A semi-empirical systematics for $^{232-239}\text{Np}(n,f)$ cross sections at 4–20 MeVMurat Dag¹

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ABSTRACT

This work presents a compact semi empirical systematics for neutron induced fission cross sections of neptunium isotopes $^{232-239}\text{Np}$ for incident neutron energies from 4 to 20 MeV. The formulation adopts a multi chance fission description in which the total (n,f) cross section is written as a sum of penetrability weighted first, second, and third chance contributions scaled by the non elastic reaction cross section. Three isotope dependent coefficients are obtained by fitting to reproduce the plateau like behaviour associated with the sequential opening of the (n, f), (n,nf), and (n,2nf) channels. The semi empirical systematics is benchmarked against evaluated nuclear data libraries, ENDF/B VIII.1 and TENDL 2023, and against experimental datasets where available. Quantitatively, the agreement is strongest for ^{234}Np , ^{235}Np , ^{237}Np , and ^{238}Np , for which χ^2/N remains between 0.001 and 0.006 with respect to ENDF/B-VIII.1 and between 0.006 and 0.036 against experimental data where available, whereas ^{236}Np and ^{239}Np exhibit somewhat larger deviations, with χ^2/N values of 0.010 and 0.048 versus ENDF/B-VIII.1 and 0.042 and 0.030 versus experiment, respectively. No EXFOR measurements are available for ^{232}Np and ^{233}Np in this energy range. In parallel, TALYS 2.0 calculations are performed using 15 combinations formed by three level density models, CTM, BSFGM, and GSM, and five fission barrier options, FIS.MODEL 1 to 5. The calculated (n,f) cross sections show a clear dependence on these modelling choices, indicating that additional high precision measurements would be valuable for strengthening model validation and reducing uncertainties in neptunium (n,f) cross section estimates.

1. Introduction

Fission cross sections constitute a foundational component of nuclear science and engineering because they underpin a wide spectrum of applications ranging from reactor energy production to advanced fuel-cycle strategies, waste-transmutation initiatives, and radiation-shielding design (Dag and Aydin, 2025). Their quantitative reliability is therefore central to the modelling of neutron-induced reactions in actinide and transuranic nuclei, where fission is initiated by interactions with incident neutrons. Nuclides capable of sustaining a self-propagating fission chain reaction are classified as fissile (or more broadly, fissionable), with uranium and plutonium serving as textbook examples. Fertile nuclides, in contrast, do not readily undergo fission; however, under sufficiently intense neutron flux they may capture neutrons and, through subsequent β -decay pathways, transform into fissile nuclei. In this regard, the neptunium isotopic chain plays a key role among the minor actinides in reactor fuel cycles, with ^{237}Np acting as a key fertile nuclide and a major contributor to the long-term radioactive inventory of spent fuel.

The present work focuses on the neutron-induced fission cross sections of the neptunium isotopes $^{232-239}\text{Np}$ for incident-neutron energies between 4 and 20 MeV. This isotopic set spans very short-lived to very long-lived nuclides, including ^{236}Np and ^{237}Np , which dominate the long-term radiotoxicity, as well as ^{238}Np and ^{239}Np , which act as short-lived precursors in capture-decay chains leading to ^{238}Pu and ^{239}Pu . The chosen 4–20 MeV interval lies in a broad continuum region within which the characteristic multi-plateau behavior arising from the successive opening of the (n,f), (n,nf), and (n,2nf) channels can be represented by a compact semi-empirical parameterization that is directly relevant to fast-spectrum reactors, accelerator-driven systems (ADSs), and shielding design. (Guo et al., 2023).

Reliable fission cross sections are required both to elucidate the underlying fission mechanism and to support the design and performance assessment of fission-based systems. In practice, phenomenological descriptions of fission cross sections remain indispensable, particularly at neutron energies where experimental information is sparse or affected by significant systematic uncertainties. Within these phenomenological approaches, analytical expressions derived from

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evaporation models and pre-equilibrium exciton-type models have been widely used to construct empirical parameterizations of reaction cross sections. Numerous studies (Abdullah and Ahmed, 2023; Jiaoletti et al., 1972; Pearlstein, 1965; Tel et al., 2007; Yigit, 2018; Young et al., 2005) have proposed semi-empirical and purely empirical systematics for neutron-induced channels such as (n,p), (n,n), (n, α), (n,f), and (n,2n) over broad neutron-energy intervals. However, these global parameterizations are generally tailored to major actinides such as uranium or to structural materials and are not specifically optimized for neptunium isotopes in the 4–20 MeV energy range. For neptunium, the available (n, f) data remain limited and, in some cases, mutually inconsistent, thereby reducing the reliability of existing systematics in applications that require accurate fission probabilities.

Against this background, there is a clear need for a dedicated semi-empirical evaluation of neutron-induced fission cross sections for neptunium isotopes between 4 and 20 MeV, in order to more tightly constrain theoretical models and refine our understanding of the fission mechanism in this energy range. In this work, we present calculations of a compact semi-empirical (n,f) systematics for the isotopic chain $^{232-239}\text{Np}$, developed on the basis of the formalism proposed by Jhingan et al. (Jhingan et al., 1979), and we benchmark the results against a comprehensive set of experimental data and evaluated nuclear-data libraries. In parallel, we perform TALYS-2.0 calculations using 15 combinations of level-density and fission-barrier models, enabling a systematic assessment of model sensitivities and an identification of energy regions where additional high-precision measurements would be particularly valuable.

2. Method

2.1. Semi-empirical (n,f) reaction cross-section formula

As the incident neutron energy E_n increases, the neutron-induced fission cross section initially rises and then reaches a first plateau at σ_1 , which is typically maintained up to about 5–6 MeV. For nuclei, whose neutron binding energy exceeds the fission barrier, this low-energy rise is absent, and the fission cross section does not exhibit the initial increasing branch. A second increase appears once the excitation energy becomes sufficiently high for the emission of one neutron without driving the residual nucleus below the fission barrier; in this case, the system retains a second opportunity to undergo fission through the (n,nf) channel. By the same mechanism, the (n,2nf) channel produces an additional enhancement between roughly 12 and 14 MeV, above the second plateau, giving rise to a third plateau in the fission cross section. In practice, however, this multi-plateau sequence should be regarded as an idealized pattern. Depending on the isotope, the opening of higher-chance fission channels may appear as a clearly resolved step, a weak shoulder, or only a modest change in slope, because the additional fission contribution remains coupled to competing neutron-emission effects.

Since the contributions from the (n,f), (n,nf), and (n,2nf) channels are additive (Jhingan et al., 1979), the total neutron-induced fission cross section for a target of mass number A , up to the onset of the fourth plateau, can be written as

$$\sigma_{(n,f)}(E_n) = P_1 \sigma_1 + \left(1 - \frac{\sigma_1}{\sigma_R}\right) K \left[P_2 \sigma_2 + \left(1 - \frac{\sigma_2}{\sigma_R}\right) P_3 \sigma_3 \right], \quad (1)$$

where σ_1 denotes the first fission plateau and corresponds to first-chance fission of the compound nucleus formed when a neutron is absorbed by a target of mass number A . The term σ_2 accounts for second-chance fission events that occur after the emission of one pre-fission neutron, i.e., fission of the residual nucleus with mass $A - 1$ proceeding through the (n,nf) channel. Likewise, σ_3 quantifies third-chance fission, arising when two neutrons are evaporated prior to fission so that the reaction proceeds via the (n,2nf) channel on the residual

nucleus of mass $A - 2$. The quantity σ_R denotes the non-elastic reaction cross section, and P_i ($i = 1, 2, 3$) are the penetrability factors for first-, second- and third-chance fission, respectively, evaluated in Hill–Wheeler form (Hill and Wheeler, 1953),

$$P_i = \left[1 + \exp\left(\frac{2\pi(E_{f,i} - \varepsilon_i)}{\hbar\omega}\right) \right]^{-1}, \quad (2)$$

where $E_{f,i}$ is the effective fission-barrier height for the i -th chance and $\hbar\omega$ is the barrier-curvature parameter.

The excitation energies ε_i associated with first-, second-, and third-chance fission are given by

$$\varepsilon_1 = E_n + S_n(A + 1), \quad \varepsilon_2 = E_n, \quad \varepsilon_3 = E_n + S_n(A), \quad (3)$$

where $S_n(A)$ is the neutron separation energy for the nucleus of mass A . The parameter K accounts for non-equilibrium neutron emission from the system and is introduced as a scaling factor (< 1) to incorporate the pre-equilibrium neutron component into the fission cross section formalism. Since these prompts, high-energy neutrons frequently deplete the excitation energy to a level below the fission barrier after the first emission, models that omit this contribution systematically overestimate fission cross section values; thus, K serves as a corrective normalization.

K is expressed as the ratio $\sigma_{n,M}/\sigma_R$, where $\sigma_{n,M}$ denotes the sum of all neutron-emission cross sections and σ_R is the non-elastic cross section. Pearlstein (Pearlstein, 1965) originally evaluated the ratio using an empirical expression proposed by Barr et al. (Barr et al., 1961), as given in Eq. (4). Subsequent studies refined the associated parameters k and m : Lu et al. (Lu et al., 1970) modified Barr's values, whereas Kondaiah and Athougies (1974) (Kondaiah, 1974; Kondaiah and Athougies, 1974) performed a weighted least-squares analysis of $\sigma_{n,M}/\sigma_R$ values derived from experimental (n,2n) cross sections for more than one hundred nuclides over the range $(N - Z)/A = 0.03$ – 0.22 . Following Kondaiah's approach, we also adopt the least-squares parameters $k = 1.365$ and $m = 10.605$, which correspond to the central fit, while acknowledging the quoted uncertainties in both constants.

$$K \equiv \frac{\sigma_{n,M}}{\sigma_R} = 1 - k \exp\left[-m \frac{(N - Z)}{A}\right], \quad (4)$$

In the numerical calculations reported here, we therefore use Eq. (4) where Z , N and A are the proton, neutron and mass numbers of the target, respectively. The non-elastic cross section σ_R is given by the empirical relation of Flerov and Talyzin (Flerov and Talyzin, 1956)

$$\sigma_R = \pi(0.12A^{1/3} + 0.21)^2 \quad (\text{barns}), \quad (5)$$

with A the target mass number.

In this article, the formalism in Eq. (1) is adopted as the basis for deriving empirical expressions that describe the dependence of the (n,f) cross section on fission-barrier penetrability in the neutron energy range 4–20 MeV. To obtain a more compact and practically useful expression, we explicitly factor out σ_R and replace the plateau cross sections σ_i by dimensionless fitting coefficients a_i scaled by σ_R . This effectively absorbs the detailed structure of the plateau sequence and the $(1 - \sigma_i/\sigma_R)$ factors into a set of isotope-dependent coefficients. For the isotopic chain $^{232-239}\text{Np}$, the resulting semi-empirical expression for the neutron induced fission cross section reads

$$\sigma_{(n,f)}(E_n) = \sigma_R[a_1 G_1 + a_2 G_2 + a_3 G_3], \quad (6)$$

where a_1 , a_2 , and a_3 are free parameters determined by fitting to experimental data, and the penetrabilities G_i are given by a generalised Hill–Wheeler form

$$G_i = \left[1 + \exp\left(\frac{2\pi[E_f(A + 2 - i) - \varepsilon_i + y_i \hbar\omega]}{x_i \hbar\omega}\right) \right]^{-1} \quad (7)$$

Table 1

Optimised plateau fitting parameters a_1 , a_2 , and a_3 of the semi-empirical (n,f) model for neptunium isotopes, together with the corresponding χ^2/N , fission-barrier heights E_f , and neutron separation energies S_n used in the calculation of neutron-induced fission cross sections. The χ^2/N columns refer to the agreement of Eq. (6) with ENDF/B-VIII.1 and with the compiled experimental dataset, respectively. Fission Barrier Heights are taken from Möller et al. (2015) (Möller et al., 2015). Neutron Separation Energies are taken from (NNDC, 2008).

Target	Optimized Plateau Fitting Parameters			Eq. (6) vs ENDF/B-VIII.1	Eq. (6) vs Exp. Data	Fission Barrier Heights E_f (MeV)			Neutron Separation Energies S_n (MeV)	
	a_1	a_2	a_3	χ^2/N	χ^2/N	(A + 1)	(A)	(A-1)	(A + 1)	(A)
^{232}Np	2.19	2.07	0.59	—	—	4.37	4.14	3.81	7.48	6.34
^{233}Np	2.60	3.70	4.19	—	—	4.63	4.37	4.14	6.07	7.48
^{234}Np	1.76	2.00	1.58	0.003	—	4.83	4.63	4.37	6.983	6.07
^{235}Np	1.78	2.04	0.33	0.002	0.036	4.81	4.83	4.63	5.73	6.983
^{236}Np	1.87	1.87	0.45	0.010	0.042	4.94	4.81	4.83	6.58	5.74
^{237}Np	1.40	1.64	0.51	0.005	0.006	5.36	4.94	4.81	5.488	6.58
^{238}Np	1.10	1.35	1.06	0.001	0.014	5.57	5.36	4.94	6.214	5.488
^{239}Np	1.09	1.09	1.00	0.048	0.030	6.01	5.57	5.36	5.066	6.214

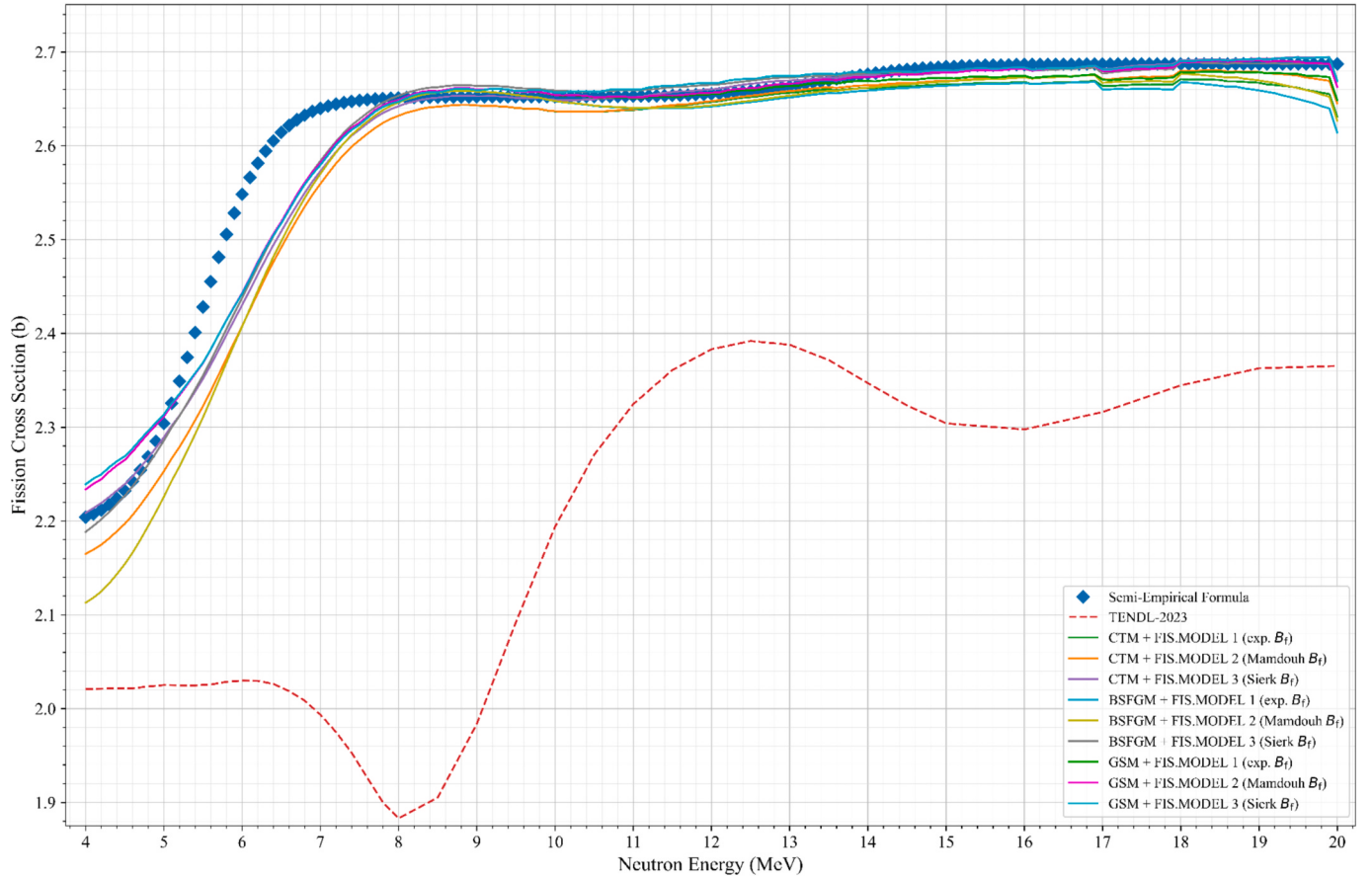


Fig. 1. Neutron-induced fission cross section of ^{232}Np versus incident neutron energy (4–20 MeV): comparison of the present systematics (Eq. (6)), TENDL-2023, and TALYS-2.0 results obtained with CTM/BSFGM/GSM level densities and FIS.MODEL 1–3.

In this expression, $\hbar\omega$ denotes the curvature of the fission barrier. A constant value of 0.667 MeV is used for all nuclei considered ($^{232-239}\text{Np}$), which is consistent with the vicinity of the local maximum of the $\hbar\omega_2(\chi)$ systematics reported by Nix (Nix, 1967). This choice provides a representative curvature for neptunium isotopes whose fissility parameters lie near this region. For first-chance fission, choosing $x_1 = 1$ and $y_1 = 0$ reduces the generalised penetrability G_i to the conventional Hill–Wheeler form. For higher-chance fission ($i = 2, 3$), the adjustable parameters x_i and y_i shift the effective threshold energy and modify the curvature, thereby accounting for the increased phase space associated with the spread in excitation energy of the fissioning nucleus after pre-fission neutron emission.

By comparison with the available experimental data for the isotopic chain $^{232-239}\text{Np}$, the parameters controlling the higher-chance

penetrabilities were found to be $x_2 = 4$, $x_3 = 6$, $y_2 = 2$, and $y_3 = 4$. These values are kept fixed throughout the present analysis, while the coefficients a_1 , a_2 , and a_3 are optimised separately for each neptunium isotope. More specifically, the coefficients a_1 , a_2 , and a_3 are obtained for each isotope by a separate least-squares fit to the selected reference cross-section dataset in the 4–20 MeV interval. In this way, the above expression provides a unified semi-empirical description of the (n,f) cross sections of neptunium isotopes in the 4–20 MeV energy range. The optimised isotope-dependent coefficients a_1 , a_2 , and a_3 , together with the corresponding χ^2/N values, fission-barrier heights E_f , and neutron separation energies S_n used in the calculations, are summarized in Table 1. It should also be noted that the relations adopted here for the K factor and for the non-elastic cross section are effective literature systematics rather than neptunium-specific microscopic expressions. Their

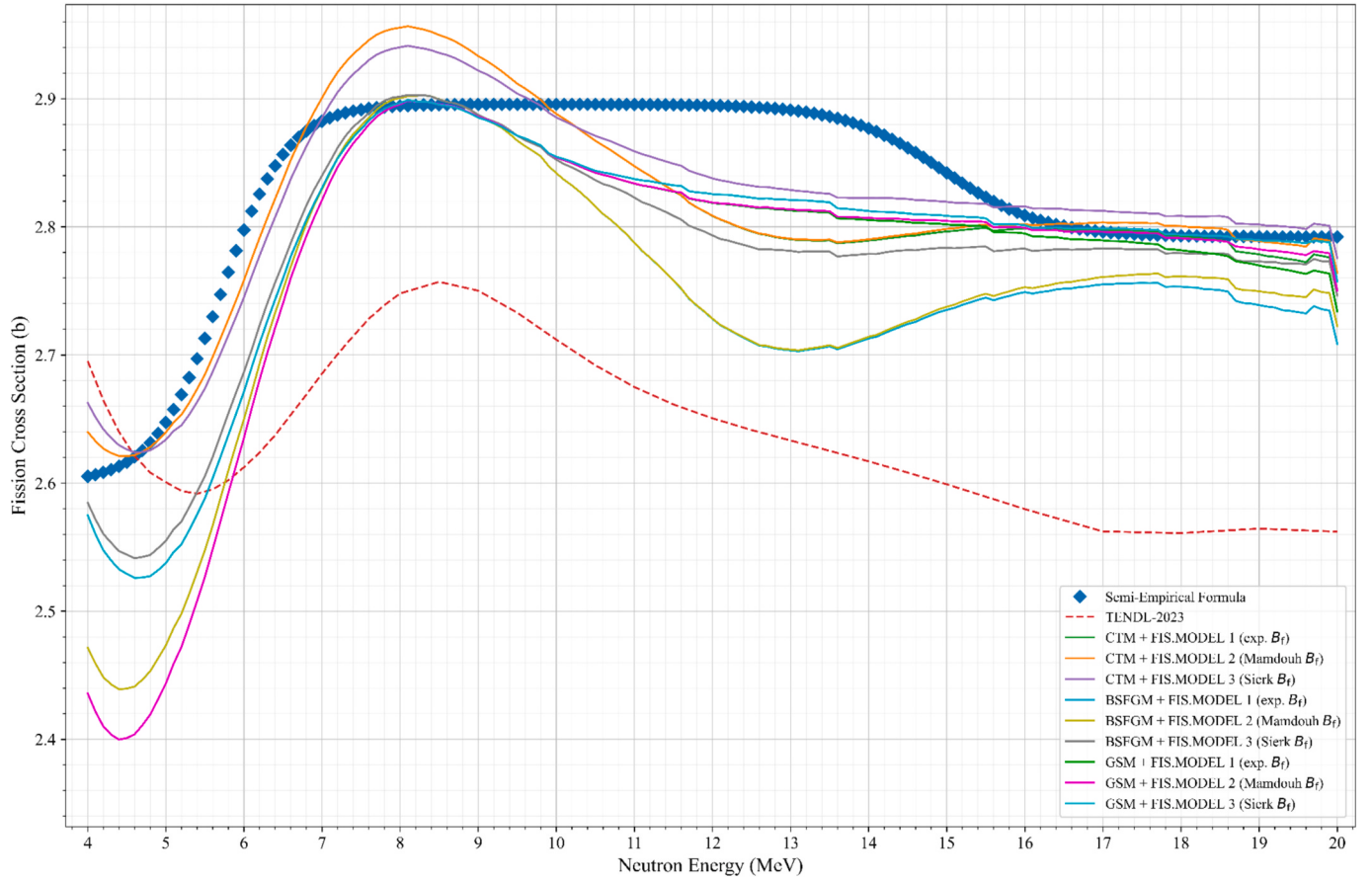


Fig. 2. Neutron-induced fission cross section of ^{233}Np versus incident neutron energy (4–20 MeV): comparison of the present systematics (Eq. (6)), TENDL-2023, and TALYS-2.0 results obtained with CTM/BSFGM/GSM level densities and FIS.MODEL 1–3.

applicability to the $^{232-239}\text{Np}$ chain in the 4–20 MeV interval is therefore assessed a posteriori through comparison with evaluated libraries and, where available, with experimental datasets.

2.2. TALYS

Computational reaction modelling plays a vital role in nuclear data research, particularly when direct measurements for a given reaction channel are unavailable or when experimental realization is limited by technical, safety-related, or economic constraints. Under such circumstances, reaction codes provide indispensable theoretical estimates by enabling the controlled exploration of model sensitivities and by extending predictions into energy regions where empirical data remain incomplete.

In the present work, theoretical (n,f) cross sections are calculated with TALYS-2.0 (Koning et al., 2021), (Koning et al., 2023), one of the most extensively used frameworks for nuclear reaction modelling and data evaluation. TALYS is designed to simulate reactions induced by neutrons, photons, protons, deuterons, tritons, ^3He , and α particles for nuclides with mass numbers $A \geq 12$. Its modular structure provides access to direct, pre-equilibrium, and compound-nuclear mechanisms within a Hauser–Feshbach statistical framework and allows users to specify model parameters through a flexible input structure. The code is continuously maintained and benchmarked against experimental datasets, and it includes the capabilities required to compute observables such as reaction cross sections, angular distributions, emission spectra, and isomeric ratios.

All calculations reported here are performed using the default global options of TALYS-2.0 unless stated otherwise. For each neptunium isotope, we consider three phenomenological level-density

prescriptions: the Constant Temperature Model (CTM) (Gilbert and Cameron, 1965), the Back-Shifted Fermi Gas Model (BSFGM) (Dilg et al., 1973), (Demetriou and Goriely, 2001), (Grossjean and Feldmeier, 1985), and the Generalized Superfluid Model (GSM) (Ignatyuk et al., 1975), (Ignatyuk et al., 1993), (Ignatyuk et al., 1979). In TALYS, the nuclear level density $\rho(E_x, J, \pi)$ denotes the number of levels per unit energy around an excitation energy E_x for a given spin J and parity π , and the total level density is obtained by summing over all spins and parities. The CTM divides the excitation-energy domain into a low-energy constant-temperature regime and a high-energy region described by a Fermi-gas expression, the BSFGM applies the Fermi-gas formula over the full excitation range using a back-shifted energy to account effectively for pairing effects, and the GSM incorporates Barden–Cooper–Schrieffer (BCS)-type pairing correlations and yields a smooth transition from a superfluid regime at low excitation energies to a normal Fermi-gas behavior at higher energies. A detailed discussion of these level-density options and their implementation in TALYS is given in (Dağ, 2025, 2021; Dag and Aydin, 2025), and only this summary is provided here.

In addition to the level density models, the present study systematically explores the impact of five fission barrier models implemented in TALYS. These models govern the transmission probability across the fission barrier and therefore play a decisive role in shaping neutron-induced fission cross sections, particularly in the 4–20 MeV energy range relevant to this work. In TALYS, the fission probability is evaluated through barrier-penetration calculations using one- or multi-humped transmission coefficients within the Hauser–Feshbach framework, where the fission width competes with particle and γ -emission widths; the adopted barrier model is thus an essential input for the calculated (n,f) cross sections.

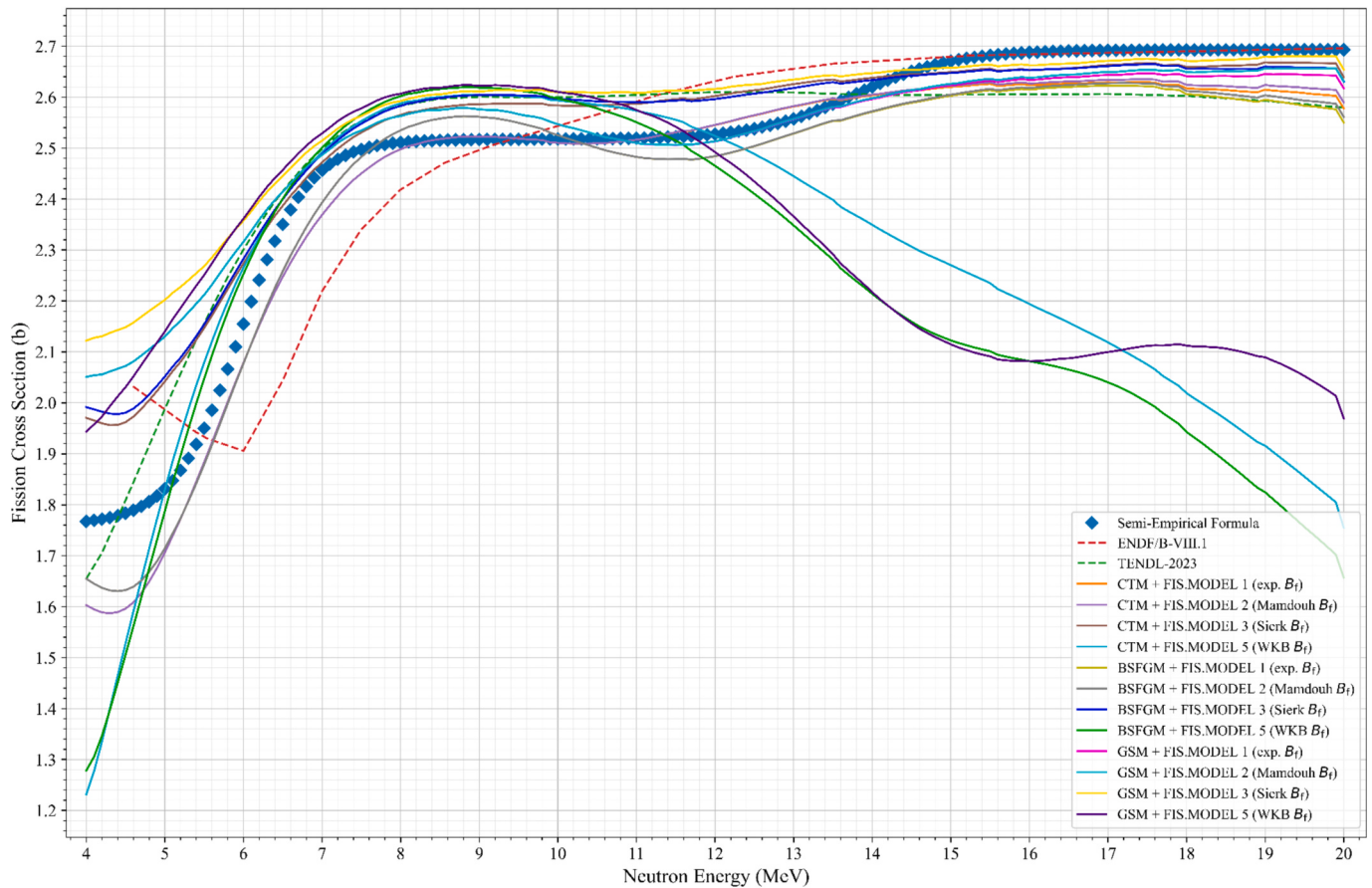


Fig. 3. Neutron-induced fission cross section of ^{234}Np versus incident neutron energy (4–20 MeV): comparison of the present systematics (Eq. (6)), ENDF/B-VIII.1 and TENDL-2023 evaluations, and TALYS-2.0 results obtained with CTM/BSFGM/GSM level densities and FIS.MODEL 1–3 and 5 (WKB).

The five fission barrier models options examined here are denoted FIS.MODEL 1–5. Fission Model 1 (Exp. Bf) (Capote et al., 2009) employs empirical barrier heights derived from evaluated data and experimental systematics whenever available; as a predominantly phenomenological prescription, it provides a reference case directly constrained by measured fission observables. Fission Model 2 (Mamdouh Bf) (Mamdouh et al., 2000) uses macroscopic–microscopic barrier calculations in which shell correction effects and deformation-energy surfaces are obtained from nuclear structure inputs and is particularly suited for heavy nuclides. Fission Model 3 (Sierk Bf) (Sierk, 1986) adopts the rotating finite-range liquid drop formalism of Sierk, accounting for deformation dependent surface energies, finite-range corrections, nuclear incompressibility, and angular momentum effects, and is widely used in heavy nucleus fission studies due to its smooth behavior across the actinide region. Fission Model 4 (RLDM Bf) (Cohen et al., 1974) implements a rotating liquid drop description without the finite-range corrections present in the Sierk prescription, offering a purely macroscopic representation of the fission barrier that highlights the interplay between Coulomb repulsion, surface tension, and angular momentum. Finally, Fission Model 5 (WKB Bf) (Sin et al., 2006) evaluates the fission transmission coefficients using a semi-classical WKB approximation along the fission path, providing a more dynamic treatment of barrier penetration in which curvature effects and barrier width variations are incorporated explicitly.

To examine the combined influence of level-density and fission-barrier models choices, each of the five fission models is paired with each of the three level density models (CTM, BSFGM, and GSM), yielding a total of 15 TALYS model combinations. For each neptunium isotope, neutron-induced fission cross sections are calculated in the energy range from 4 to 20 MeV in steps of 0.1 MeV, using the default settings for all

other nuclear model inputs. The resulting cross sections are then compared, where available, with experimental data compiled from the literature and with selected evaluated nuclear data libraries (ENDF/B-VIII.1, TENDL-2023) in order to assess the performance of both the semi-empirical (n,f) formula and the different TALYS model combinations, and to identify energy regions in which additional measurements would be particularly valuable.

For a more quantitative comparison, the TALYS predictions and the semi-empirical estimates are interpolated onto the experimental energy grid for each isotope and dataset. For every model combination, we compute the reduced chi-square value χ^2/N . These statistical indicators are then used in the Results and Discussion section to characterize systematic trends and to quantify the dispersion of deviations between the calculated and experimental cross sections. Because the TALYS calculations are performed here with default global inputs, the resulting spread among model combinations is interpreted primarily as a measure of sensitivity to the adopted barrier and level-density ingredients. In the actinide region, where the calculated fission probability depends strongly on barrier transmission and its competition with particle and γ -emission widths, such differences are physically meaningful and help identify the energy intervals in which model assumptions become most discriminating for the Np isotopes considered.

3. Results

The calculated neutron-induced fission cross sections for the selected neptunium isotopes were compared, over the energy range from 4 to 20 MeV, with available experimental data (Britt and Wilhelmy, 1979, 1979; Czeszumski et al., 2013; Diakaki et al., 2016; Kalinin and Pankratov, 1958; Lisowski et al., 1988; Pal et al., 2015; Paradela et al., 2010;

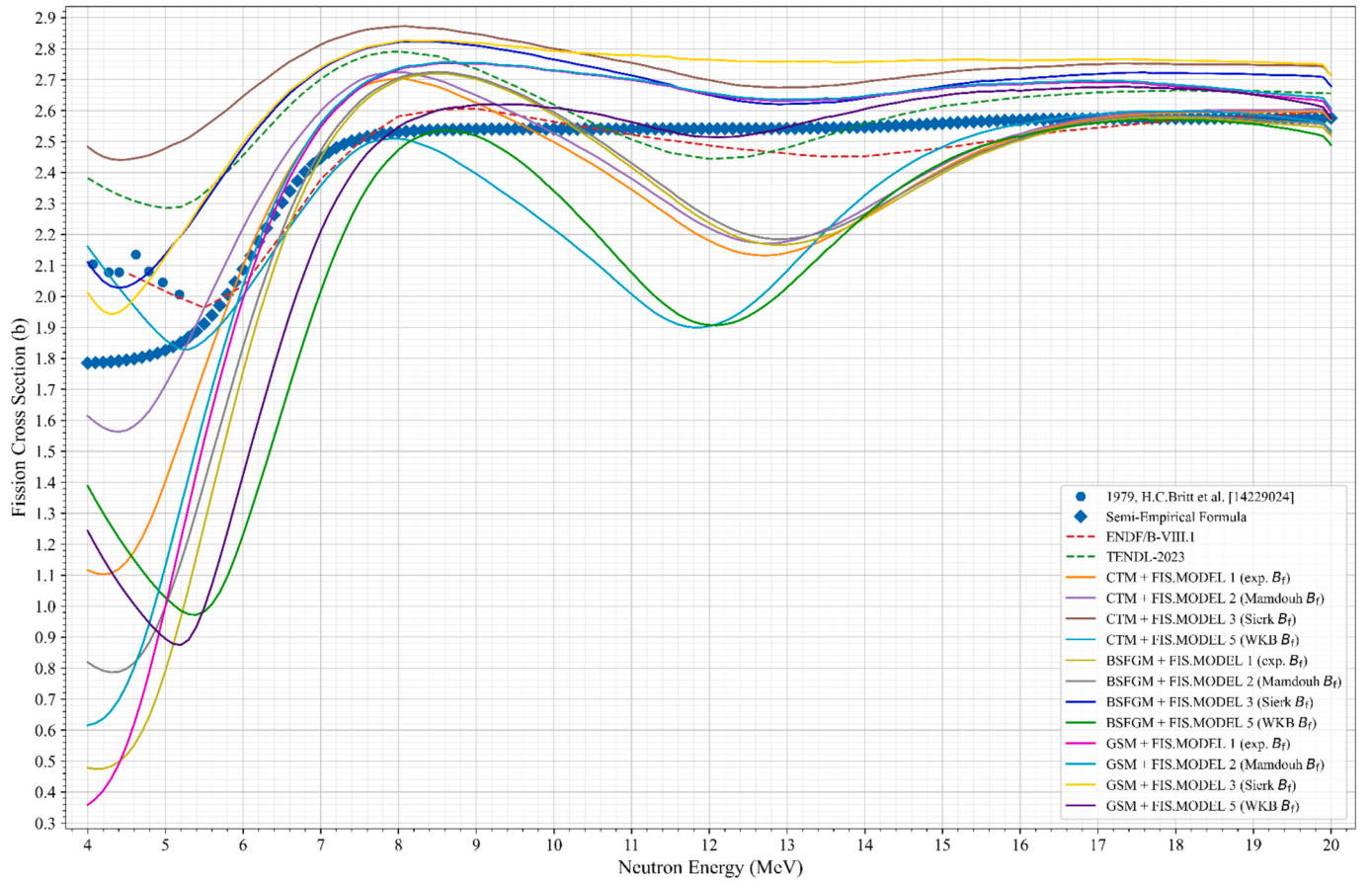


Fig. 4. Neutron-induced fission cross section of ^{235}Np versus incident neutron energy (4–20 MeV): comparison of experimental data, the present systematics (Eq. (6)), evaluated libraries (ENDF/B-VIII.1, TENDL-2023), and TALYS-2.0 results obtained with CTM/BSFGM/GSM level densities and FIS.MODEL 1–3 and 5 (WKB).

Schmitt and Murray, 1959; Shcherbakov et al., 2002; Vorobyev et al., 2025) and with evaluated nuclear data libraries (ENDF/B-VIII.1 (Brown et al., 2018; Nobre et al., 2025), TENDL-2023 (Koning et al., 2019)). The comparison reveals differences between the semi-empirical (n,f) systematics developed in this work and the various TALYS level-density-fission-barrier model combinations. In the following subsections, the results for each reaction are presented and discussed individually, with particular emphasis on the role of the plateau parameters a_i , the choice of level density model, and the adopted fission barrier model. Table 1 summarizes the fitted plateau coefficients for each neptunium isotope and the corresponding reference quantities used in the semi-empirical calculations. In particular, the parameters a_1 , a_2 , and a_3 control the relative contributions of the first-, second-, and third-chance fission components in Eq. (6), while the listed χ^2/N values provide a compact measure of agreement with ENDF/B-VIII.1 and, where available, with the experimental datasets. The tabulated E_f and S_n values define the energetic inputs entering the penetrability-based description.

3.1. $^{232}\text{Np}(n,f)$

In Fig. 1, the semi-empirical systematics for $^{232}\text{Np}(n,f)$ increases quickly from 4 MeV to about 7 MeV. Above this region, the curve changes only slightly with energy, but a small upward change in slope is visible around ~ 12 –14 MeV, leading to a modestly higher level toward 20 MeV. The TALYS-2.0 results (CTM/BSFGM/GSM with FIS.MODEL 1–3) show the same overall pattern: a rapid rise at low energies followed by a broad high-energy region with limited variation. The spread among TALYS combinations is most noticeable below ~ 6.5 MeV, while the curves become much closer to each other above ~ 7 MeV. This suggests that, for ^{232}Np , the main TALYS sensitivity is concentrated in the

threshold-to-rise region, where barrier penetrability and the near-threshold level density appear to influence the onset of fission most strongly. Above ~ 7 MeV, the reduced spread suggests a more stable balance among the competing decay widths. There is no experimental data in EXFOR for $^{232}\text{Np}(n,f)$ reaction.

3.2. $^{233}\text{Np}(n,f)$

In Fig. 2, the semi-empirical systematics for $^{233}\text{Np}(n,f)$ rises sharply from 4 MeV to about 7–8 MeV and reaches values near ~ 2.9 b. It then varies only weakly up to about 13–14 MeV. Above this range, the curve decreases smoothly and approaches ~ 2.80 b by about 16 MeV, remaining close to that level up to 20 MeV. This behaviour indicates that, for ^{233}Np , the incremental third-chance fission contribution is not sufficiently strong to overcome the competing depletion associated with neutron-emission channels in the present compact semi-empirical representation. Accordingly, the opening of an additional fission chance does not translate here into a further net rise of the total (n,f) cross section. The TALYS-2.0 calculations (CTM/BSFGM/GSM with FIS.MODEL 1–3) follow the same general energy dependence, but the spread across combinations is largest at ~ 4.5 –6 MeV and becomes again pronounced over ~ 11 –14 MeV, with noticeable curvature differences already developing around ~ 8 –10 MeV. Physically, the lower-energy spread is consistent with sensitivity to barrier transmission near threshold, whereas the renewed separation at ~ 11 –14 MeV may reflect differences in how the model combinations balance additional fission opportunity against continued neutron evaporation. Above ~ 15 –16 MeV, many TALYS-2.0 calculations result collapse into a narrower band, indicating reduced sensitivity at higher energies. With no experimental data available for this figure, the largest inter-model differences occur at

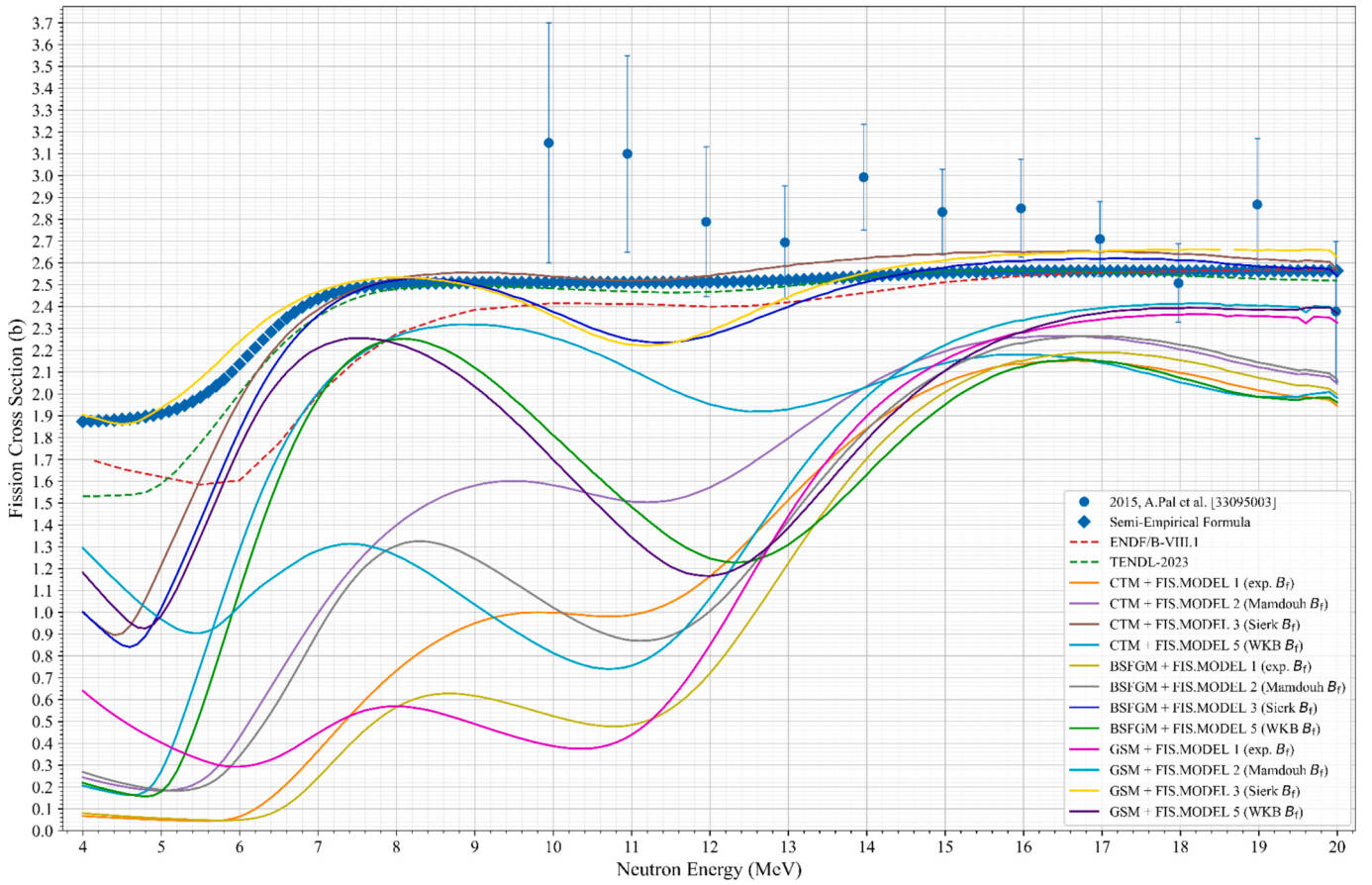


Fig. 5. Neutron-induced fission cross section of ^{236}Np versus incident neutron energy (4–20 MeV): comparison of experimental data, the present systematics (Eq. (6)), evaluated libraries (ENDF/B-VIII.1, TENDL-2023), and TALYS-2.0 results obtained with CTM/BSFGM/GSM level densities and FIS.MODEL 1–3 and 5 (WKB).

~ 4.5–6.5 MeV and ~ 11–14 MeV, while the high-energy region exhibits reduced dispersion among model predictions.

3.3. $^{234}\text{Np}(n,f)$

In Fig. 3, the semi-empirical systematics for $^{234}\text{Np}(n,f)$ rises rapidly from 4 MeV to about 10 MeV (around 2.5b). It then remains only weakly energy dependent up to roughly 11–12 MeV. Above ~ 12 MeV, the curve increases gradually and reaches ~ 2.7b by about 15–16 MeV, staying close to that level up to 20 MeV. The close correspondence with ENDF/B-VIII.1 is consistent with the low reduced chi-square for $^{234}\text{Np}(n,f)$ reaction ($\chi^2/N = 0.003$), which supports the stability of the fitted parametrization against the selected reference dataset. The TALYS-2.0 calculations (CTM/BSFGM/GSM with FIS.MODEL 1–3 and 5) exhibit a consistent low- and mid-energy dependence in Fig. 3; however, the inter-model spread widens markedly above ~ 10 MeV. In particular, the FIS.MODEL 5 variants (CTM, BSFGM, and GSM) diverge from the other TALYS combinations and decrease with increasing energy toward 20 MeV, whereas the remaining combinations remain nearly flat or show a mild rise at high energies. This suggests that, for ^{234}Np , the dominant physical sensitivity lies in the high-energy treatment of fission transmission rather than in the threshold region itself. The decreasing FIS.MODEL 5 trends are consistent with a relatively stronger effective competition from neutron-emission channels at higher excitation energies. Consequently, the ~ 11–16 MeV range constitutes the most discriminating interval with respect to model choice in Fig. 3.

3.4. $^{235}\text{Np}(n,f)$

In Fig. 4, the semi-empirical systematics for $^{235}\text{Np}(n,f)$ increases with

neutron energy up to 7 MeV, where it reaches roughly 2.5b, and then remains nearly constant up to 20 MeV. The experimental data of Britt et al. (1979) are confined to a narrow window around 4–5 MeV and lie near 2.0–2.1b; in this interval, the semi-empirical curve is systematically lower, but it trends toward the broader plateau level as energy increases. This contrast is reflected in the reduced chi-square values: the semi-empirical description agrees well with ENDF/B-VIII.1 ($\chi^2/N = 0.002$), whereas the agreement with the available experimental dataset is much poorer ($\chi^2/N = 0.036$), which is consistent with the limited energy coverage of the measurements and the local deviation observed near 4–5 MeV. The nearly constant behaviour above about 7 MeV also indicates that, for ^{235}Np , the opening of the $(n,2n_f)$ channel does not appear as a sharply resolved third plateau in the present semi-empirical representation. Rather, the third-chance contribution is expressed mainly as a weak modification of the high-energy trend. The TALYS-2.0 calculations (CTM/BSFGM/GSM combined with FIS.MODEL 1–3 and 5) exhibit considerable model dependence at low and intermediate energies in the plot. The TALYS model combinations spreads at largest in the 4.5–6.5 MeV transition region and in the 10–14 MeV. The first region appears to reflect sensitivity to how the models complete the initial rise toward the plateau, whereas the second is consistent with differences in how weak higher-chance fission effects compete with neutron evaporation. Above ~ 15 MeV, many TALYS curves become closer to each other.

3.5. $^{236}\text{Np}(n,f)$

In Fig. 5, the semi-empirical systematics for $^{236}\text{Np}(n,f)$ increases up to 8 MeV, reaching roughly 2.5b. It then varies only weakly with energy up to about 12–13 MeV. Above this range, the curve rises gently and

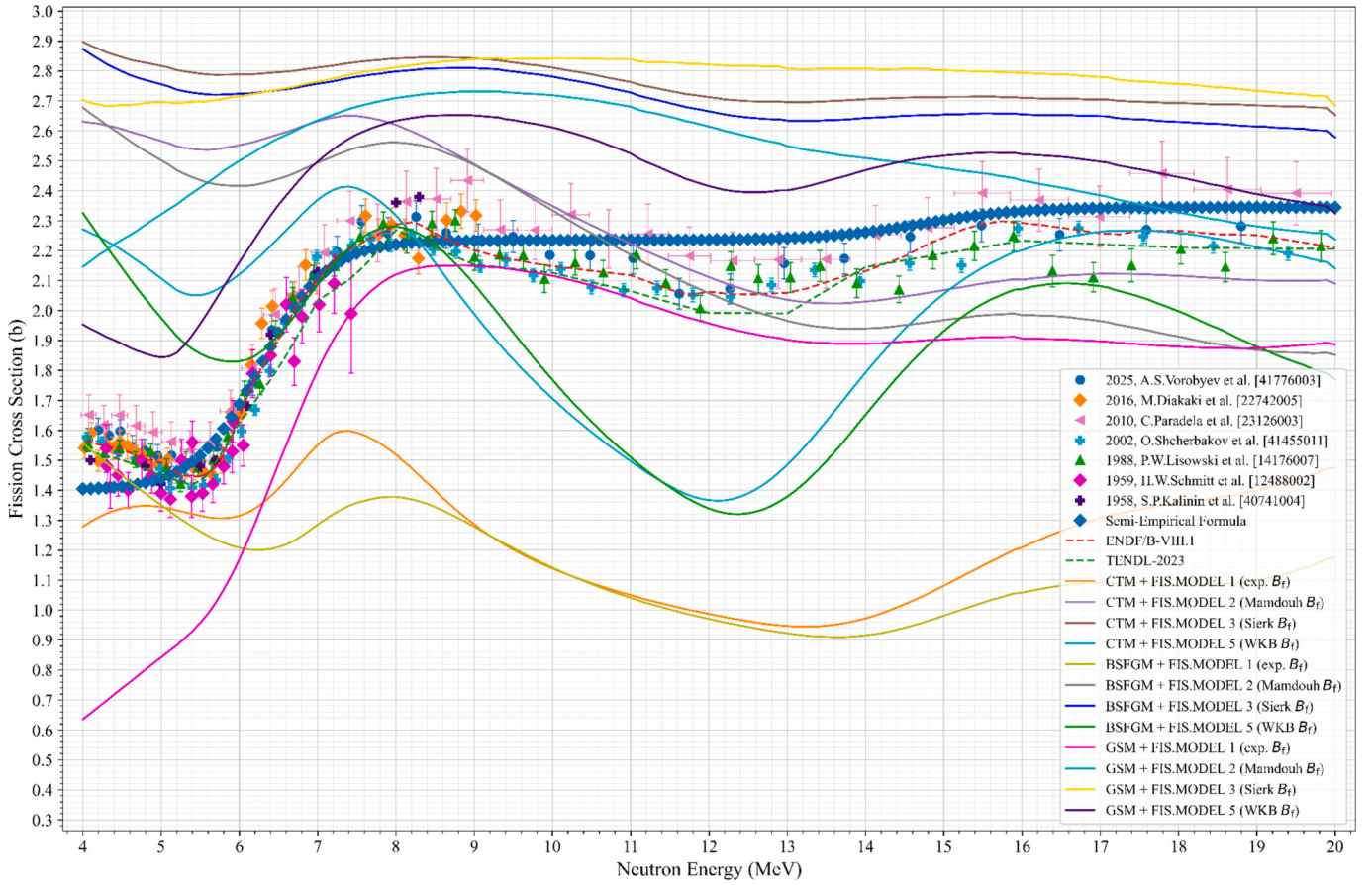


Fig. 6. Neutron-induced fission cross section of ^{237}Np versus incident neutron energy (4–20 MeV): comparison of experimental datasets, the present systematics (Eq. (6)), ENDF/B-VIII.1 and TENDL-2023, and TALYS-2.0 results obtained with CTM/BSFGM/GSM level densities and FIS.MODEL 1–3 and 5 (WKB).

approaches approximately 2.6b by about 16 MeV, remaining close to this level up to 20 MeV. In this case, the absence of an obvious third plateau suggests that the $(n,2nf)$ opening is expressed as a broadened and only weakly resolved third-chance contribution, rather than as a sharply separated new step. The “experimental” points shown in Fig. 5 correspond to the derived $^{236}\text{Np}(n,f)$ cross sections data reported by Pal et al. (2015), which extend over 10–20 MeV and carry relatively large uncertainties; within these limits, they are broadly consistent with the magnitude and mild energy dependence implied by the semi-empirical trend. Quantitatively, the semi-empirical systematics shows a mixed level of agreement depending on the benchmark: relative to ENDF/B-VIII.1 it yields $\chi^2/N = 0.010$ but $R^2 = -0.152$, whereas the comparison against the Pal et al. derived dataset gives $\chi^2/N = 0.042$ and $R^2 = 0.439$, indicating a more consistent reproduction of the derived data trend despite the sizeable scatter. The TALYS-2.0 calculations (CTM/BSFGM/GSM combined with FIS.MODEL 1–3 and 5) show pronounced model-to-model differences, particularly at low and intermediate energies. The spread is largest in the 4.5–6.5 MeV transition region and in the 9–13 MeV interval. The lower-energy spread appears to be associated mainly with near-threshold barrier sensitivity, whereas the 9–13 MeV separation is consistent with differences in how the model combinations partition the available excitation energy between renewed fission and continued neutron evaporation. Above about 14–15 MeV, many TALYS curves move closer together, indicating that the sensitivity to the fission-model option diminishes but does not fully disappear at high energies. Overall, Fig. 5 indicates that 4.5–6.5 MeV and 9–13 MeV are the most informative energy windows for discriminating between the TALYS model combination options considered for $^{236}\text{Np}(n,f)$.

3.6. $^{237}\text{Np}(n,f)$

In Fig. 6, the semi-empirical systematics for $^{237}\text{Np}(n,f)$ stays near 1.4–1.5b over 4–6 MeV, then rises rapidly between about 6 and 8 MeV to approximately 2.2–2.3b. From roughly 8 MeV to 20 MeV, it shows only a weak energy dependence, with a gentle upward tendency toward the upper end of the range. The compiled experimental datasets form a broad but largely coherent band: they cluster around 1.4–1.6b below about 6 MeV, increase toward 2.2–2.3b around 7–9 MeV, and then scatter around roughly 2.0–2.3b above about 10 MeV with visible dataset-to-dataset dispersion. Consistent with this overall behaviour, the semi-empirical systematics compares well with both experimental datasets and ENDF/B-VIII.1, giving $\chi^2/N = 0.005$ and $R^2 = 0.841$ against ENDF/B-VIII.1 and $\chi^2/N = 0.006$ and $R^2 = 0.907$ compared to experimental datasets. The TALYS-2.0 curves (CTM/BSFGM/GSM with FIS.MODEL 1–3 and 5) differ strongly from each other across the figure. The differences are easiest to see in the 5.5–7.5 MeV region, where the curves start to rise at different energies and with different steepness. Another clear separation appears between 10 and 14 MeV: some model options show a noticeable dip in this interval, while others stay flatter or remain higher. This indicates that the TALYS spread is physically informative: the 5.5–7.5 MeV interval appears to be influenced mainly by the onset of strong fission transmission, whereas the 10–14 MeV interval is more consistent with competition between higher-chance fission and neutron emission. Above about 15 MeV, several curves come closer together, but a few still stay apart, so the high-energy predictions do not fully line up. Overall, the 5.5–7.5 MeV and 10–14 MeV ranges are the most useful parts of the plot for distinguishing between the TALYS options considered.

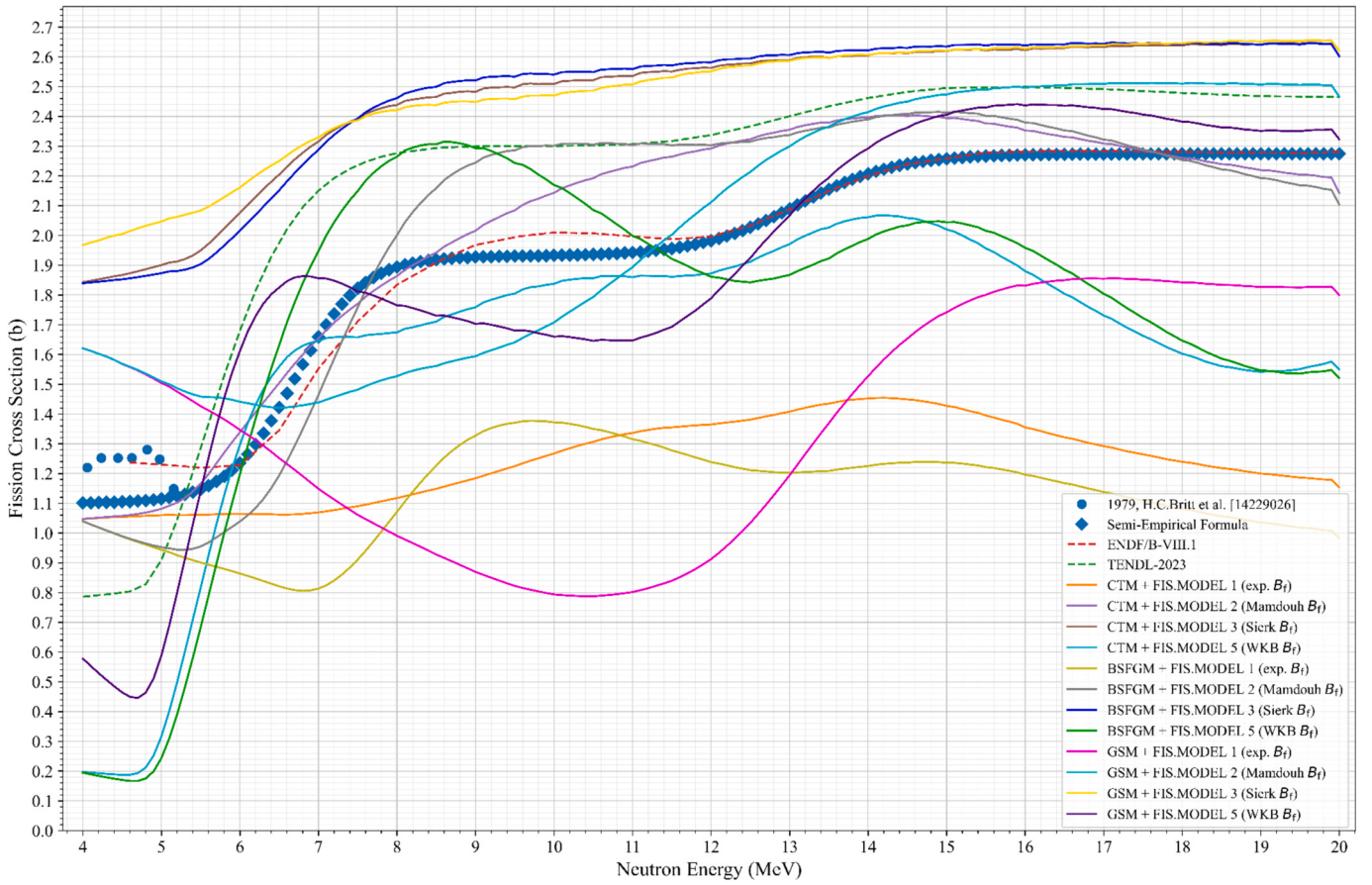


Fig. 7. Neutron-induced fission cross section of ^{238}Np versus incident neutron energy (4–20 MeV): comparison of experimental data, the present systematics (Eq. (6)), evaluated libraries (ENDF/B-VIII.1, TENDL-2023), and TALYS-2.0 results obtained with CTM/BSFGM/GSM level densities and FIS.MODEL 1–3 and 5 (WKB).

3.7. $^{238}\text{Np}(n,f)$

In Fig. 7, the semi-empirical systematics for $^{238}\text{Np}(n,f)$ increases gradually from about 1.1b at 4 MeV to ~ 1.2 – 1.3 b near 5–6 MeV, followed by a steep rise between roughly 6 and 8 MeV to around 1.9b. From about 8 to 12 MeV, the curve varies only weakly, after which a second increase becomes visible over ~ 12 – 15 MeV, bringing σ_f to approximately 2.25–2.30b; the curve then remains close to this level up to 20 MeV. The available low-energy points of Britt et al. (1979) in the 4–5 MeV region lie near ~ 1.2 – 1.3 b and provide a limited constraint on the onset behaviour. The very low reduced chi-square reported for ^{238}Np ($\chi^2/N = 0.007$) is consistent with a quantitatively stable parametrization with respect to the selected reference dataset used in the fit. The TALYS-2.0 model combinations calculations (CTM/BSFGM/GSM combined with FIS.MODEL 1–3 and 5) show a broad spread in both magnitude and energy dependence across the range. The largest dispersion occurs in the low-energy transition region (~ 5.5 – 7.5 MeV), and in the ~ 12 – 16 MeV where the high-energy trend separates into distinct behaviours (ranging from a continued rise to a flattening or a decrease). Physically, the first window appears to reflect sensitivity to barrier transmission near the onset of the rapid fission increase, whereas the second is consistent with a region in which higher-chance fission becomes more influential relative to neutron evaporation. The persistent high-energy separation further suggests that this balance remains model dependent in ^{238}Np . Above ~ 16 MeV, the TALYS results do not collapse onto a single trend; instead, they form a near-semi-empirical systematics line and a persistently separated band at lower cross sections.

3.8. $^{239}\text{Np}(n,f)$

In Fig. 8, the semi-empirical systematics for $^{239}\text{Np}(n,f)$ stays close to about 1.0b in the 4–6 MeV region and then increases sharply between roughly 6 and 8 MeV to about 1.65–1.70b. From around 8 to 13 MeV the curve changes only weakly, after which a second rise becomes visible from about 13 to 16 MeV, bringing the fission cross section to approximately 2.05–2.10b; the trend then remains near this level up to 20 MeV. The experimental dataset of Czeszumski et al. (2013) broadly follows the same two-step behaviour, but with sizable scatter and uncertainties, especially below about 6 MeV and above about 15 MeV. Consistent with this picture, the semi-empirical trend shows only moderate agreement with the benchmarks: against ENDF/B-VIII.1 it gives $\chi^2/N = 0.048$ and $R^2 = 0.309$, while against the experimental dataset it gives $\chi^2/N = 0.030$ and $R^2 = 0.460$. The TALYS-2.0 calculations (CTM/BSFGM/GSM with FIS.MODEL 1–3 and 5) span a wide range in both absolute level and energy dependence. The separation is clearest in the 5.5–7.5 MeV transition region, where the onset and slope of the rise differ strongly between model options. Another clear split appears in the 13–16 MeV range, where the semi-empirical curve shows its second rise while the TALYS curves respond with noticeably different changes in slope. From a physical standpoint, the 5.5–7.5 MeV interval appears to be the main threshold-sensitive window associated with the onset of strong fission transmission, whereas the 13–16 MeV region is more consistent with enhanced sensitivity to higher-chance fission effects, where the balance between renewed fission and neutron evaporation is treated differently by the competing model combinations. In addition, the 8–13 MeV interval remains sensitive because the TALYS curves populate distinctly different mid-energy levels and shapes relative to the semi-empirical

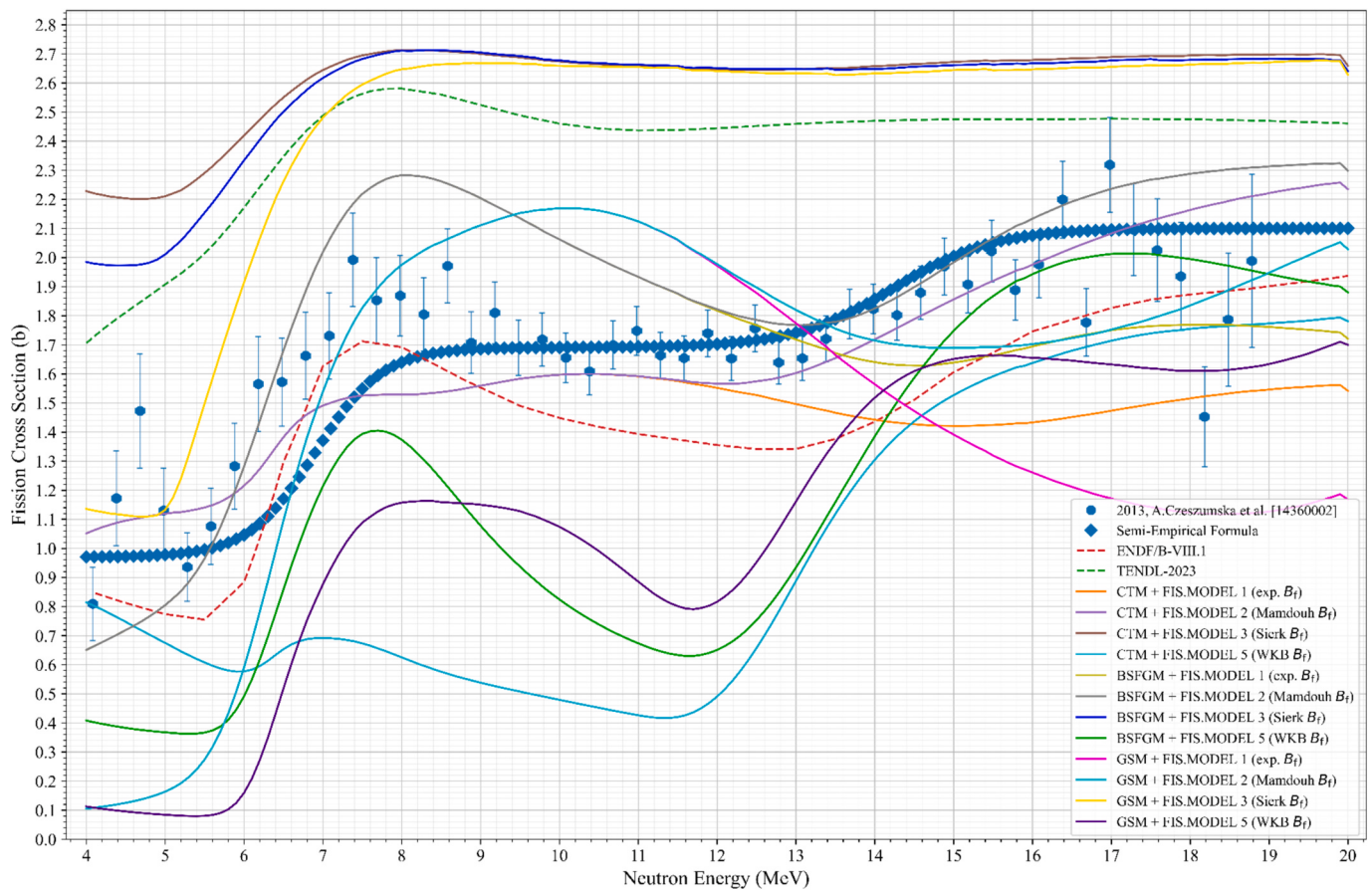


Fig. 8. Neutron-induced fission cross section of ^{239}Np versus incident neutron energy (4–20 MeV): comparison of experimental data, the present systematics (Eq. (6)), evaluated libraries (ENDF/B-VIII.1, TENDL-2023), and TALYS-2.0 results obtained with CTM/BSFGM/GSM level densities and FIS.MODEL 1–3 and 5 (WKB).

and evaluated trends. Overall, Fig. 8 points to 5.5–7.5 MeV and 13–16 MeV as the most model-discriminating windows for ^{239}Np , with additional sensitivity across 8–13 MeV driven by the spread in mid-energy behaviour.

4. Conclusion

This study developed and assessed a compact semi-empirical systematics for neutron-induced fission cross sections of the neptunium isotopic chain $^{232}\text{--}^{239}\text{Np}$ in the 4–20 MeV range. The formulation represents the total (n,f) cross section through penetrability-weighted contributions associated with first-, second-, and third-chance fission. By factoring out the non-elastic reaction cross section and introducing isotope-dependent coefficients, the resulting expression provides a practical parameterization that reproduces the characteristic multi-plateau behaviour expected from the successive opening of the (n,f), (n,nf), and (n,2nf) channels. At the same time, the present results show that this multi-chance pattern does not always appear as a sharply resolved sequence of plateaus for every isotope; depending on the balance between higher-chance fission and competing neutron emission, it may instead be expressed as a weak shoulder, a mild slope change, or a near-saturated trend. In parallel, TALYS-2.0 calculations were performed systematically using all 15 combinations formed by three level-density prescriptions (CTM, BSFGM, GSM) and five fission-barrier options (FIS.MODEL 1–5). For clarity of presentation, only a representative subset of TALYS level density model and fission model combinations that show the closest agreement with the reference trends is displayed in the figures for comparisons.

For ^{232}Np and ^{233}Np , no experimental (n,f) data are available in

EXFOR within the investigated range, so the results primarily provide evaluated trends and a controlled inter-model comparison. These cases highlight that new measurements would be decisive for both semi-empirical fitting and reaction-model calibration. For ^{234}Np and ^{235}Np , the semi-empirical systematics exhibits very close correspondence with ENDF/B-VIII.1, reflected by very small reduced chi-square values, indicating that the fitted coefficients provide a stable representation of the selected evaluated reference in the 4–20 MeV interval. ^{236}Np and ^{239}Np show only moderate statistical agreement with the certain uncertainties in the available experimental information. For ^{238}Np , the fitted systematics is quantitatively stable against the selected dataset. The best overall agreement is obtained for ^{237}Np , where both the reduced chi-square and the coefficient of determination indicate that the semi-empirical curve captures the measured energy dependence and the evaluated trend with high fidelity. Overall, the semi-empirical systematics proposed here provides an efficient and interpretable description of neptunium (n,f) cross sections between 4 and 20 MeV and complements reaction-model calculations by clarifying where theoretical sensitivities are largest. The present results therefore support the practical merit of the proposed model in this energy interval, although the extent to which this merit is demonstrated remains limited for some neptunium isotopes by the scarcity of experimental constraints.

Declaration of competing interest

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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