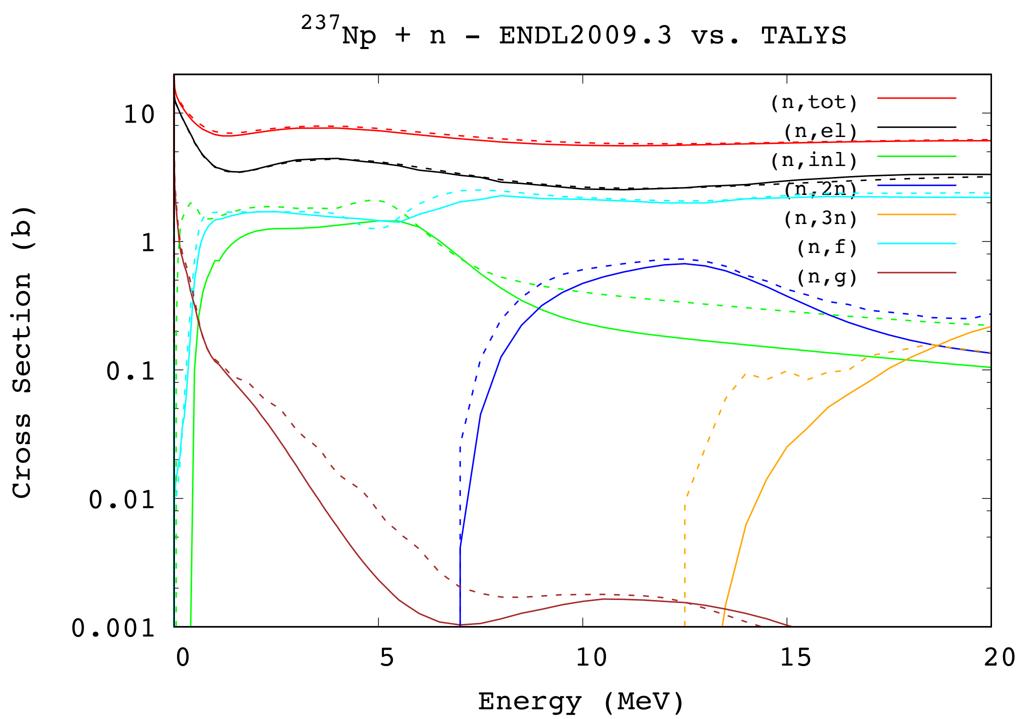


Figure 10. ENDL2009.3 (solid lines) vs. ENDL2009.3-ex15 (dashed lines) neutron induced cross sections on ^{237}Np and ^{239}Np target nuclei.

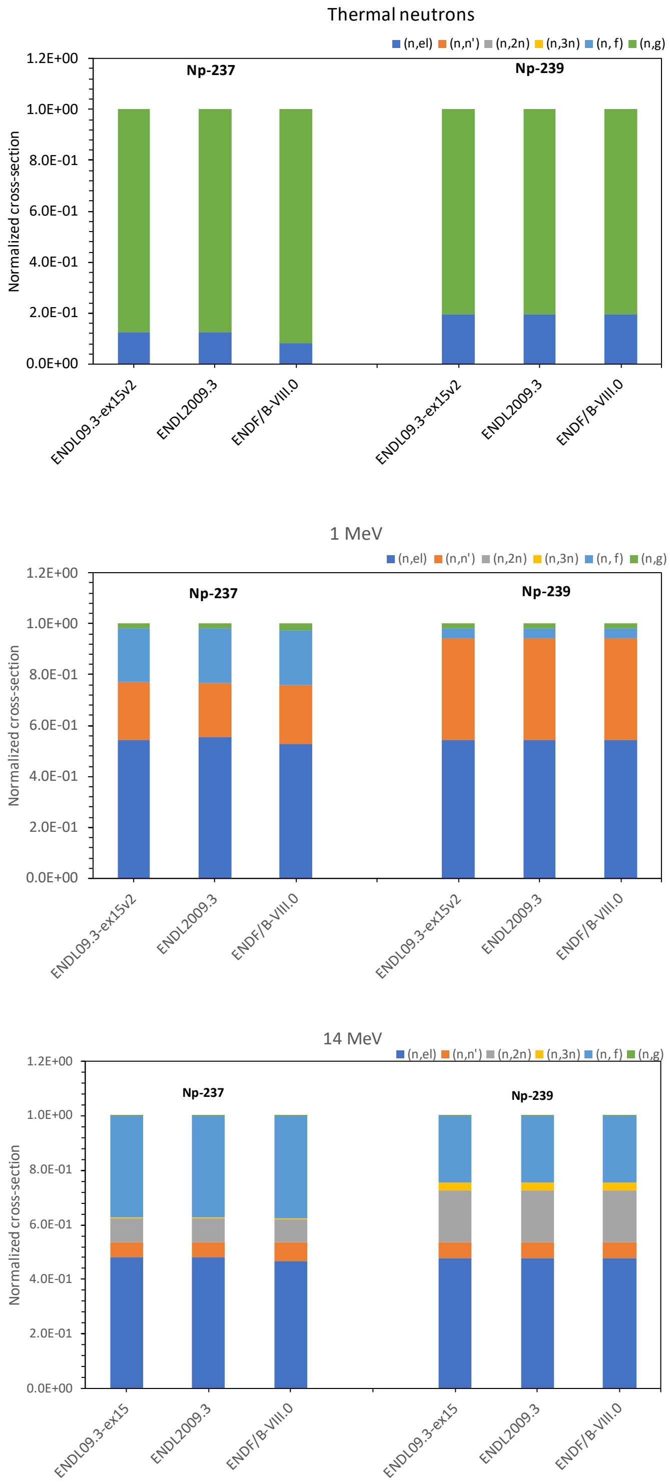


Figure 11. Normalized summed cross-section contributions obtained from Mercury simulations for thermal (top), 1 MeV (center) and 14 MeV (bottom) neutrons incident on a thin cylinder of ^{237}*Np and* ^{392}*Np respectively. Results are shown for the new Neptunium evaluations in ENDL2009.3-ex15, and existing evaluations in ENDL2009.3 and ENDF/B-VIII.0 cross-section libraries.*

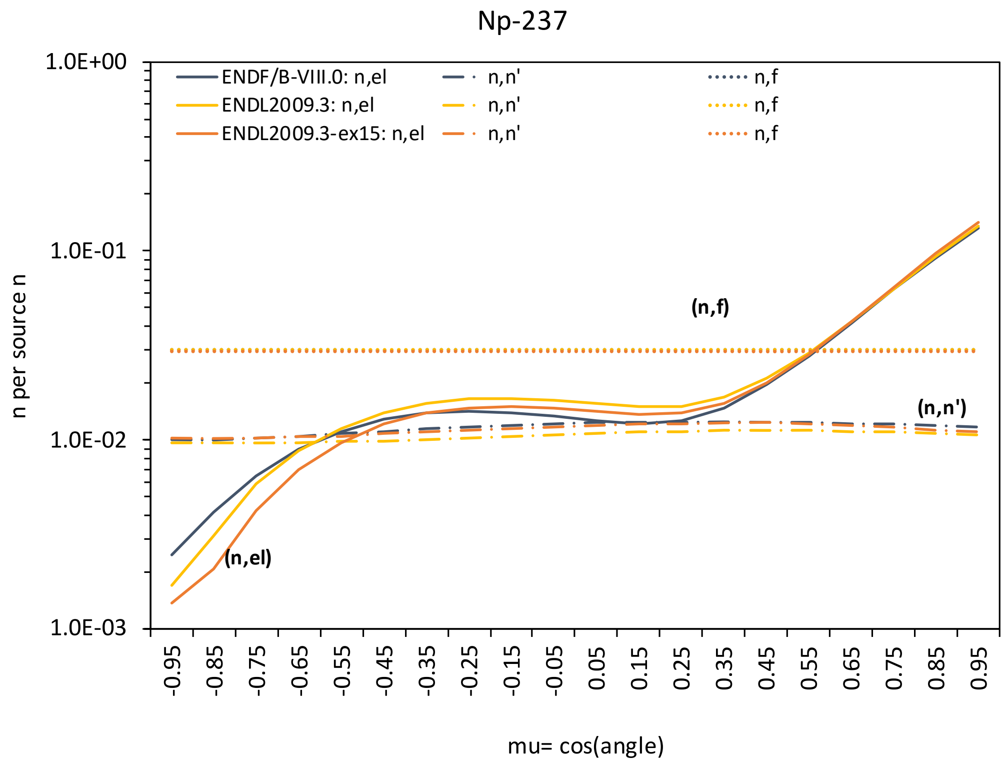


Figure 12. ^{237}Np: Simulated angular distribution of outgoing neutrons following a single (n,el) reaction (full line), (n,n') reaction (dot-dashed line), and (n,f) reaction (dotted line) for 1 MeV neutrons incident on ^{237}Np. Results for three nuclear data cross section libraries are plotted: ENDL2009.3-ex15 (orange), ENDF/B-VIII.0 (black), and END2009.3 (yellow).

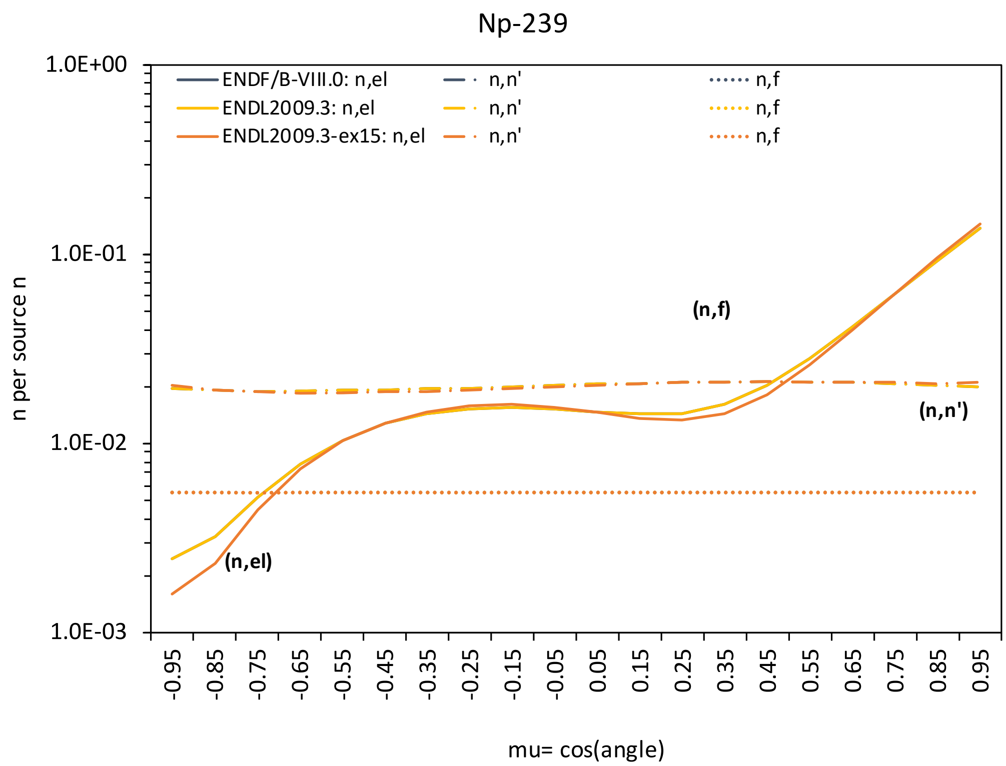


Figure 13. ^{239}Np: Simulated angular distribution of outgoing neutrons following a single (n,el) reaction (full line), (n,n') reaction (dot-dashed line), and (n,f) reaction (dotted line) for 1 MeV neutrons incident on ^{239}Np. Results for three nuclear data cross section libraries are plotted ENDL2009.3-ex15 (orange), ENDF/B-VIII.0 (black), and END2009.3 (yellow).

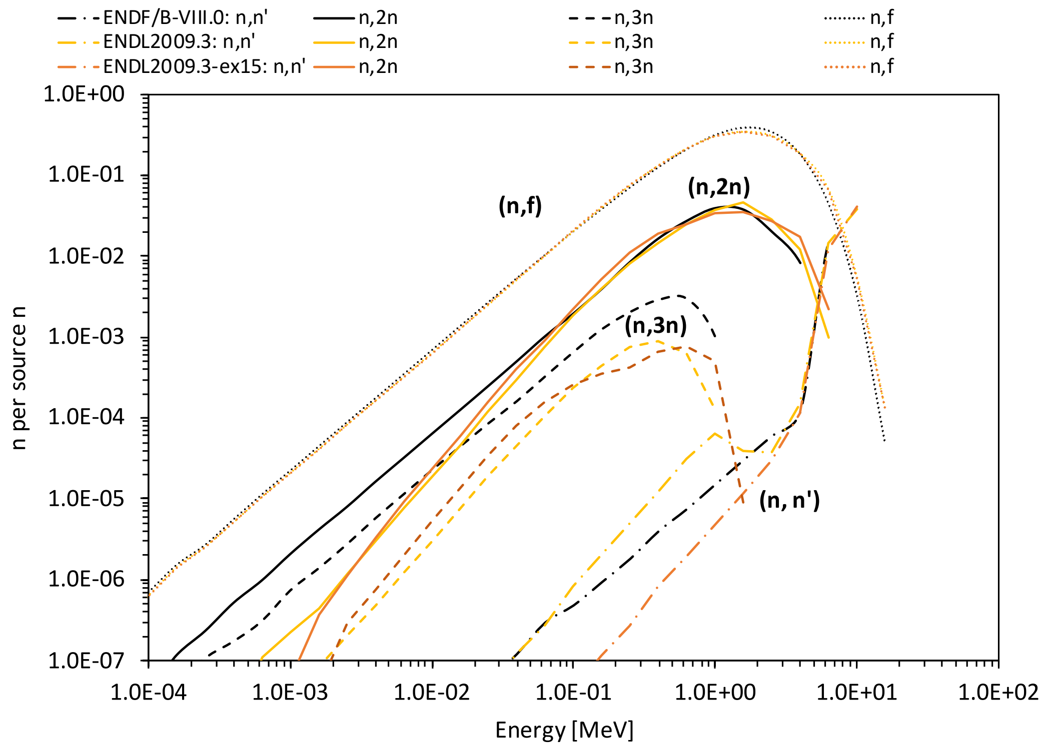


Figure 14. ^{237}Np: Simulated energy distribution of outgoing neutrons following a single (n,n') reaction (dot-dashed line), (n,2n) reaction (full line), (n,3n) reaction (dashed line) and (n,f) reaction (dotted line) for 14 MeV neutrons incident on ^{237}Np. Results for three nuclear data cross section libraries are plotted: ENDL2009.3-ex15 (orange), ENDF/B-VIII.0 (black), and END2009.3 (yellow).

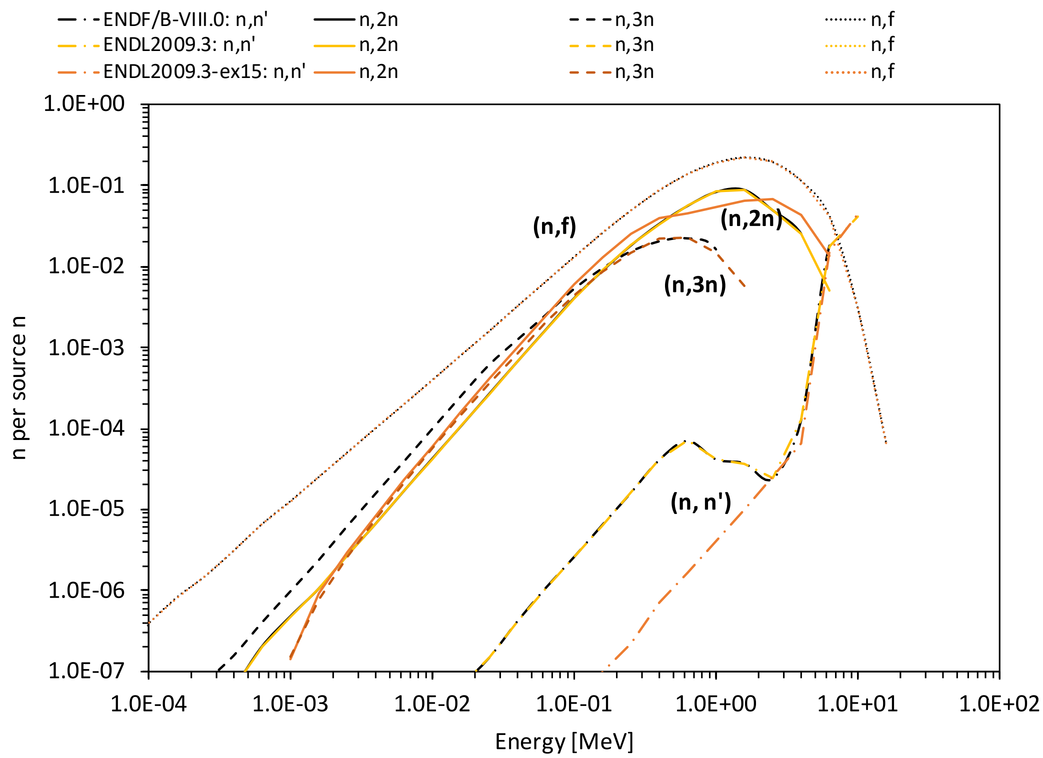


Figure 15. ^{239}Np: Simulated energy distribution of outgoing neutrons following a single (n,n') reaction (dot-dashed line), (n,2n) reaction (full line), (n,3n) reaction (dashed line) and (n,f) reaction (dotted line) for 14 MeV neutrons incident on ^{239}Np. Results for three nuclear data cross section libraries are plotted: ENDL2009.3-ex15 (orange), ENDF/B-VIII.0 (black), and END2009.3 (yellow).

Appendix 1. TALYS input parameters – Np237+n

```
#
# General parameters - Np237 + n
#
# attempt to reproduce JENDL/AC-2008  #evaluation for Np in ENDL system
#
projectile n
element    Np
mass       237
energy     energies_final
#
# Assumed Models
#
# Level Density - BSFG + CTM - disc levels exp & theory to 100
ldmodel 1
disctable 1
# Gamma strength functions - EGLO
strength 1
# Width Fluctuations - Moldauer
widthmode 1
# Pre-equillibrium - 2-component exciton model with analytical trans rates
preeqmode 1
twocomponent y
#
# Restriction on exit particles (no charged particles - very heavy targets)
ejectiles g n
#
# Local files that override discrete level and deformation files - Np only
#
levelfile  93 Np_lev.loc.max
deformfile 93 Np_def.loc.max
#
# Ecis run parameters - set inncalc and eciscalc #to "n" after first calculation
localomp y
ecissave y
inccalc y
eciscalc y
ecisdwba y
#
# General parameters
best y
maxrot 5
gammax 2
asys n
hbstate n
class2 n
#
```

```
# Output
partable y
channels y
filechannels y
outfission y
outgamma y
outdensity y
outomp y
outdirect y
outdwba y
# for full output to eric jurgenson - process endl/gnd
endfecis y
endf y
endfdetail y
fileelastic y
filespectrum g n
#
# Specific target Level Densities and gamma-gamma parameters
#
##
## Parameters for 238Np
##
## Level density
##
a              93 238  33.32396
aadjust        93 238   1.00000
gammald        93 238   0.07407
pair           93 238   0.00000
Pshift         93 238   0.00000   0
deltaW         93 238   2.27197   0
T              93 238   0.37329   0
E0             93 238  -1.06954   0
Exmatch        93 238   2.79081   0
Ntop           93 238  15   0
Nlow           93 238   2   0
Krotconstant   93 238   1.00000   0
Pshift         93 238   0.00000   1
deltaW         93 238   2.21589   1
T              93 238   0.42821   1
E0             93 238  -2.47064   1
Exmatch        93 238   3.08700   1
Ntop           93 238   1   1
Nlow           93 238   0   1
Krotconstant   93 238   1.00000   1
Pshift         93 238   0.00000   2
deltaW         93 238   1.51465   2
T              93 238   0.40519   2
E0             93 238  -2.36510   2
```

```
Exmatch         93 238   3.40590   2
Ntop            93 238   1   2
Nlow            93 238   0   2
Krotconstant    93 238   1.00000   2
D0              93 238   5.70000E-04
g               93 238  15.86667
gp              93 238   6.20000
gn              93 238   9.66667
##
## Gamma-ray
##
gamgam          93 238   0.04100
sgr             93 238 711.797 E1
egr             93 238  13.310 E1
ggr             93 238   3.649 E1
sgr             93 238   1.124 M1
egr             93 238   6.616 M1
ggr             93 238   4.000 M1
sgr             93 238   0.610 E2
egr             93 238  10.166 E2
ggr             93 238   3.254 E2
sgr             93 238   0.001 M2
egr             93 238   6.616 M2
ggr             93 238   4.000 M2
##
## Fission parameters
##
fisbar          93 238   5.57910  1
fishw           93 238   0.46000  1
fisbar          93 238   6.02344  2
fishw           93 238   0.37740  2
##----------------------------------
##
## Parameters for 237Np
##
## Level density
##
a               93 237  27.43487
aadjust         93 237   1.00000
gammald         93 237   0.07417
pair            93 237   0.77948
Pshift          93 237   0.00000   0
deltaW          93 237   2.43490   0
T               93 237   0.44252   0
E0              93 237  -1.22075   0
Exmatch         93 237   4.91457   0
Ntop            93 237  18   0
Nlow            93 237   8   0
```

```
Krotconstant     93 237   1.00000   0
Pshift          93 237   0.00000   1
deltaW          93 237   1.62327   1
T               93 237   0.43712   1
E0              93 237  -1.32610   1
Exmatch         93 237   5.24392   1
Ntop            93 237   1   1
Nlow            93 237   0   1
Krotconstant     93 237   1.00000   1
Pshift          93 237   0.00000   2
deltaW          93 237   1.62327   2
T               93 237   0.44494   2
E0              93 237  -0.85437   2
Exmatch         93 237   4.57852   2
Ntop            93 237   1   2
Nlow            93 237   0   2
Krotconstant     93 237   1.00000   2
D0              93 237   6.00000E-04
g               93 237  15.80000
gp              93 237   6.20000
gn              93 237   9.60000
##
## Gamma-ray
##
gamgam          93 237   0.03000
sgr             93 237 311.000 E1
egr             93 237  10.980 E1
ggr             93 237   2.170 E1
sgr             93 237 540.000 E1 2
egr             93 237  14.080 E1 2
ggr             93 237   4.660 E1 2
sgr             93 237   1.735 M1
egr             93 237   6.625 M1
ggr             93 237   4.000 M1
sgr             93 237   0.610 E2
egr             93 237  10.180 E2
ggr             93 237   3.266 E2
sgr             93 237   0.001 M2
egr             93 237   6.625 M2
ggr             93 237   4.000 M2
##
## Fission parameters
##
fisbar          93 237   3.05000  1
fishw           93 237   1.00000  1
fisbar          93 237   5.32000  2
fishw           93 237   0.50000  2
##---------------------------------
```

```
##
## Parameters for 236Np
##
## Level density
##
a              93 236  25.06857
aadjust        93 236   1.00000
gammald        93 236   0.07427
pair           93 236   0.00000
Pshift         93 236   0.00000   0
deltaW         93 236   2.13178   0
T              93 236   0.35851   0
E0             93 236  -0.76324   0
Exmatch        93 236   2.31631   0
Ntop           93 236  30   0
Nlow           93 236   2   0
Krotconstant   93 236   1.00000   0
Pshift         93 236   0.00000   1
deltaW         93 236   1.42119   1
T              93 236   0.25851   1
E0             93 236  -1.21768   1
Exmatch        93 236   2.18534   1
Ntop           93 236   1   1
Nlow           93 236   0   1
Krotconstant   93 236   1.00000   1
Pshift         93 236   0.00000   2
deltaW         93 236   1.42119   2
T              93 236   0.24851   2
E0             93 236  -0.63604   2
Exmatch        93 236   3.74203   2
Ntop           93 236   1   2
Nlow           93 236   0   2
Krotconstant   93 236   1.00000   2
g              93 236  15.73333
gp             93 236   6.20000
gn             93 236   9.53333
##
## Gamma-ray
##
gamgam         93 236   0.03000
sgr            93 236 705.312 E1
egr            93 236  13.335 E1
ggr            93 236   3.662 E1
sgr            93 236   1.111 M1
egr            93 236   6.635 M1
ggr            93 236   4.000 M1
sgr            93 236   0.609 E2
egr            93 236  10.195 E2
```

```
ggr            93 236   3.278 E2
sgr            93 236   0.001 M2
egr            93 236   6.635 M2
ggr            93 236   4.000 M2
##
## Fission parameters
##
fisbar         93 236   5.38200  1
fishw          93 236   0.60000  1
fisbar         93 236   5.40000  2
fishw          93 236   0.40000  2
##----------------------------------
##
## Parameters for 235Np
##
## Level density
##
a              93 235  28.95287
gammald        93 235   0.07438
pair           93 235   0.78279
Pshift         93 235   0.00000   0
deltaW         93 235   2.29037   0
T              93 235   0.34681   0
E0             93 235   0.02011   0
Exmatch        93 235   3.08554   0
Ntop           93 235  15   0
Nlow           93 235   7   0
Krotconstant   93 235   1.00000   0
Pshift         93 235   0.00000   1
deltaW         93 235   1.52691   1
T              93 235   0.36506   1
E0             93 235   0.00002   1
Exmatch        93 235   3.24678   1
Ntop           93 235   1   1
Nlow           93 235   0   1
Krotconstant   93 235   1.00000   1
Pshift         93 235   0.00000   2
deltaW         93 235   1.52691   2
T              93 235   0.36605   2
E0             93 235   0.00005   2
Exmatch        93 235   3.26337   2
Ntop           93 235   1   2
Nlow           93 235   0   2
Krotconstant   93 235   1.00000   2
g              93 235  15.66667
gp             93 235   6.20000
gn             93 235   9.46667
##
```

```
## Gamma-ray
##
gamgam         93 235   0.03000
sgr            93 235 702.051 E1
egr            93 235  13.348 E1
ggr            93 235   3.669 E1
sgr            93 235   1.104 M1
egr            93 235   6.644 M1
ggr            93 235   4.000 M1
sgr            93 235   0.609 E2
egr            93 235  10.209 E2
ggr            93 235   3.290 E2
sgr            93 235   0.001 M2
egr            93 235   6.644 M2
ggr            93 235   4.000 M2
##
## Fission parameters
##
fisbar         93 235   4.90000  1
fishw          93 235   1.00000  1
fisbar         93 235   3.60000  2
fishw          93 235   0.60000  2
##----------------------------------
##
## Parameters for 234Np
##
## Level density
##
a              93 234  28.62355
gammald        93 234   0.07449
pair           93 234   0.00000
Pshift         93 234   0.00000   0
deltaW         93 234   2.13129   0
T              93 234   0.35085   0
E0             93 234  -0.76798   0
Exmatch        93 234   2.32900   0
Ntop           93 234   4   0
Nlow           93 234   2   0
Krotconstant   93 234   1.00000   0
Pshift         93 234   0.00000   1
deltaW         93 234   1.42086   1
T              93 234   0.35085   1
E0             93 234  -0.62155   1
Exmatch        93 234   2.19712   1
Ntop           93 234   1   1
Nlow           93 234   0   1
Krotconstant   93 234   1.00000   1
Pshift         93 234   0.00000   2
```

```
deltaW        93 234   1.42086   2
T             93 234   0.35085   2
E0            93 234  -0.44108   2
Exmatch       93 234   3.75120   2
Ntop          93 234   1   2
Nlow          93 234   0   2
Krotconstant  93 234   1.00000   2
g             93 234  15.60000
gp            93 234   6.20000
gn            93 234   9.40000
##
## Gamma-ray
##
gamgam        93 234   0.03000
gamgamadjust  93 234   1.00000
sgr           93 234 698.776 E1
egr           93 234  13.362 E1
ggr           93 234   3.676 E1
sgr           93 234   1.097 M1
egr           93 234   6.653 M1
ggr           93 234   4.000 M1
sgr           93 234   0.608 E2
egr           93 234  10.224 E2
ggr           93 234   3.302 E2
sgr           93 234   0.001 M2
egr           93 234   6.653 M2
ggr           93 234   4.000 M2
##
## Fission parameters
##
fisbar        93 234   5.00000  1
fishw         93 234   1.00000  1
fisbar        93 234   3.60000  2
fishw         93 234   0.60000  2
##----------------------------------
##
## Parameters for 233Np
##
## Level density
##
a             93 233  28.79168
gammald       93 233   0.07459
pair          93 233   0.78615
Pshift        93 233   0.00000   0
deltaW        93 233   2.36062   0
T             93 233   0.34785   0
E0            93 233   0.01990   0
Exmatch       93 233   3.09311   0
```

```
Ntop          93 233  10   0
Nlow          93 233   2   0
Krotconstant    93 233   1.00000   0
Pshift         93 233   0.00000   1
deltaW         93 233   1.57374   1
T             93 233   0.34785   1
E0            93 233   0.17618   1
Exmatch        93 233   2.95232   1
Ntop          93 233   1   1
Nlow          93 233   0   1
Krotconstant    93 233   1.00000   1
Pshift         93 233   0.00000   2
deltaW         93 233   1.57374   2
T             93 233   0.34785   2
E0            93 233   0.36600   2
Exmatch        93 233   4.54198   2
Ntop          93 233   1   2
Nlow          93 233   0   2
Krotconstant    93 233   1.00000   2
g             93 233  15.53333
gp            93 233   6.20000
gn            93 233   9.33333
##
## Gamma-ray
##
gamgam         93 233   0.03000
sgr           93 233 695.489 E1
egr           93 233  13.375 E1
ggr           93 233   3.683 E1
sgr           93 233   1.091 M1
egr           93 233   6.663 M1
ggr           93 233   4.000 M1
sgr           93 233   0.608 E2
egr           93 233  10.238 E2
ggr           93 233   3.314 E2
sgr           93 233   0.001 M2
egr           93 233   6.663 M2
ggr           93 233   4.000 M2
##
## Fission parameters
##
fisbar         93 233   4.30000  1
fishw          93 233   1.00000  1
fisbar         93 233   3.30000  2
fishw          93 233   0.60000  2
##----------------------------------
##
## General parameters
```

```
##
## Level density
##
alphald          0.06660
betald           0.25800
gammashell1      0.45900
gammashell2      0.00000
pairconstant    12.00000
pshiftconstant   0.00000
Rspincut         1.00000
cglobal          1.00000E-20
pglobal          1.00000E-20
Ufermi          30.00000
cfermi           5.00000
Ufermibf        45.00000
cfermibf         5.00000
Kph             15.00000
##
## Gamma-ray
##
gnorm            1.00000
xscaptherm       1.76000E+05
##
## Pre-equilibrium
##
M2constant       0.45000
M2limit          1.00000
M2shift          1.00000
Rpipi            1.00000
Rnunu            1.50000
Rpinu            1.00000
Rnupi            1.00000
Rgamma           2.00000
Esurf           13.59825
##
## Optical model – default Soukhovitskii [14]
##
## all OM adjustment parameters set to 1.0 by default
##
## Resonance parameters
##   Z   A    S0          R           xs(therm)   D0          a           P           Sn
##  93 237 2.927E-01 5.042E+00 1.760E+05 1.035E-01 3.332E+01 0.000E+00 5.488E+00
```

TALYS input parameters – Np239+n.

```
#
# General parameters - Np239 + n
#
projectile n
element    Np
mass       239
energy     energies_final
#
# Assumed Models
#
# Level Density - BSFG + CTM - disc levels exp & theory to 100
ldmodel 1
disctable 1
# Gamma strength functions - EGLO
strength 1
# Width Fluctuations - Moldauer
widthmode 1
# Pre-equillibrium - 2-component exciton model with analytical trans rates
preeqmode 1
twocomponent y
#
# Restriction on exit particles (no charged particles - very heavy targets)
ejectiles g n
#
# Local files that override discrete level and deformation files - Np only
#
localomp y
deformfile 93 Np_def.loc.max
levelfile  93 Np_lev.loc.max
#
# Ecis run parameters - set inncalc and eciscalc to "n" after first calculation
ecissave y
inccalc y
eciscalc y
ecisdwba y
#
# General parameters
best y
maxrot 5
gammax 2
asys n
hbstate n
class2 n
#
# Output
partable y
```

```
channels y
filechannels y
outfission y
outgamma y
outdensity y
outomp y
outdirect y
outdwba y
# for full output to eric jurgenson - process endl/gnd
endfecis y
endf y
endfdetail y
fileelastic y
filespectrum g n
#
# Specific target Level Densities and gamma-gamma parameters
#
## Parameters for 240Np
##
## Level density
##
a              93 240  16.19884
gammald        93 240   0.07621
pair           93 240   0.00000
Pshift         93 240   0.00000   0
deltaW         93 240   2.69583   0
T              93 240   0.33264   0
E0             93 240  -1.06552   0
Exmatch        93 240   2.13673   0
Ntop           93 240   1   0
Nlow           93 240   0   0
Krotconstant   93 240   1.00000   0
Pshift         93 240   0.00000   1
deltaW         93 240   2.50000   1
T              93 240   0.33264   1
E0             93 240  -1.72663   1
Exmatch        93 240   2.29649   1
Ntop           93 240   1   1
Nlow           93 240   0   1
Krotconstant   93 240   1.00000   1
Pshift         93 240   0.00000   2
deltaW         93 240   0.60000   2
T              93 240   0.33265   2
E0             93 240  -1.04182   2
Exmatch        93 240   1.65367   2
Ntop           93 240   1   2
Nlow           93 240   0   2
Krotconstant   93 240   1.00000   2
```

```
g              93 240  16.00000
gp              93 240   6.20000
gn              93 240   9.80000
##
## Gamma-ray
##
gamgam          93 240   0.03000
sgr             93 240 718.234 E1
egr             93 240  13.284 E1
ggr             93 240   3.635 E1
sgr             93 240   1.138 M1
egr             93 240   6.598 M1
ggr             93 240   4.000 M1
sgr             93 240   0.612 E2
egr             93 240  10.138 E2
ggr             93 240   3.230 E2
sgr             93 240   0.001 M2
egr             93 240   6.598 M2
ggr             93 240   4.000 M2
##
## Fission parameters
##
# ENDL barriers
fisbar          93 240   6.154    1
fishw           93 240   0.45540  1
fisbar          93 240   4.973    2
fishw           93 240   0.37000  2
##--------------------------------------------
##
## Parameters for 239Np
##
## Level density
##
a               93 239  15.79437
gammald         93 239   0.07632
pair            93 239   0.77622
Pshift          93 239   0.00000   0
deltaW          93 239   0.1       0
#deltaW         93 239   2.68315   0
#T              93 239   0.39395   0
#E0             93 239  -0.96990   0
#Exmatch        93 239   3.86011   0
Ntop            93 239  18   0
Nlow            93 239   3   0
Krotconstant    93 239   1.00000   0
Pshift          93 239   0.00000   1
deltaW          93 239   2.50000   1
T               93 239   0.24629   1
```

```
E0             93 239   0.00004   1
Exmatch         93 239   1.74469   1
Ntop           93 239   1   1
Nlow           93 239   0   1
Krotconstant     93 239   1.00000   1
Pshift          93 239   0.00000   2
deltaW          93 239   0.60000   2
T              93 239   0.30409   2
E0             93 239   0.00003   2
Exmatch         93 239   1.92803   2
Ntop           93 239   1   2
Nlow           93 239   0   2
Krotconstant     93 239   1.00000   2
D0             93 239 4.10000E-04
g              93 239  15.93333
gp             93 239   6.20000
gn             93 239   9.73333
##
## Gamma-ray
##
gamgam          93 239   0.03000
sgr            93 239 715.022 E1
egr            93 239  13.297 E1
ggr            93 239   3.642 E1
sgr            93 239   1.131 M1
egr            93 239   6.607 M1
ggr            93 239   4.000 M1
sgr            93 239   0.611 E2
egr            93 239  10.152 E2
ggr            93 239   3.242 E2
sgr            93 239   0.001 M2
egr            93 239   6.607 M2
ggr            93 239   4.000 M2
##
## Fission parameters - ENDL
##
fisbar          93 239   5.00000  1
fishw           93 239   0.80000  1
fisbar          93 239   5.20000  2
fishw           93 239   0.60000  2
##--------------------------------------------
##
## Parameters for 238Np
##
## Level density
##
a              93 238  14.87898
gammald         93 238   0.07643
```

```
pair           93 238   0.00000
Pshift          93 238   0.00000   0
deltaW          93 238   2.27197   0
T              93 238   0.33229   0
E0             93 238  -0.89573   0
Exmatch         93 238   1.88983   0
Ntop           93 238  15   0
Nlow           93 238   2   0
Krotconstant    93 238   1.00000   0
Pshift          93 238   0.00000   1
deltaW          93 238   2.50000   1
T              93 238   0.34243   1
E0             93 238  -1.74336   1
Exmatch         93 238   2.30713   1
Ntop           93 238   1   1
Nlow           93 238   0   1
Krotconstant    93 238   1.00000   1
Pshift          93 238   0.00000   2
deltaW          93 238   0.60000   2
T              93 238   0.34243   2
E0             93 238  -1.04214   2
Exmatch         93 238   1.64431   2
Ntop           93 238   1   2
Nlow           93 238   0   2
Krotconstant    93 238   1.00000   2
D0             93 238 5.70000E-04
g              93 238  15.86667
gp             93 238   6.20000
gn             93 238   9.66667
##
## Gamma-ray
##
gamgam          93 238   0.04100
sgr            93 238 711.797 E1
egr            93 238  13.310 E1
ggr            93 238   3.649 E1
sgr            93 238   1.124 M1
egr            93 238   6.616 M1
ggr            93 238   4.000 M1
sgr            93 238   0.610 E2
egr            93 238  10.166 E2
ggr            93 238   3.254 E2
sgr            93 238   0.001 M2
egr            93 238   6.616 M2
ggr            93 238   4.000 M2
##
## Fission parameters
##
```

```
fisbar       93 238  5.40000  1
fishw        93 238  0.60000  1
fisbar       93 238  5.25000  2
fishw        93 238  0.60000  2
##--------------------------------------------
##
## Parameters for 237Np
##
## Level density
##
a            93 237  13.04771
gammald      93 237   0.07653
pair         93 237   0.77948
Pshift       93 237   0.00000   0
deltaW       93 237   2.43490   0
T            93 237   0.46080   0
E0           93 237  -1.30221   0
Exmatch      93 237   4.36286   0
Ntop         93 237  18   0
Nlow         93 237   8   0
Krotconstant 93 237   1.00000   0
Pshift       93 237   0.00000   1
deltaW       93 237   1.50000   1
T            93 237   0.35203   1
E0           93 237   0.00004   1
Exmatch      93 237   2.44489   1
Ntop         93 237   1   1
Nlow         93 237   0   1
Krotconstant 93 237   1.00000   1
Pshift       93 237   0.00000   2
deltaW       93 237   0.60000   2
T            93 237   0.33122   2
E0           93 237   0.00001   2
Exmatch      93 237   1.87972   2
Ntop         93 237   1   2
Nlow         93 237   0   2
Krotconstant 93 237   1.00000   2
D0           93 237 6.00000E-04
g            93 237  15.80000
gp           93 237   6.20000
gn           93 237   9.60000
##
## Gamma-ray
##
gamgam       93 237   0.03000
sgr          93 237 311.000 E1
egr          93 237  10.980 E1
ggr          93 237   2.170 E1
```

```
sgr           93 237 540.000 E1 2
egr           93 237  14.080 E1 2
ggr           93 237   4.660 E1 2
sgr           93 237   1.735 M1
egr           93 237   6.625 M1
ggr           93 237   4.000 M1
sgr           93 237   0.610 E2
egr           93 237  10.180 E2
ggr           93 237   3.266 E2
sgr           93 237   0.001 M2
egr           93 237   6.625 M2
ggr           93 237   4.000 M2
##
## Fission parameters
##
fisbar         93 237   0.02000  1
fishw          93 237   2.00000  1
fisbar         93 237   5.48800  2
fishw          93 237   0.50000  2
##--------------------------------------------
##
## Parameters for 236Np
##
## Level density
##
a             93 236  15.46388
gammald        93 236   0.07664
pair           93 236   0.00000
Pshift         93 236   0.00000   0
deltaW         93 236   2.13178   0
T             93 236   0.34730   0
E0            93 236  -1.10041   0
Exmatch        93 236   2.20939   0
Ntop           93 236  30   0
Nlow           93 236   2   0
Krotconstant    93 236   1.00000   0
Pshift         93 236   0.00000   1
deltaW         93 236   1.50000   1
T             93 236   0.34730   1
E0            93 236  -1.03535   1
Exmatch        93 236   2.06481   1
Ntop           93 236   1   1
Nlow           93 236   0   1
Krotconstant    93 236   1.00000   1
Pshift         93 236   0.00000   2
deltaW         93 236   0.60000   2
T             93 236   0.34730   2
E0            93 236  -1.15572   2
```

```
Exmatch         93 236   1.83895   2
Ntop            93 236   1   2
Nlow            93 236   0   2
Krotconstant     93 236   1.00000   2
g               93 236  15.73333
gp              93 236   6.20000
gn              93 236   9.53333
##
## Gamma-ray
##
gamgam          93 236   0.03000
sgr             93 236 705.312 E1
egr             93 236  13.335 E1
ggr             93 236   3.662 E1
sgr             93 236   1.111 M1
egr             93 236   6.635 M1
ggr             93 236   4.000 M1
sgr             93 236   0.609 E2
egr             93 236  10.195 E2
ggr             93 236   3.278 E2
sgr             93 236   0.001 M2
egr             93 236   6.635 M2
ggr             93 236   4.000 M2
##
## Fission parameters
##
fisbar          93 236   5.90000  1
fishw           93 236   0.60000  1
fisbar          93 236   5.40000  2
fishw           93 236   0.40000  2
##--------------------------------------------
##
## Parameters for 235Np
##
## Level density
##
a               93 235  15.51682
gammald         93 235   0.07675
pair            93 235   0.78279
Pshift          93 235   0.00000   0
deltaW          93 235   2.29037   0
T               93 235   0.34550   0
E0              93 235  -0.31505   0
Exmatch         93 235   2.98684   0
Ntop            93 235  15   0
Nlow            93 235   7   0
Krotconstant     93 235   1.00000   0
Pshift          93 235   0.00000   1
```

```
deltaW        93 235   1.50000   1
T             93 235   0.32095   1
E0            93 235   0.00002   1
Exmatch       93 235   2.42011   1
Ntop          93 235   1   1
Nlow          93 235   0   1
Krotconstant  93 235   1.00000   1
Pshift        93 235   0.00000   2
deltaW        93 235   0.60000   2
T             93 235   0.30449   2
E0            93 235   0.00002   2
Exmatch       93 235   1.94444   2
Ntop          93 235   1   2
Nlow          93 235   0   2
Krotconstant  93 235   1.00000   2
g             93 235  15.66667
gp            93 235   6.20000
gn            93 235   9.46667
##
## Gamma-ray
##
gamgam        93 235   0.03000
sgr           93 235 702.051 E1
egr           93 235  13.348 E1
ggr           93 235   3.669 E1
sgr           93 235   1.104 M1
egr           93 235   6.644 M1
ggr           93 235   4.000 M1
sgr           93 235   0.609 E2
egr           93 235  10.209 E2
ggr           93 235   3.290 E2
sgr           93 235   0.001 M2
egr           93 235   6.644 M2
ggr           93 235   4.000 M2
##
## Fission parameters
##
fisbar        93 235   4.90000  1
fishw         93 235   1.00000  1
fisbar        93 235   3.60000  2
fishw         93 235   0.60000  2
##-------------------------------------------
##
## General parameters
##
## Level density
##
alphald       0.02073
```

```
betald          0.22954
gammashell1      0.47363
gammashell2      0.00000
pairconstant    12.00000
pshiftconstant   0.00000
Rspincut        1.00000
cglobal       1.00000E-20
pglobal       1.00000E-20
Ufermi         30.00000
cfermi          5.00000
Ufermibf       45.00000
cfermibf        5.00000
Kph           15.00000
##
## Gamma-ray
##
#gnorm          2.22385
#xscaptherm     3.60000E+04
gnorm           1.0
##
## Pre-equilibrium
##
M2constant      0.30000
M2limit         1.00000
M2shift         1.00000
Rpipi          1.00000
Rnunu           1.50000
Rpinu          1.00000
Rnupi          1.00000
Rgamma          2.00000
Esurf          13.61507
Cstrip      n   1.00000
Cknock      n   1.00000
Cbreak      n   1.00000
Cstrip      p   1.00000
Cknock      p   1.00000
Cbreak      p   1.00000
Cstrip      d   1.00000
Cknock      d   1.00000
Cbreak      d   1.00000
Cstrip      t   1.00000
Cknock      t   1.00000
Cbreak      t   1.00000
Cstrip      h   1.00000
Cknock      h   1.00000
Cbreak      h   1.00000
Cstrip      a   1.00000
Cknock      a   1.00000
```

```
Cbreak        a   1.00000
##
## Optical model - default Soukovitskii [14]
##
## all OM adjustment parameters set to 1.0 by default
##
## Resonance parameters
##  Z   A      S0             R                xs(therm)   D0            a               P               Sn
##  93 239 2.912E-01 5.044E+00 3.600E+04 5.452E-01 1.620E+01 0.000E+00 5.066E+00
```