Exploring the Role of Nuclear Structure Effects in Photofission Mechanism of ^{237}Np

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Mehdi Nasri Nasrabadi
Mohamad Sepiani

Faculty of Physics, University of Isfahan, 81746-73441, Isfahan, Iran
Frank Laboratory of Neutron Physics, Joint Institute for Nuclear Research, Joliot-Curie 6, 141980 Dubna, Russia

Photoabsorption mechanisms

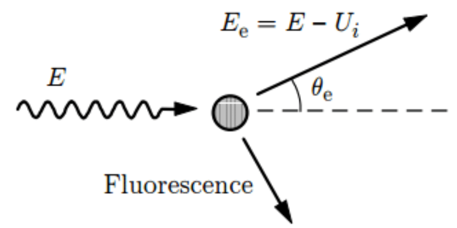
Interaction of Radiation-Matter

- Main mechanisms of the photon-matter interactions
  - ❖ Photoelectric effect
  - ❖ Compton scattering
  - ❖ Pair production
  - ❖ Photo-induced nuclear reaction

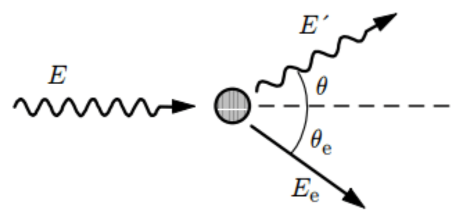
(Photoelectric effect, Compton scattering, Pair production: Electron emission)

High energy induced photon

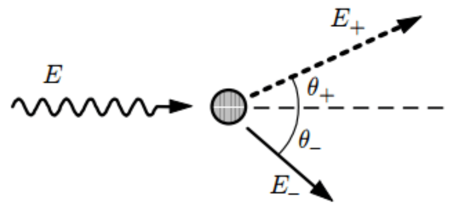
- ❖ Gamma emission
- ❖ Photoabsorption
  - ➢ Photodisintegration (knock out a nucleon)
  - ➢ Photofission



Photoelectric absorption



Compton scattering



Pair production

Nuclear Structure Effects in Photofission Mechanism

Photoabsorption mechanisms

➤ **Giant dipole resonan**

... s one in which the **electric** ... energy to the nucleus by ... **onance oscillation)** which ... ound neutrons and protons ... **ow 30 MeV** follows GDR

... with the **dipole moment of** ... ather than with the nucleus ... . At photon **energies >35** ... eutron production is due to

➤ **Quasi-deuteron (QD)**

First effective factor in the photon-induced reactions is GSF

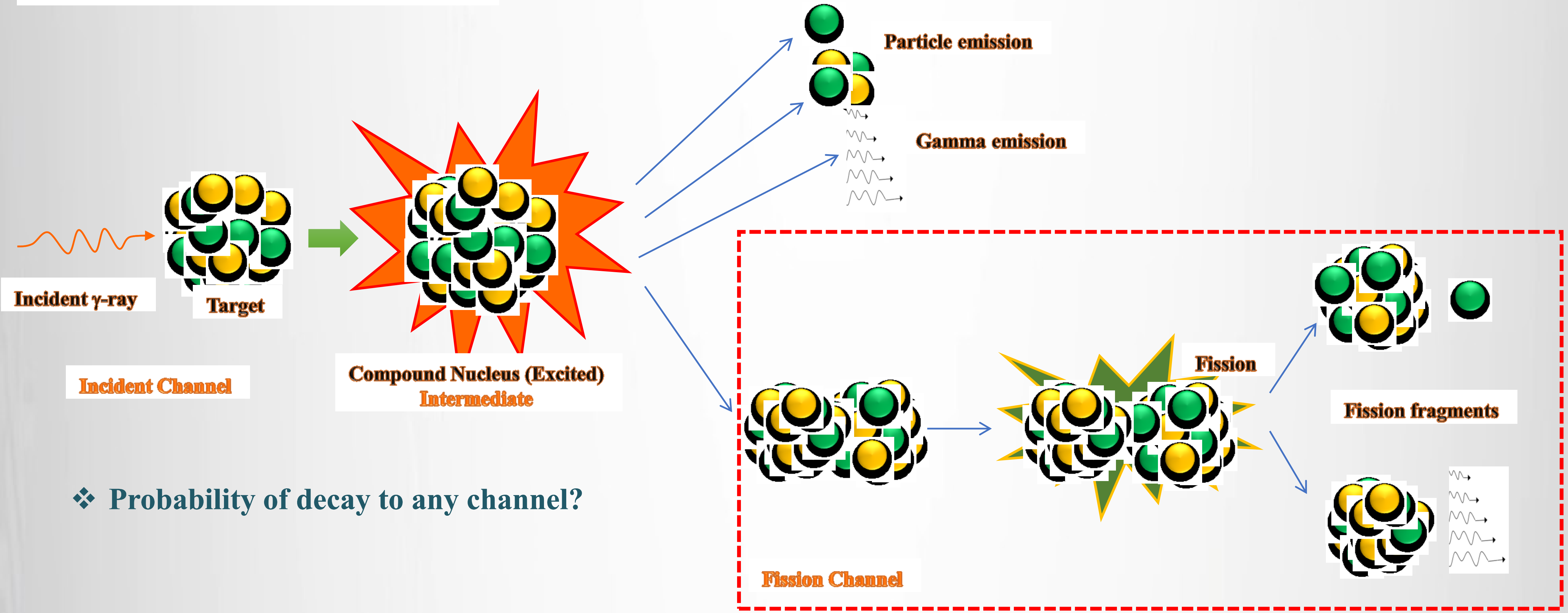
$$\sigma_{abs}(E_\gamma) = \sigma_{GDR}(E_\gamma) + \sigma ...$$

Gamma-ray strength function (GSF)

$$\sigma_{GDR}(E_\gamma) = 3(\pi\hbar c)^2 \cdot E_\gamma \cdot \vec{f}(E_\gamma)$$

Nuclear Structure Effects in Photofission Mechanism

Photofission mechanism



- ❖ Probability of decay to any channel?

Nuclear Structure Effects in Photofission Mechanism

❖ **Probability of decay to any channel?**

Compound reaction cross-section (Hauser-Feshbach formalism)

Typical reaction *a* + A → b + B (*a* or b can be γ-ray)

$$\sigma_{\alpha\beta}^{comp} = D^{comp}\frac{\pi}{k_\alpha^2}\sum_{J_{CN}=|I_A-s_a|}^{l_a^{\max}+I_A+s_a}\sum_{\pi_{CN}=+,-}\frac{2J_{CN}+1}{(2I_A+1)(2s_a+1)}\sum_{j_a=|J_{CN}-I_A|}^{J_{CN}+I_A}\sum_{l_a=|j_a-s_a|}^{j_a+s_a}\sum_{j_b=|J_{CN}-I_B|}^{J_{CN}+I_B}\sum_{l_b=|j_b-s_b|}^{j_b+s_b}$$

$$\times\delta(\pi_\alpha,\pi_{CN})\delta(\pi_{CN},\pi_\beta)\frac{T_{\alpha,l_a,j_a}^{J_{CN}}(E_a)\langle T_{\beta,l_b,j_b}^{J_{CN}}(E_b)\rangle}{\sum_{\gamma,l_c,j_c}\delta(\pi_{NC},\pi_\gamma)\langle T_{\gamma,l_c,j_c}^{J_{CN}}(E_c)\rangle}W_{\alpha,l_a,j_a,\beta,l_b,j_b}^{J_{CN}}$$

T : Transmission coefficients

$$\sigma_{\alpha\beta}^{comp} = \sum_{J_{CN}=|I_A-s_a|}^{l_a^{\max}+I_A+s_a}\sum_{\pi_{CN}=+,-}\sigma_{J_{CN}^{\pi_{CN}}}^{CF}(E_{CN}^*)\frac{\Gamma_\beta(E_{CN}^*,J_{CN},\pi_{CN}\to E_x,I_B,\pi_B)}{\Gamma^{tot}(E_{CN}^*,J_{CN},\pi_{CN})}$$

Γ : Partial widths

$$\sigma_{J_{CN}^{\pi_{CN}}}^{CF}(E_{CN}^*) = D^{comp}\frac{\pi}{k_\alpha^2}\frac{2J_{CN}+1}{(2I_A+1)(2s_a+1)}\sum_{j_a=|J_{CN}-I_A|}^{J_{CN}+I_A}\sum_{l_a=|j_a-s_a|}^{j_a+s_a}T_{\alpha,l_a,j_a}^{J_{CN}}(E_a)\delta(\pi_\alpha,\pi_{CN})$$

$$\Gamma_\beta(E_{CN}^*,J_{CN},\pi_{CN}\to E_x,I_B,\pi_B) = \frac{1}{2\pi.\rho(E_{CN}^*,J_{CN},\pi_{CN})}\sum_{j_b=|J_{CN}-I_B|}^{J_{CN}+I_B}\sum_{l_b=|j_b-s_b|}^{j_b+s_b}\left(\delta(\pi_{CN},\pi_\beta)\langle T_{\beta,l_b,j_b}^{J_{CN}}(E_b)\rangle\right)$$

Nuclear Structure Effects in Photofission Mechanism

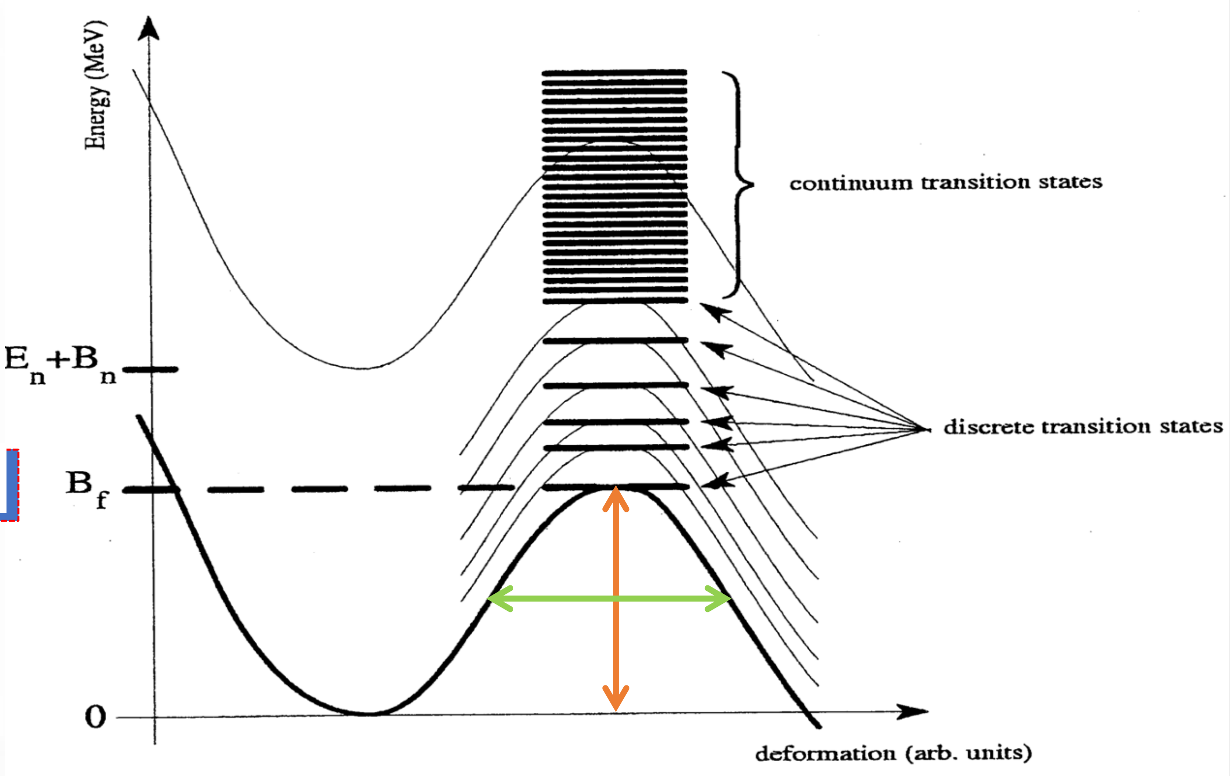
Fission probability and fission transmission coefficients

Fission transmission coefficient is usually calculated using the Hill-Wheeler model and based on the transition state model proposed by Bohr:

$$T_f^{HW}(E_{CN}^*) = \frac{1}{1 + \exp\left[-2\pi \frac{(E_{CN}^* - B_f)}{\hbar\omega_f}\right]}$$

Barrier width (curvature)

Barrier high



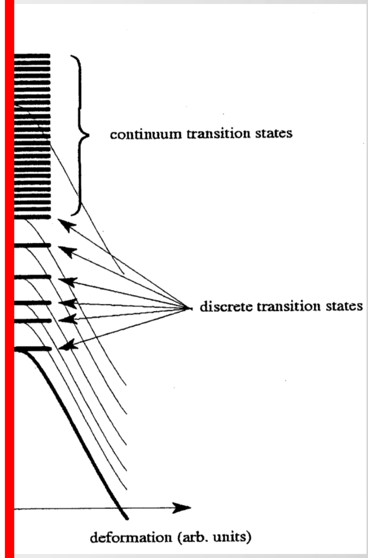
Nuclear Structur

Fission probabilit

In the transition state m
compound nucleus, anc
intermediate levels. Th
function of deformatior
this barrier, there may b
assigned to each of th
approximation, the barr
which is shifted by the
the ground state. The tr
ε^i above the peak of the

$T_f^{HW}(E^*_{CN}, \varepsilon_i) = \frac{\quad}{1 + \text{ex}\ldots}$

2^{nd} and 3th effective factors are:
Nuclear level densities (NLD) & Fission barrier model



fission barrier)

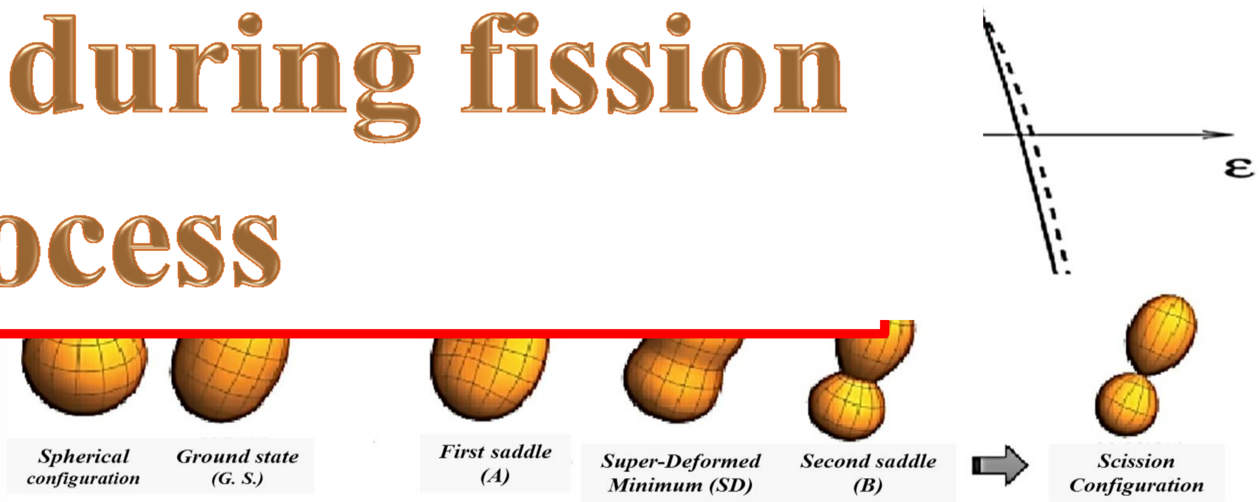
$$T_f^{J^{\pi CN}_{CN}}(E^*_{CN}) = \sum_i T_f^{HW}(E^*_{CN})\delta(i, J^{\pi_{CN}}_{CN}) + \int_{E_{Th}}^{E_{CN}} \rho_f(\varepsilon, J_{CN}, \pi_{CN}) T_f^{HW}(E^*_{CN}, \varepsilon) d\varepsilon$$

Nuclear Structure Effects in Photofission Mechanism

Dynamic fission process and multi-humped barriers:

$$T_{eff}^{J_{CN}^{\pi CN}}$$

Main Challenge:
Effective factors and their parameters during fission process



Nuclear Structure Effects in Photofission Mechanism

Nuclear Level Densities at ground state and fission saddle points (NLD)

- ❖ Constant temperature model (CTM)

- ➢ **NLD models (implemented in TALYS reaction code)**

All NLD models adjusted by experimental low levels data (if exist)

...del (SHFBM)

... model (SHFBCM)

- ➢ Microscopic models

- ❖ Temperature-dependent Gogny-Hartree-Fock-Bogolyubov combinatorial (GHFBCM)

$$\rho_{Mic,adj}(E_x, J, \pi) = exp\left(c_{adj}\sqrt{E_x - \delta_{adj}}\right)\rho_{Mic}(E_x - \delta_{adj}, J, \pi)$$

Nuclear Structure Effects in Photofission Mechanism

➢ Phenomenological models (based on fermi gas model)

All phenomenological models of NLD at energies higher than a few MeV (after matching energy E_M) use the well-known Fermi gas relation:

$$\rho_{FG}(U) = \frac{\sqrt{\pi}}{12} \frac{e^{2\sqrt{aU}}}{a^{1/4}U^{5/4}} \qquad U = E_{ex} - \Delta_{pairing}$$

$$a(E_{ex}) = \tilde{a}\left(\quad \frac{1-exp(-\gamma E_{ex})}{E_{ex}} \right)$$

NLDP parameters that may change during the fission process. Asymptotic NLDP, Shell correction term, Damping parameter, Matching energy respectively

NLDP (a) and paring parameter ($\Delta_{pairing}$) are adjustable parameter with experimental low levels data.

Nuclear Structure Effects in Photofission Mechanism

➢ Phenomenological models (based on fermi gas model)

Deformation effects as collective rotational and vibrational enhancement factors for NLD:

$$\rho_{def}(E_x,J,\pi)=K_{Rot}(E_x,J)K_{Vib}(E_x)\rho_{\text{int}}(E_x,J,\pi)=K_{Coll}(E_x,J)\rho_{\text{int}}(E_x,J,\pi)$$

$$K_{Rot}=\sigma^2_{cut-off\perp}=0.01389A^{5/3}(1+\beta_2/3)\sqrt{E_{ex}/a}$$ For ground state deformation

The K_{Rot} for barriers depends on the type of symmetry or asymmetry of barriers. For axially asymmetric in barriers:

$$K_{Rot}=\left[\sqrt{\frac{\pi}{2}}\sigma^2_{cut-off\perp}(1+2\beta_2/3)\sigma^2_{cut-off\parallel}-1\right]f(E_{ex})+1$$

$$\sigma^2_{cut-off\parallel}=0.01389A^{5/3}\sqrt{aE_{ex}}/\tilde{a}$$

$$f(E_{ex})=1/\left(1+exp\left(E_{ex}-U^{bar}_{fermi}/C^{bar}_{fermi}\right)\right)$$

parallel spin cut off parameter

combination of Fermi functions

Nuclear Structure Effects in Photofission Mechanism

➢ Phenomenological models (based on fermi gas model)

Deformation effects as collective rotational and vibrational enhancement factors for NLD:

$$K_{Rot} = \left(\frac{E_{ex}}{a_{eff}}\right)^{1/4}\left(1 - f(E_{ex})\right) + f(E_{ex}), \quad f(E_{ex}) = \frac{1}{1+\exp(-0.5(E_{ex}-18))}$$

for tri-axial barriers

The effective asymptotic NLDP for fission barrier:

$$f(E_{ex}) = 1\Big/\left[1 + exp - \left(\left(E_{ex} - U_{fermi}^{bar}\right)\Big/C_{fermi}^{bar}\right)\right]$$

Nuclear Structure Effects in Photofission Mechanism

Fission barrier models for fission barrier parameters :

- **Fis. Barrier models (implemented in TALYS reaction code)**

❖ Experimental fission barriers model

❖ Mamdouh model

❖ Rotating-Finite-Range Model (RFRM) or Sierk model

❖ Rotating-Liquid-Drop Model (RLDM)

❖ There is a WKB approximation model to calculate fission transmission coefficients as an alternative to the Hill-Wheeler approach [40]

Nuclear Structure Effects in Photofission Mechanism

➢ Results for ^{237}Np photofission

The parameters of fission barrier models for ^{237}Np(γ,f) reaction.

Table 1. The parameters of fission barrier models for ^{237}Np(γ,f) reaction.

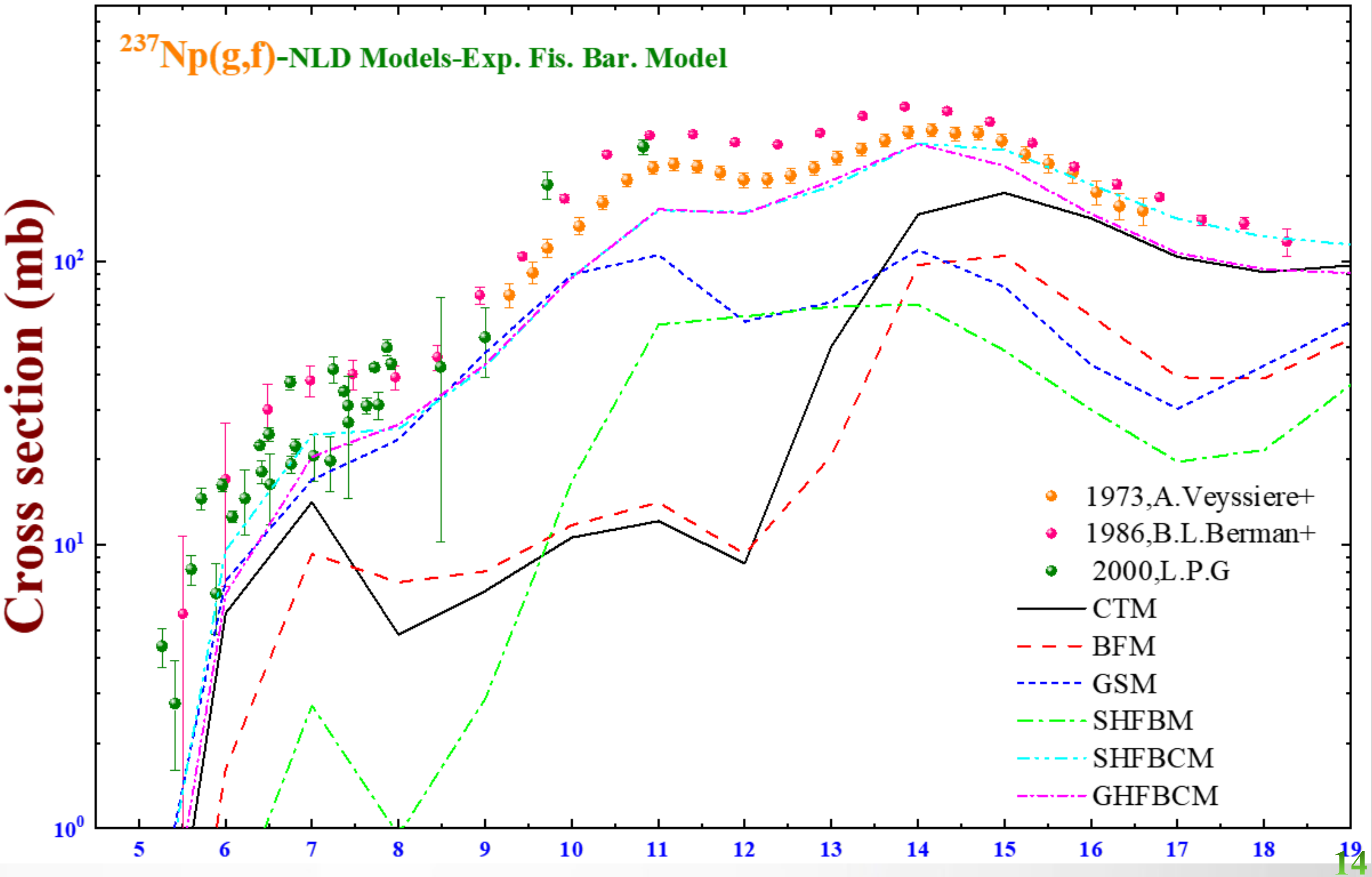
Fission Barrier models	No. of barriers	1st B_f (MeV)	1st ħω (MeV)	1st Barrier symmetry	2nd B_f (MeV)	2nd ħω (MeV)	2nd Barrier symmetry
Experimental Fission Barriers l	2	6.00	1.00	axial symmetry	5.40	0.50	left-right asymmetry
Theoretical Mamdouh	2	5.40	1.00	axial symmetry	3.80	0.60	left-right asymmetry
Theoretical Sierk	1	5.12	0.24	axial symmetry	-	-	-
Theoretical Rotating Liquid Drop (RLD)	1	7.62 9	0.24	axial symmetry	-	-	-
WKB Approximation For Fission Path	2	5.27 2	0.627	triaxial and left-right asymmetry	5.234	0.578	axial symmetry

Nuclear Structure Effects in Photofission Mechanism

➢ Results for ^{237}Np photofission

Comparison of photofission cross section of ^{237}Np calculated through different NLD models with experimental data

(Experimental fission barrier model)

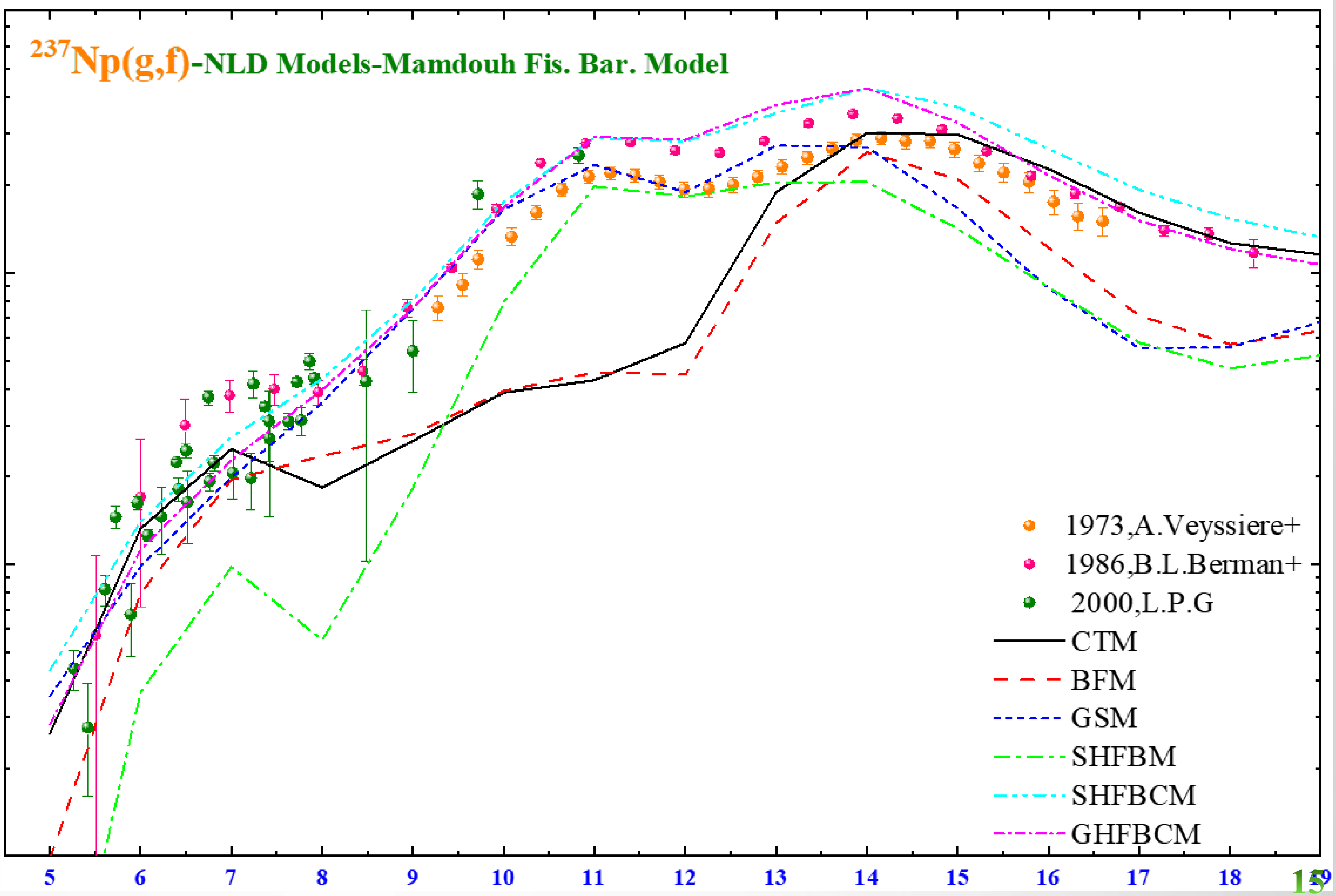


Nuclear Structure Effects in Photofission Mechanism

➢ Results for ^{237}Np photofission

Comparison of photofission cross section of ^{237}Np calculated through different NLD models with experimental data

(Mamdouh fission barrier model)

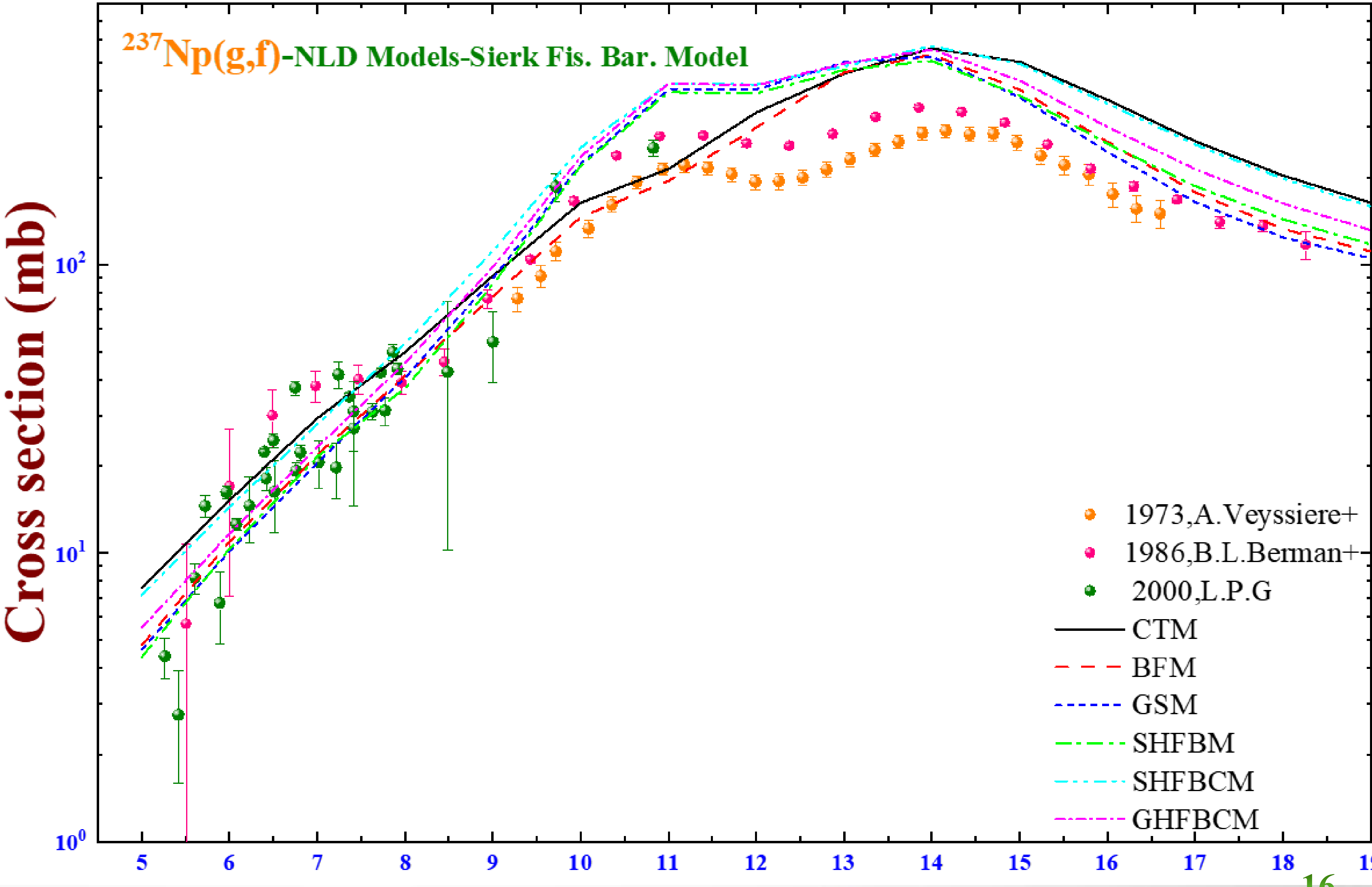


Nuclear Structure Effects in Photofission Mechanism

➢ Results for ^{237}Np photofission

Comparison of photofission cross section of ^{237}Np calculated through different NLD models with experimental data

(Sierk fission barrier model)

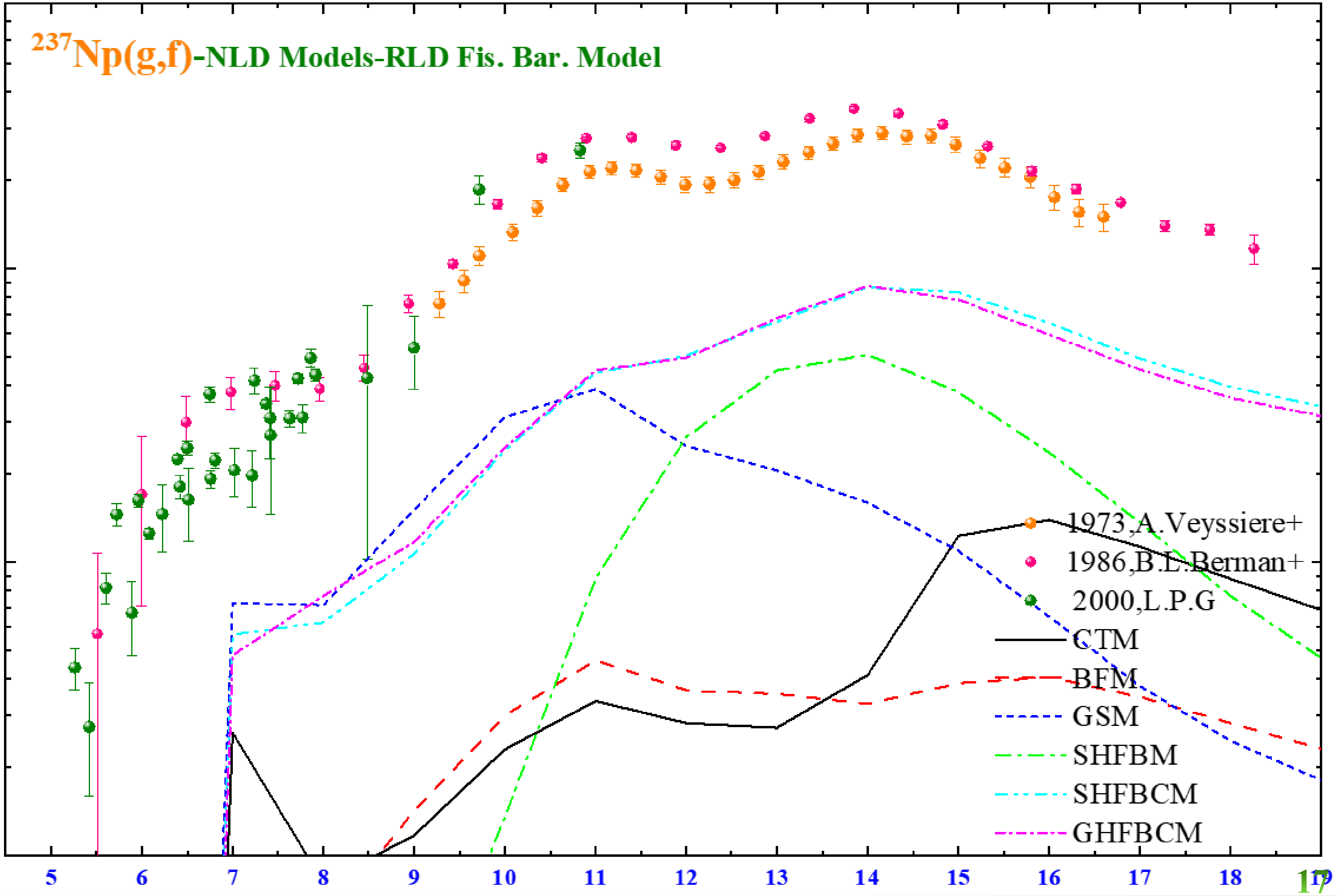


Nuclear Structure Effects in Photofission Mechanism

➢ Results for ^{237}Np photofission

Comparison of photofission cross section of ^{237}Np calculated through different NLD models with experimental data

(RLD fission barrier model)



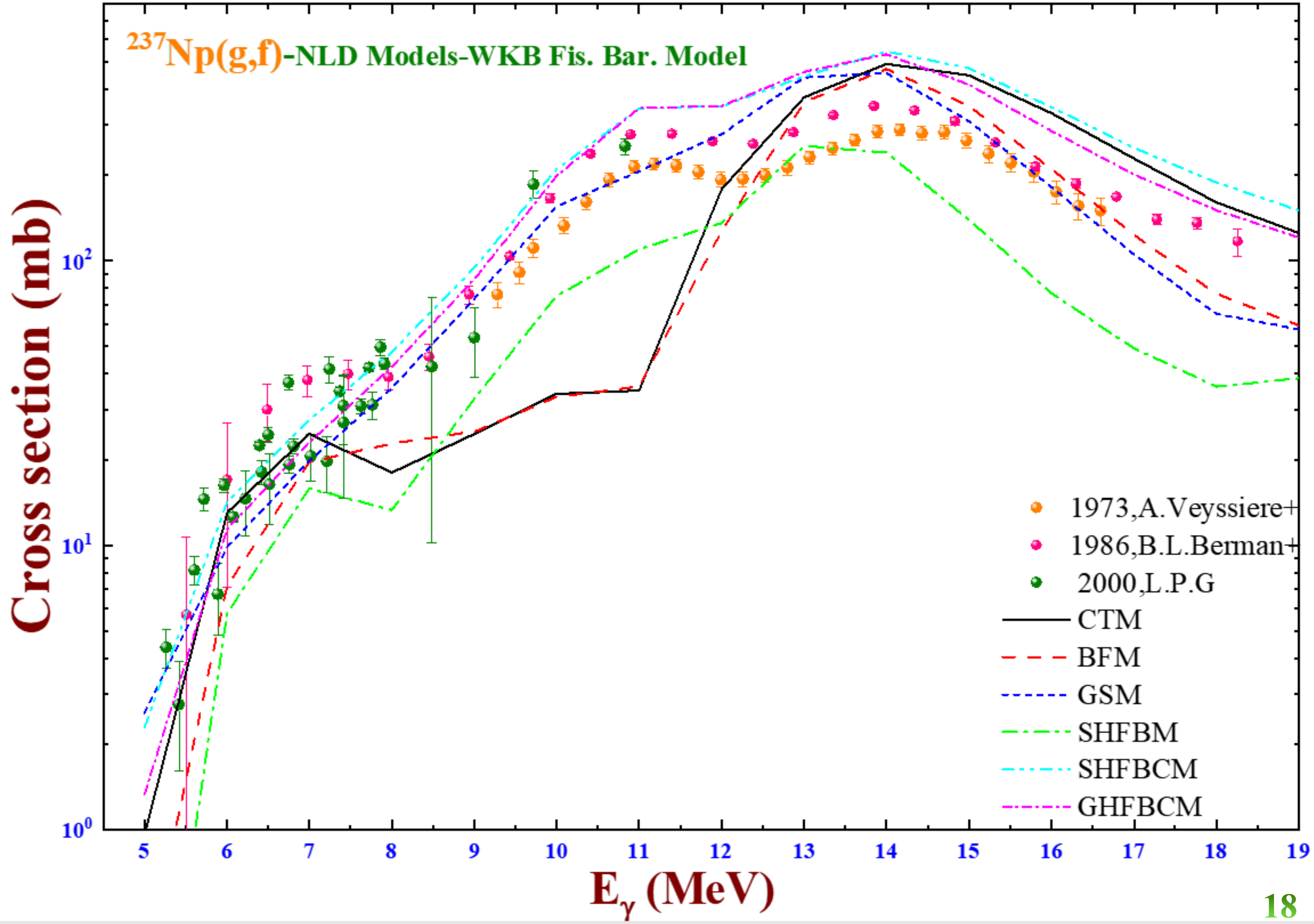
RLD fission barrier model significantly underestimates the cross-section values for all NLD models

Nuclear Structure Effects in Photofission Mechanism

➢ Results for ^{237}Np photofission

Comparison of photofission cross section of ^{237}Np calculated through different NLD models with experimental data

(WKB approximation model)



Nuclear Structure Effects in Photofission Mechanism

➢ Results for ^{237}Np photofission

The parameters of NLD models for ^{237}Np.

Table 2. The parameters of NLD models for ^{237}Np.

M

C 517

490

973

rmi

B 0

0

0

M

G 056

097

665

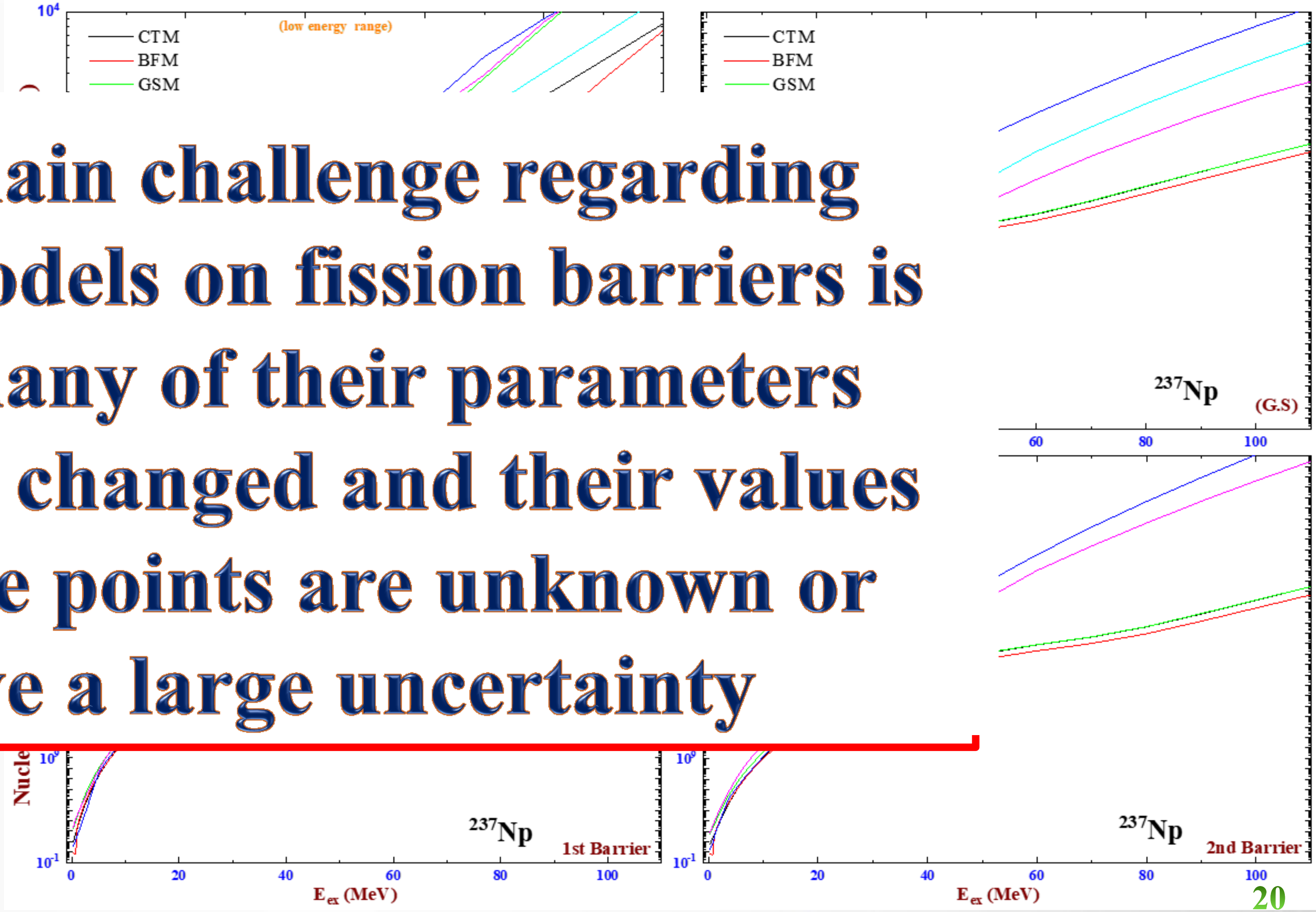
Different NLD models predict very different behavior at energies higher than a few MeV, and there is a significant difference in the NLD results of each model

Microscopic NLD models											
	Barrier	c_{adj}	δ_{adj}		Barrier	c_{adj}	δ_{adj}		Barrier	c_{adj}	δ_{adj}
SHFBM	g. s.	-0.46731	0.03566	SHFBCM	g. s.	-0.2119	-0.1375	GHFBCM	g. s.	-0.6372	-0.2162
	barriers	0.00000	0.00000		barriers	0.00000	0.00000		barriers	0.00000	0.00000

Nuclear Structure Effects in Photofission Mechanism

➢ Results for ^{237}Np NLD models

Comparison of NI
^{237}Np at ground st
barriers

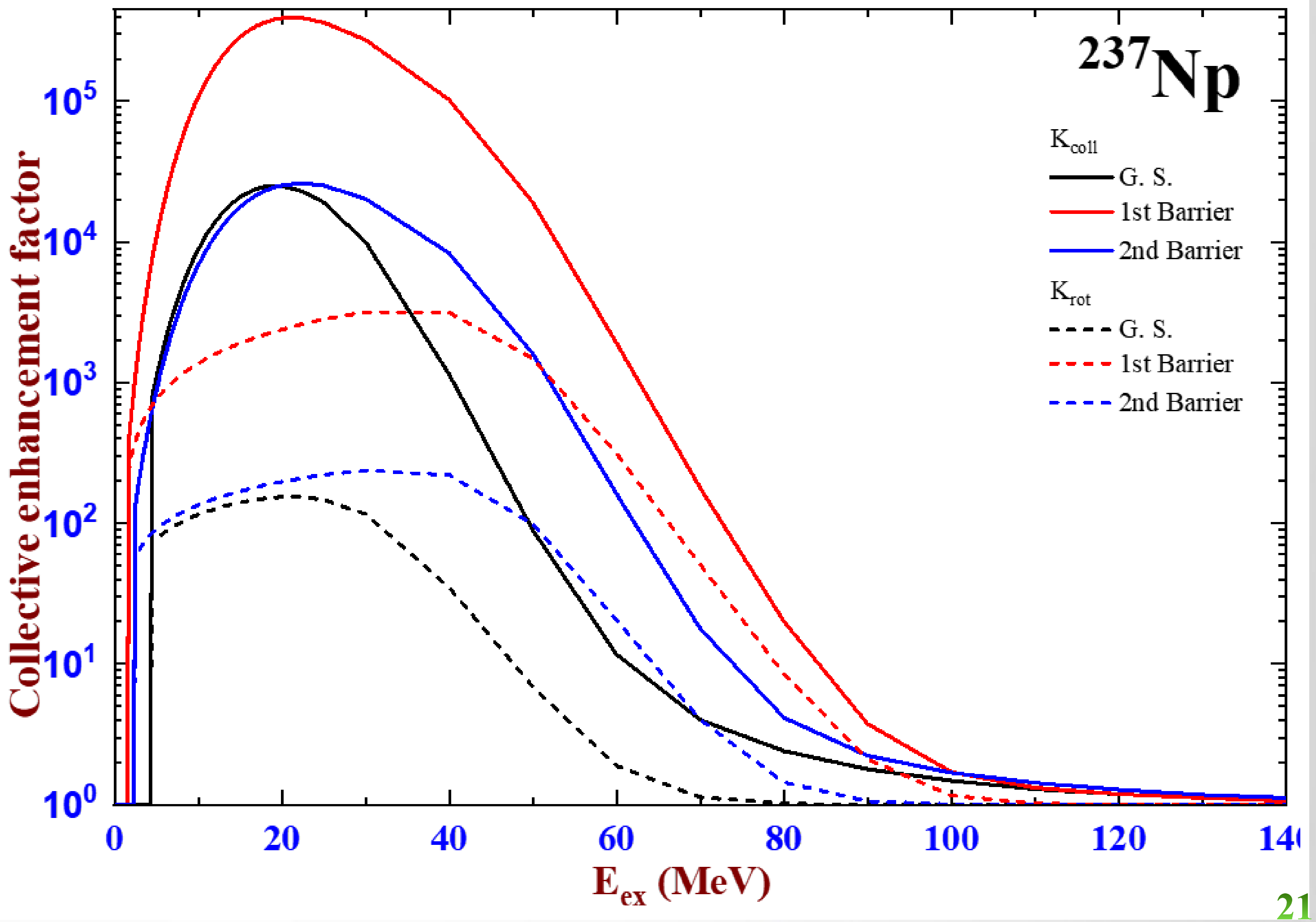


The main challenge regarding NLD models on fission barriers is that many of their parameters must be changed and their values at these points are unknown or have a large uncertainty

Nuclear Structure Effects in Photofission Mechanism

➢ Results for ^{237}Np – Collective enhancement factors for ground state and fission barriers

Comparison of collective enhancement factors of phenomenological NLD models of ^{237}Np at ground state and fission barriers



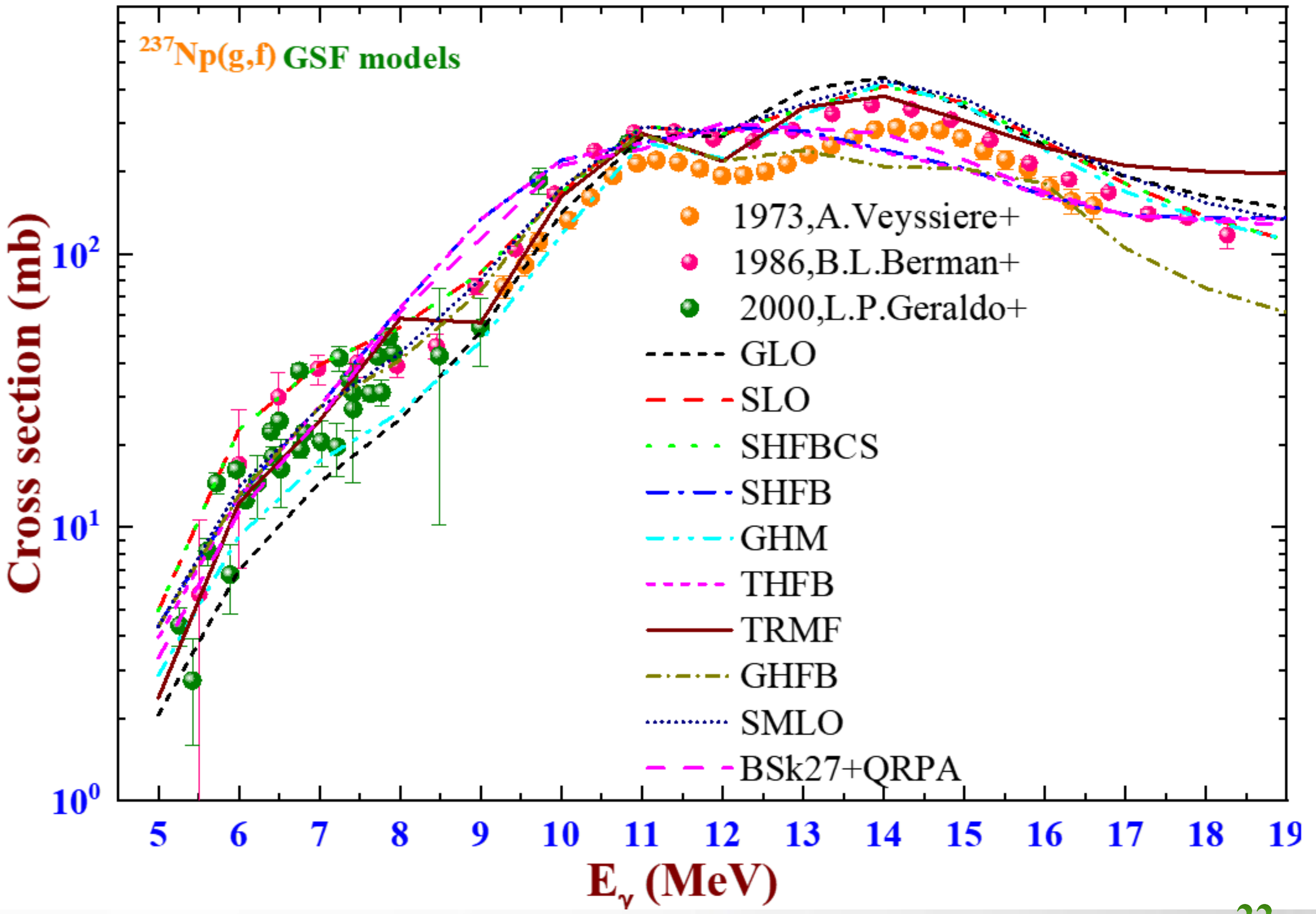
Nuclear Structure Effects in Photofission Mechanism

➢ Results for ^{237}Np – Gamma ray strength function (GSF) models

(GSF) models (implemented in TALYS reaction code)

- ❖ Kopecky-Uhl generalized Lorentzian model (GLO)
- ❖ Brink-Axel Standard Lorentzian model (SLO)
- ❖ Skyrme-Hartree-Fock- BCS model (SHFBCS)
- ❖ Skyrme-Hartree-Fock-Bogoliubov model (SHFB)
- ❖ Goriely Hybrid model (GHM)
- ❖ Temperature-dependent HFB model (THFB)
- ❖ Temperature-dependent Relativistic Mean Field model (TRMF)
- ❖ Gogny-Hartree-Fock-Bogoliubov model (GHFB)
- ❖ Simplified Modified Lorentzian model (SMLO)
- ❖ BSk27+QRPA model

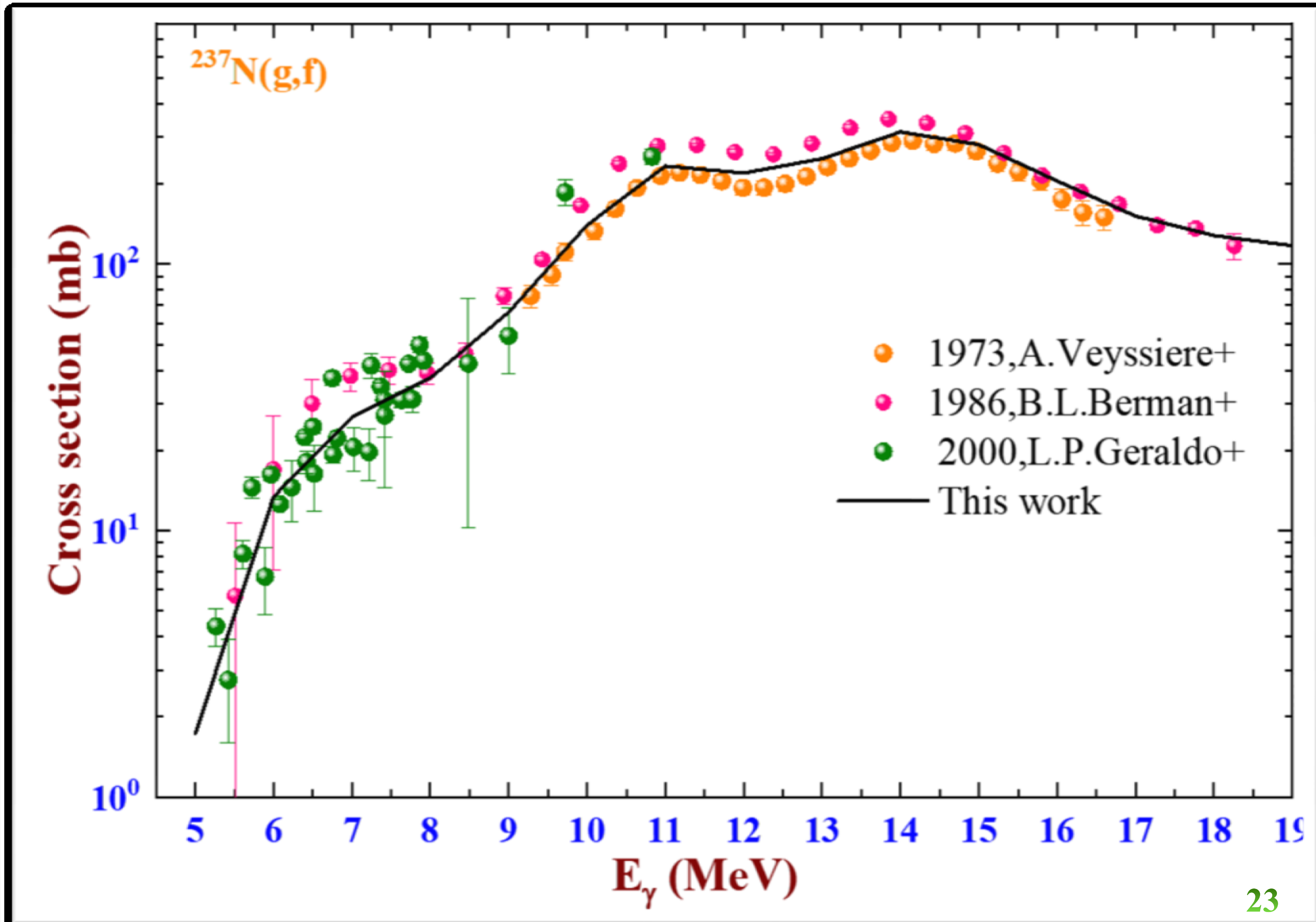
TRMF, GHM and SLO and SMLO models respectively show the best fit with the behavior of the experimental photofission cross section.



Nuclear Structure Effects in Photofission Mechanism

➢ Best Results for ^{237}Np

According to these studies and considering most of the effective components and parameters, the best adaptation is obtained by several combinations of the models of these components, the best of which are shown in this fig.



Nuclear Structure Effects in Photofission Mechanism

➢ Best Results for ^{237}Np

Table 3. The parameters of combination of best components for $^{237}Np(\gamma,f)$ reaction.

Fission Barrier model parameters						Fission NLD model parameters					GSF
1^{st} B_f (MeV)	1^{st} $h\omega$ (MeV)	1^{st} Barrier symmetry	2^{nd} B_f (MeV)	2^{nd} $h\omega$ (MeV)	2^{nd} Barrier symmetry	Model	c_{adj} (g.s)	c_{adj} (barriers)	δ_{adj} (g.s)	δ_{adj} (barriers)	Model
5.6	1.00	axial symmetry	5.2	0.55	left-right asymmetry	SHFBCM	-0.212	0.0000	-0.138	0.0000	SLO

Nuclear Structure Effects in Photofission Mechanism

Conclusion

- The photofission reaction of ^{237}NP is a complex dynamic process
- many factors and components are simultaneously influential in modeling this reaction
- Studying and determining the behavior of each of these components and investigating the extent and manner of their influence on the photofission reaction mechanism is a very important challenge in nuclear physics and technology.
- These factors are fission barrier models, NLD models and GSF models.
- Each of these factors and models also has several parameters that can be changed during the fission process
- It was found that these nuclear structural effects are very effective in the fission process and it is necessary to determine their behavior in a valid and accurate manner.
- the best combination of models and parameters was introduced to achieve the best fit with the experimental data for photofission cross section of ^{237}Np.

Thank you for your attention