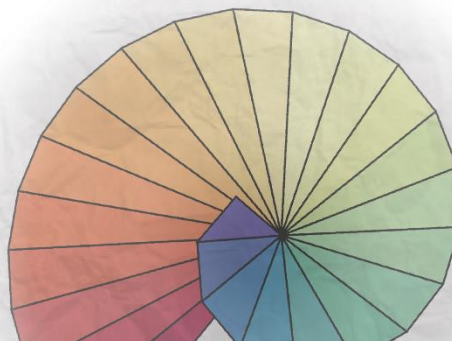


Jedrske reakcije za meritve specifičnih področij nevtronskega spektra

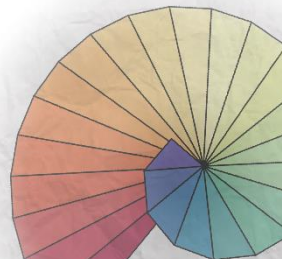
Vladimir Radulović

vabljeni predavatelj, 3. konferenca ŠFOSM
Reaktorski center Podgorica, 29. 2. 2016



Vsebina

- Aktivacijske meritve
- Jedrske reakcije
- RR_UNC
- Primer: meritve epitermičnega fluksa
- Primer: nizkoenergijske resonance
- Primer: meritve DT in TT vrhov
- Zaključek

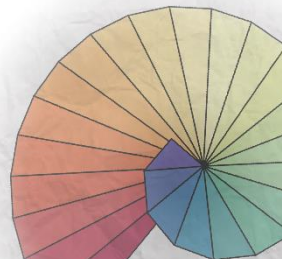


Aktivacijske meritve

- Certificirani materiali
- Obsevanje + merjenje induciranih aktivnosti (gama spektrometrija)
- Rezultat: saturacijske aktivnosti na atom

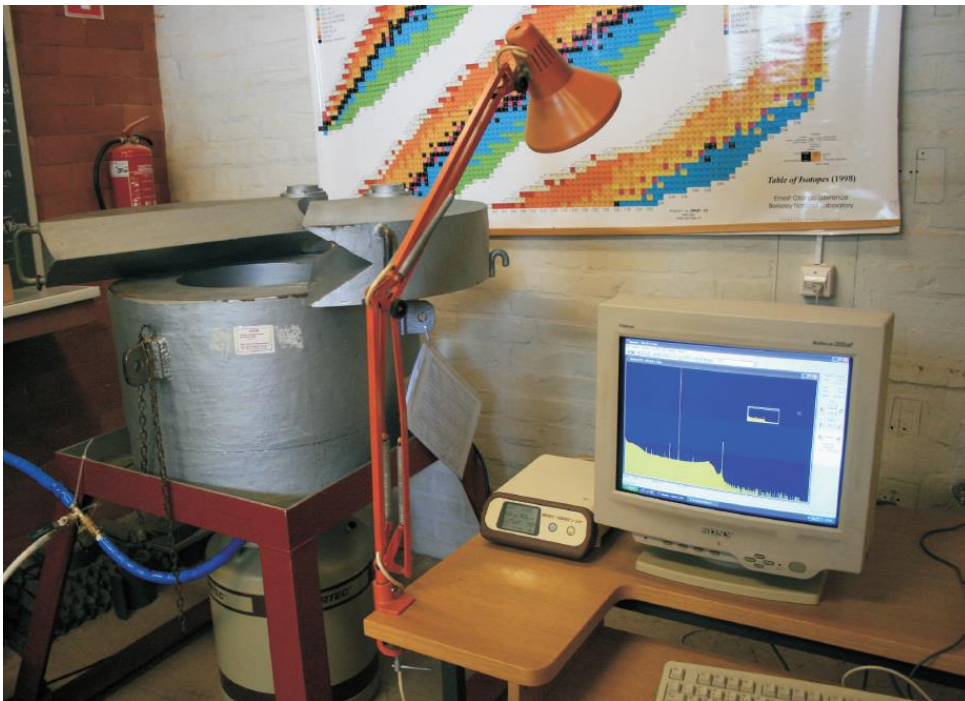


PE zajček + capsules, Cd škatlica, Al-0.1%Au vzorčki



Aktivacijske meritve

- HPGe detektor
- Kalibracija (E , ϵ)
- Obdelava gama spektrov
- k_0 podatki - E_γ

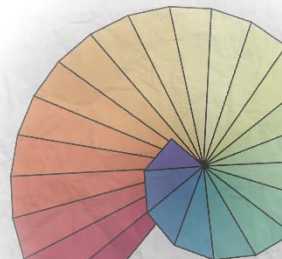


HPGe detektor OF8

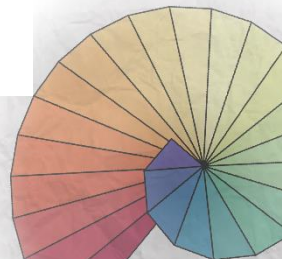
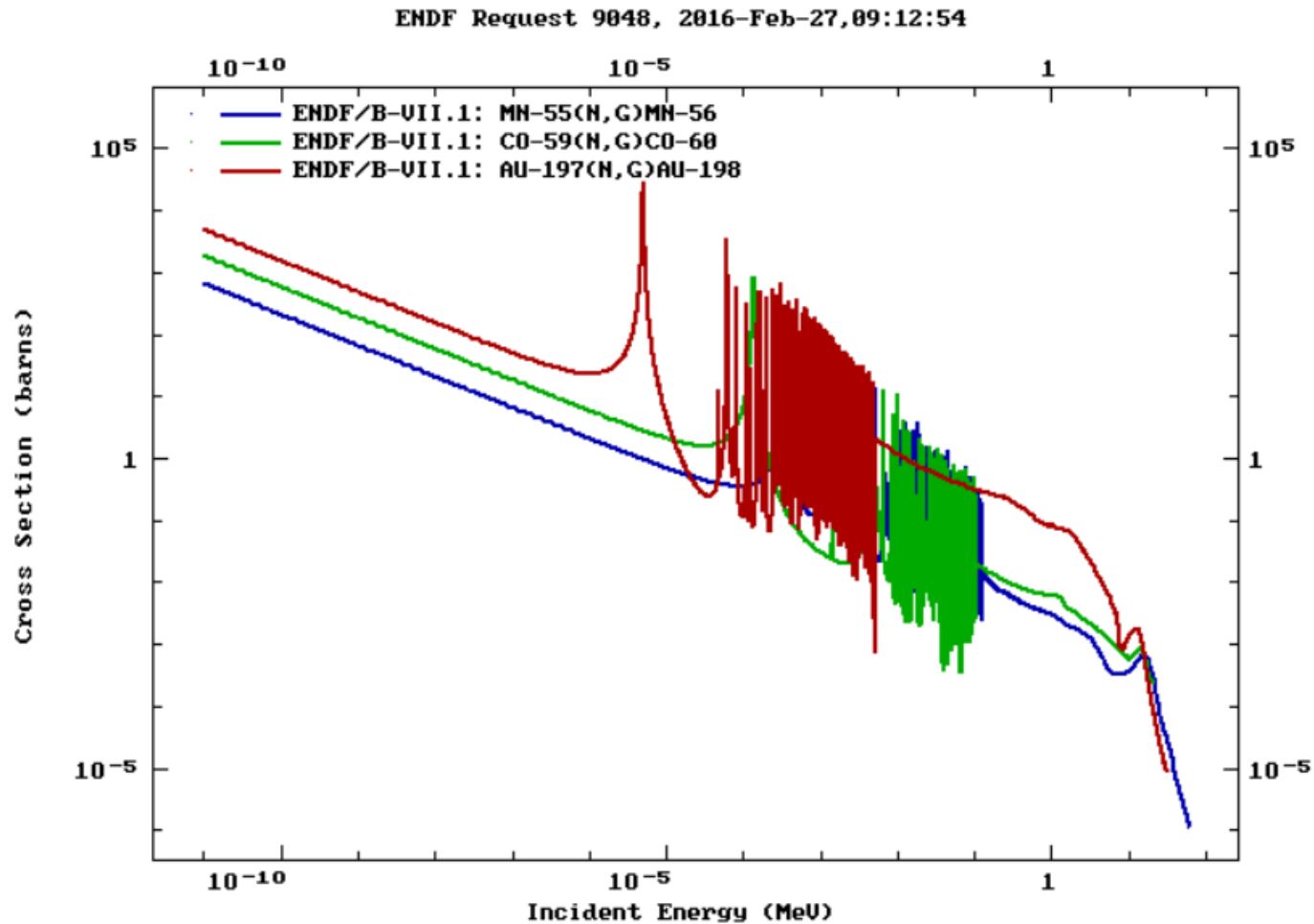


Jedrske reakcije

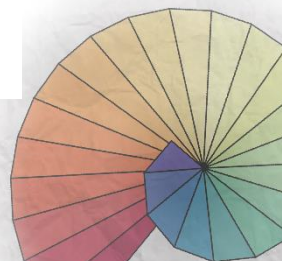
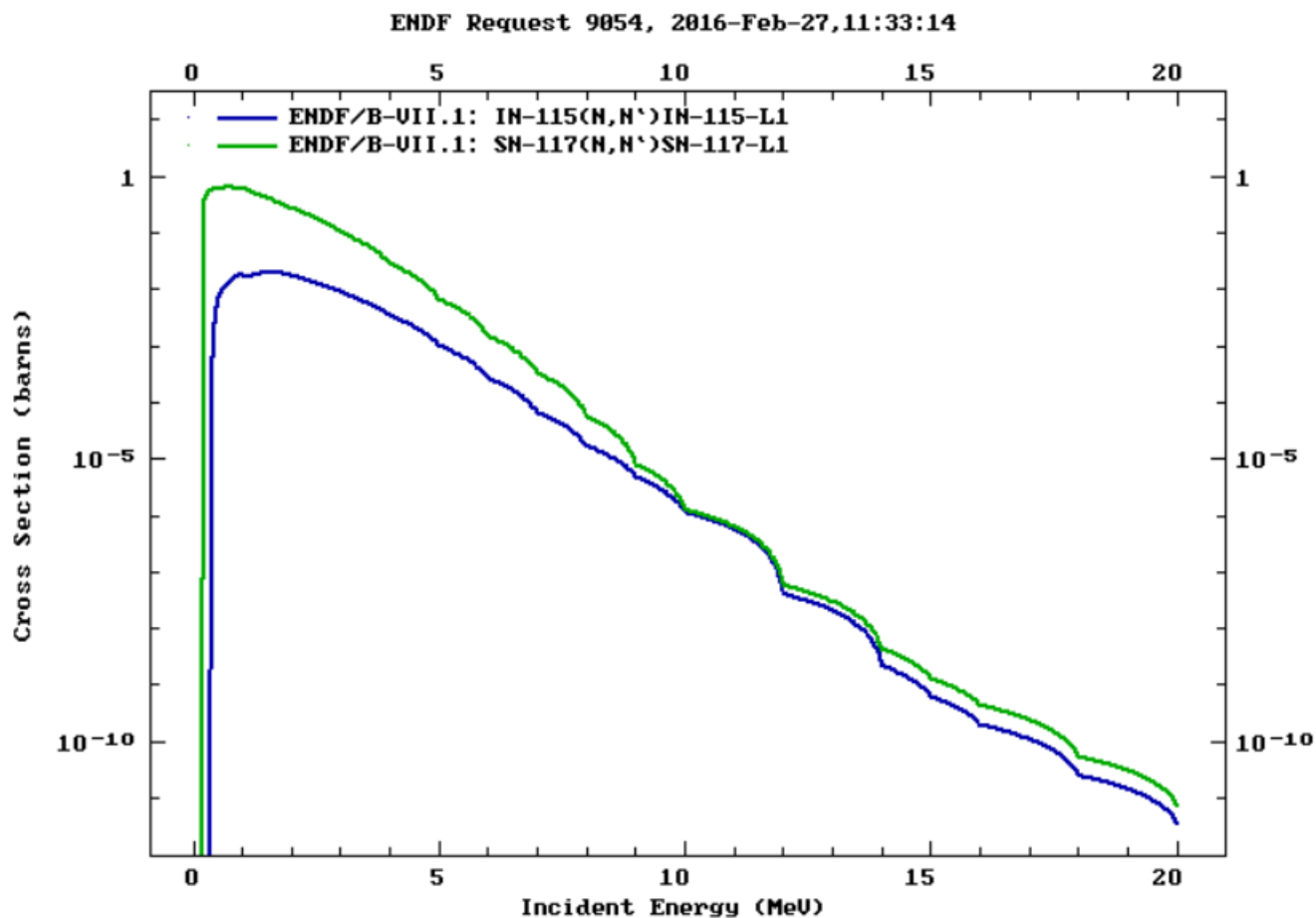
- Radiativno zajetje - (n, γ)
1/v + resonance
- Neelastično sipanje - (n, n')
nižji energijski prag
- Izbitje sekundarnih - (n, p) , $(n, 2n)$, (n, α) , ...
višji energijski prag
- (fisija)
1/v + resonance; mnogo različnih produktov



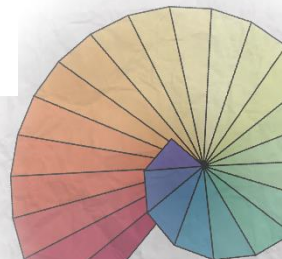
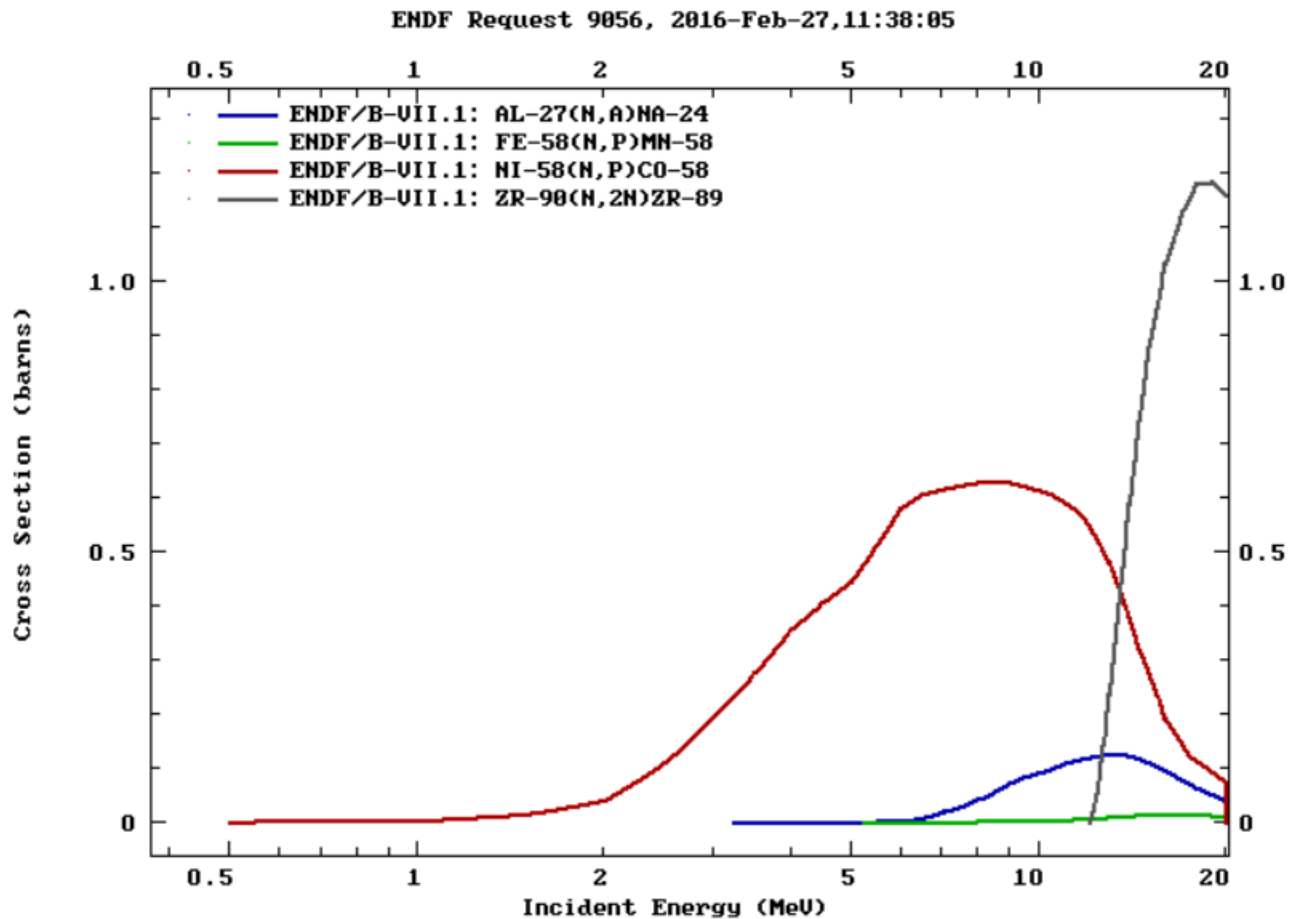
Jedrske reakcije - (n,γ)



Jedrske reakcije - (n,n')



Jedrske reakcije - (n,p), (n, α), (n,2n)



Občutljivost jedrskih reakcij

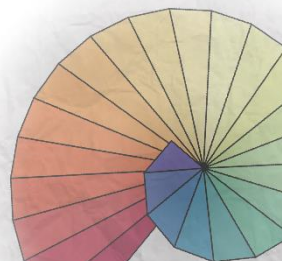
$$R = N_{at} \int \sigma(E) \phi(E) dE$$

$$\phi_{tot} = \int \phi(E) dE$$

- Kumulativna reakcijska hitrost

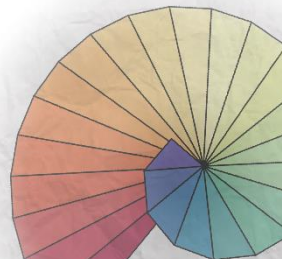
$$Y(E) = \frac{\sum \sigma_i \phi_i, i = 1, \dots, E_i}{\sum \sigma_i \phi_i, i = 1, \dots, E_{max}}$$

$$Y(E) \in [0,1]; Y(E_{50\%}) = 0.5$$



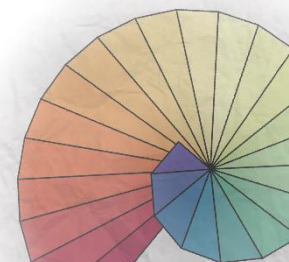
Program RR_UNC

- Nevtronski spekter v 640 grupah, v ENDF formatu (MF=3, MT=261)
- Knjižnica presekov v 640 grupah, v ENDF formatu
- Po možnosti kovariančne matrike spektra in presekov (MF 33)
- **Output:**
 1. reakcijske hitrosti + negotovosti (zaradi negotovosti v spektru in v presekih)
 2. Funkcije $Y(E)$ v .CUR formatu (za risanje s programom PLOTTAB)
 3. $E_{50\%}$

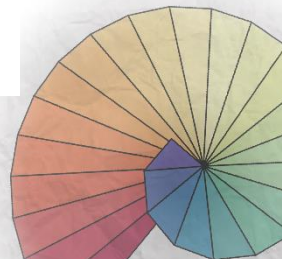
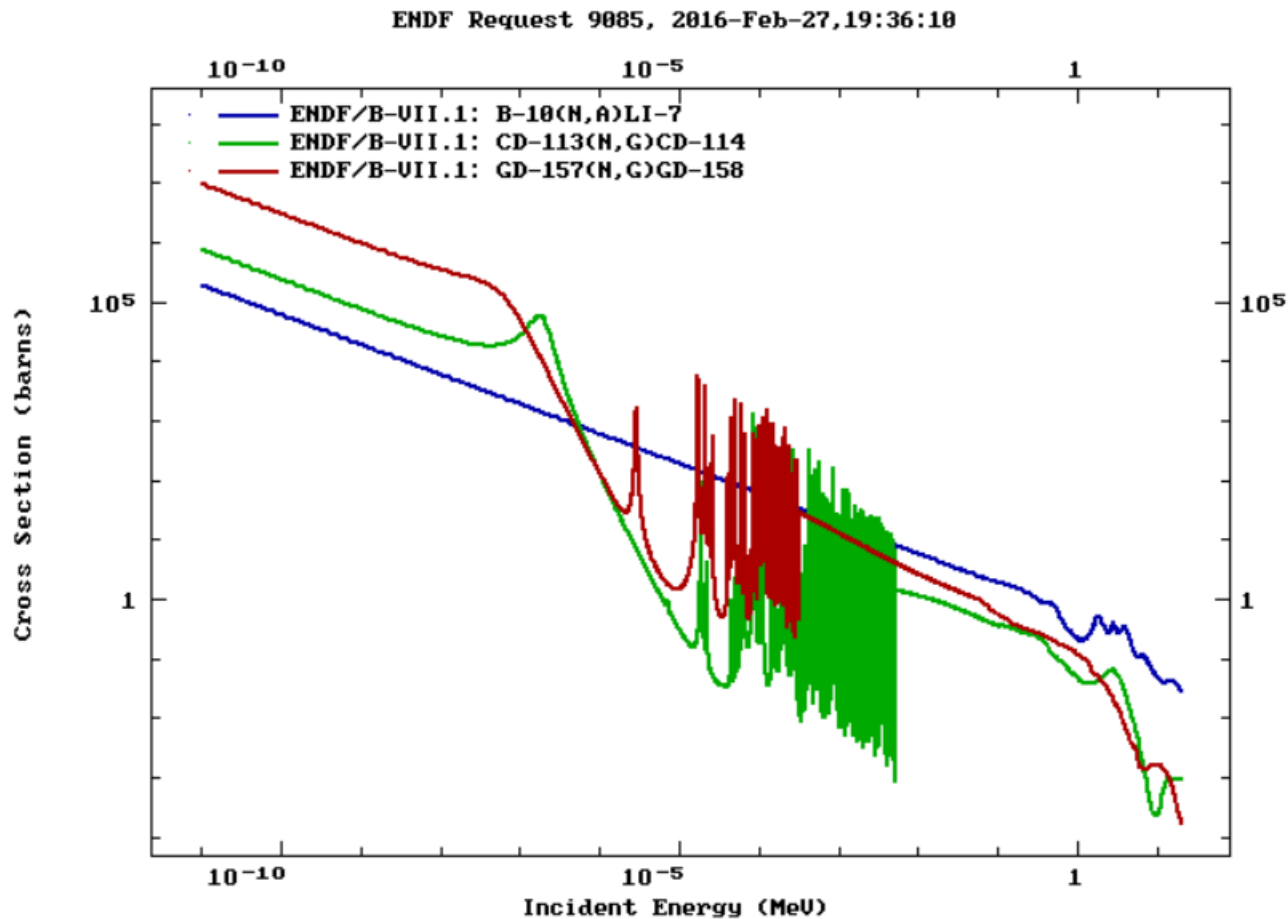


Meritve ϕ_{epi}

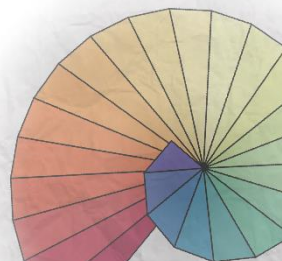
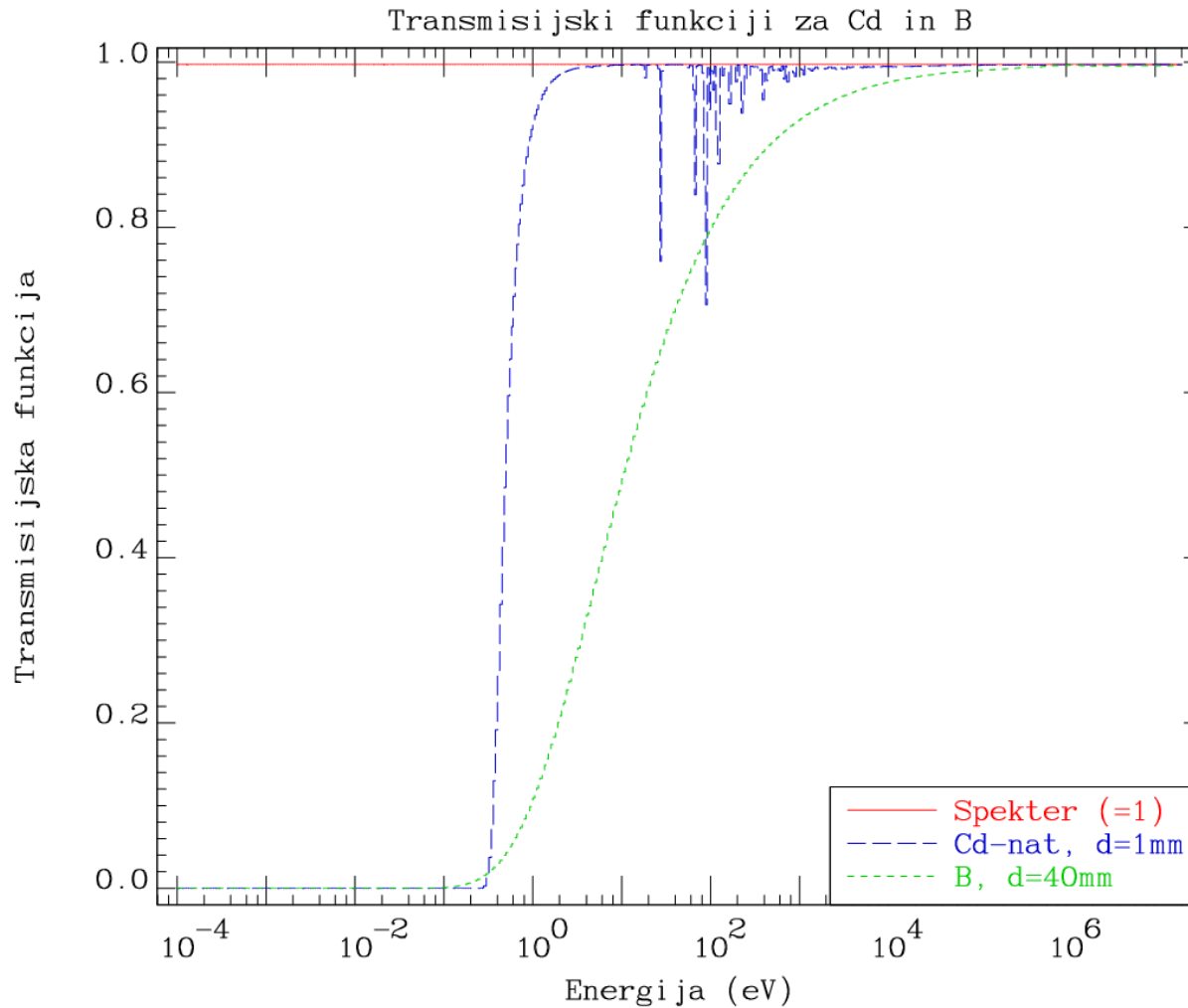
- Ni reakcij občutljivih samo na ϕ_{epi}
- Uporaba BN kot filtra - znebimo se nevtronov od 0 do ~ 10 eV; premaknemo občutljivost (n, γ) reakcij na epitermično področje.



Meritve ϕ_{epi}

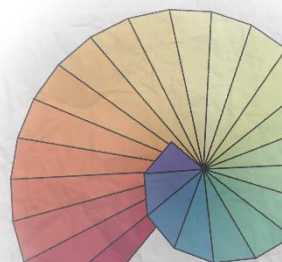


Meritve ϕ_{epi}



Meritve ϕ_{epi}

- Izračuni za spekter v TRIGA PT (F24), znotraj BN vsebnika
- ENDF/B-VII.1 knjižnica procesirana v 640 grup (PREPRO)
- Iskanje (n, γ) reakcij s čim višjim $E_{50\%}$



Meritve ϕ_{epi}

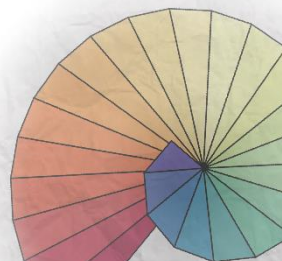
MT 102 Sorted by E50

No.	Mat.	Meta	MT	MeV E(50%) MeV	mb RR mb	+/-	UNC	Unc xs %	RR/RR_Au	Target	Product	T1/2	Disadvantage	Advantage	Verdict
286	7015		102	0.94623	2.45E-01	+/-	1.35E-01	55.16	2.92E-04	N-15		7.13 s	Nitrogen, O16(n,p)		
307	8016		102	0.71112	1.51E+00	+/-	5.47E-01	36.21	1.80E-03	O-16			Stable product		
14156	82208		102	0.65685	1.33E+01	+/-	4.02E+00	30.2	1.59E-02	Pb-208		3.253 h	Only beta rays	large xs	
4420	38088		102	0.48897	6.10E+01	+/-	0.00E+00	0	7.27E-02	Sr-88		50.53 d	1 gamma ray w/ low intensity	large xs	
8	1002		102	0.48041	1.23E-01	+/-	3.66E-02	29.62	1.47E-04	H-2		12.3 a	Deuterium, only beta		
509	12026		102	0.2165	8.33E+00	+/-	9.40E-01	11.28	9.93E-03	Mg-26		9.458 m	27Al(n,p), but low	large xs, high intensity gamma rays	GOOD
3836	34082		102	0.09615	3.04E+02	+/-	0.00E+00	0	3.63E-01	Se-82		22.3 m	large xs, high intensity gamma rays	GOOD	
4471	38090		102	0.08503	1.31E+02	+/-	0.00E+00	0	1.56E-01	Sr-90		9.63 h	Non-existent in nature	large xs, high intensity gamma rays	
459	12024		102	0.08033	1.92E+01	+/-	2.30E+00	12.01	2.28E-02	Mg-24			Stable product	large xs	COMBO Mg
4157	36086		102	0.05484	3.09E+01	+/-	0.00E+00	0	3.68E-02	Kr-86		76.3 m	Krypton, gamma rays w/ low intensity	large xs	
4719	40090		102	0.03864	2.25E+02	+/-	2.61E+01	11.59	2.68E-01	Zr-90			Stable product	large xs	
13977	82206		102	0.03717	1.38E+02	+/-	4.71E+00	3.41	1.65E-01	Pb-206			Stable product	large xs	
385	9019		102	0.02751	1.70E+01	+/-	6.04E-01	3.55	2.03E-02	F-19		11.07 s	short T1/2, gamma rays w/ low intens	large xs	
9303	58140		102	0.02666	1.62E+02	+/-	0.00E+00	0	1.94E-01	Ce-140		32.508 d		large xs, high intensity gamma rays	GOOD
2875	30070		102	0.02261	1.03E+02	+/-	0.00E+00	0	1.23E-01	Zn-70		2.45 m	0.61% natural, only 1 gamma at 511.6	large xs	
1779	22046		102	0.01977	2.02E+02	+/-	5.39E+00	2.68	2.40E-01	Ti-46			Stable product	large xs	
486	12025		102	0.01841	3.86E+01	+/-	1.14E+01	29.64	4.60E-02	Mg-25			Stable product	large xs	COMBO Mg
7608	50126		102	0.01733	1.59E+02	+/-	0.00E+00	0	1.89E-01	Sn-126		2.10 h	Non-existent in nature	large xs	From spent fuel?
5007	40094		102	0.01722	3.93E+02	+/-	2.24E+01	5.69	4.68E-01	Zr-94		64.032 d		large xs, high intensity gamma rays	GOOD
729	14029		102	0.01551	4.44E+01	+/-	4.06E+00	9.14	5.29E-02	Si-29			Stable product	large xs	
2074	24054		102	0.01431	8.62E+01	+/-	0.00E+00	0	1.03E-01	Cr-54		3.497 m	gamma rays w/ low intensity (max 0.0	large xs	
10169	62144		102	0.01268	1.74E+03	+/-	0.00E+00	0	2.07E+00	Sm-144		340 d	low E gamma rays, long T1/2	larger xs than Au!	Possible
1300	20040		102	0.01056	8.40E+01	+/-	0.00E+00	0	1.00E-01	Ca-40		1.02E+5 y	Only low energy x-rays	large xs	
2580	28064		102	9.30E-03	3.36E+02	+/-	0.00E+00	0	4.00E-01	Ni-64		2.5175 h		large xs, high intensity gamma rays	GOOD
1387	20042		102	9.23E-03	1.61E+02	+/-	0.00E+00	0	1.92E-01	Ca-42			Stable product	large xs	
5342	42094		102	8.48E-03	1.66E+03	+/-	1.41E+02	8.51	1.98E+00	Mo-94			Stable product	larger xs than Au!	
8042	52132		102	7.74E-03	1.89E+02	+/-	0.00E+00	0	2.25E-01	Te-132			Non-existent in nature	large xs	
6816	48106		102	7.51E-03	6.78E+03	+/-	0.00E+00	0	8.08E+00	Cd-106		6.50 h	gamma rays w/ low intensity (max 0.2	larger xs than Au!	Possible
3311	32074		102	7.34E-03	5.33E+02	+/-	0.00E+00	0	6.36E-01	Ge-74		82.78 m	1 gamma ray w/ low intensity	large xs	Possible
5303	42092		102	7.18E-03	1.14E+03	+/-	1.18E+02	10.3	1.36E+00	Mo-92		6.85 h (metastable)	several gamma rays	larger xs than Au, high intensity gamma rays	GOOD
4850	40092		102	6.75E-03	7.47E+02	+/-	5.19E+01	6.94	8.91E-01	??					
2205	26054		102	6.09E-03	4.56E+02	+/-	2.87E+01	6.28	5.44E-01	Fe-54		2.744 y	1 gamma ray w/ low intensity	large xs	
8783	55137		102	6.05E-03	3.11E+02	+/-	0.00E+00	0	3.71E-01	Cs-137		33.41 m	Pure Cs-137?	large xs, high intensity gamma rays	Possible??

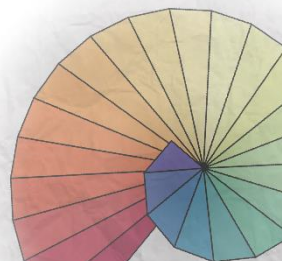
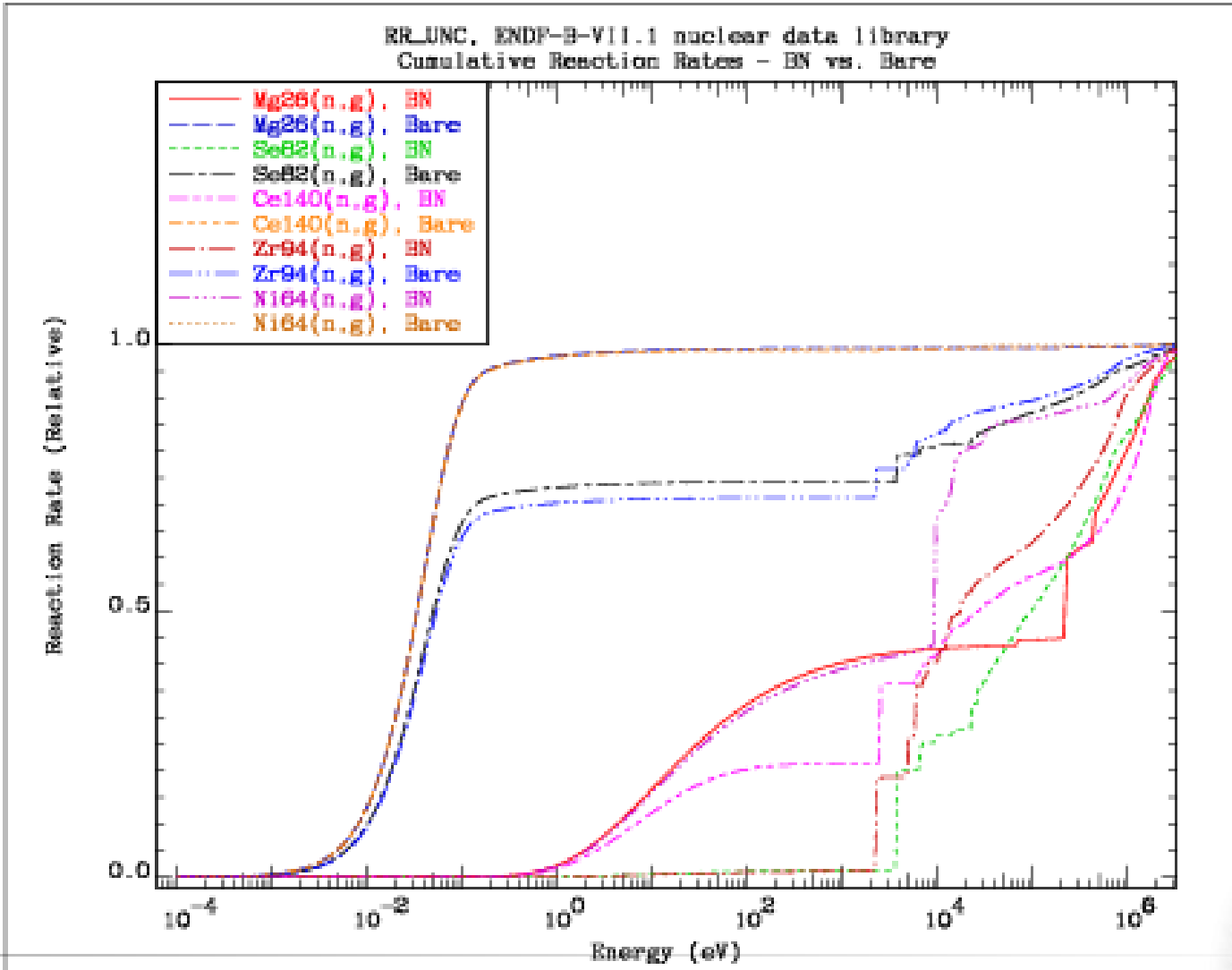


Meritve ϕ_{epi}

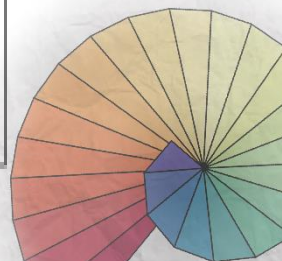
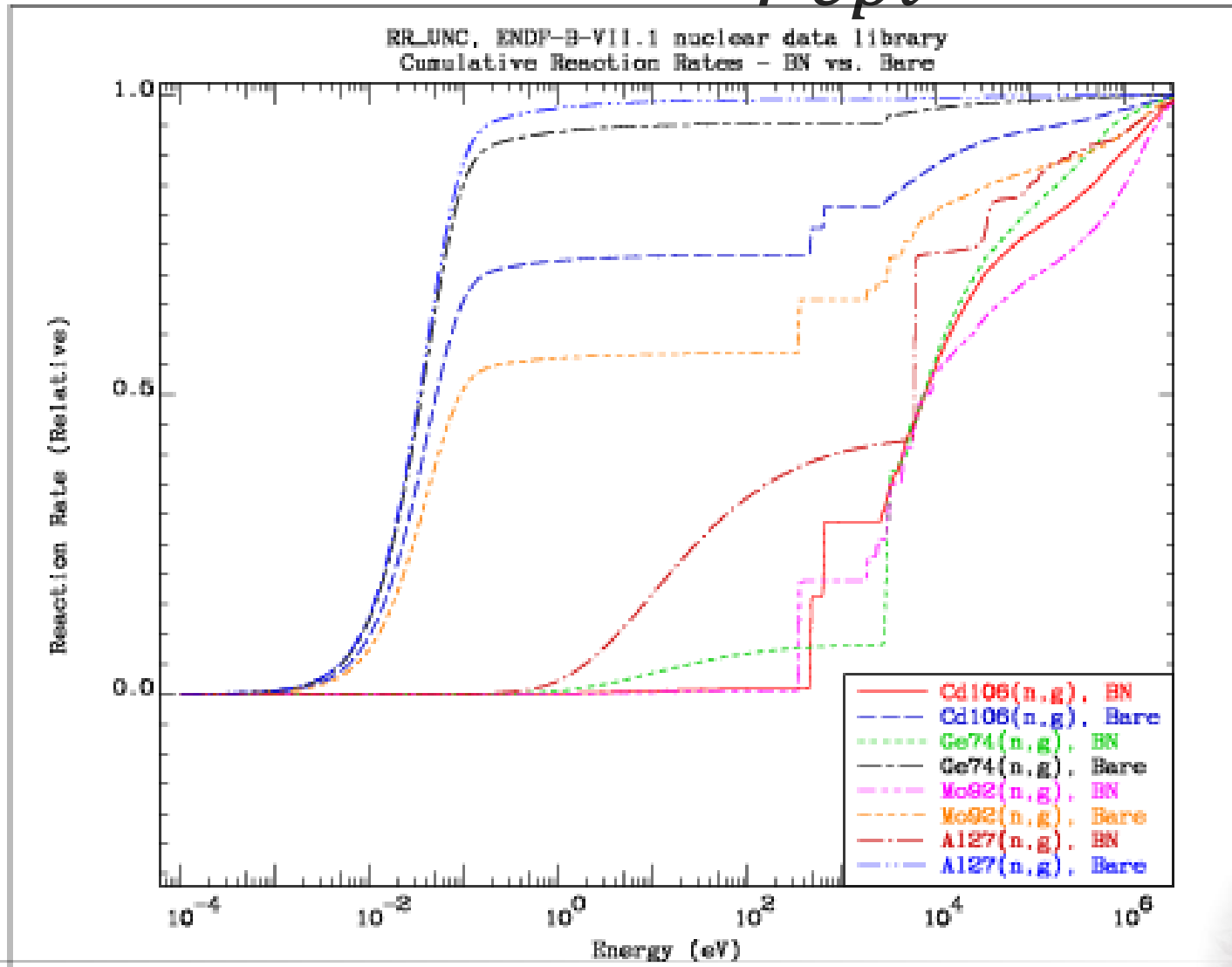
- Veliko reakcij, za katere je $E_{50\%}$ visoka
- Večina reakcij nemerljivih (stabilen ali kratkoživ product, plin, ni primernih gama žarkov, ...)
- Identificirane: Mg-26 (0.2 MeV), Se-82 (0.1 MeV), Ce-140 (0.03 MeV), Zr-94 (0.02 MeV), Sm-144 (0.01 MeV), Ni-64 (0.01 MeV), ...
- Veliko več reakcij z $E_{50\%}$ okrog 1keV.



Meritve ϕ_{epi}

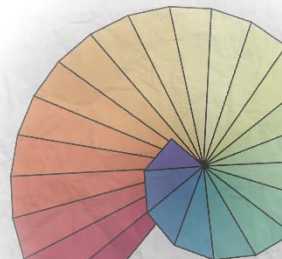


Meritve ϕ_{epi}

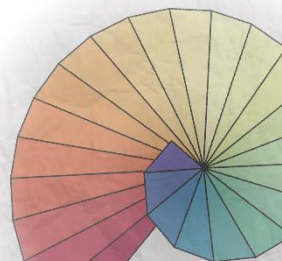
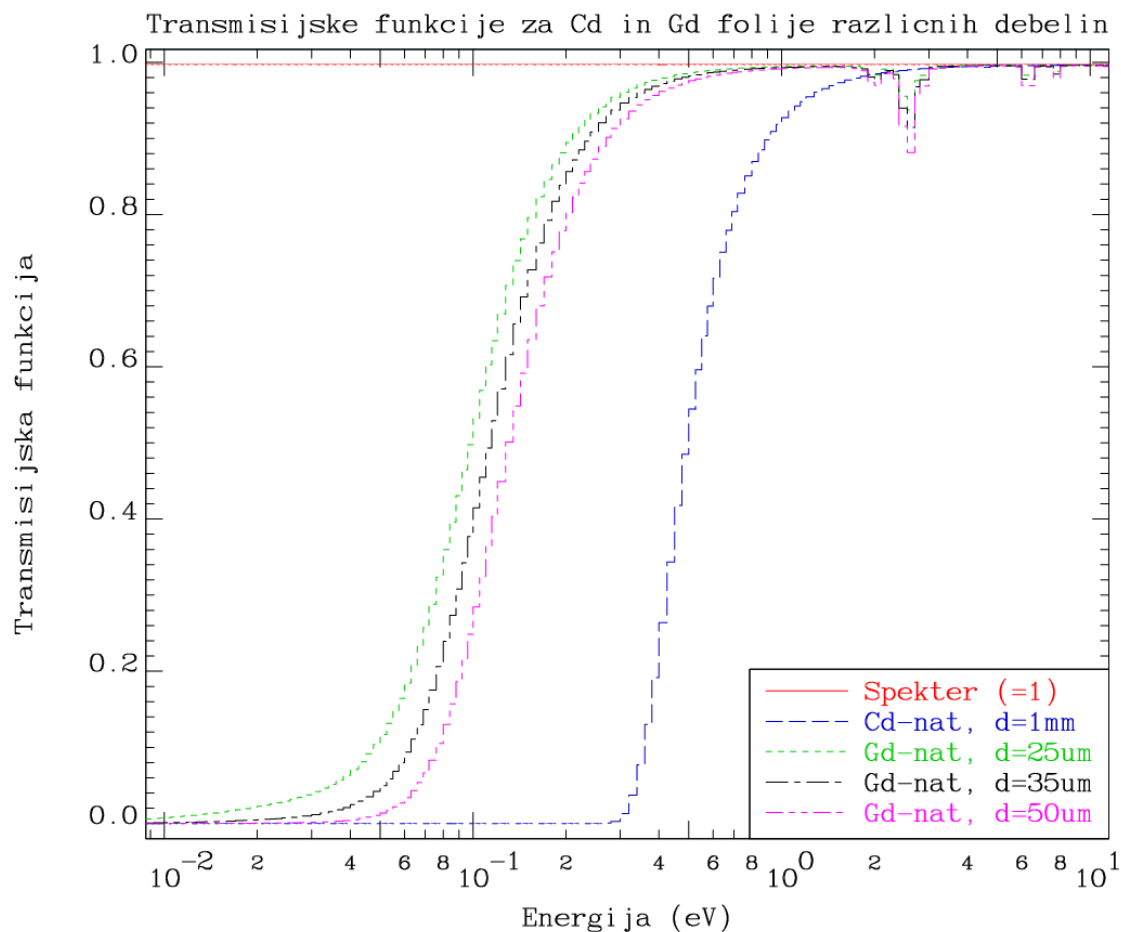


Nizkoenergijske resonance

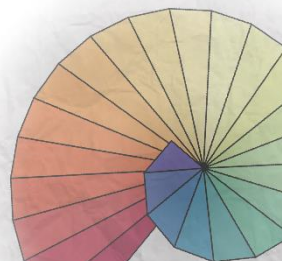
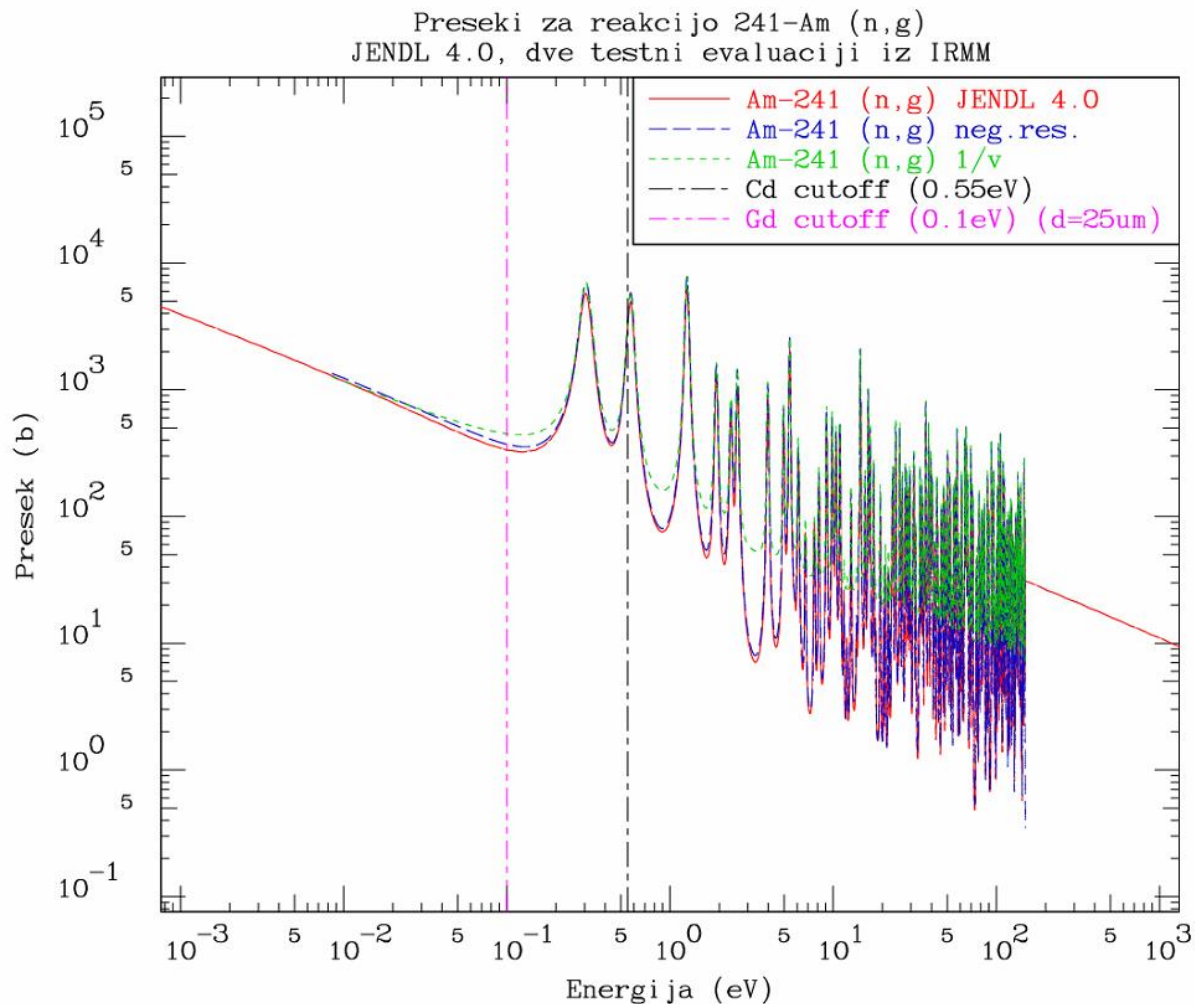
- Cd cutoff (1 mm) = 0.55 eV
- Cd rob se uporablja v definicijah parametrov pri k_0 -NAA
- Večina reakcij nima resonanc pod 0.55 eV
- razločimo termični in resonančni prispevek



Nizkoenergijske resonance

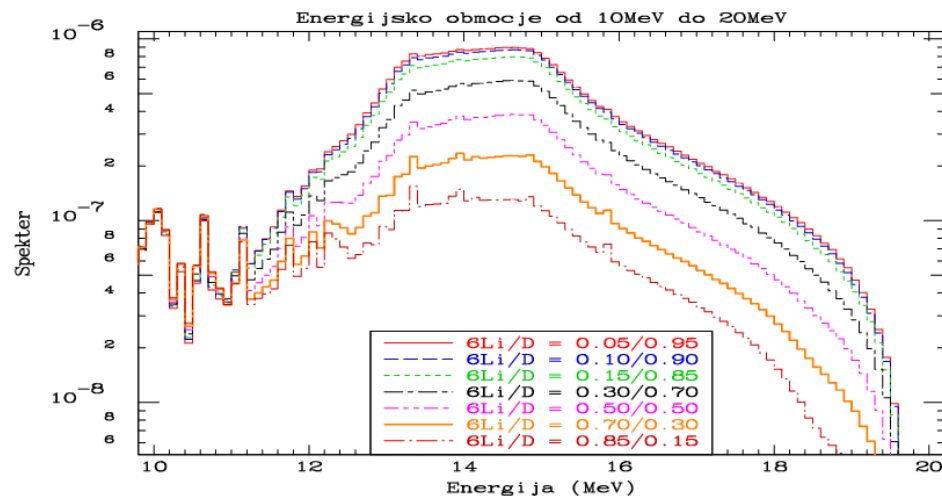
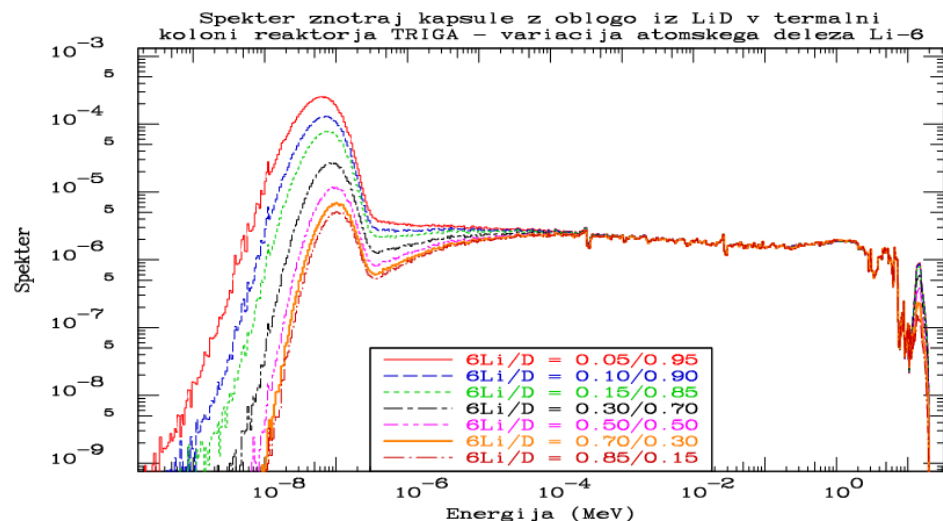


Nizkoenergijske resonance



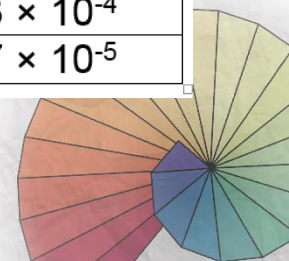
Fuzija

- Nevtroni iz DT: 14 MeV
- Nevtroni iz TT: 8-9 MeV
- Iskanje reakcij v knjižnici IRDFF (International Reactor Dosimetry & Fusion File) - dozimetrijski standard



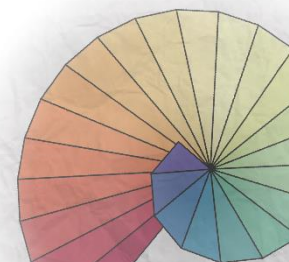
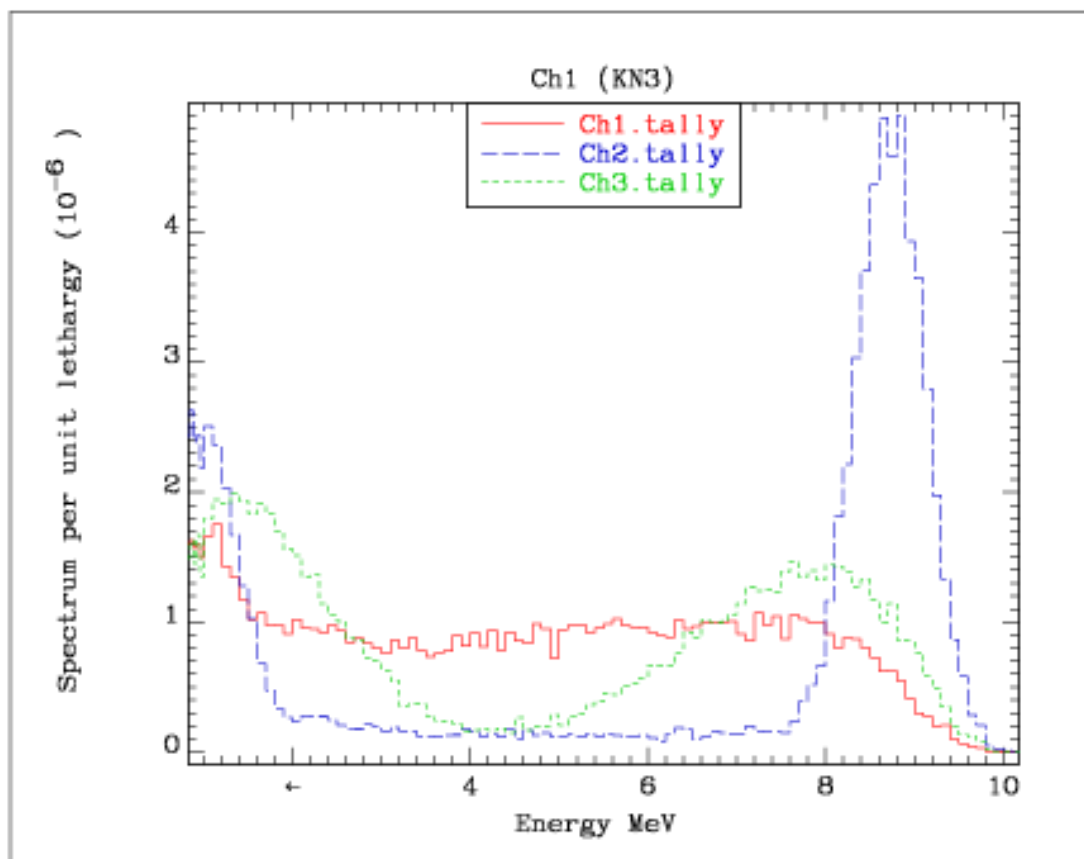
Fuzija - DT nevtroni

Target	Reaction	Product T1/2 [h]	E50% [MeV]	RR/atom rel. to 197Au(n, γ)	Sample	Density [g/cm ³]	Sample RR rel. to 197Au(n, γ) in <u>AlAu</u>
¹⁹⁷ Au	(n, γ)	64.68	42 <u>meV</u>	1	Al(Au)	2.70	1
²⁷ Al	(n,p)	0.16	6.52	5.83×10^{-7}	Al(Au)	2.70	4.25×10^{-3}
²⁷ Al	(n, α)	15.00	13.40	2.32×10^{-7}	Al(Au)	2.70	1.69×10^{-3}
⁹³ Nb	(n,2n)	243.6	14.18	6.66×10^{-7}	<u>Nb</u>	8.57	4.48×10^{-3}
¹²⁷ I	(n,2n)	310.32	14.27	2.13×10^{-6}	I	4.93	6.03×10^{-3}
⁶⁵ Cu	(n,2n)	12.70	14.45	1.26×10^{-6}	Cu	8.96	8.96×10^{-3}
⁵⁵ Mn	(n,2n)	7490.9	14.46	9.79×10^{-7}	<u>Mn</u>	7.21	9.38×10^{-3}
⁵⁹ Co	(n,2n)	1700.6	14.49	9.62×10^{-7}	Co	8.90	1.06×10^{-2}
⁶³ Cu	(n,2n)	0.16	14.71	6.50×10^{-7}	Cu	8.96	2.06×10^{-3}
⁹⁰ Zr	(n,2n)	78.41	14.84	8.88×10^{-7}	<u>Zr</u>	6.52	2.38×10^{-3}
¹⁹ F	(n,2n)	1.83	14.85	5.62×10^{-8}	CaF ₂	3.18	3.34×10^{-4}
⁵² Cr	(n,2n)	664.86	14.98	4.25×10^{-7}	Cr	7.19	3.59×10^{-3}
⁵⁸ Ni	(n,2n)	36.60	15.11	4.22×10^{-8}	Ni	7.81	2.80×10^{-4}
²³ Na	(n,2n)	22800	15.35	4.26×10^{-8}	<u>NaCl</u>	2.17	2.93×10^{-4}
⁴⁶ Ti	(n,2n)	3.08	15.90	6.16×10^{-8}	<u>Ti</u>	4.51	3.47×10^{-5}



Fuzija - TT nevtroni

- Sistematsko Iskanje reakcij z občutljivostjo med 8 in 9 MeV
- Veliko reakcij v ENDF, večinoma so izločene.



Zaključek

- Sistematsko iskanje reakcij za specifična področja nevtronskega spektra
- Motivacija: nekaj jih lahko najdemo
- Meritve / Izračuni = validacija jedrskih presekov
- Dobro ujemanje: karakterizacija spektrov, merjenje fluksa, moči pulza ...

