

**Tehnike merenja podataka za neutronske
nuklearne reakcije i eksperimentalno određivanje
parametara strukture atomskog jezgra**

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Sadržaj

1. Važnost merenja nuklearnih podataka; baze podataka
2. Efikasni presek za neutronima indukovanu fisiju ^{242}Pu u energetskom opsegu od 15 MeV do 20 MeV
3. Funkcije efikasnih preseka za neutronske reakcije na izotopima renijuma u energetskom opsegu 13.0 -19.5 MeV
4. Modelovanje neutronske spektra na osnovu aktivacione analize
5. Određivanje parametara nuklearne strukture metodom merenja dvostepenih gama kaskada nakon neutronske zahvata

Potreba za nuklearnim podacima

- Osnovna istraživanja

Struktura atomskog jezgra, nuklearne reakcije, neutrinska fizika

- Medicina

primena radionuklida u dijagnostičke i terapijske svrhe

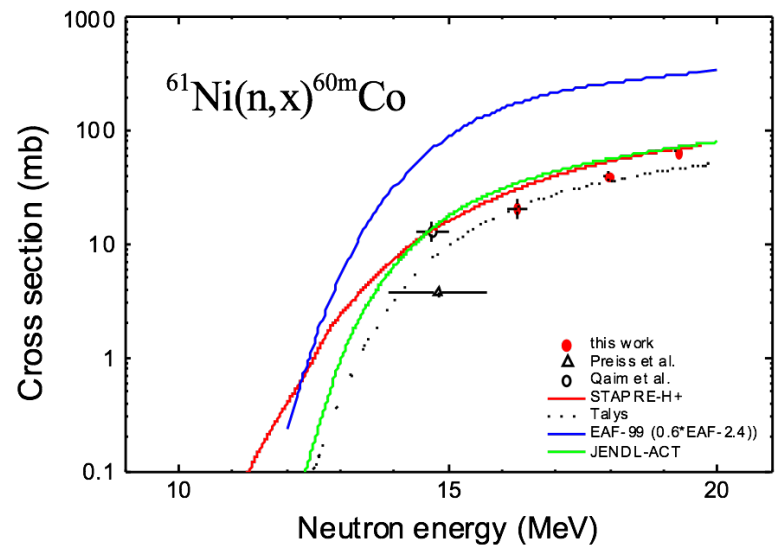
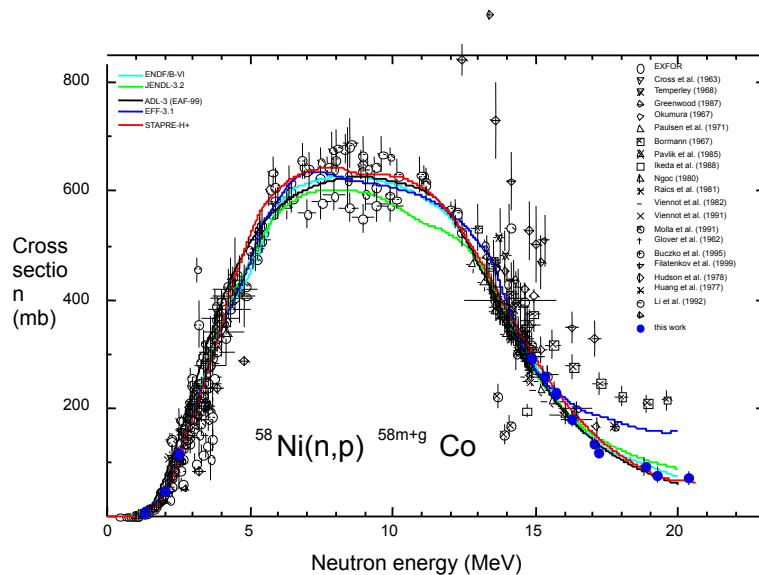
- Astrofizika

- IV generacija nuklearnih reaktora

novi dizajn fisionih i prvi fuzioni reaktor ITER

Potreba za nuklearnim podacima

- Oko 10000 uobičajenih nuklearnih reakcija
- IAEA - 255 neutronske reakcije važnih za različite primjene
- 100 od njih ima 5 ili manje merenih vrednosti za efikasni presek



Baze podataka

- <https://www-nds.iaea.org/>
- <https://www.nndc.bnl.gov/>

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EXFOR Experimental nuclear reaction data	LiveChart of Nuclides Interactive Chart of Nuclides	CINDA Nuclear reaction bibliography
ENDF Evaluated nuclear reaction libraries	ENSDF evaluated nuclear structure and decay data (+XUNDL) **	NSR Nuclear Science References *
NuDat 2.6 selected evaluated nuclear structure data **	RIPL reference parameters for nuclear model calculations	IBANDL Ion Beam Analysis Nuclear Data Library
PGAA Prompt gamma rays from neutron capture	FENDL Fusion Evaluated Nuclear Data Library	Charged particle reference cross section Beam monitor reactions
NAA Neutron Activation Analysis Portal	Safeguards Data recommendations, August 2008	IRDF International Reactor Dosimetry and Fusion File
Photonuclear cross sections and spectra up to 140MeV	Medical Portal Data for Medical Applications	Standards - Neutron cross-sections, 2006 - Decay data, 2005

*Database at the IAEA, Vienna **Database at the US NNDC

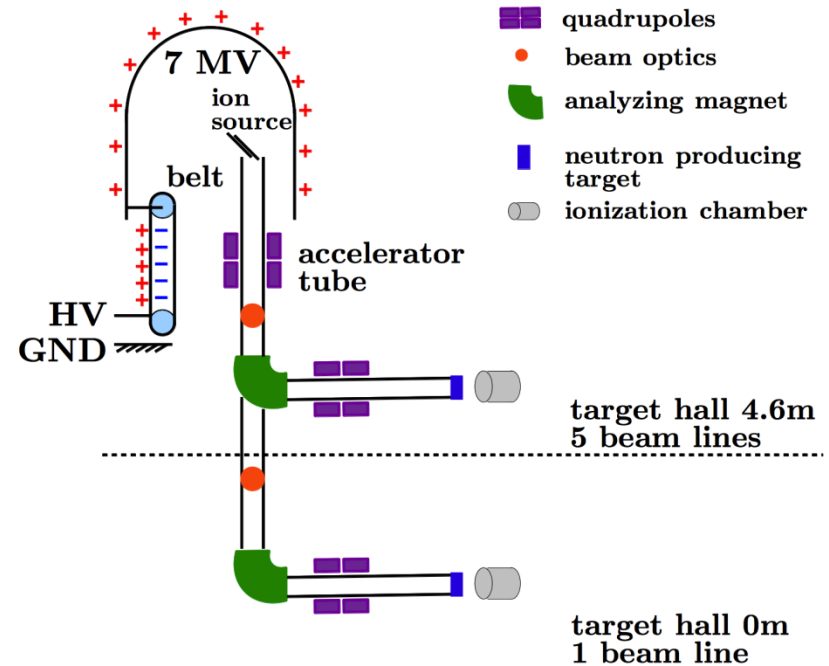
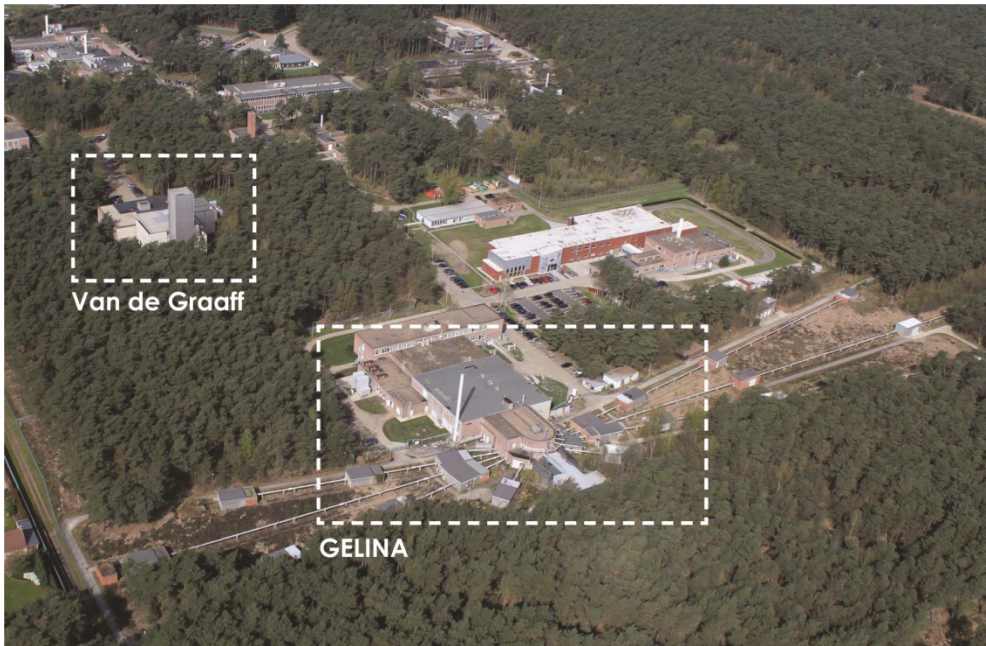
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7FP GENTLE course:
Nuclear data processing
and use in nuclear
application
November 14-18, 2016
EC-JRC Geel, Belgium
Int'l. Conference on Mathematics & Computational Methods Applied to Nuclear Science & Engineering (M&C2017)
April 16-20, 2017
ICC Jeju, Jeju, Korea

Efikasni presek za neutronima indukovanu fisiju ^{242}Pu u energetsom opsegu od 15 MeV do 20 MeV

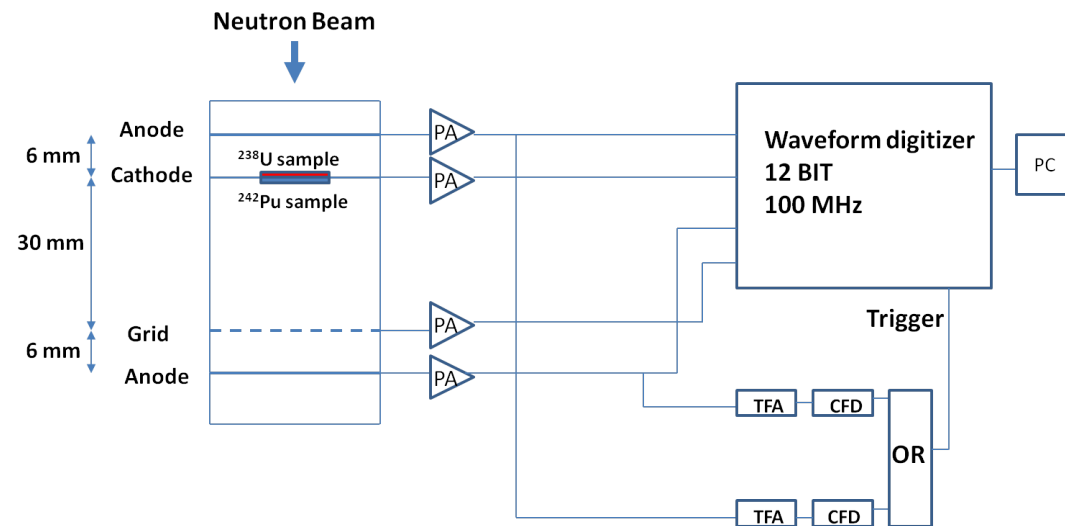
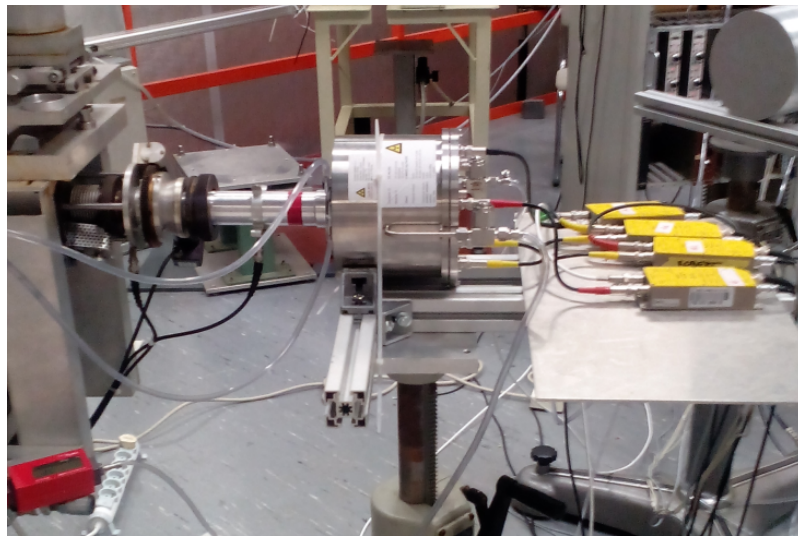
- JRC - IRMM, Geel, Belgija



$^7\text{Li}(p,n)^7\text{Be}$, En: 0 - 5.3 MeV
 $\text{T}(p,n)^3\text{He}$, En: 0 - 6.2 MeV
 $\text{D}(d,n)^3\text{He}$, En: 1.8 - 10.1 MeV
 $\text{T}(d,n)^4\text{He}$, En: 12.1 - 24.1 MeV

Efikasni presek za neutronima indukovanu fisiju ^{242}Pu u energetsom opsegu od 15 MeV do 20 MeV

- A twin Frisch-grid ionization chamber.
- Efikasni presek za $^{242}\text{Pu}(n,f)$ je normiran na efikasni presek za $^{238}\text{U}(n,f)$.
- ^{242}Pu - 0.625 mg; ^{238}U - 0.861 mg



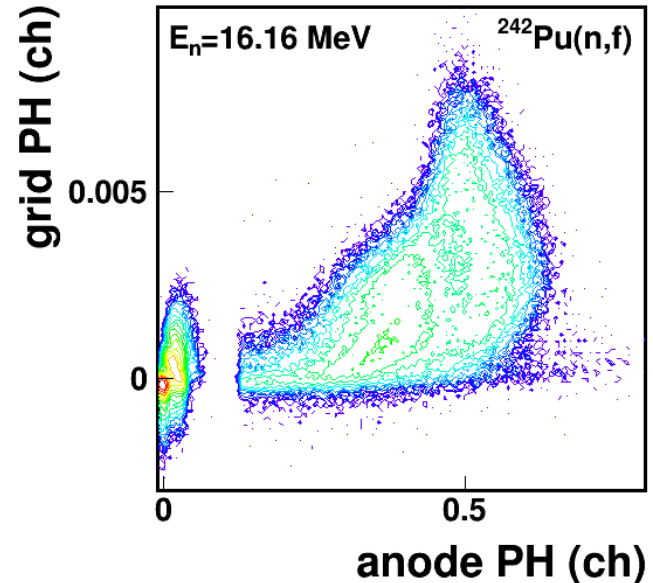
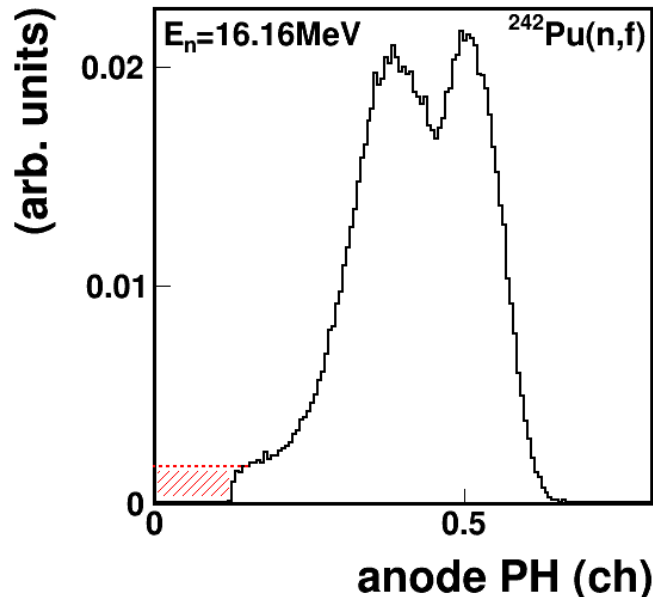
Efikasni presek za neutronima indukovanu fisiju ^{242}Pu u energetsom opsegu od 15 MeV do 20 MeV

- Ozračivanje** $^3\text{H}(d,n)^4\text{He}$, Ti- ^3H target of 2.293 mg cm⁻².

Measurement No.	E_i (MeV)	E_n (MeV)	t (s)
1	0.800(11)	15.28(30)	15161.0(5)
2	1.000(11)	16.16(20)	58149.0(5)
3			2906.0(5)
4			13164.0(5)
5	1.500(11)	17.22(30)	19163.0(5)
6			15954.0(5)
7	2.000(11)	18.02(20)	62363.0(5)
8			55991.0(5)
9	2.500(11)	18.74(30)	56353.0(5)
10			63436.0(5)
11	3.000(11)	19.81(18)	47811.0(5)

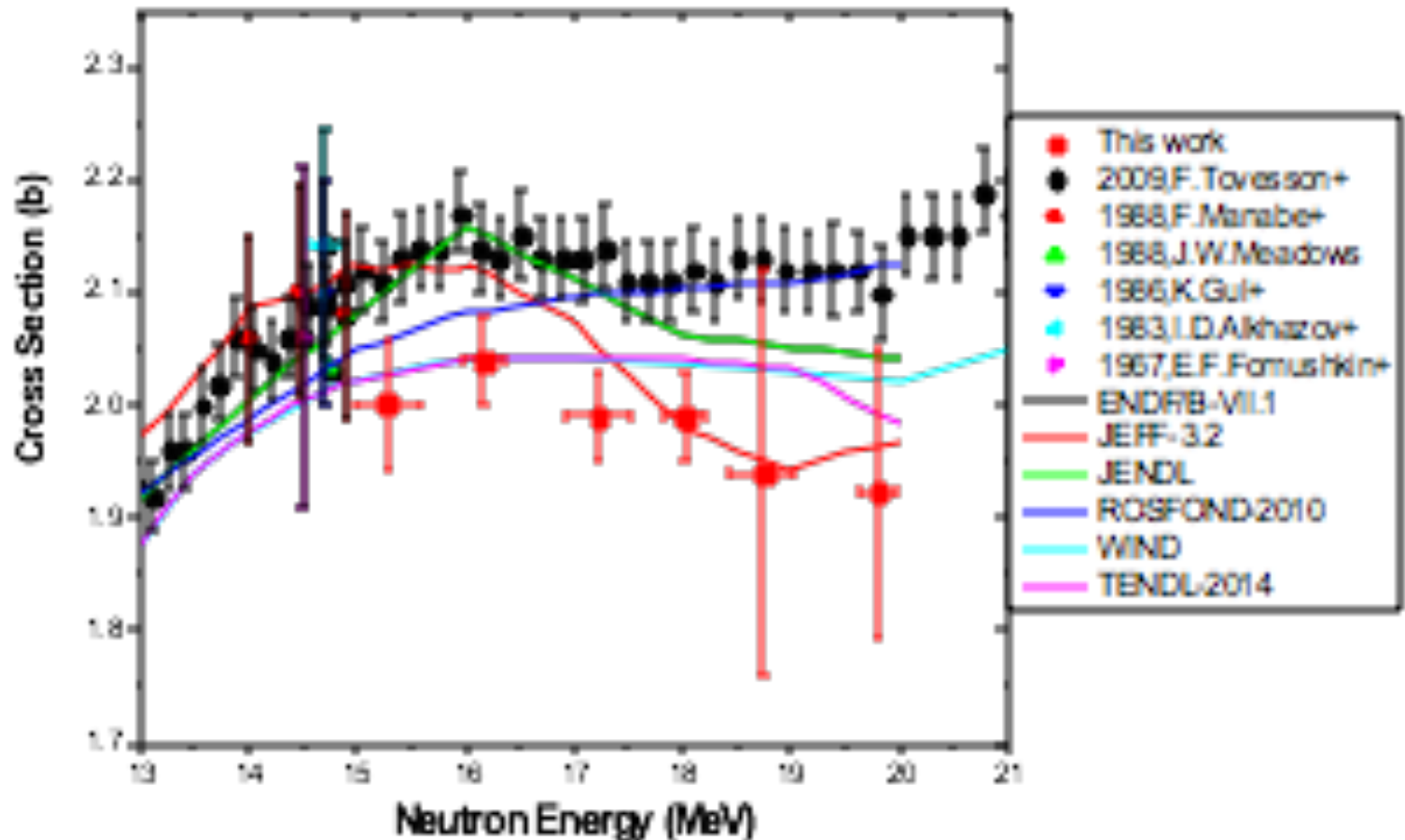
Efikasni presek za neutronima indukovanu fisiju ^{242}Pu u energetsom opsegu od 15 MeV do 20 MeV

- **Obrada eksperimentalnih podataka**
- Signali sa detektora su tretirani za korekciju osnovne linije, balistički deficit i α background korekcije.
- Visine signala su korigovane za neefikasnost grida, alfa pile-up i ekstrapolaciju do nule.



Efikasni presek za neutronima indukovanu fisiju ^{242}Pu u energetsom opsegu od 15 MeV do 20 MeV

$$\sigma_{Pu} = \frac{(N_{Pu} - N_{Pu_sf})}{N_{U238}} \cdot \sigma_{U238} \cdot \frac{m_{U238} \cdot M_{Pu}}{m_{Pu} \cdot M_{U238}}$$



Funkcije efikasnih preseka za neutronske reakcije na izotopima renijuma u energetskom opsegu 13.0 -19.5 MeV

- NAXSUN metod
 - Merenja funkcije efikasnih preseka neutronima indukovane reakcije na Re
 1. Materijali
 2. Neutronske spektar i ozračivanje
 3. Gama spektroskopsko merenje
 - Rezultati
- Renijum (^{185}Re (37.4%) and ^{187}Re (62.6%))
- otporan na visoke temperature i koroziju
 - koristi se za dijagnostiku i tretman tumora
 - Re/Os cosmos-chronometry
- Nedostatak zadovoljavajućih eksperimentalnih podataka za neutronima indukovane nuklearne reakcije na Re.
- $^{187}\text{Re}(n, \alpha)^{184}\text{Ta}$, $^{187}\text{Re}(n, 2n)^{186}\text{Re}$, $^{185}\text{Re}(n, 2n)^{184}\text{Re}$, $^{187}\text{Re}(n, p)^{187}\text{W}$ i $^{185}\text{Re}(n, 3n)^{183}\text{Re}$ for $E_n = 13.0 - 19.5\text{MeV}$

Funkcije efikasnih preseka za neutronske reakcije na izotopima renijuma u energetsom opsegu 13.0 -19.5 MeV

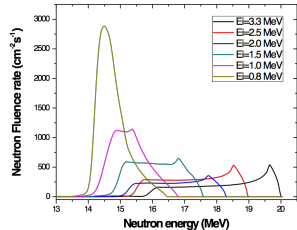
NAXSUN metod (Neutron Activation X-Section determined using UNfolding)

$$A_k + \varepsilon_k = \sum_i \Phi_{ki} \sigma_i, i = 1, 2, \dots, c, k = 1, 2, \dots, m$$

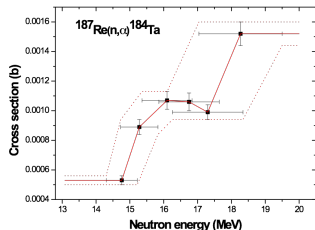
A_k = merene vrednosti
 ε_k = greške merenja
 σ_i = efikasni preseki
 Φ_{ki} = neutronske spektri

Disk No	A (Br/atom)
1	
2	
...	

Merena aktivnost diskova



Podaci o neutronsom fluksu

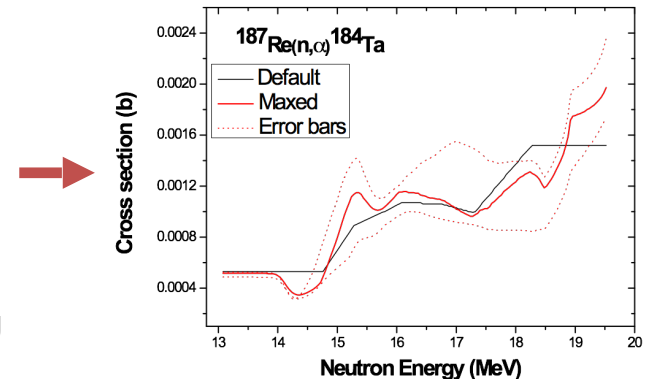


Inicijana funkcija efikasnog preseka



Spectrum unfolding

(MAXED, GRAVEL)



Efikasni presek - funkcija pobude

Funkcije efikasnih preseka za neutronske reakcije na izotopima renijuma u energetskom opsegu 13.0 -19.5 MeV

- The maximum entropy code **MAXED**

$$S = -\int \left\{ \sigma(E) \ln \left(\frac{\sigma(E)}{\sigma_{def}(E)} \right) + \sigma_{def}(E) - \sigma(E) \right\} dE$$

- GRAVEL iterative algorithm**

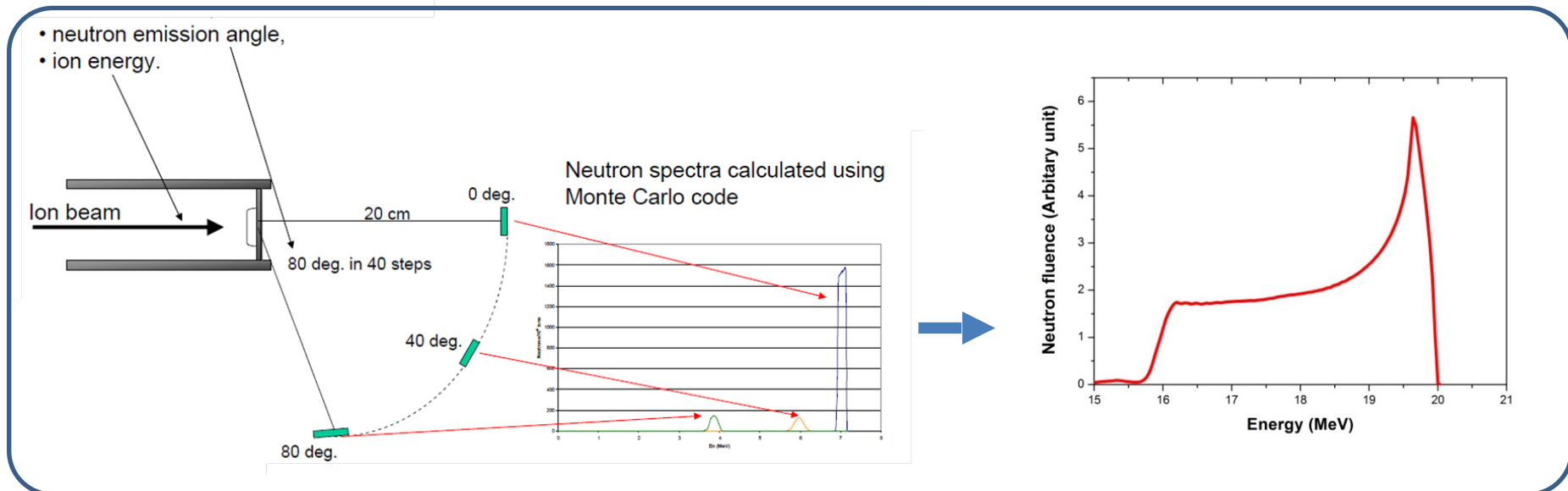
$$\sigma_i^{J+1} = \sigma_i^J \cdot f(A_k, \varepsilon_k, \Phi_{ki}, \sigma_i^J)$$

$$f = \exp \left(\frac{\sum W_{ik}^J \log \left(\frac{A_k}{\sum \Phi_{ki} \sigma_i^J} \right)}{\sum_k W_{ik}^J} \right)$$

$$W_{ik}^J = \frac{\Phi_{ki} \cdot \sigma_i^J}{\sum_i \Phi_{ki} \sigma_i^J} \frac{A_k^2}{\varepsilon_k^2}$$

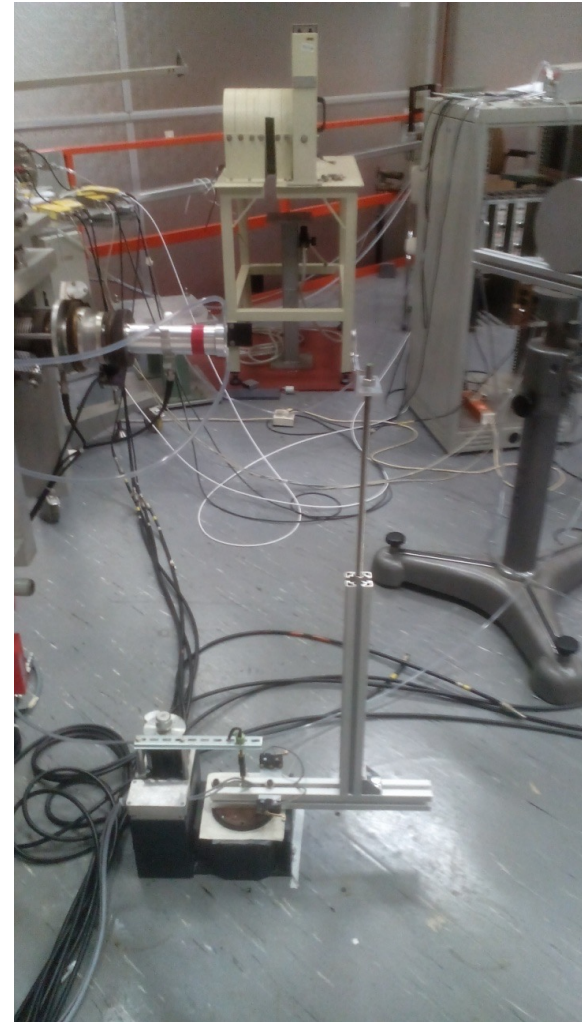
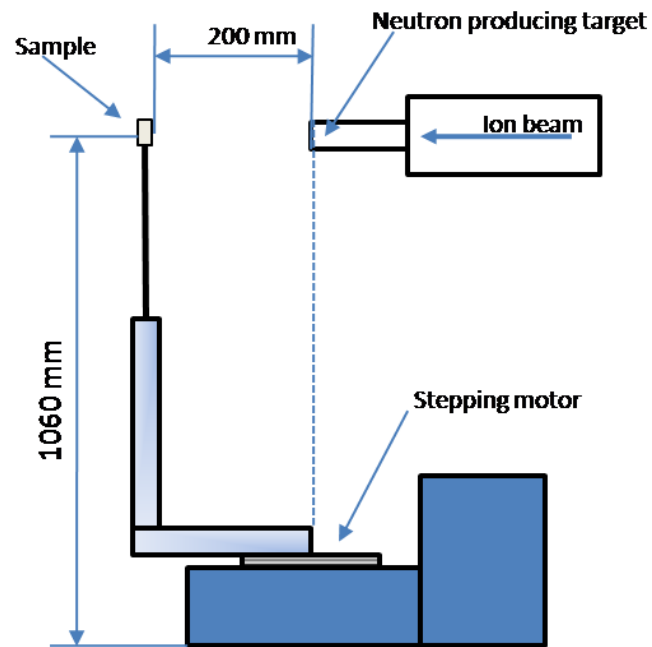
Funkcije efikasnih preseka za neutronske reakcije na izotopima renijuma u energetsom opsegu 13.0 -19.5 MeV

- Široko-energetski neutronske snopovi (energetski se preklapaju)
- Ozračivanjem **diskova na različitim uglovima** relativno na snop jona, uzorak je izložen totalnom neutronsom spektru u širokom energetsom opsegu.
- Reakcije za produkciju neutrona
 - ${}^7\text{Li}(p,n){}^7\text{Be}$, En: 0 - 5.3 MeV
 - $\text{T}(p,n){}^3\text{He}$, En: 0 - 6.2 MeV
 - $\text{D}(d,n){}^3\text{He}$, En: 1.8 - 10.1 MeV
 - $\text{T}(d,n){}^4\text{He}$, En: 12.1 - 24.1 MeV



Funkcije efikasnih preseka za neutronske reakcije na izotopima renijuma u energetsom opsegu 13.0 -19.5 MeV

- Uređaj za ozračivanje



Funkcije efikasnih preseka za neutronske reakcije na izotopima renijuma u energetsom opsegu 13.0 -19.5 MeV

Neutronska polje i ozračivanje

- JRC-IRMM Van de Graff akcelerator
- 6 Re-diskova (dijametar: 20 mm, 5 mm debljina) ozračeni svaki na različitoj neutronske energiji u intervalu od 0° do 80° relativno na snop
- 41 različite pozicije u koracima od po 2°
- Jedan disk je ozračen na fiksnoj poziciji 0° pri inicijalnoj energiji neutrona od 18.1 MeV

Disk No.	E_i (MeV)	E_n (MeV)	t (s)
1	3.3	19.78(20)	86921(10)
2	2.5	18.71(20)	248402(10)
3	2.0	18.10(28)	157632(10)
4	2.0	18.10(28)	166564(10)
5	1.5	17.16(30)	231958(10)
6	1.0	15.9(8)	243608(10)
7	0.8	15.26(13)	144831(10)

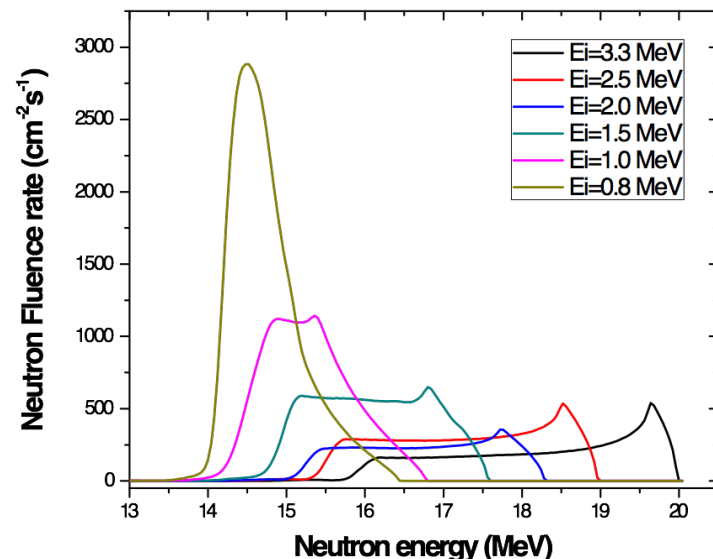
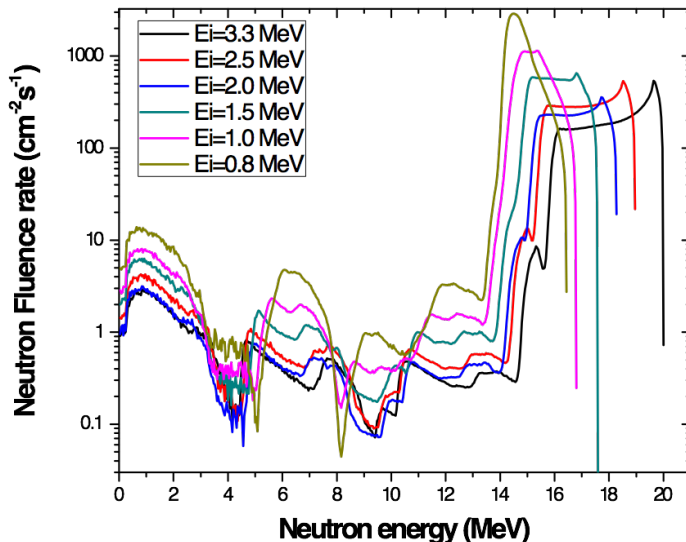
Funkcije efikasnih preseka za neutronske reakcije na izotopima renijuma u energetsom opsegu 13.0 -19.5 MeV

Neutronska polje i ozračivanje

- neutronske spektri simulirani (TARGET kod) i korigovani za vremena ozračivanja i promene struje akceleratora

$$\Phi_k = \Phi_{Tk} \cdot b_k$$

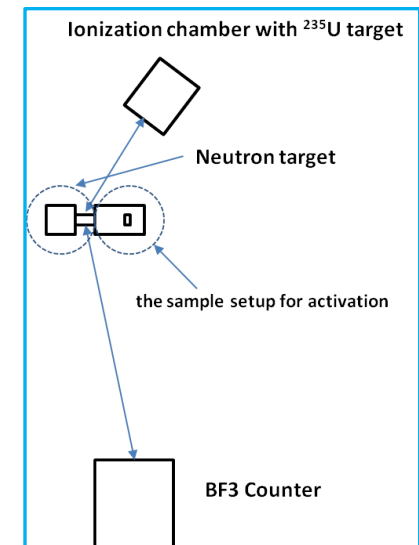
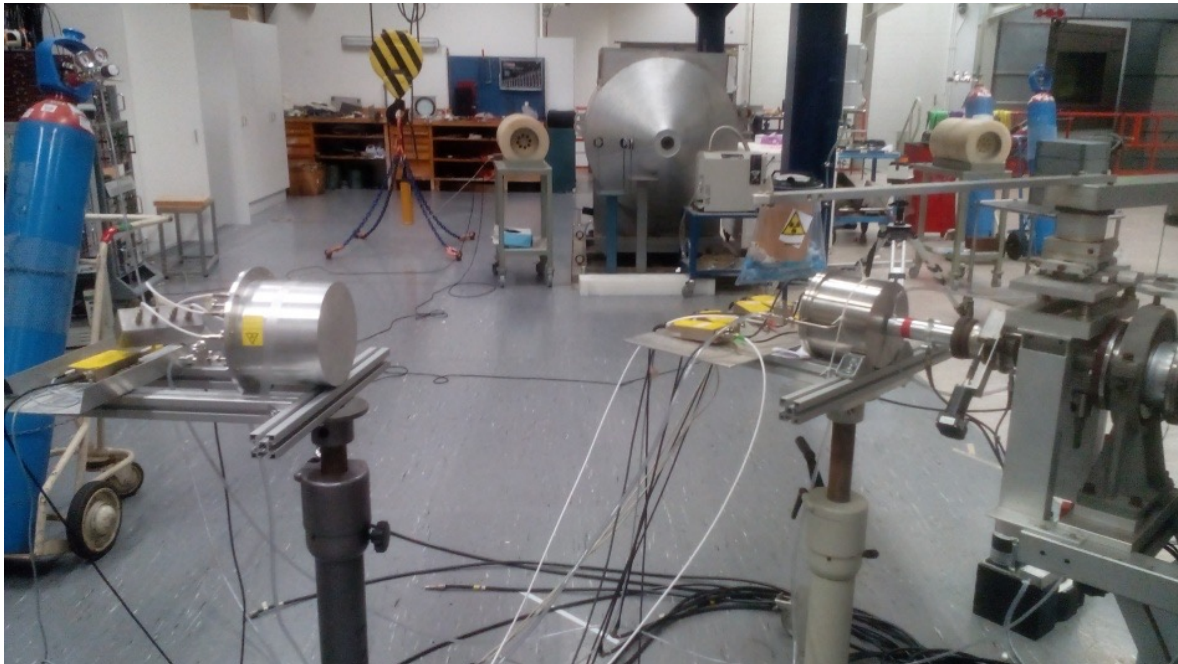
$$b_k = \sum_{i=1}^n \left(\frac{q_i}{t_{aki}} \left(1 - e^{-\lambda t_{aki}} \right) e^{-\lambda t_{cki}} \right)$$



Funkcije efikasnih preseka za neutronske reakcije na izotopima renijuma u energetsom opsegu 13.0 -19.5 MeV

Monitoring neutronskega fluksa tokom ozračivanja

- Dve jonizacione komore (sa ^{235}U i ^{238}U metama), BF3 brojač

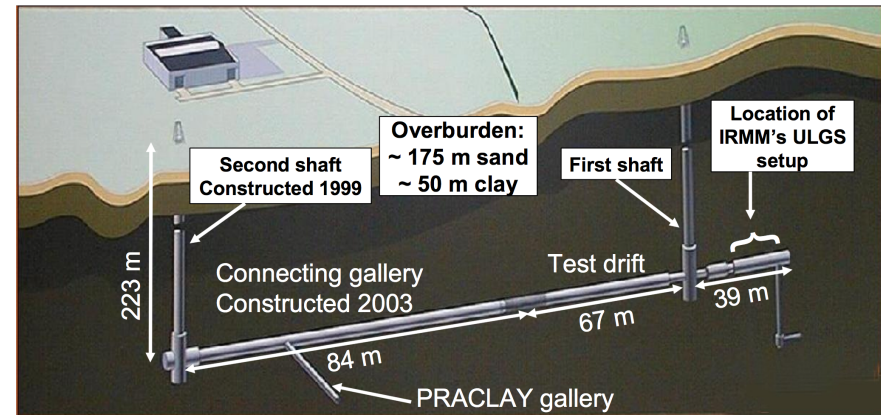
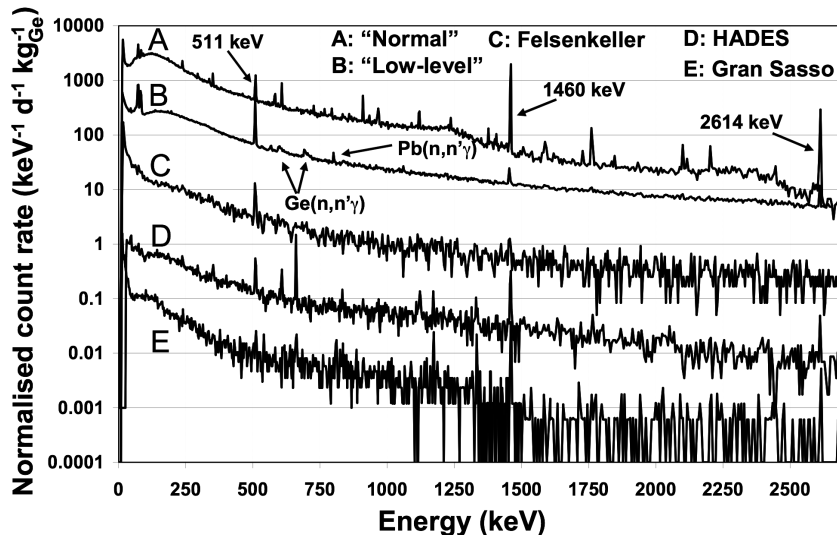
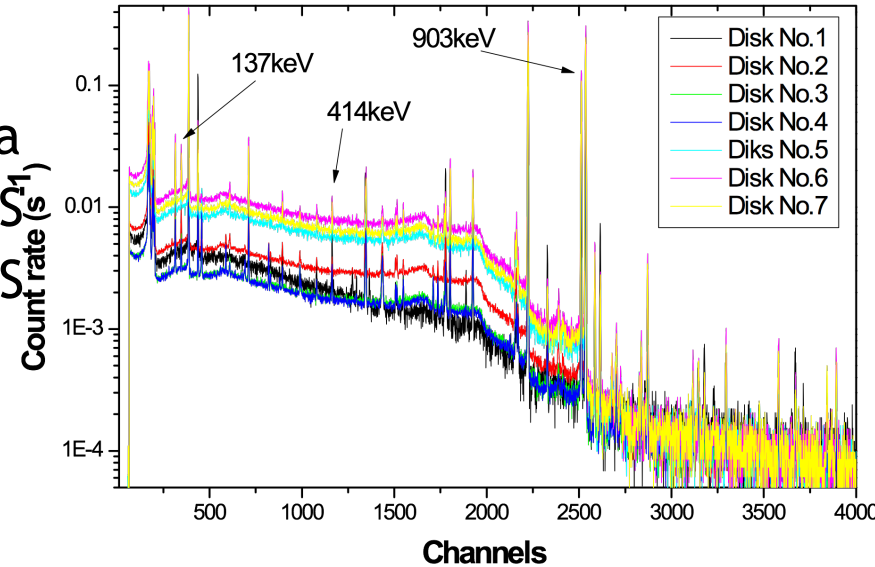


Funkcije efikasnih preseka za neutronske reakcije na izotopima renijuma u energetsom opsegu 13.0 -19.5 MeV

Gama spektroskopska merenja

- Prvo merenje 20 min nakon ozračivanja
- Drugo merenje nakon dva dana - HADES^{1,1}
- Treće merenje nakon 2 meseca - HADES^{1,1}

HADES



Funkcije efikasnih preseka za neutronske reakcije na izotopima renijuma u energetsom opsegu 13.0 -19.5 MeV

Gama spektroskopska merenja

➤ Specifična aktivnost po atomu aktiviranog izotopa mete, A_k na kraju aktivacije

$$A_k = \frac{CM}{N_a m \epsilon P_\gamma I_A} \left(\frac{\lambda}{1 - e^{-\lambda t_m}} \right) e^{\lambda t_c}$$

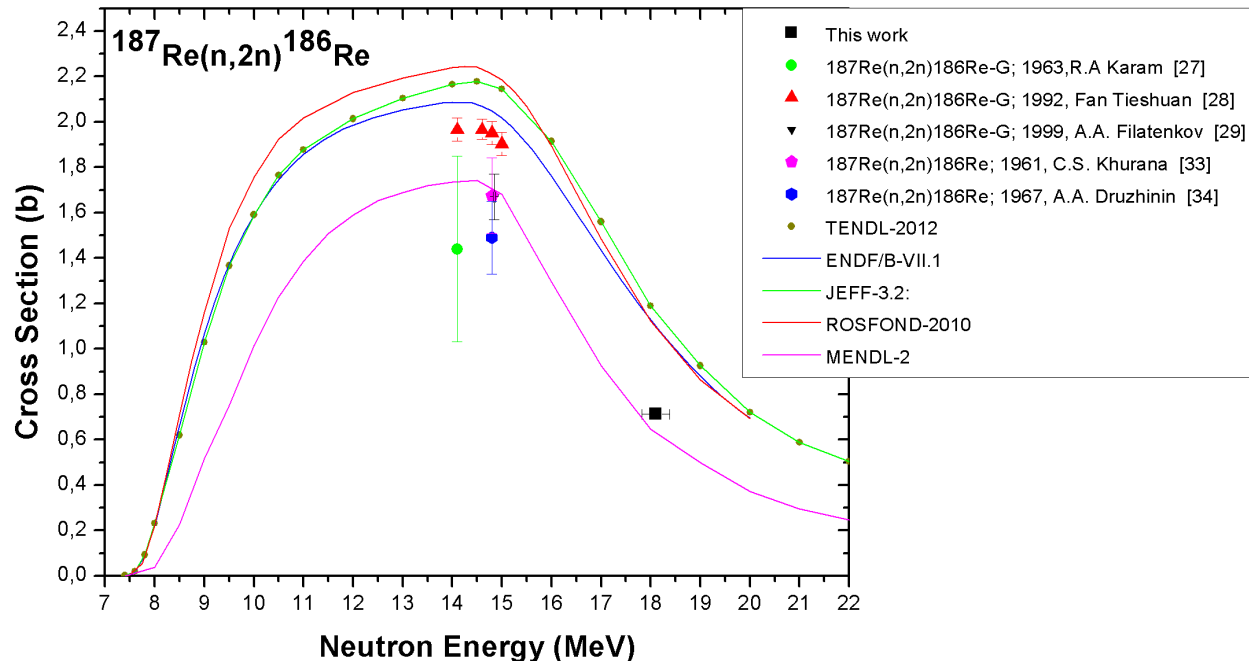
Reaction	E_γ [keV] (I_γ , %)	Disk No.1	Disk No.2	Disk No.3	Disk No.4	Disk No.5	Disk No.6	Disk No.7
		A_k (10^{-24} Bq/atom)						
$^{187}\text{Re}(n,2n)^{186}\text{Re}$	137.2 (9.4)	3430(50)	9850(14)	4490(60)	4790(70)	14680(210)	26800(400)	24700(300)
$^{187}\text{Re}(n,a)^{184}\text{Ta}$	414.0 (73.9)	29.10(40)	23.10(30)	16.72(23)	37.30(50)	32.00(40)	32.40(50)	31.20(40)
$^{185}\text{Re}(n,2n)^{184}\text{Re}$	903 (37.9)	334.0(50)	1315(19)	676(9)	733(10)	2250(30)	3600(50)	3260(50)
$^{185}\text{Re}(n,3n)^{183}\text{Re}$	162.3 (22.3)	165.6(29)	187(3)	119.0(20)	318(6)	237(4)	113.4(20)	67.2(12)
$^{187}\text{Re}(n,p)^{187}\text{W}$	618.3 (7.6)	45.5(8)	66.1(11)	50.3(8)	82.4(14)	118.1(20)	93.5(16)	96.8(17)

Funkcije efikasnih preseka za neutronske reakcije na izotopima renijuma u energetsom opsegu 13.0 -19.5 MeV

- Rezultati
- Efikasni preseki za normalizaciju pri energiji od 18.1 MeV

$$\sigma = \frac{A_k}{\Phi_1}$$

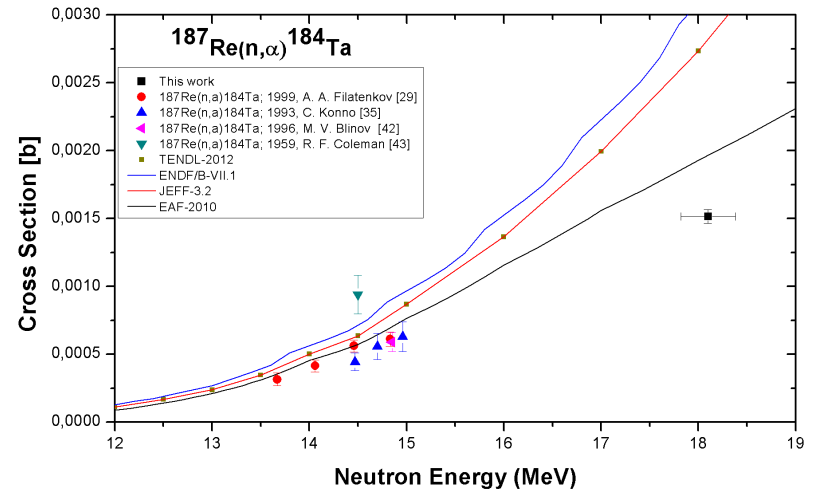
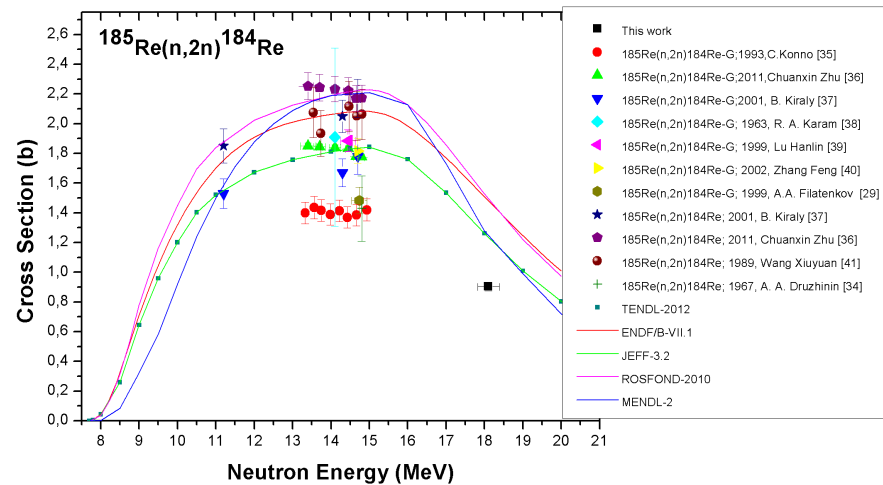
$$\Phi_1 = \Phi \cdot \sum_i^n \frac{j}{j_{avg}} \cdot \left(1 - e^{-\lambda_{ai}}\right) e^{-\lambda_{ci}}$$



Funkcije efikasnih preseka za neutronske reakcije na izotopima renijuma u energetskom opsegu 13.0 -19.5 MeV

Rezultati

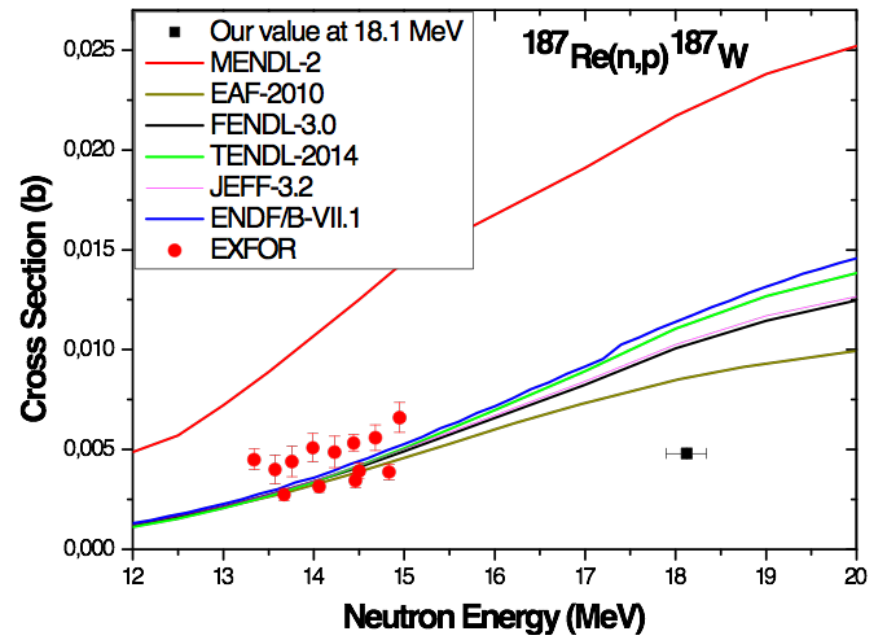
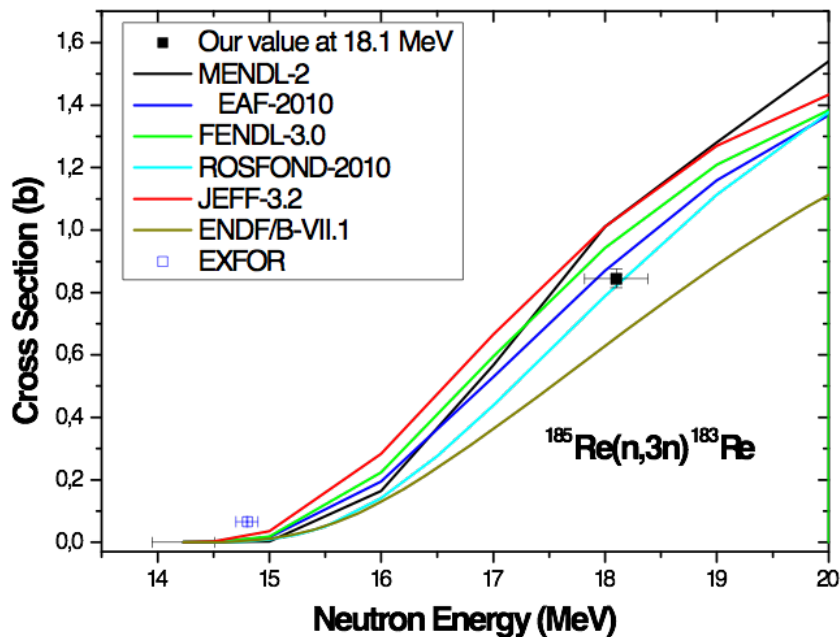
- Efikasni preseki za normalizaciju pri energiji od 18.1 MeV



Funkcije efikasnih preseka za neutronske reakcije na izotopima renuma u energetsom opsegu 13.0 -19.5 MeV

Rezultati

- Efikasni preseki za normalizaciju pri energiji od 18.1 MeV



Funkcije efikasnih preseka za neutronske reakcije na izotopima renuma u energetsom opsegu 13.0 -19.5 MeV

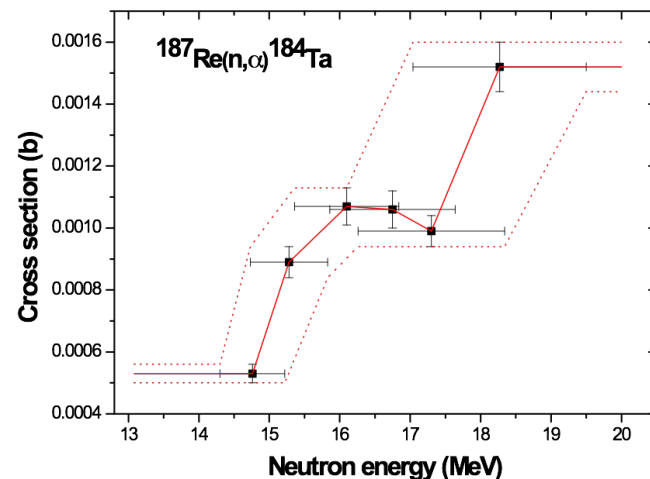
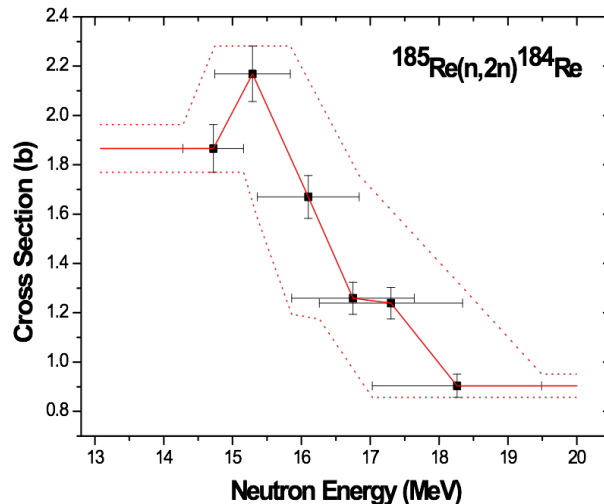
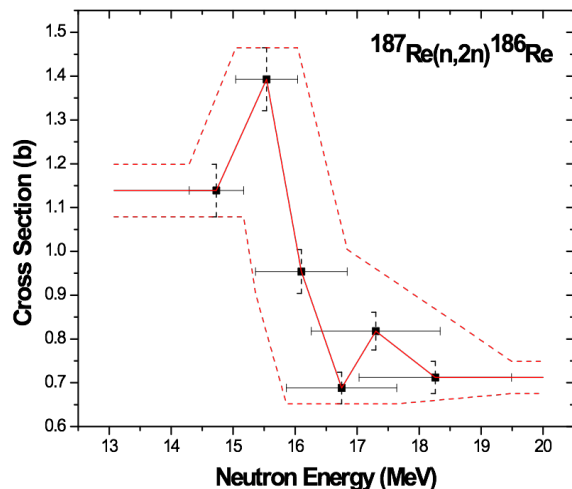
Rezultati

- Definisanje početne funkcije za unfolding postupak

1. Srednji efikasni presek $\langle \sigma_k \rangle \approx \frac{A_{sk}}{\sum_i \Phi_{ki}}$

2. Odgovarajuća srednja energija neutrona $\langle E \rangle_k \approx \frac{\sum_i \Phi_{ki} \cdot E_i}{\sum_i \Phi_{ki}}$

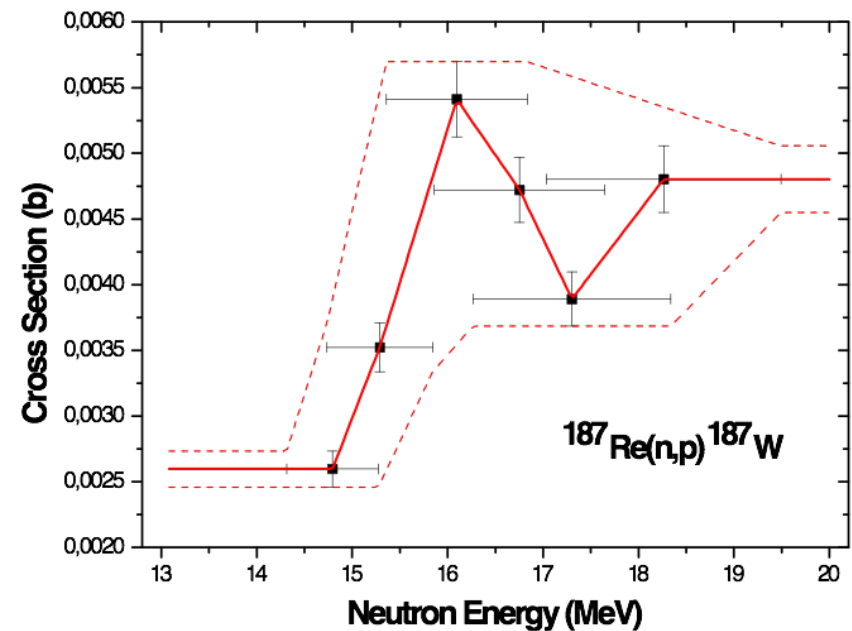
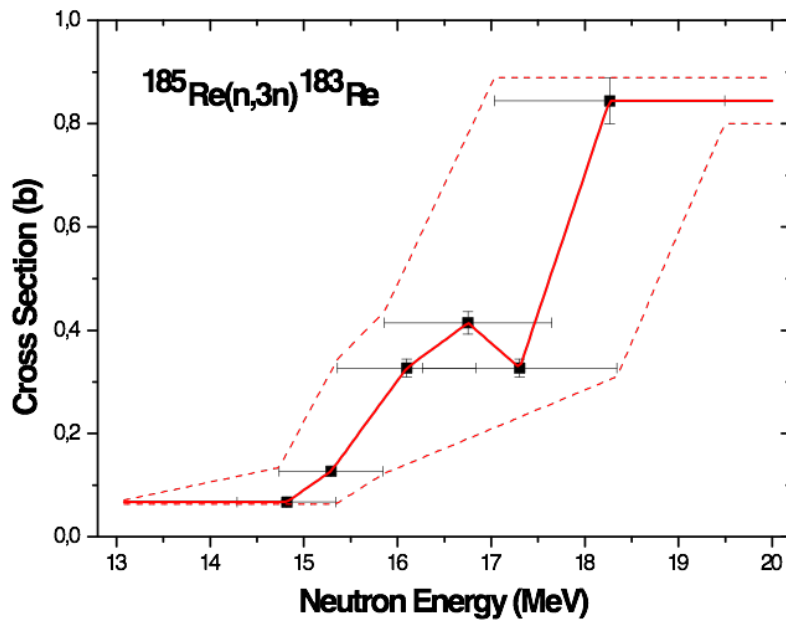
3. Linearna interpolacija zavisnosti $\langle \sigma_k \rangle$ od $\langle E \rangle_k$



Funkcije efikasnih preseka za neutronske reakcije na izotopima renijuma u energetsom opsegu 13.0 -19.5 MeV

Rezultati

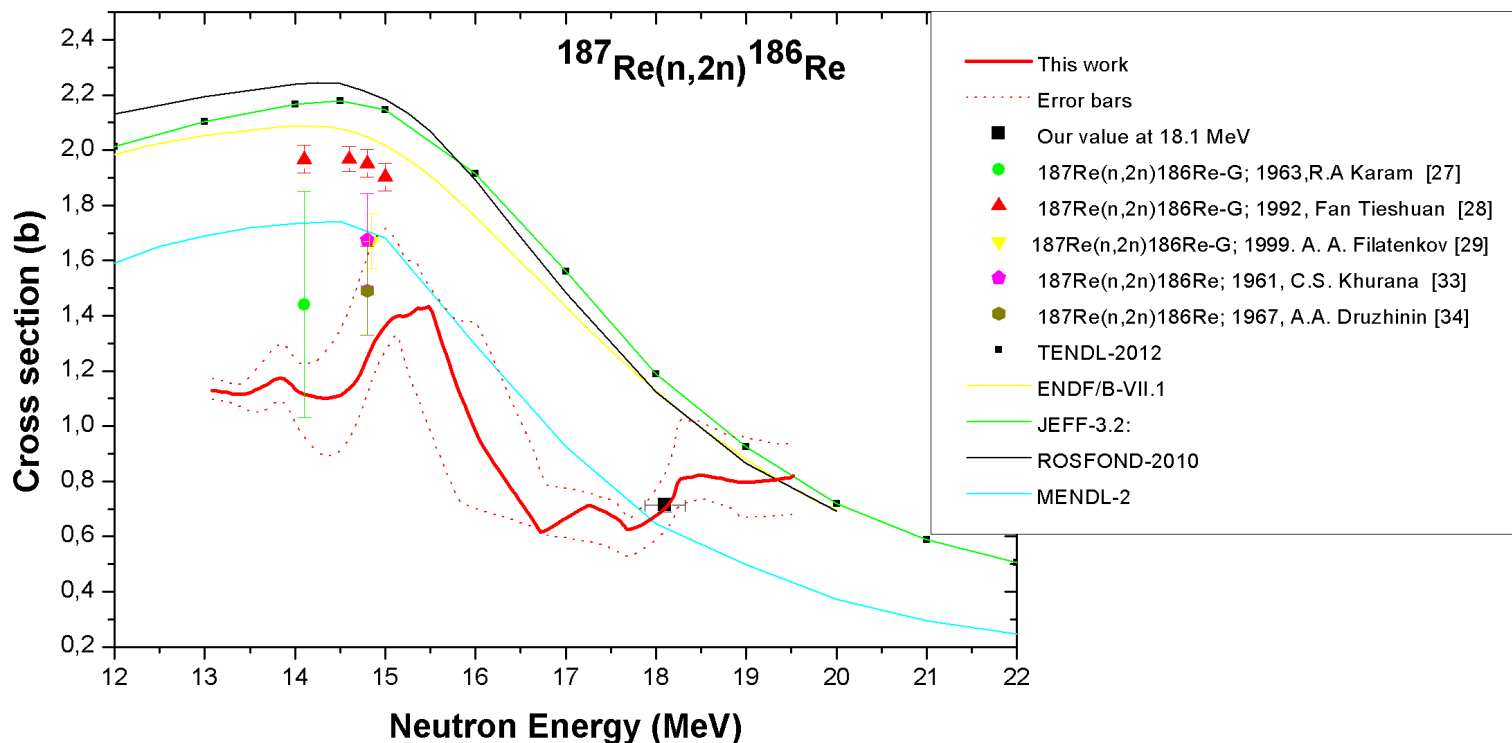
- Definisiranje početne funkcije za unfolding postupak



Funkcije efikasnih preseka za neutronske reakcije na izotopima renijuma u energetskom opsegu 13.0 -19.5 MeV

Rezultati

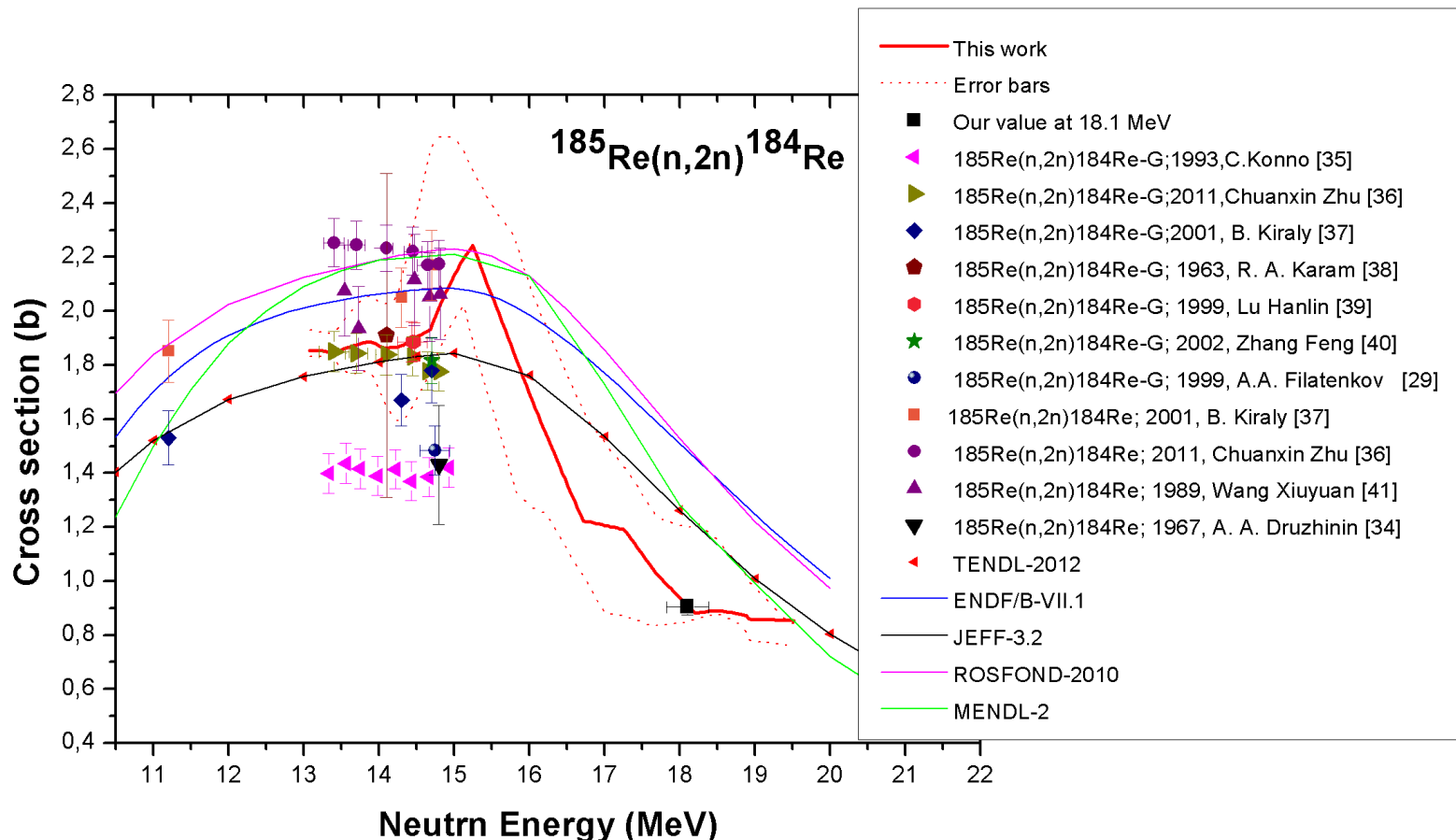
- Unfolded excitation function
- Ujedinjene vrednosti rezultata GRAVEL i MAXED koda



Funkcije efikasnih preseka za neutronske reakcije na izotopima renijuma u energetsom opsegu 13.0 -19.5 MeV

Rezultati

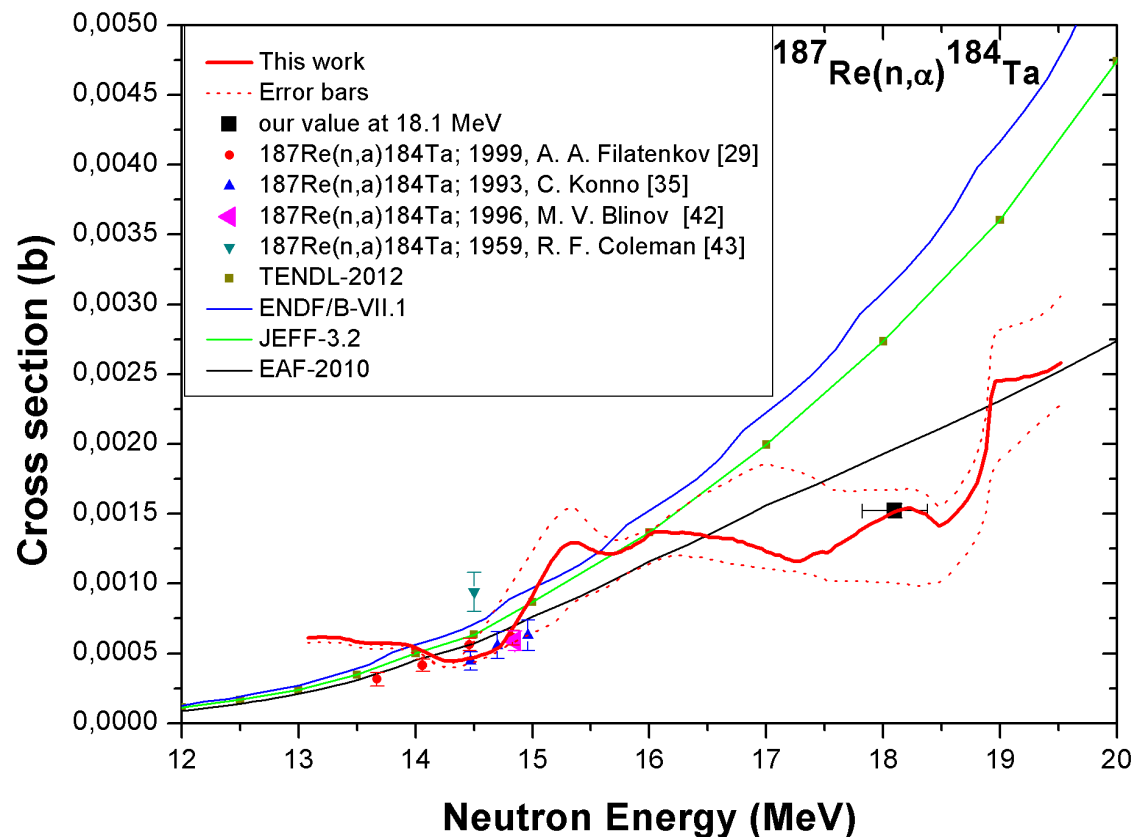
- Unfolded excitation function



Funkcije efikasnih preseka za neutronske reakcije na izotopima renijuma u energetsom opsegu 13.0 -19.5 MeV

Rezultati

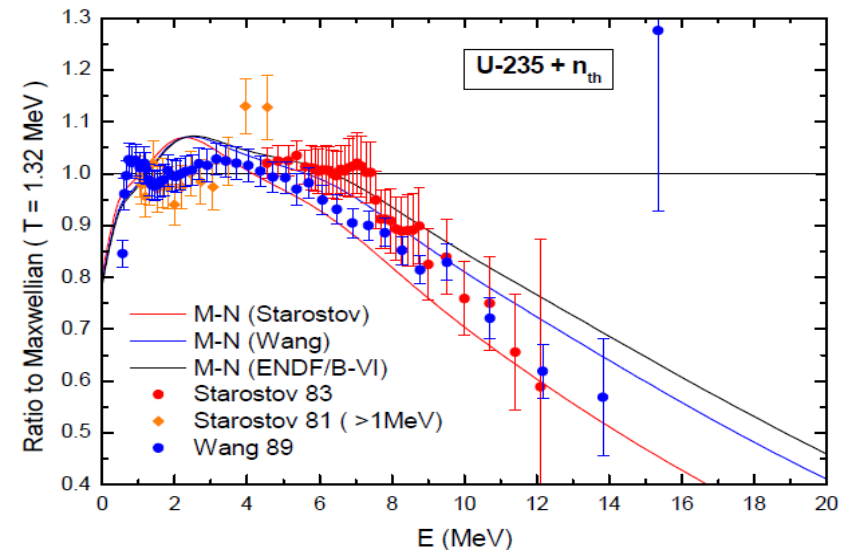
- Unfolded excitation function



Modelovanje neutronskeg spektra na osnovu aktivacione analize

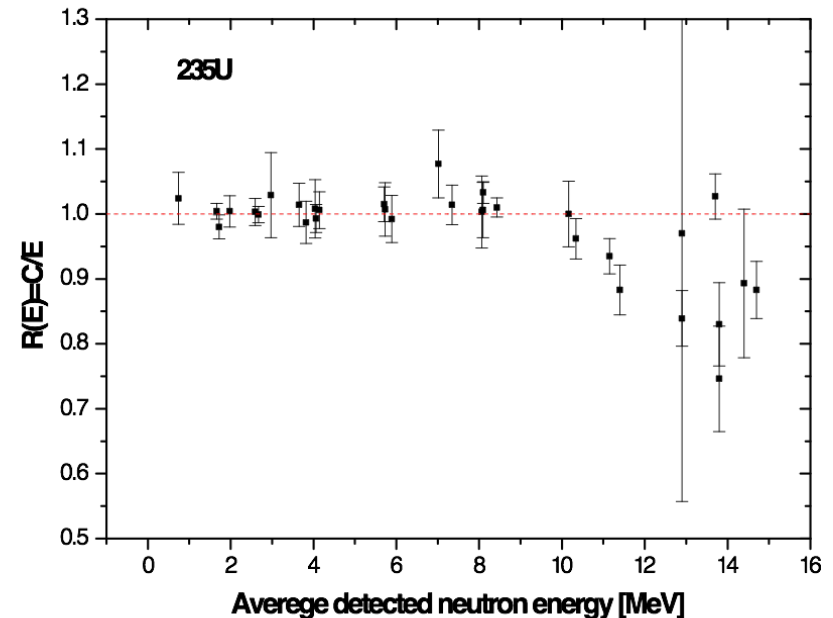
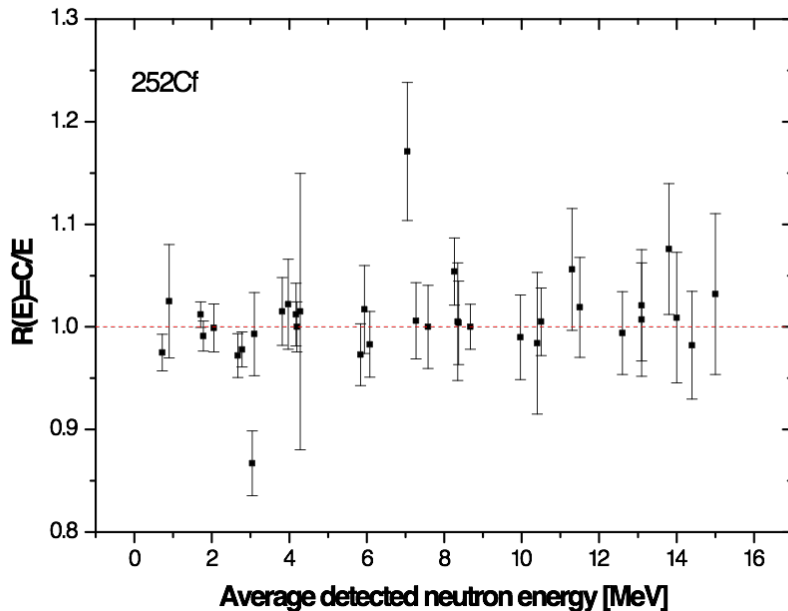
- Pouzdani eksperimentalni podaci o PFNS su veoma važni za bolje razumevanje procesa fisije kao i dizajn inovativnih reaktora.
- Razumevanje ^{235}U PFNS je od velike važnosti za ekonomičnu i sigurnu upotrebu nuklearne energije.

- Neslaganja između eksperimentalnih i modeliranih podataka
- Neslaganja između mikroskopskih i makroskopskih podataka
- Modeliranje neutronskeg spektra na osnovu aktivacione analize može dati neke nove informacije.



Modelovanje neutronskega spektra na osnovu aktivacione analize

- Računate srednje vrednosti efikasne preseka za određene neutronske reakcije, korišćenjem diferencijalnih eksperimentalnih PFNS, u mnogim slučajevima ne mogu na zadovoljavajući način reprodukovati integralna merenja efikasne preseka.
 - $C/E = \text{Calc.} / \text{Exp. spectrum-averaged cross sections} = \int \sigma(E) N(E) dE / \int N(E) dE$



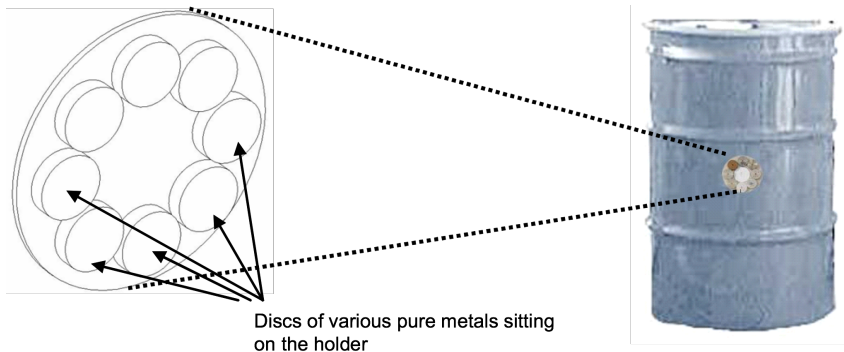
Odnos računatih i eksperimentalnih srednjih efikasne preseka za ^{252}Cf and ^{235}U

Modelovanje neutronskog spektra na osnovu aktivacione analize

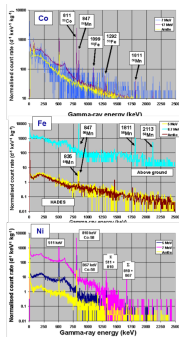
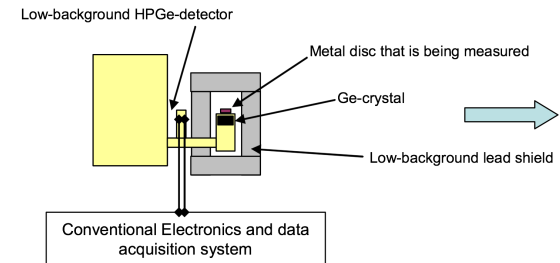
•DONA method

$$A_k \propto \sum_i \sigma_{ki} \Phi_i$$

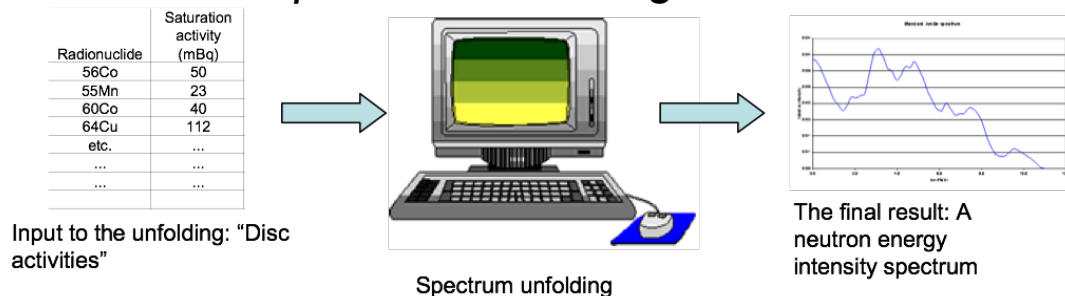
Step 1 Irradiation at measurement site



Step 2 Gamma measurements

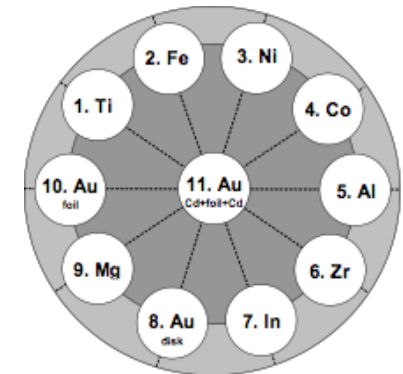
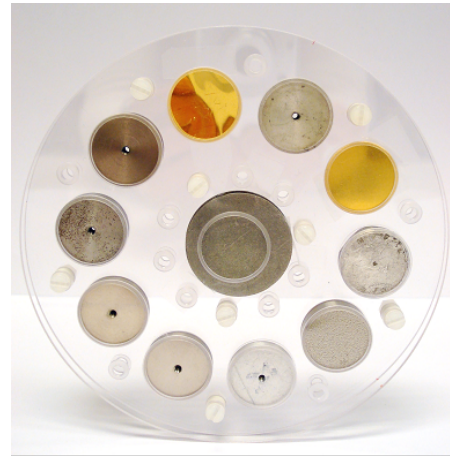


Step 3 Spectrum unfolding

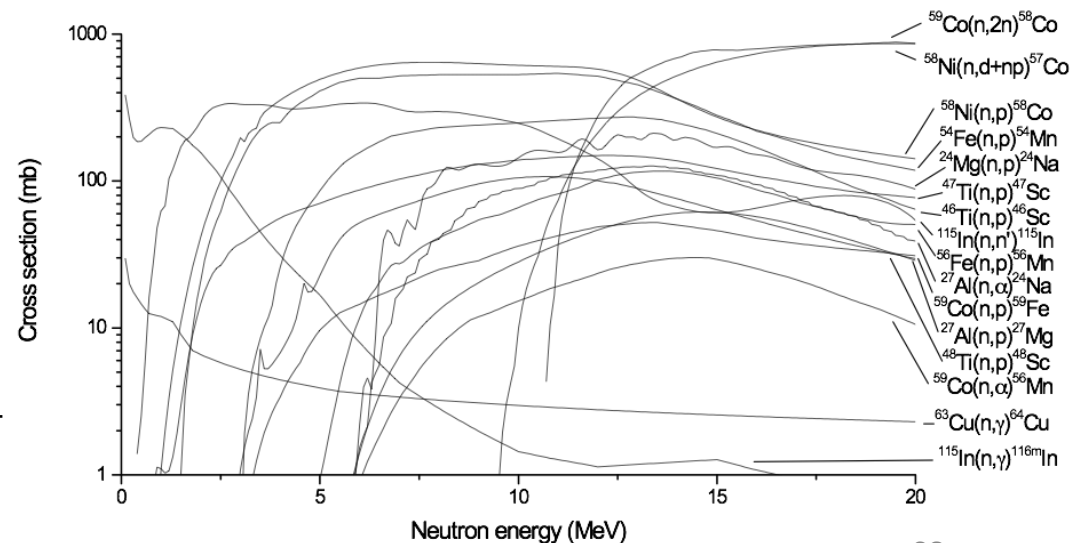


Modelovanje neutronskega spektra na osnovu aktivacione analize

•DONA detector



	Disk material	Diameter (mm)	thickness (mm)	inner hole	mass (g)
1	Ti	20	5	Yes	7
2	Fe	20	5	Yes	12,1
3	Ni	20	5	Yes	13,8
4	Co	20	5	Yes	13,6
5	Al	20	5	Yes	4,2
6	Zr	20	5		
7	In	20	5	No	11,4
8	Au-disk	20	5	No	
9	Mg	20	5	Yes	2,7
10	Au-foil	20	1	No	
11	Au-foil in Cd	20	1	No	



Modelovanje neutronskog spektra na osnovu aktivacione analize

Unfolding postupak

$$M_k + \varepsilon_k = \sum_i \sigma_{ik} \Phi_i \quad k = 1,10; \quad i = 1,100$$

}

M_k = merena aktivnost

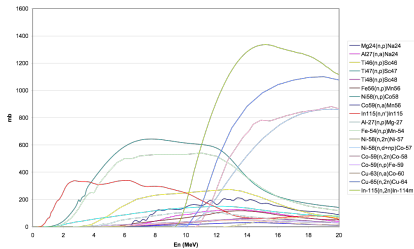
ε_k = greška merenja

σ_{ki} = efikasni presek

Φ_i = neutronski spektar

Radionuclide	Specific activity (mBq/g)
⁵⁶ Co	50
⁵⁵ Mn	23
⁶⁰ Co	40
⁶⁴ Cu	112
...	...
...	...

Measured disk activities

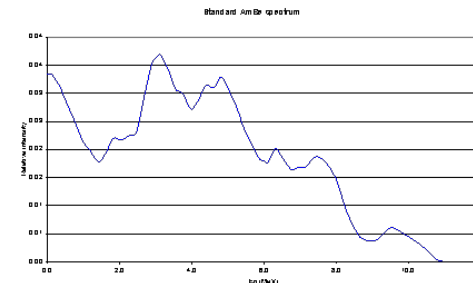


Default neutron spectra

Cross section data



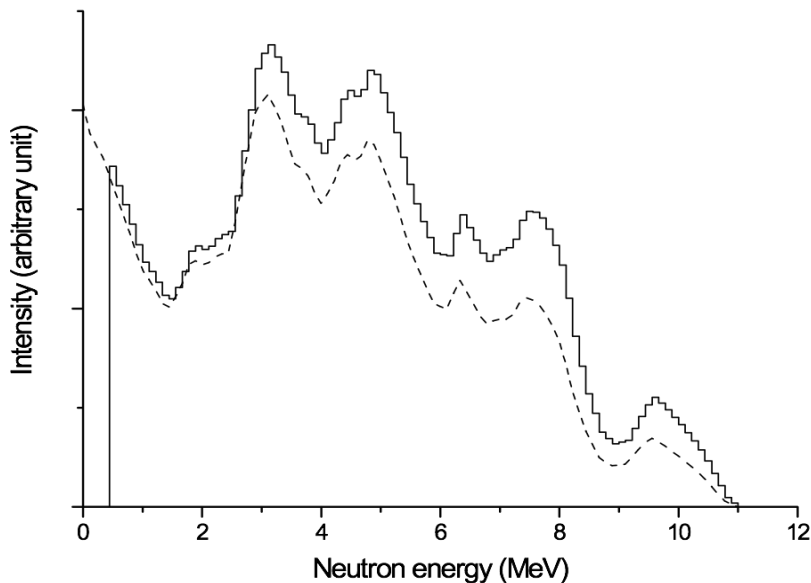
Spectrum unfolding



The final result: a neutron energy intensity spectrum

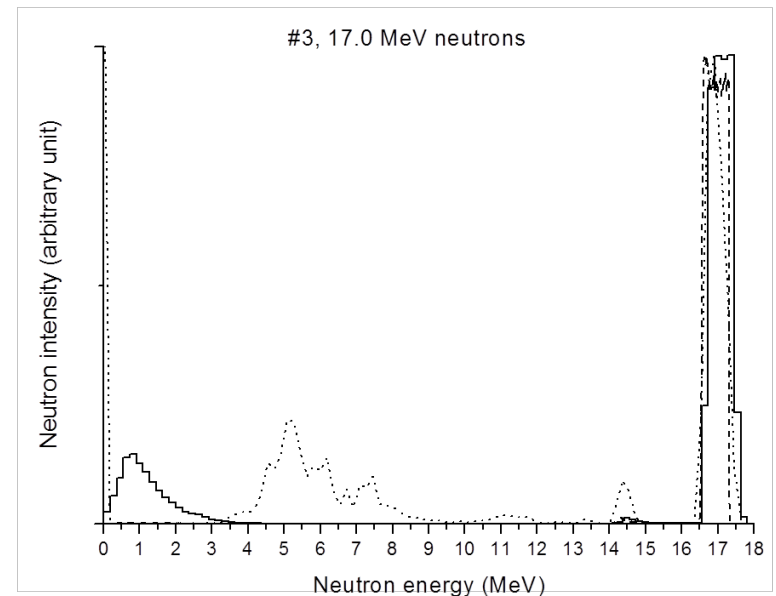
Modelovanje neutronskega spektra na osnovu aktivacione analize

DONA test i validacija



AmBe reference source

fluence rate = 40 n/cm² s
irradiation time = 3.8 d
chi-2 value = 1.24

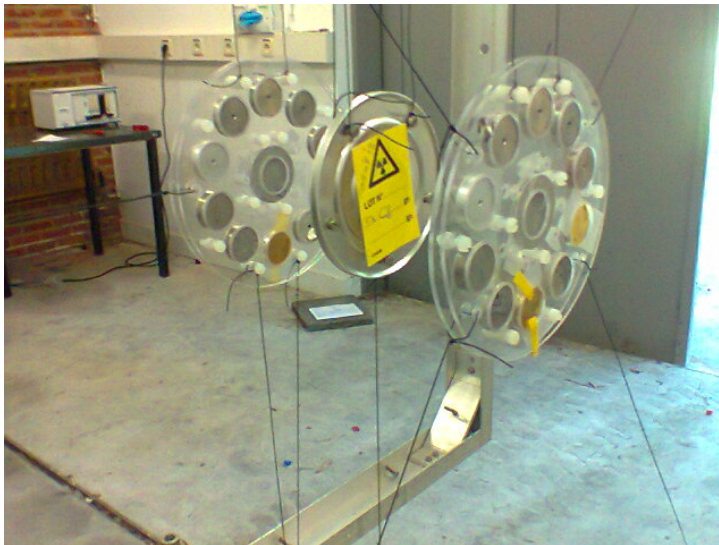


Quasi mono-energetic neutron fields
at the IRMM Van de Graaff accelerator

————— Measured
..... Bonner spheres
- - - - - MC calculated

Modelovanje neutronskega spektra na osnovu aktivacione analize

- Testiranje DONA metoda sa standardnim neutronskega spektrom nakon spontane fisije ^{252}Cf
- 2 DONA diska
- 42 dana ozračivanja
 - Neutronskega fluks: $\sim 220 \text{ ncm}^{-2}\text{s}^{-1}$
 - Rastojanje izvor - detektor: 7.7 cm



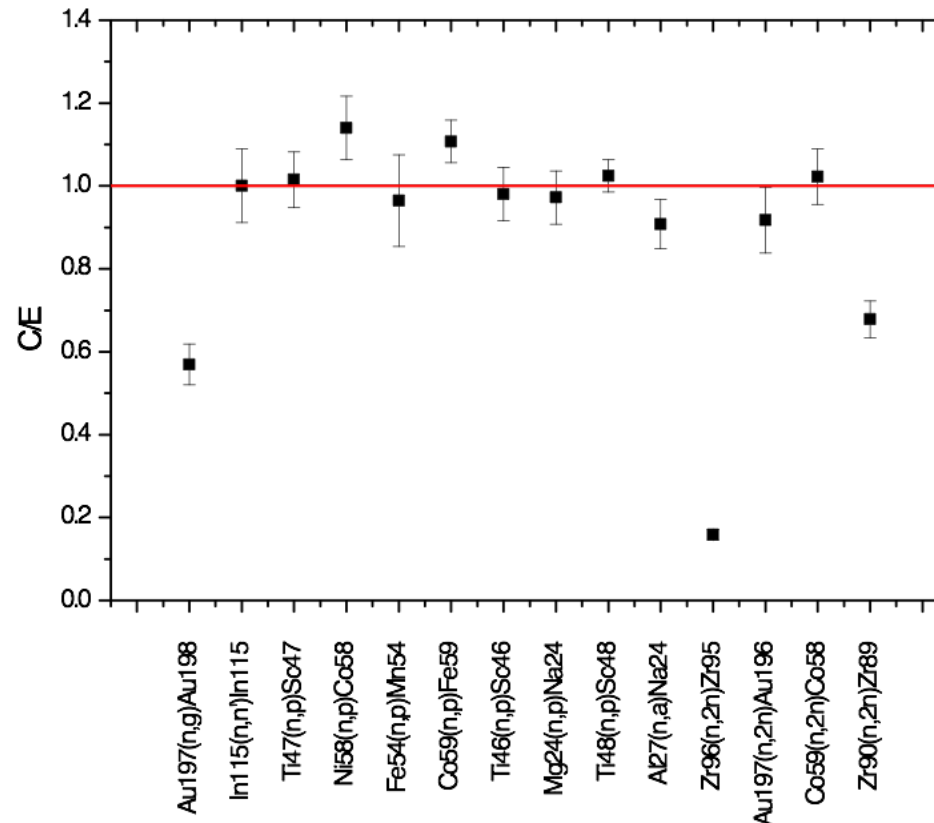
Modelovanje neutronskega spektra na osnovu aktivacione analize

- Gama spektroskopsko merenje - HADES

Activation reaction	$\langle E \rangle$ [MeV]	Half life	Main gamma-ray line [keV]	A_{sk} [10 ⁻²⁴ Bq atom ⁻¹]
¹⁹⁷ Au(n,g) ¹⁹⁸ Au, foil	0.72	2.68 d	411	26.2(25)
¹⁹⁷ Au(n,g) ¹⁹⁸ Au, foil Cd shielded	0.72	2.68 d	411	26.3(25)
¹⁹⁷ Au(n,2n) ¹⁹⁶ Au foil	10.5	6.18 d	333	1.45(19)
¹⁹⁷ Au(n,2n) ¹⁹⁶ Au foil Cd shielded	10.5	6.18 d	333	1.37(9)
¹⁹⁷ Au(n,g) ¹⁹⁸ Au	0.72	2.68 d	411	26.2(23)
¹¹⁵ In(n,n') ¹¹⁵ In	2.67	4.49 h	336	38.3(32)
⁴⁸ Ti(n,p) ⁴⁸ Sc	3.82	3.35 d	159	3.84(25)
⁵⁸ Ni(n,p) ⁵⁸ Co	4.2	70.8 d	811	20.6(14)
⁵⁴ Fe(n,p) ⁵⁴ Mn	4.28	312 d	835	18.2(12)
⁵⁹ Co(n,p) ⁵⁹ Fe	5.94	44.5 d	1099	0.309(14)
⁴⁶ Ti(n,p) ⁴⁶ Sc	6.08	3.35 d	889	2.81(18)
²⁴ Mg(n,p) ²⁴ Na	8.26	15.0 h	1369	0.430(28)
⁴⁸ Ti(n,p) ⁴⁸ Sc	8.35	1.82 d	159	0.083(3)
²⁷ Al(n,a) ²⁴ Na	8.67	15.0 h	1369	0.224(15)
⁹⁰ Zr(n,2n) ⁸⁹ Zr	10.2	64.03 d	724	8.82(64)
¹⁹⁷ Au(n,2n) ¹⁹⁶ Au	10.5	6.18 d	333	1.20(10)
⁵⁹ Co(n,2n) ⁵⁸ Co	13.1	70.9 d	811	0.079(5)
⁹⁰ Zr(n,2n) ⁸⁹ Zr	14.4	3.27 d	909	0.064(4)

Modelovanje neutronskega spektra na osnovu aktivacione analize

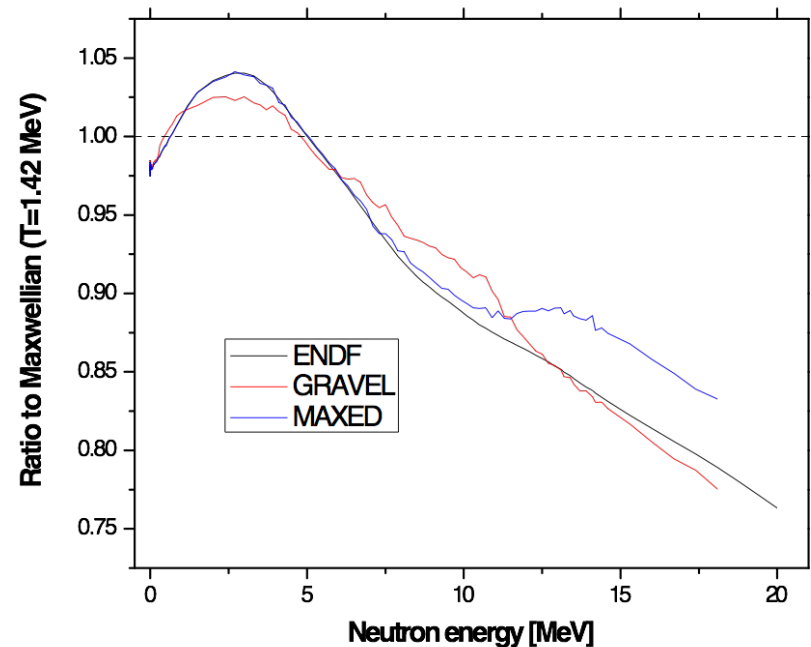
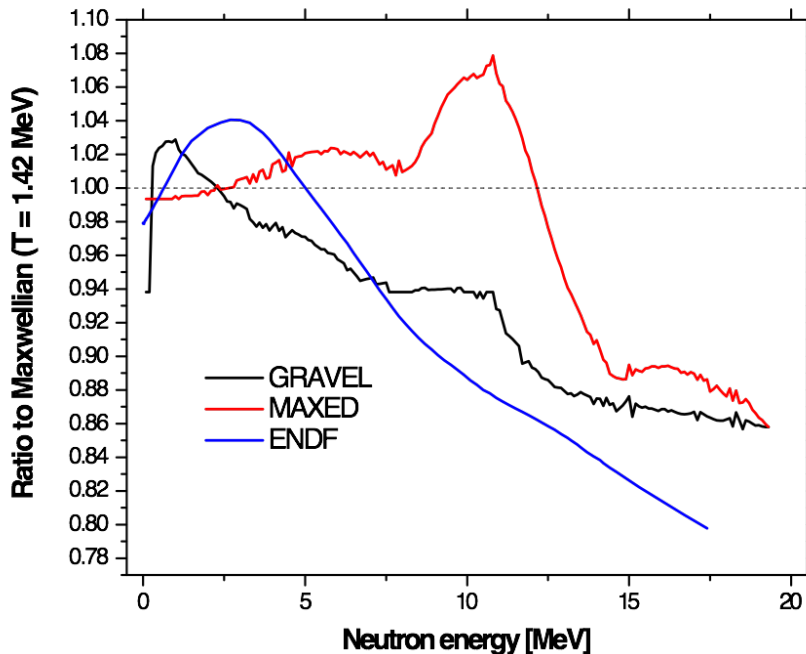
- Poređenje merenih i računatih vrednosti



Modelovanje neutronskega spektra na osnovu aktivacione analize

Neutronske spektr

- Unfolding
 - 1) Maxwellian spectrum with $T=1.42$ MeV
 - 2) Mannhart calculated ^{252}Cf neutron spectrum



Poređenje dobijenog spektra sa standardnim ENDF ^{252}Cf spektrom

Određivanje parametara nuklearne strukture metodom merenja dvostepenih gama kaskada nakon neutronskeg zahvata

- Neophodno je dobijanje pouzdanih eksperimentalnih podataka za gustinu stanja jezgra i funkciju jačine prelaza
- **Razvoj metoda za određivanje ρ i Γ**
- Glavni problem : **FWHM $\gg D_i$**
- Metod merenja dvostepenih gama kaskada
- Model kaskadnog gama raspada
- Rezultati za 43 nuklida od ^{28}Al do ^{200}Hg

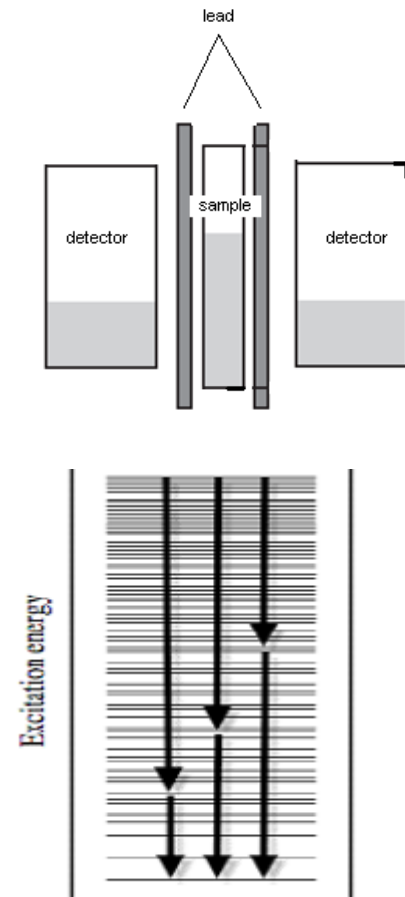
Određivanje parametara nuklearne strukture metodom merenja dvostepenih gama kaskada nakon neutronskeg zahvata

- Dubna metod (FLNF, JINR)
- Merenje dvostepenih gama kaskada nakon neutronskeg zahvata ($n,2\gamma$)



Određivanje parametara nuklearne strukture metodom merenja dvostepenih gama kaskada nakon neutronskeg zahvata

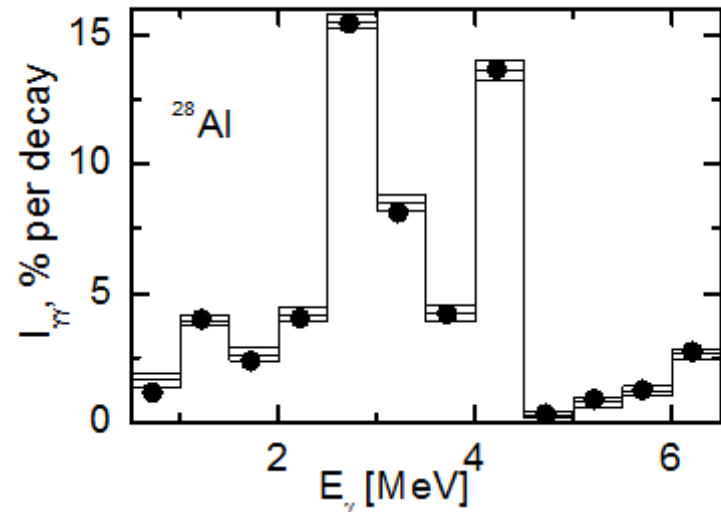
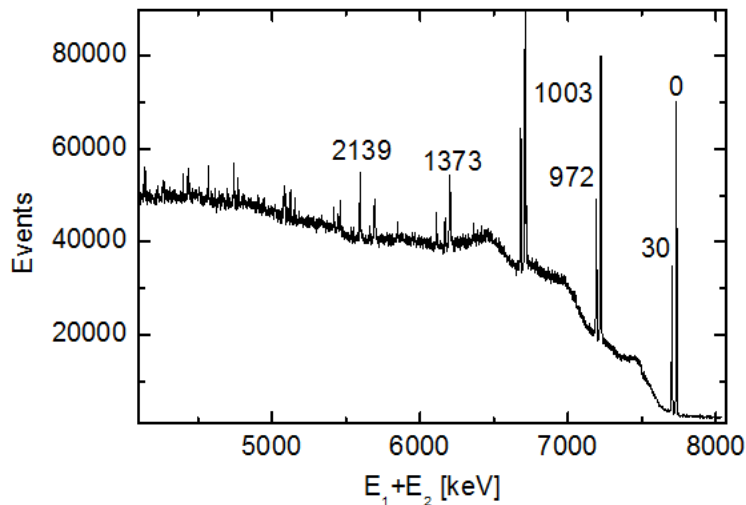
- Merenje dvostepenih gama kaskada nakon neutronskeg zahvata ($n,2\gamma$)
- HPGe detektori u koincidentnom režimu merenja



Određivanje parametara nuklearne strukture metodom merenja dvostepenih gama kaskada nakon neutronskeg zahvata

Intenzitet dvostepenih gama kaskada:

$$I_{\gamma\gamma}(E_1) = \sum_{\lambda,f} \sum_i \frac{\Gamma_{\lambda i}}{\Gamma_{\lambda}} \frac{\Gamma_{if}}{\Gamma_i} = \sum_{\lambda,f,i} \frac{\Gamma_{\lambda i}}{\langle \Gamma_{\lambda i} \rangle} \rho_{\lambda} \Delta E_i \frac{\Gamma_{if}}{\langle \Gamma_{if} \rangle m_{if}}$$



Određivanje parametara nuklearne sutrukture metodom merenja dvostepenih gama kaskada nakon neutronskeg zahvata

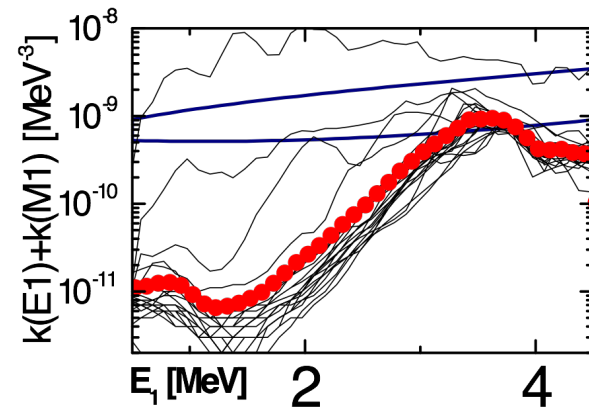
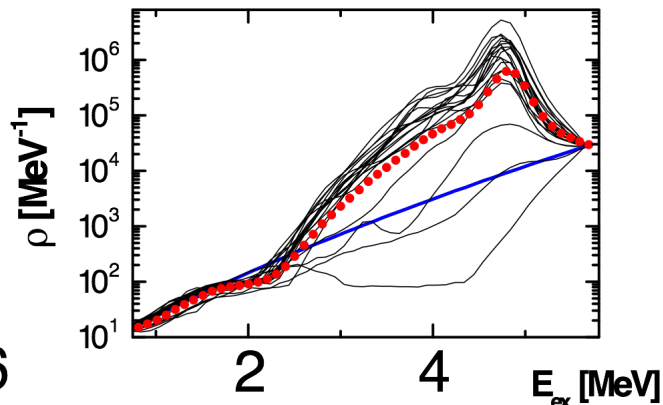
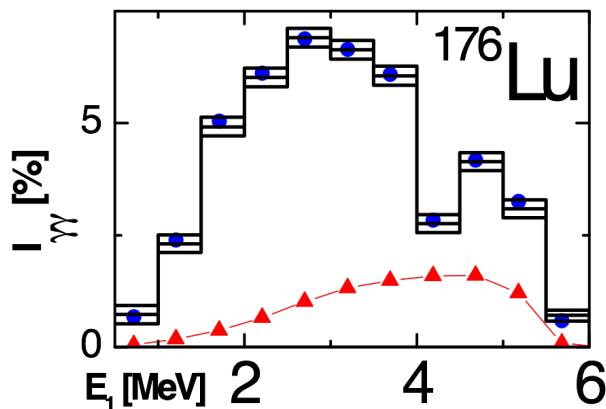
Interativni metod

Korišćenjem iterativnog postupka sa slučajno odabranim funkcijama ρ i Γ , moguće je dobiti najverovatnije vrednosti gustine stanja i radijacione jačine.

N vrednosti eksperimentalnih intenziteta kaskada mogu uvek biti konvertovani u $\sim 2N$ vrednosti ρ i Γ u određenom intervalu:

$$\rho_1 \leq \rho \leq \rho_2$$

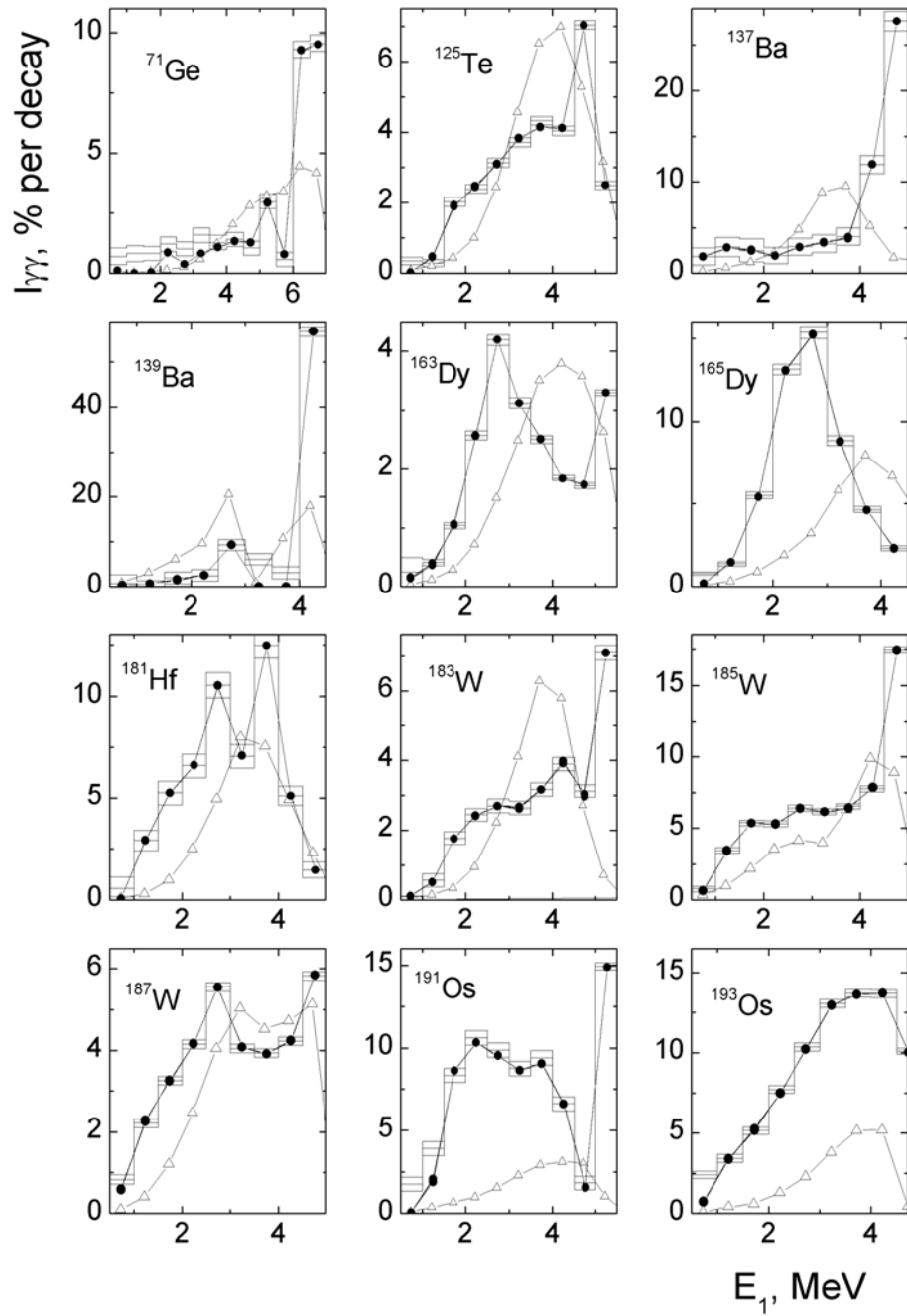
$$\Gamma_1 \leq \Gamma \leq \Gamma_2$$

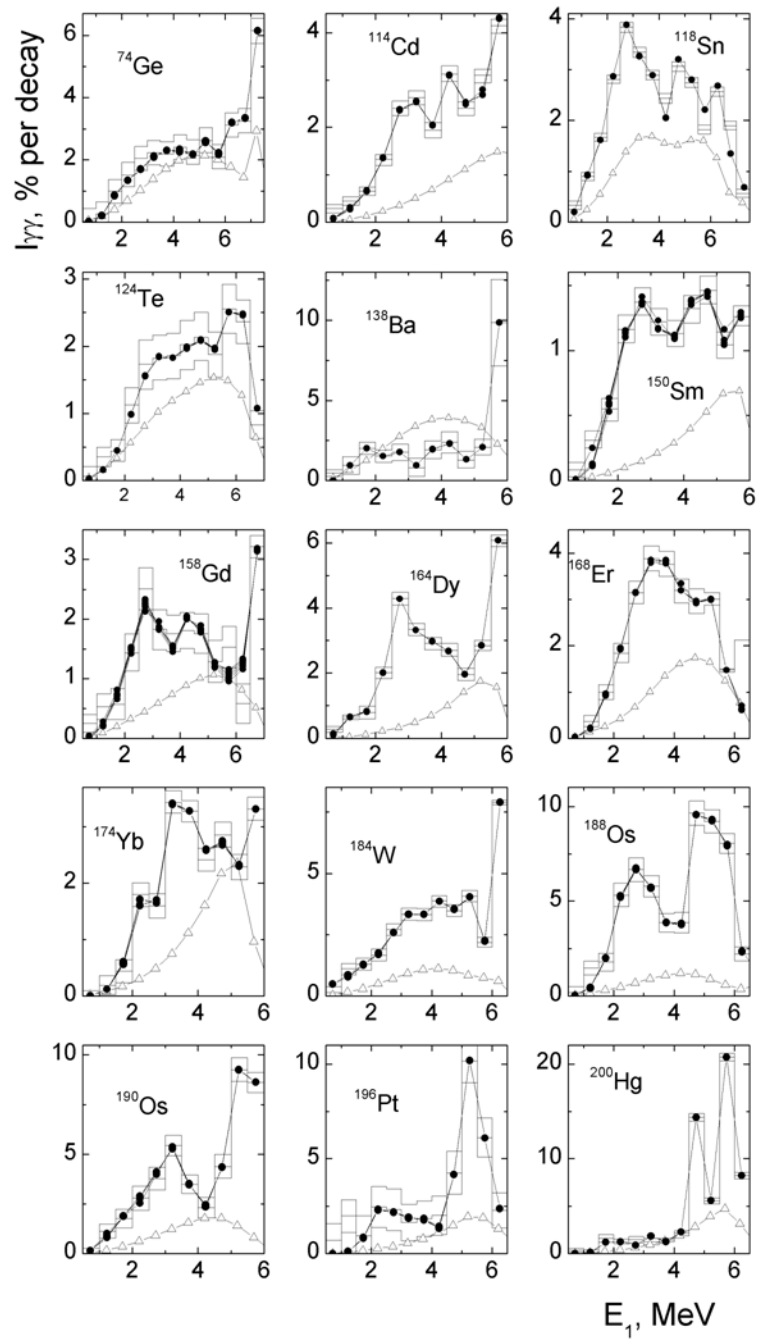


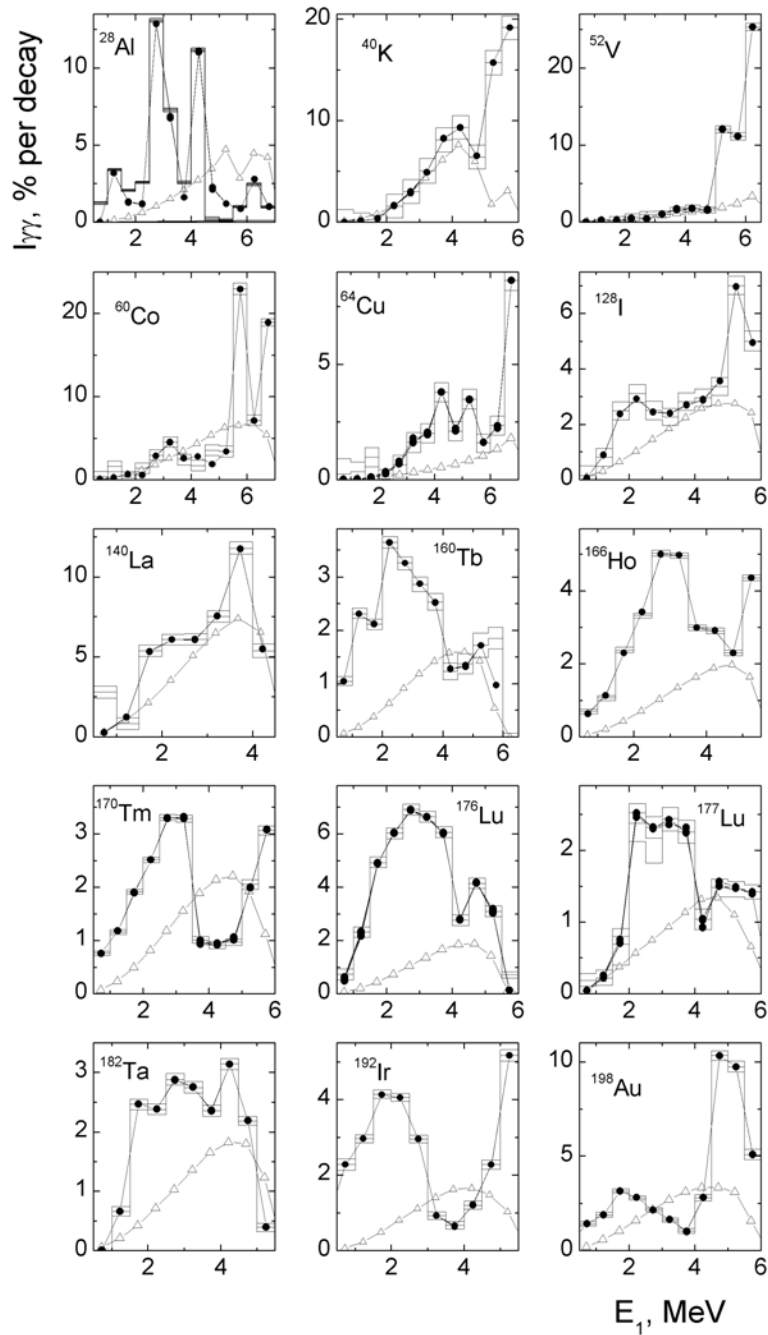
Zaključak

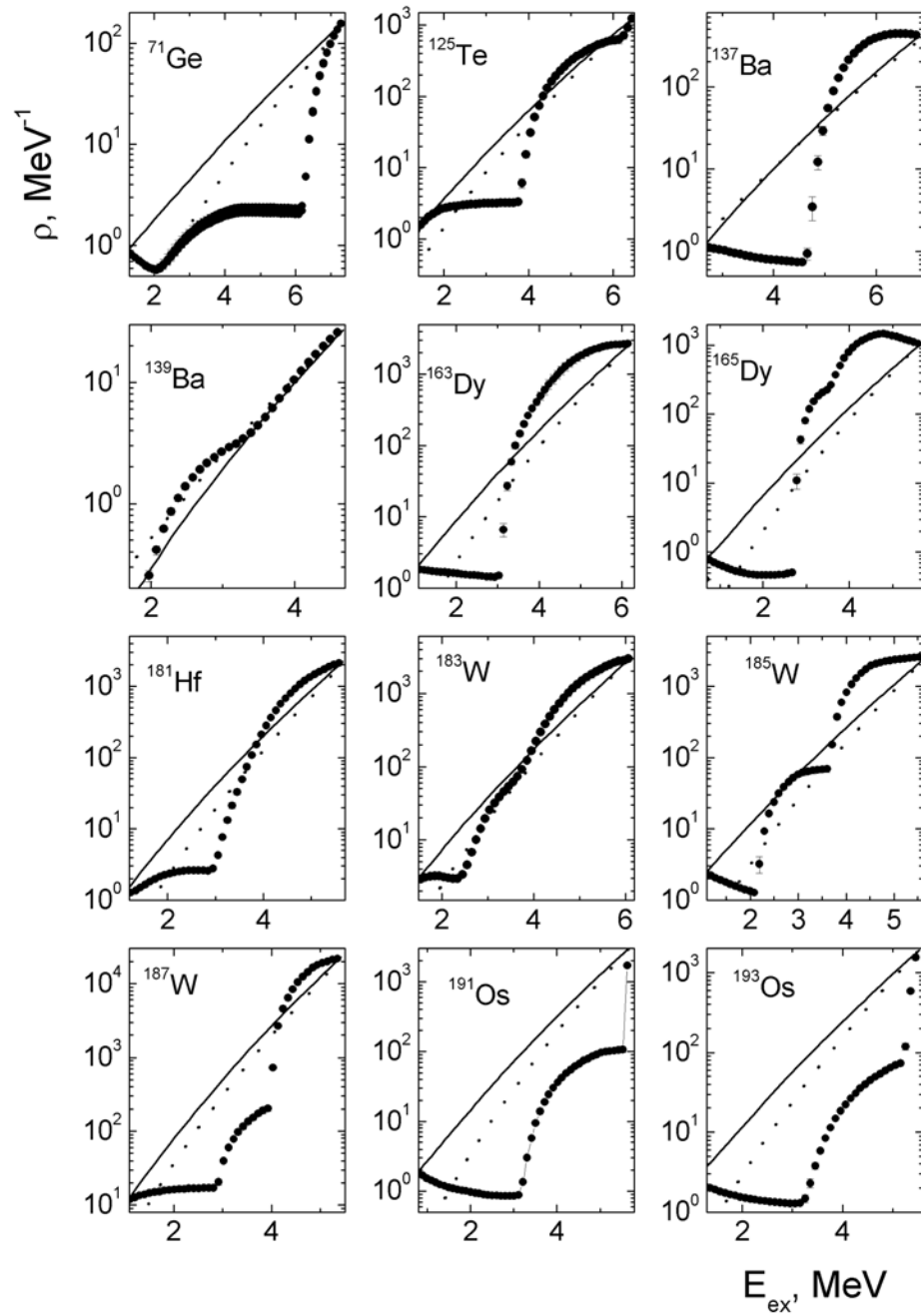
- Nuklearni podaci su važni kako za fundamentalna tako i za primenjena istraživanja.
- Postoji velika potreba za novim merenjima efikasnih preseka za različite neutronske nuklearne reakcije.
- Neophodno je bolje pozavanje PFNS.
- Dosadašnji podaci nameću potrebu za razvojem novih eksperimenata za određivanje parametara strukture atomskog jezgra.

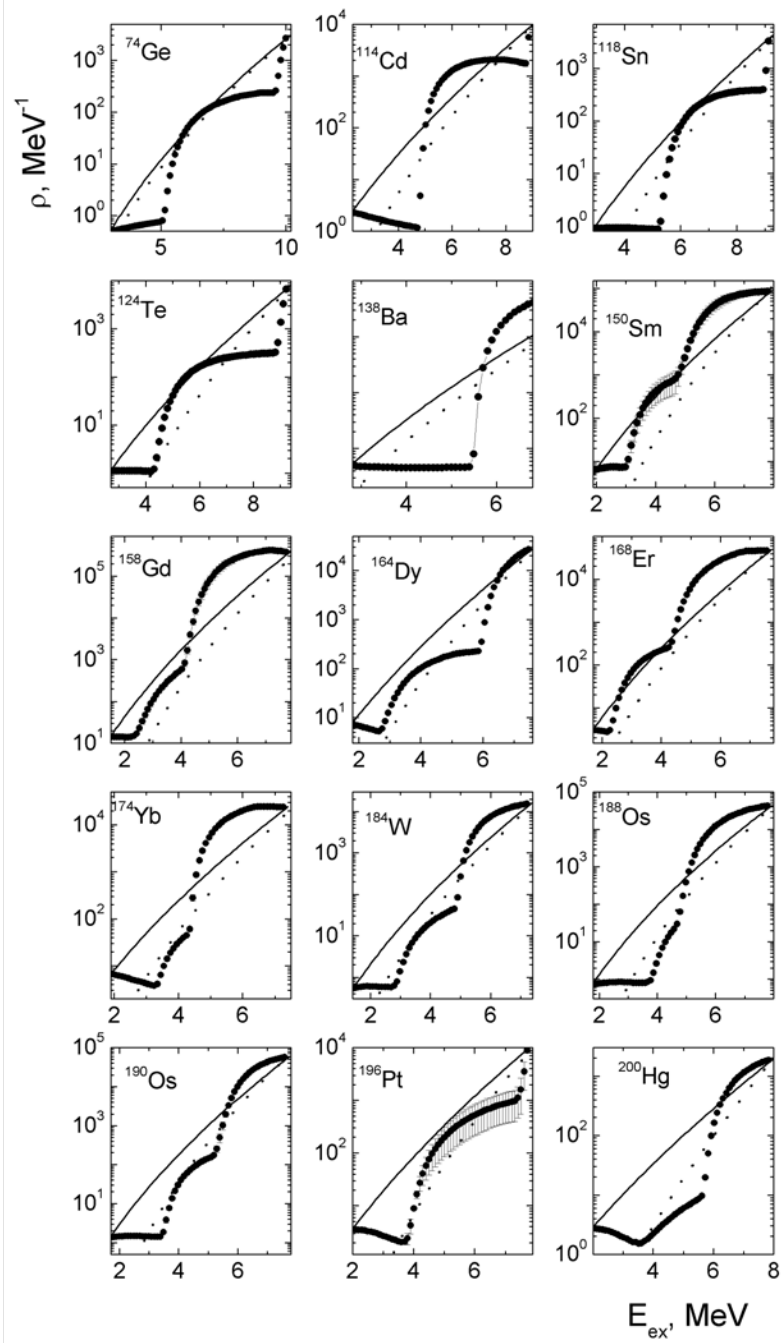
HVALA VAM NA VAŠOJ PAŽNJI!

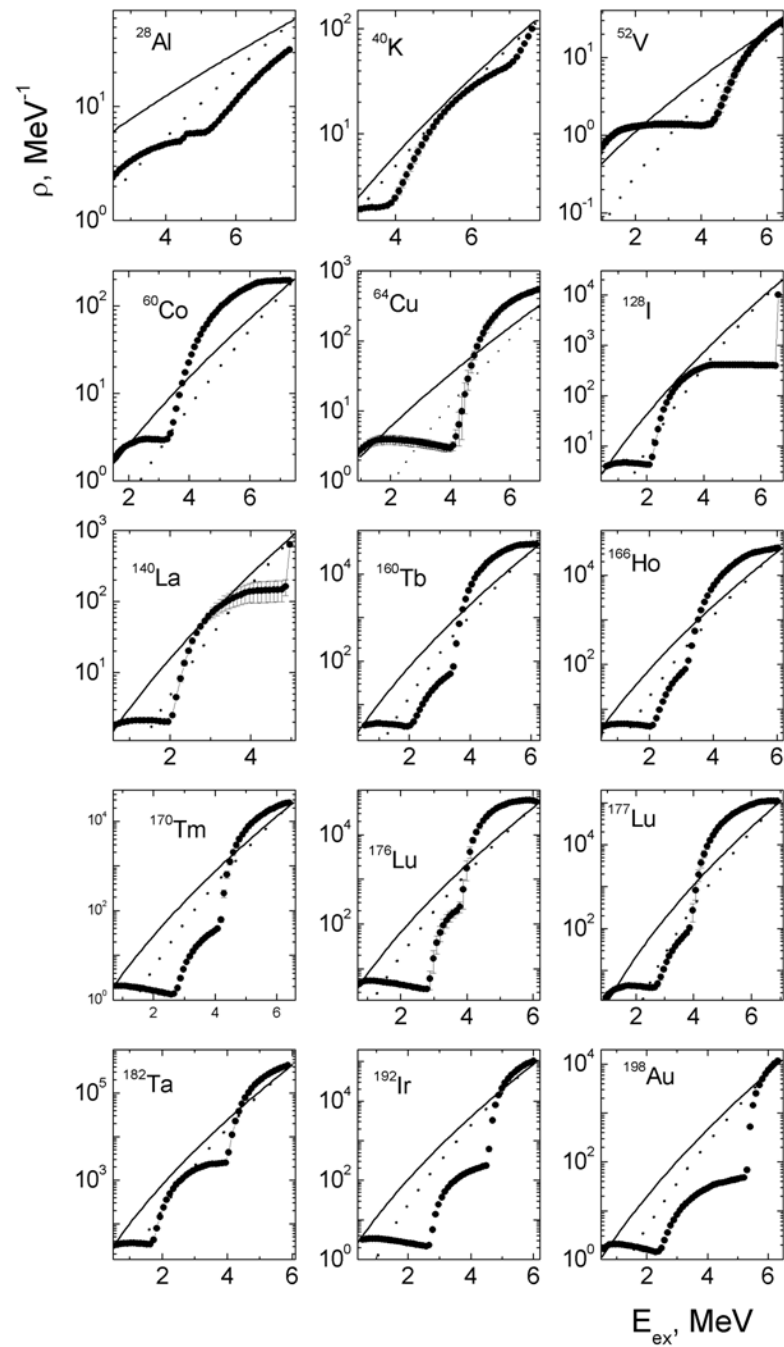


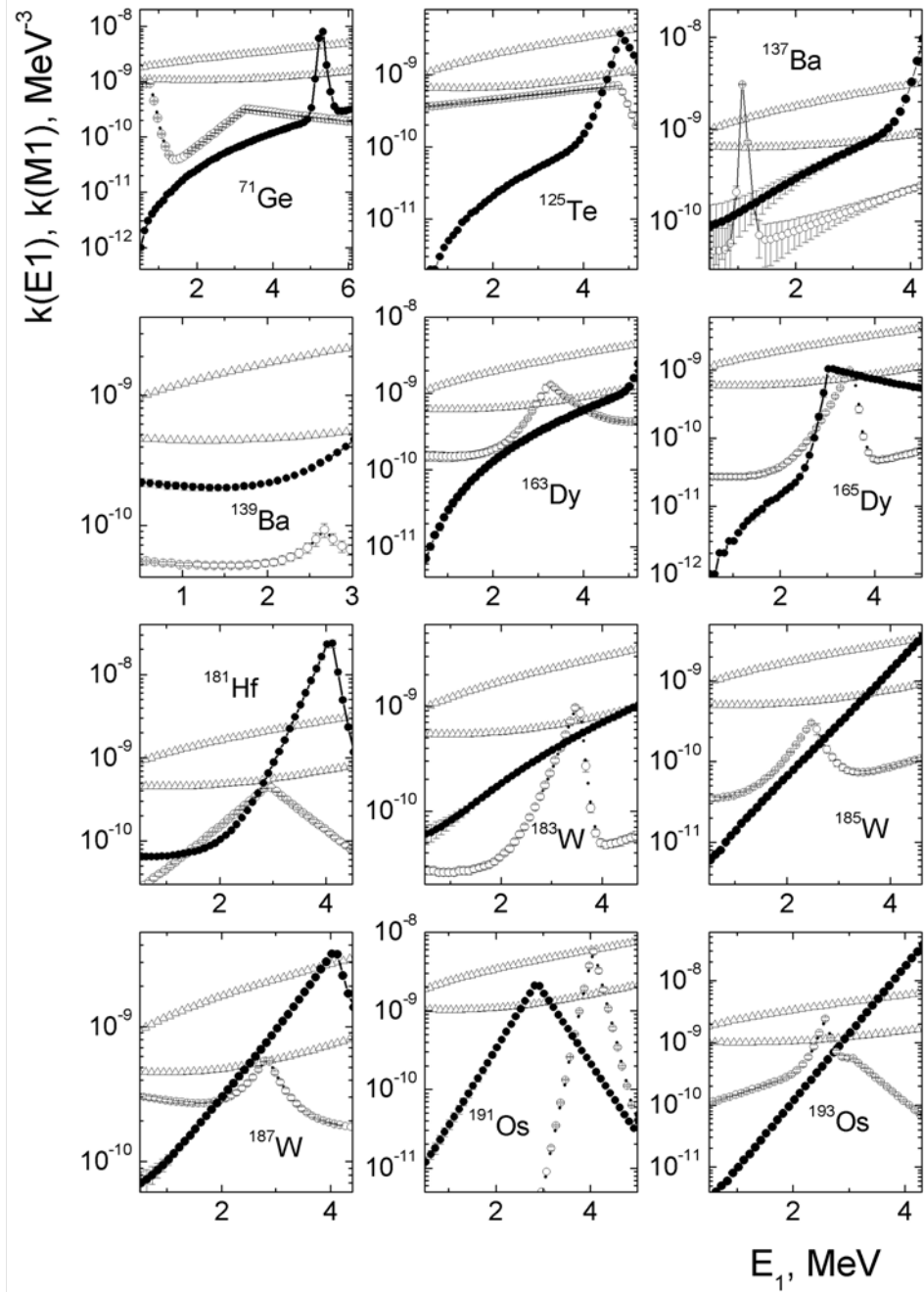


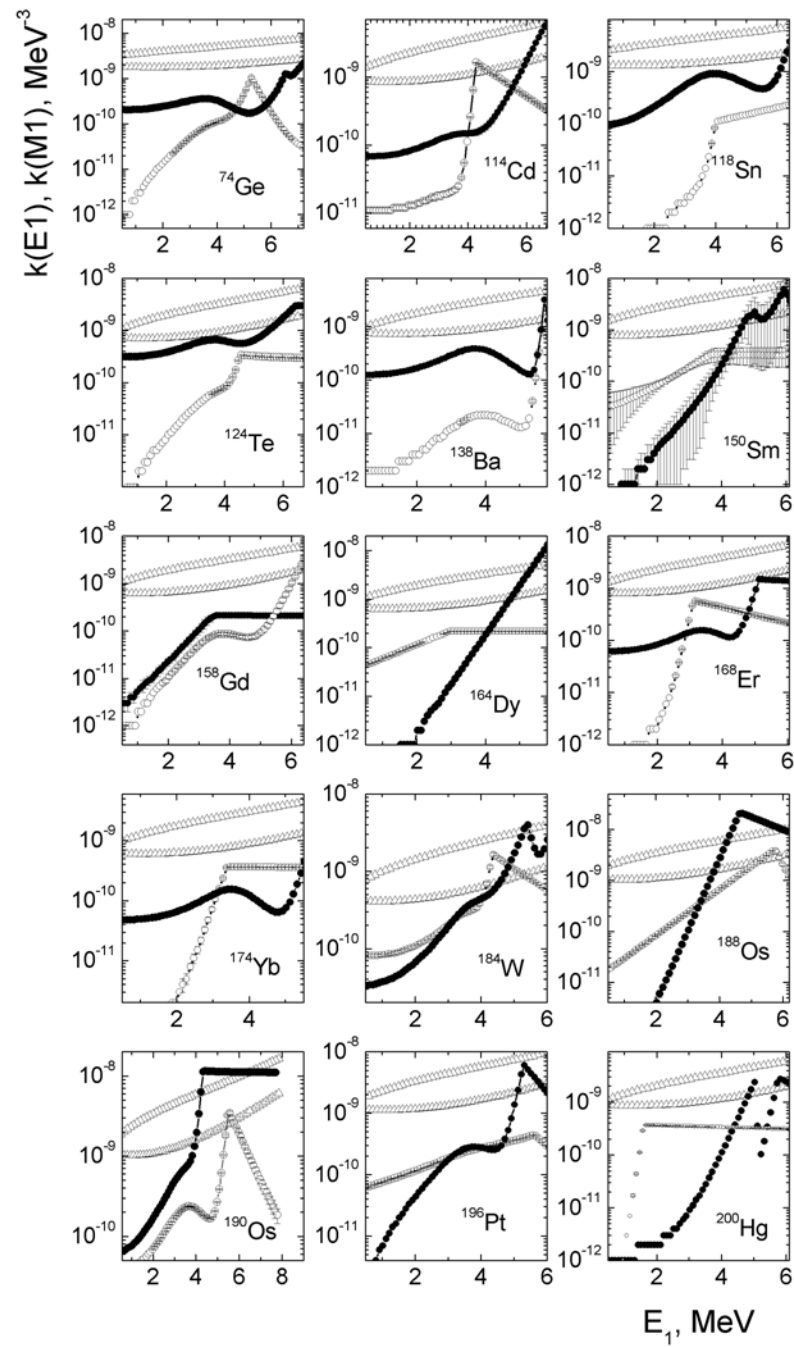


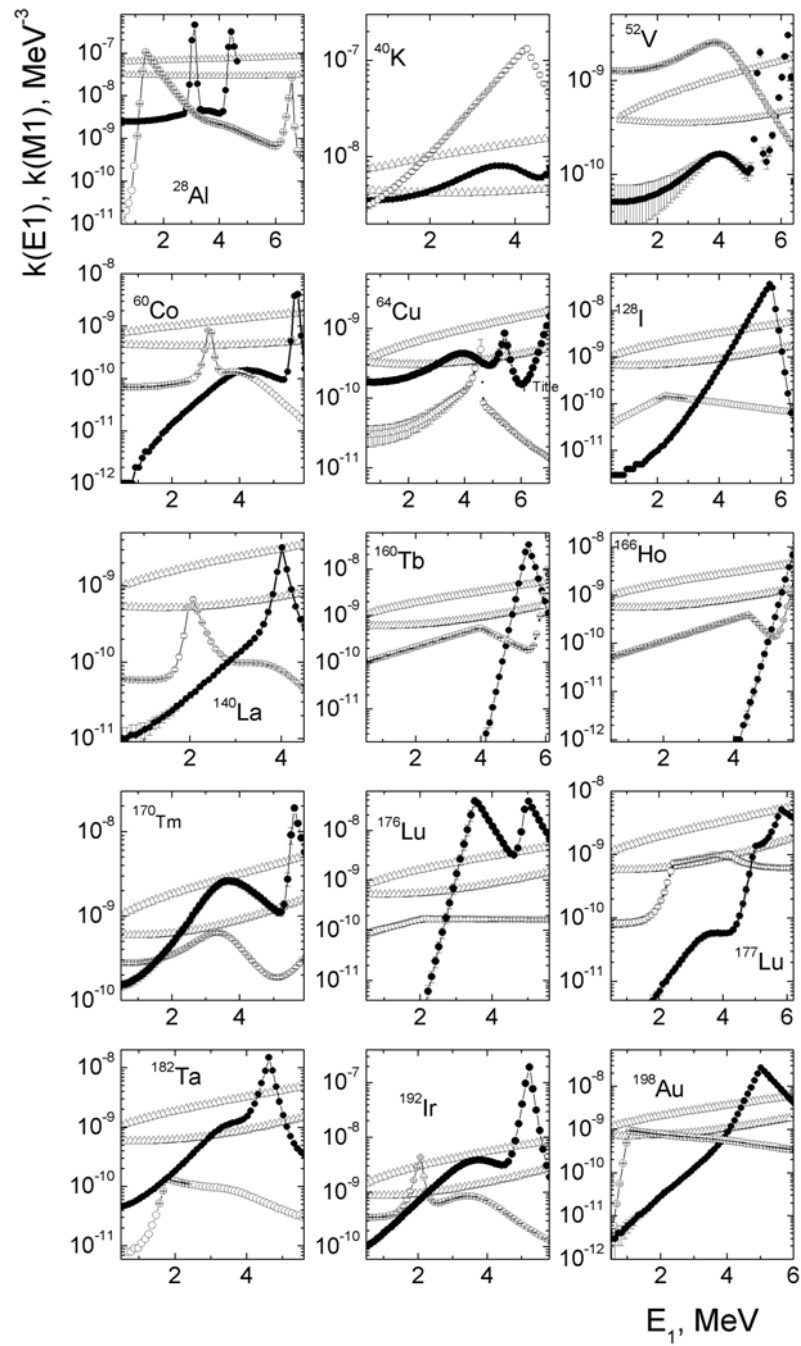


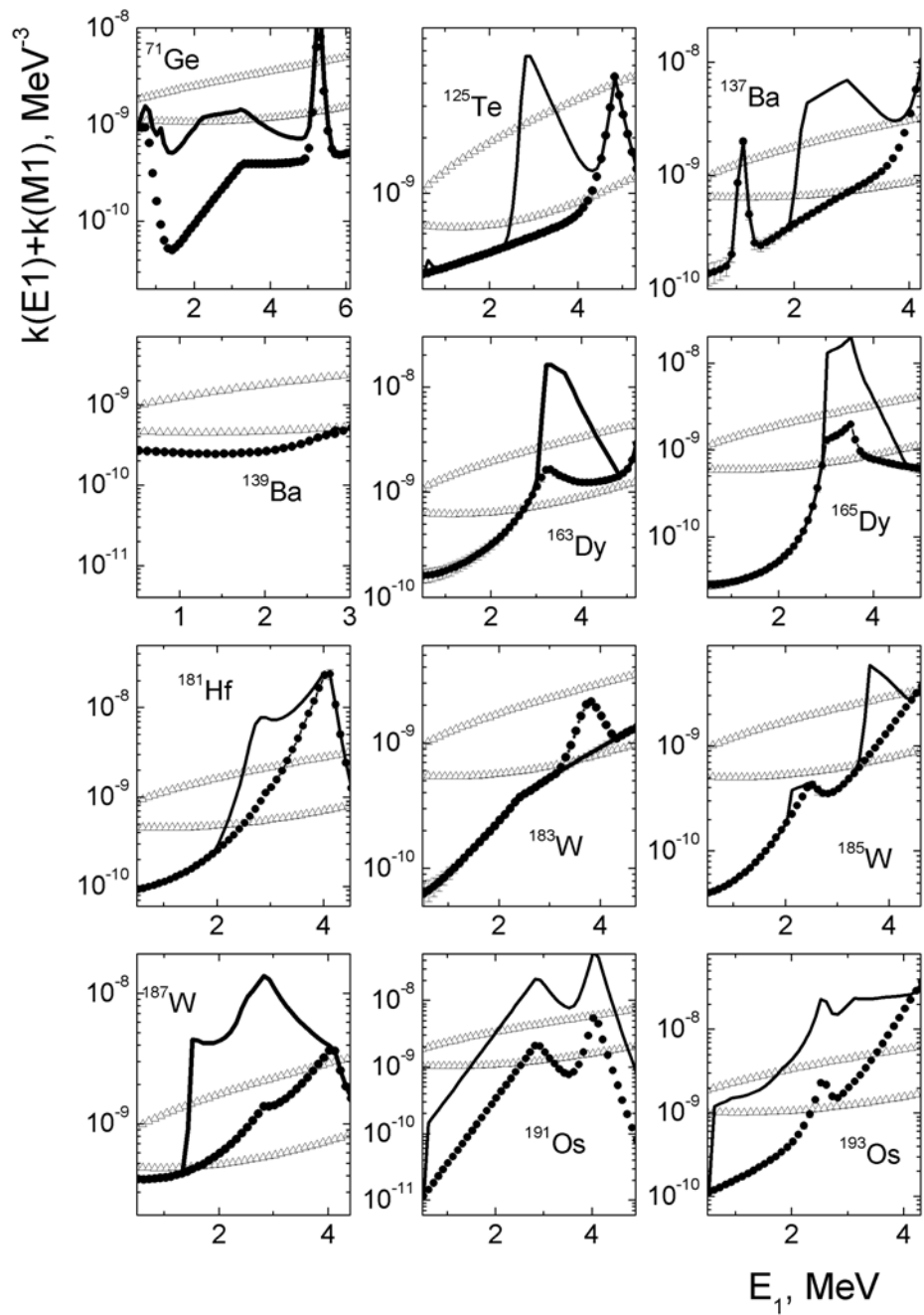


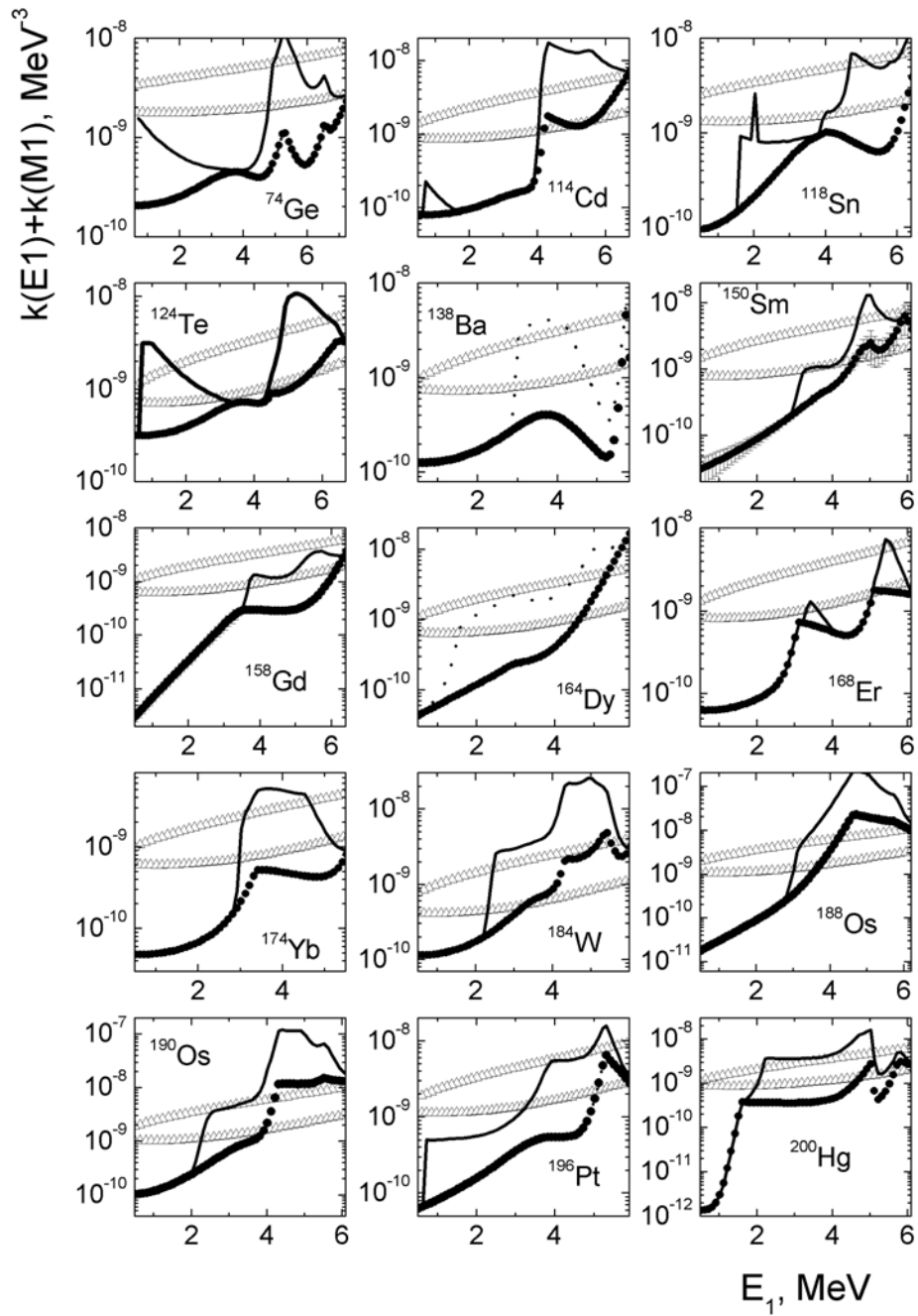


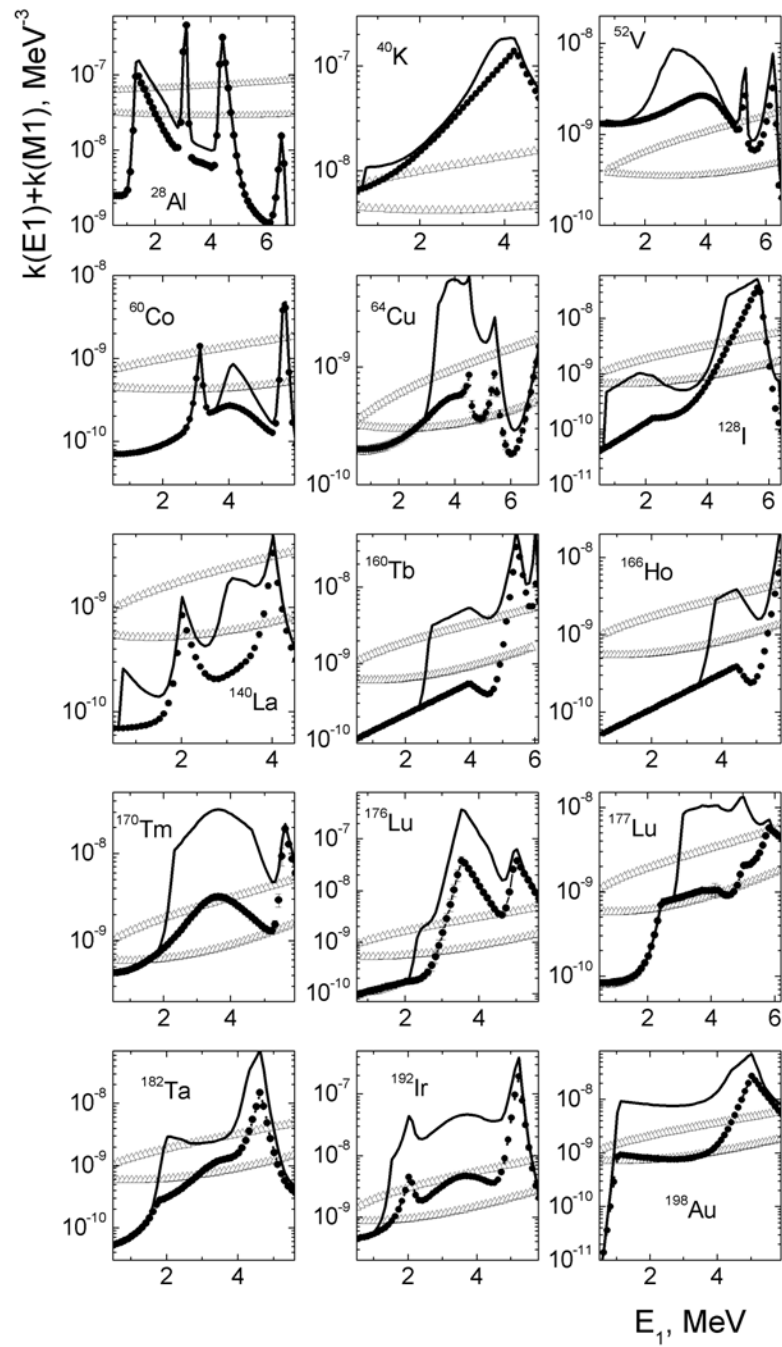


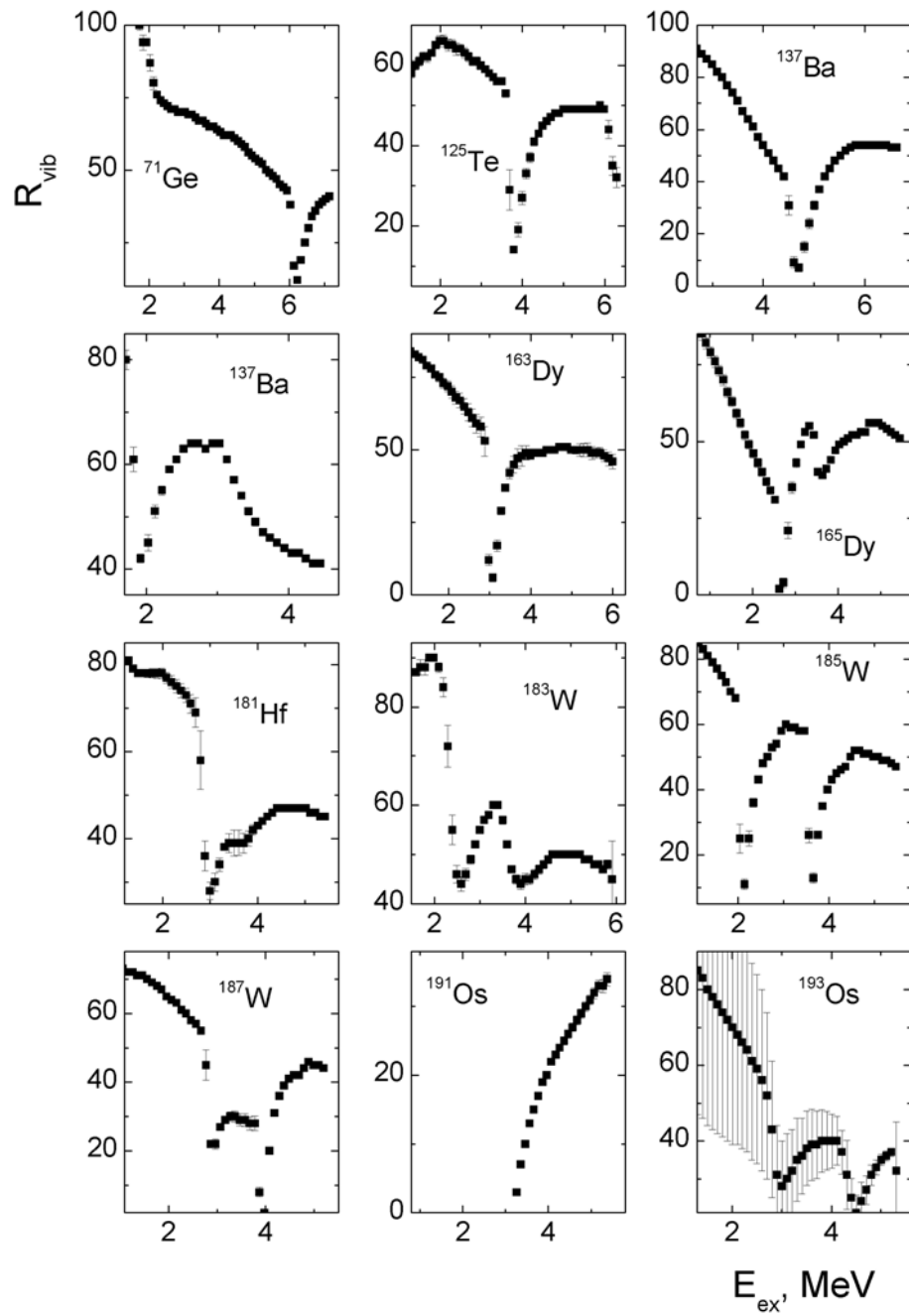


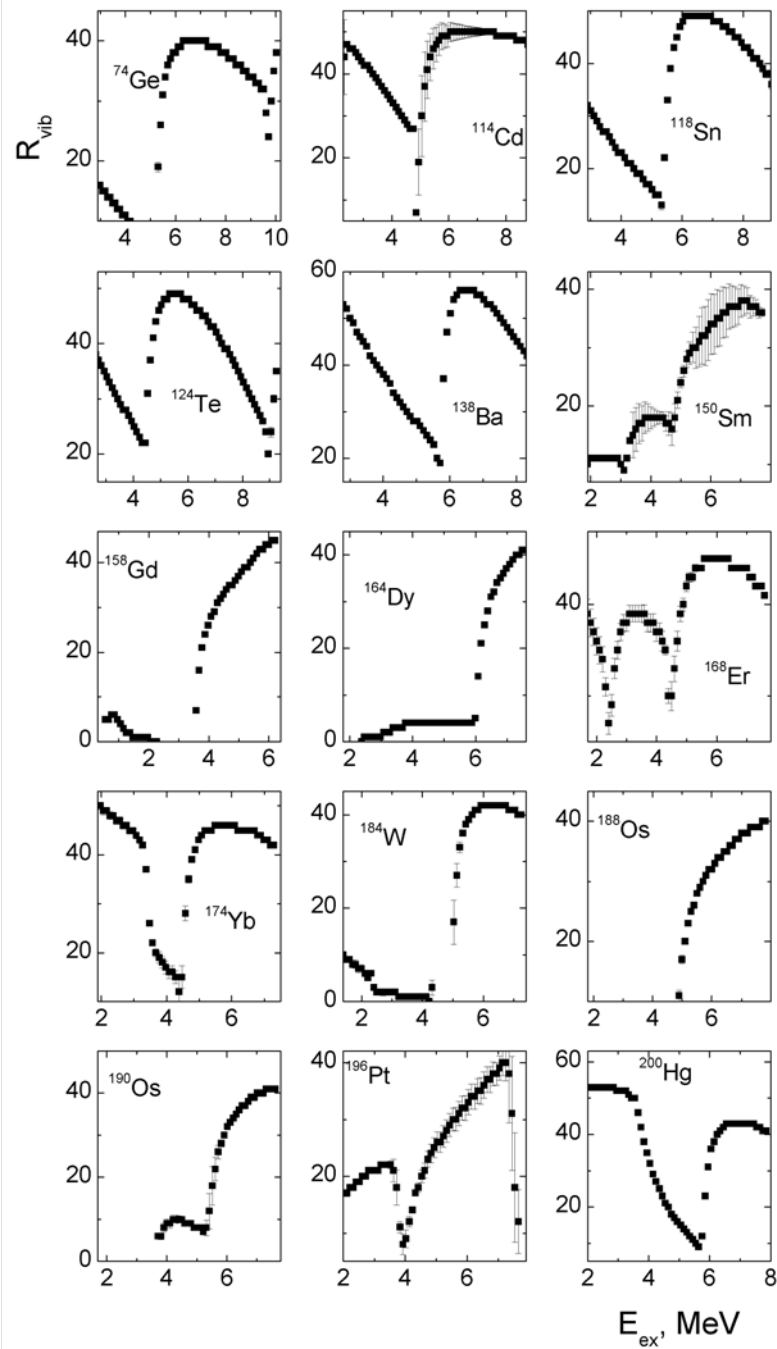


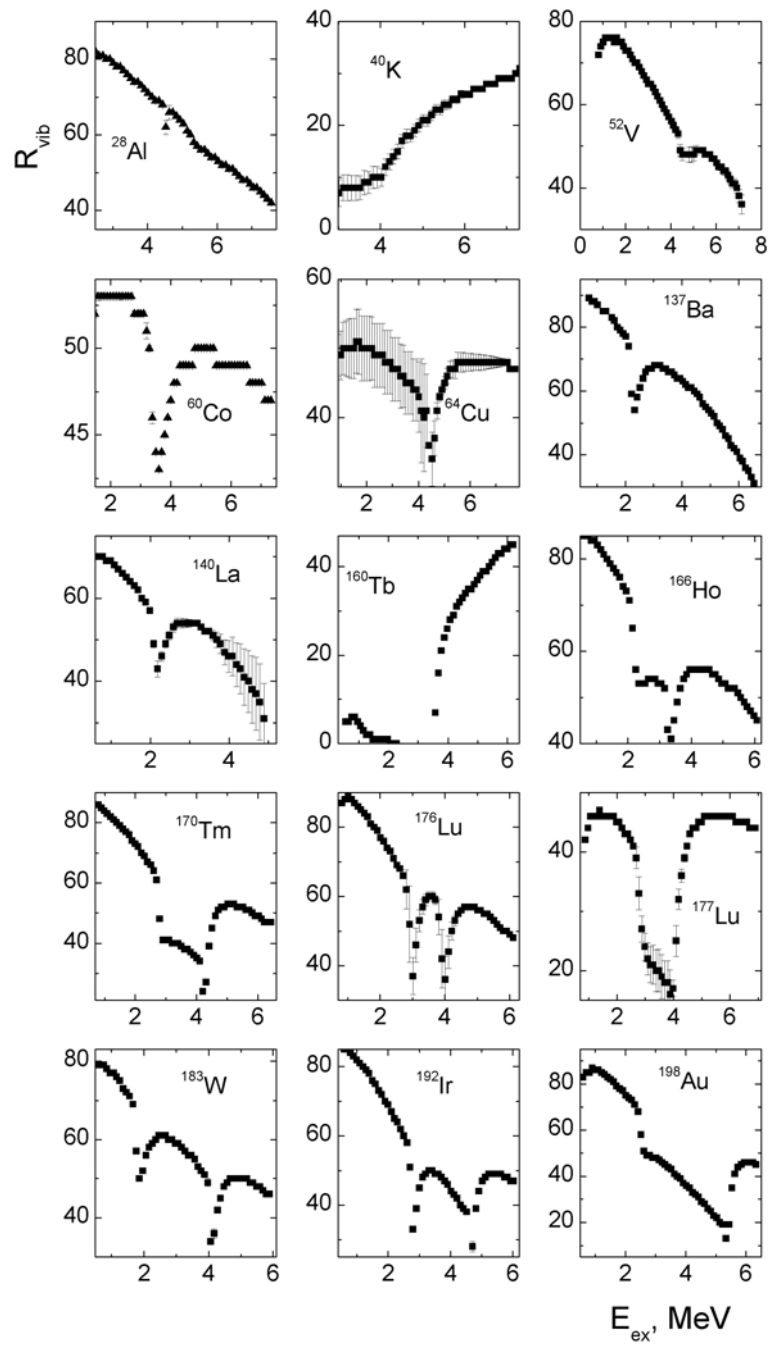


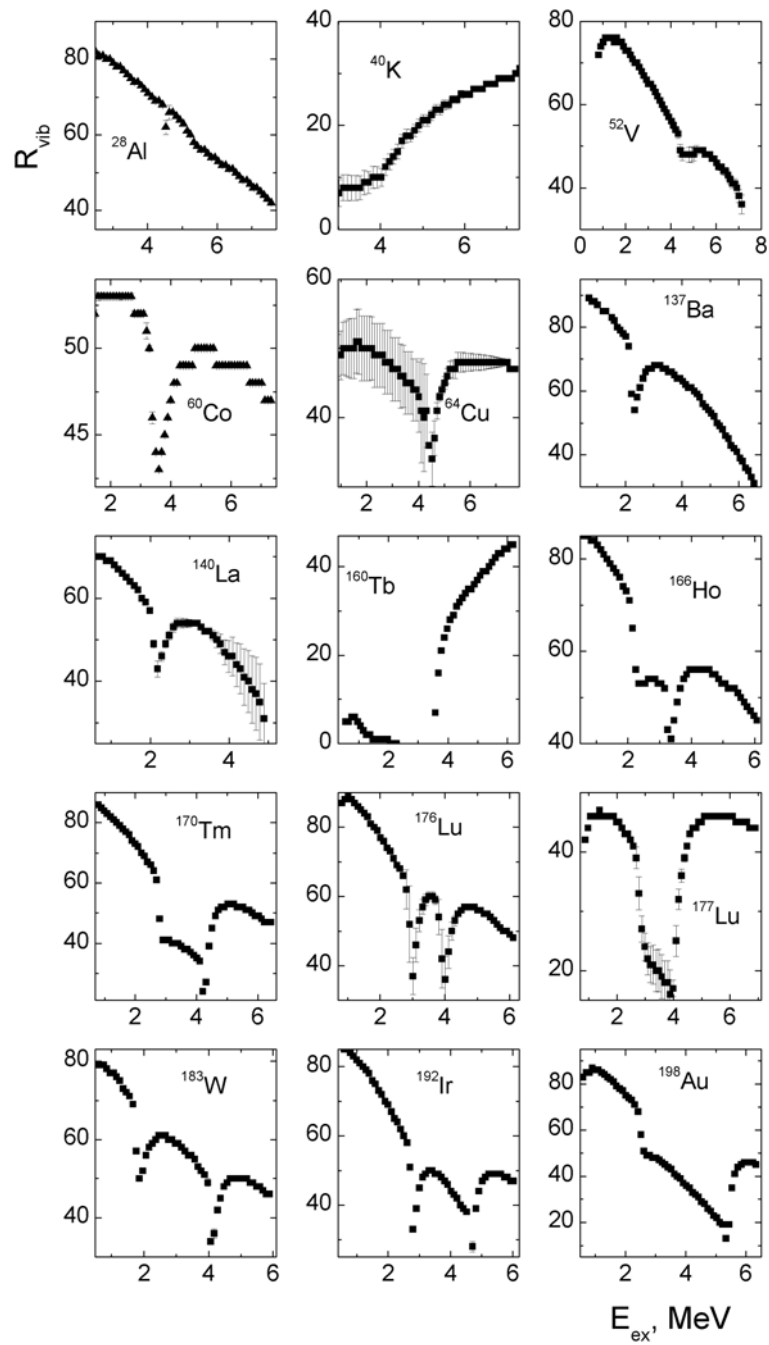












Određivanje parametara nuklearne sutrukture metodom merenja dvostepenih gama kasakada nakon neutronskeg zahvata

- Phenomenological and theoretical representations are combined
-

The model level density

$$\rho_l = \frac{(2J+1)\exp(-(J+1/2)^2/2\sigma^2)}{2\sqrt{(2\pi)}\sigma^3} \Omega_n(E_{ex}) \quad \Omega_n(E_{ex}) = \frac{g^n (E_{ex} - U_l)^{n-1}}{((n/2)!)^2 (n-1)!}$$

The phenomenological coefficient C_{col} of the collective enhancement:

$$C_{col} = A_l \exp(\sqrt{(E_{ex} - U_l)/E_v} - (E_{ex} - U_l)/E_\mu) + \beta$$

$g=6a/\pi^2$ is the density of single-particle states

$$a(A,Z,E_{ex}) = \tilde{a} (1 + ((1 - \exp(-\gamma E_{ex})) \delta E/E_{ex}))$$

$$\tilde{a} = 0.114A + 0.162A^{2/3} \text{ and } \gamma = 0.054$$

Određivanje parametara nuklearne sutrukture metodom merenja dvostepenih gama kasakada nakon neutronskeg zahvata

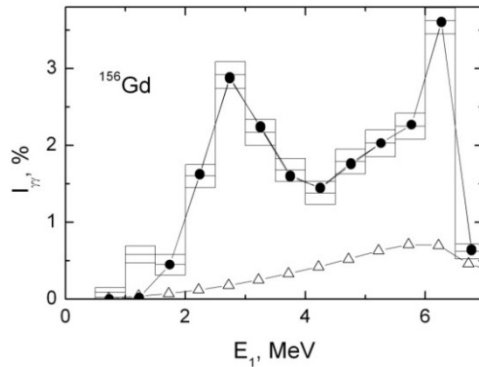
The model for $E1$ - and $M1$ -transition strength functions

$$k(E1, E_\gamma) + k(M1, E_\gamma) = w \frac{1}{3\pi^2 \hbar^2 c^2 A^{2/3}} \frac{\sigma_G \Gamma_G^2 (E_\gamma^2 + \kappa 4\pi^2 T^2)}{(E_\gamma^2 - E_G^2)^2 + E_\gamma^2 \Gamma_\gamma^2} + P\delta^- \exp(\alpha_p (E_\gamma - E_p)) + P\delta^+ \exp(\beta_p (E_p - E_\gamma))$$

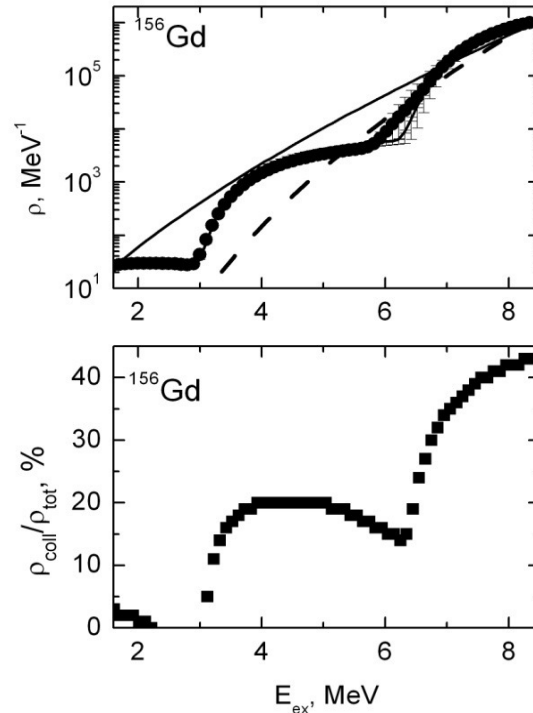
For our proposed model the set of fitted parameters is as following:

- 1) the break up thresholds **energies** U_l up to $l=4$,
- 2) the E_μ and E_ν **parameters**, which are common for all Cooper pairs,
- 3) the mutually independent **parameters** A_l of the density of vibrational levels above the break up threshold U_l ,
- 4) the **coefficients** w , κ and β ,
- 5) the **ratio** r of negative parity and the total level density.

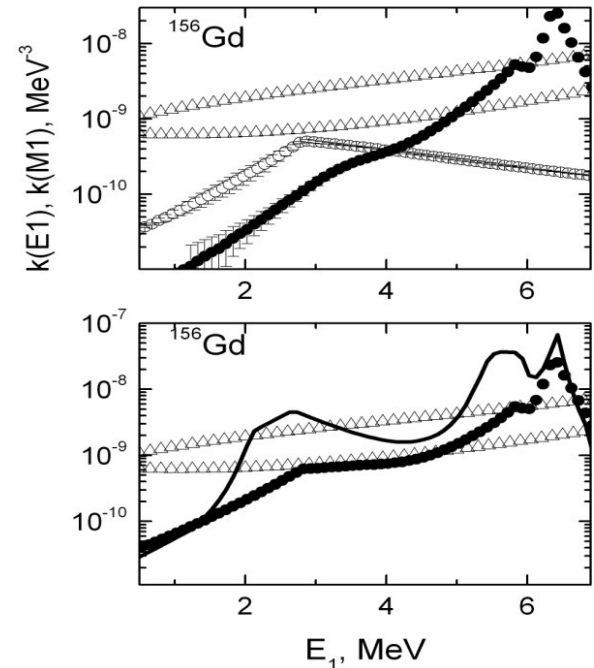
Određivanje parametara nuklearne sutrukture metodom merenja dvostepenih gama kasakada nakon neutronskeg zahvata



43 nuclei
 $28 \leq A \leq 200$

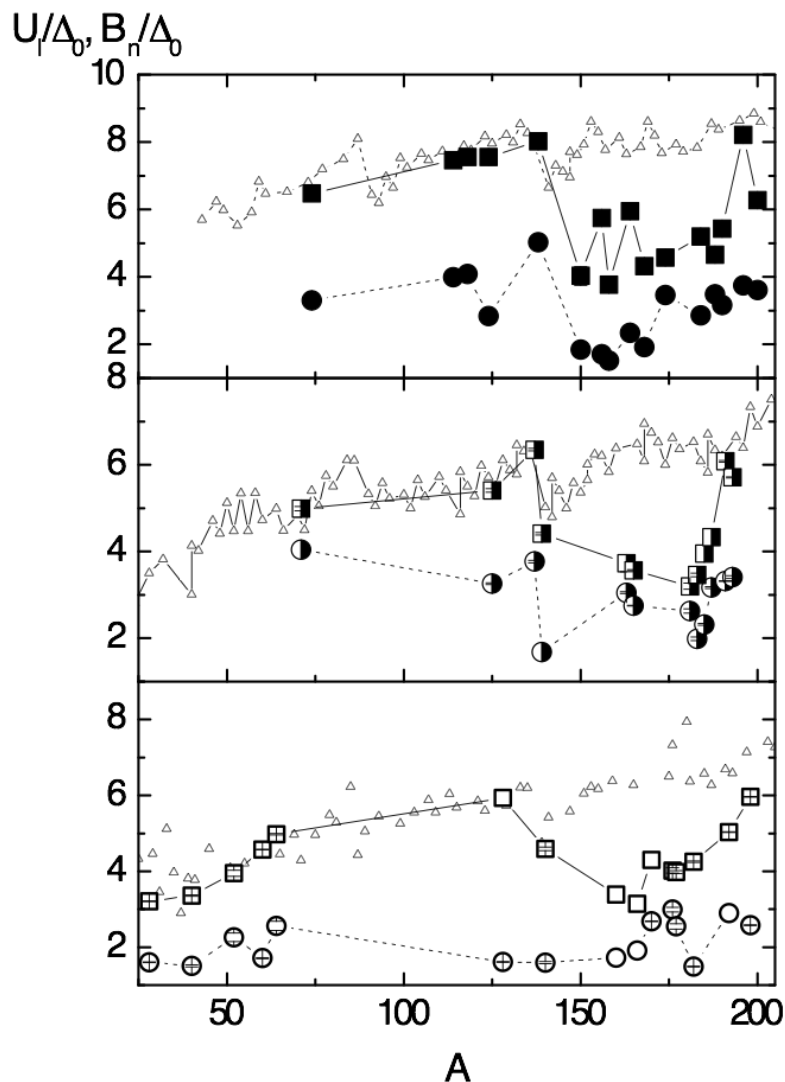


Level density of ^{156}Gd . Top panel: points are the best fit of level dashed line - using a value. Lower panel: calculated ratio of density of collective level to density of both collective and quasi-particle levels.



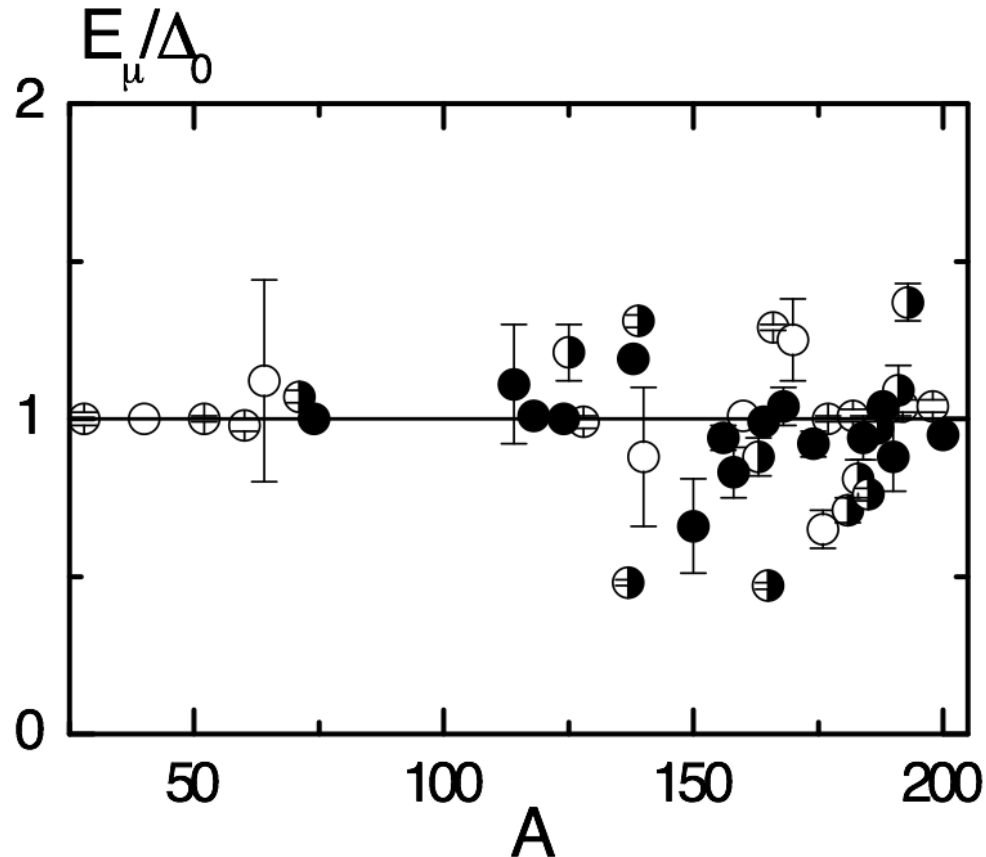
Strength function for ^{156}Gd . Top panel: solid points are the best fit of the strength function of $E1$ -transitions; open points are the best fit of the strength function of $M1$ -transitions. Lower panel: solid points are a sum of $E1$ - and $M1$ - strength functions; solid line is the sum of strength functions with taking into accounts condition $\rho_{\text{mod}}/\rho_{\text{exp}}$.

Određivanje parametara nuklearne sutrukture metodom merenja dvostepenih gama kasakada nakon neutronskeg zahvata



Dependence of break-up thresholds of the second (points) and the third (squares) Cooper pair on the nuclear mass A . Full points are even-even, half-open points are even-odd and open points are odd-odd compound nuclei. Triangles show the mass dependence of B_n/Δ_0 .

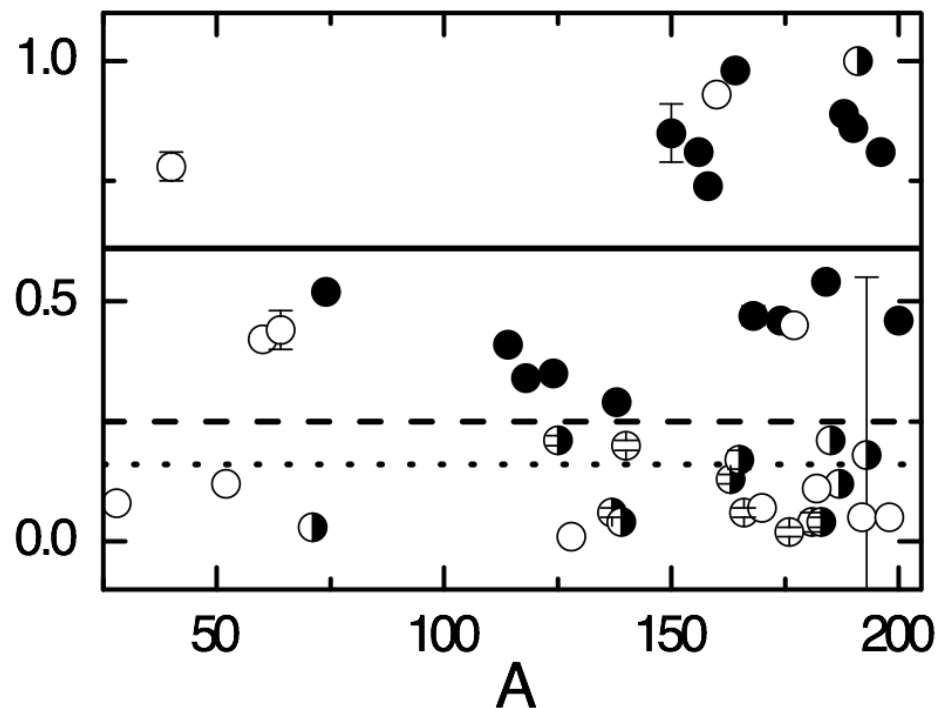
Određivanje parametara nuklearne sutrukture metodom merenja dvostepenih gama kasakada nakon neutronskeg zahvata



Dependence of E_μ and E_ν model parameters on the nuclear mass A . Full points are even-even, half-open are even-odd and open points are odd-odd nuclei.

Određivanje parametara nuklearne sutrukture metodom merenja dvostepenih gama kasakada nakon neutronskeg zahvata

$$\rho(\pi=-)/(\rho(\pi=-)+\rho(\pi=+))$$



0.61(22) for even-even nuclei
 0.25(28) for even-odd nuclei
 0.16(16) for odd-odd nuclei

Mass dependence of the ratio of the level density with negative level parity to the total level density in the point E_d (upper border of the level discrete region) and its middle value for even-even nuclei (solid lines), even-odd (dashed lines) and odd-odd nuclei (dotted lines).