The investigations of reaction rates in Th interacted with neutrons in QUINTA subcritical assembly irradiated by 2, 4, and 6 GeV deuterons.

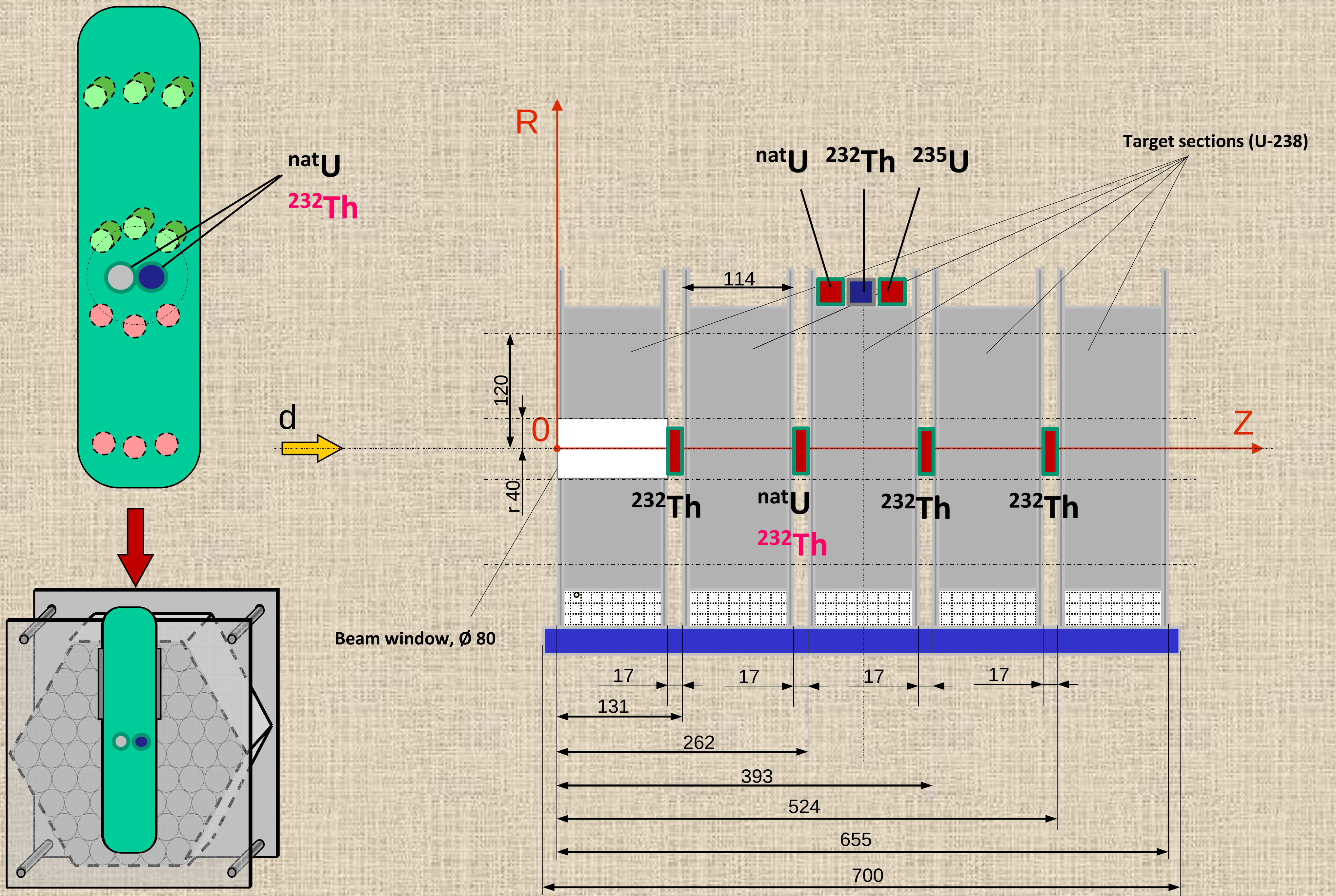
“Energy and transmutation RAW” collaboration

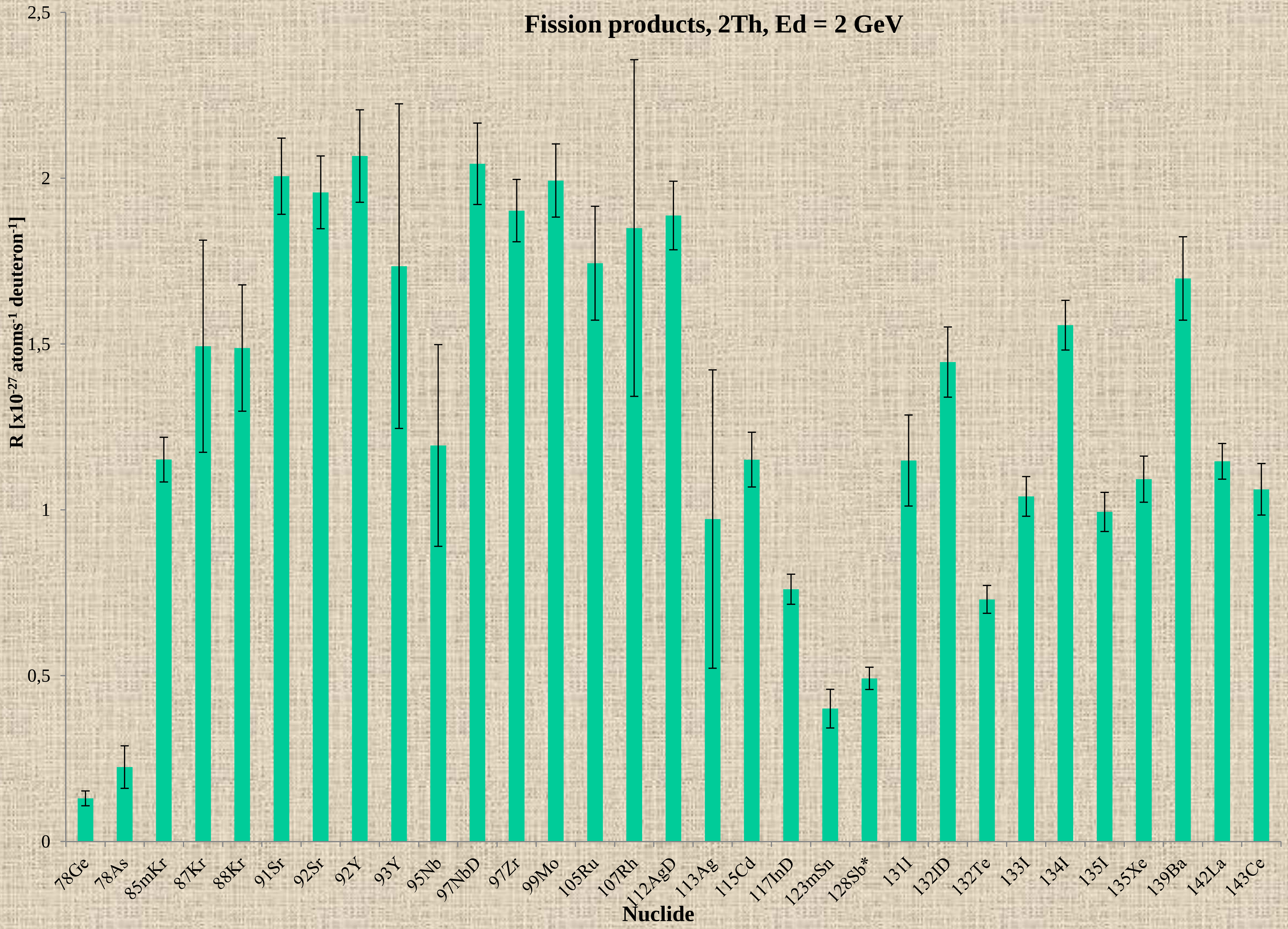
Joint Institute for Nuclear Research at Dubna, Moscow region, Russia

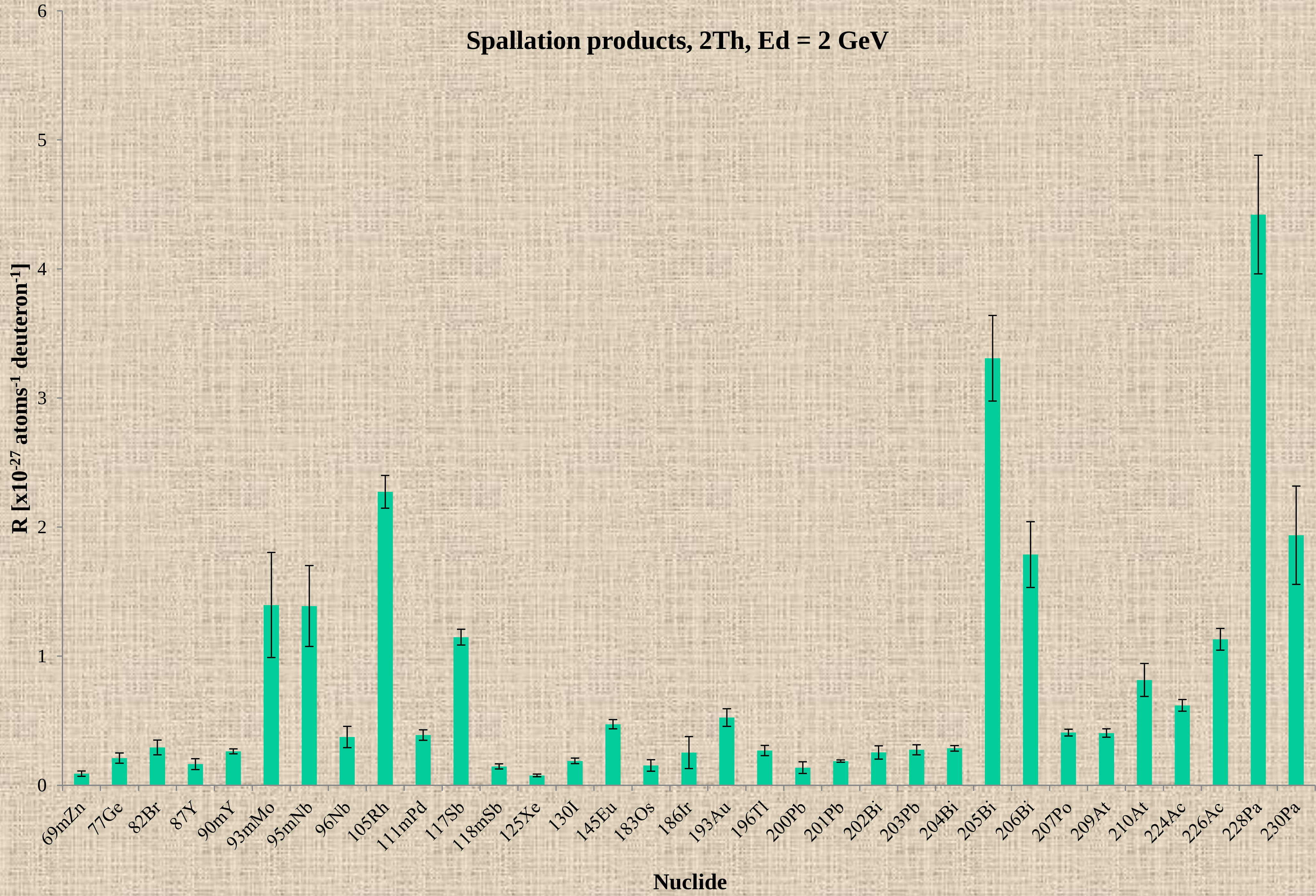
- **J.Adam, N. Asquith, A.Baldin, V.Chilap, M.Kadykov, J.Khushvaktov, V.Kumar, Yu. I.Mar'in, Reza Hashemi-Nezhad, A.Solnyshkin, O.Svoboda, M.Suchopar, V.Tsupko-Sitnikov, S.Tyutyunnikov, J.Vrzalova, V.Wagner, W.Westmeier, L. Zavorka**,

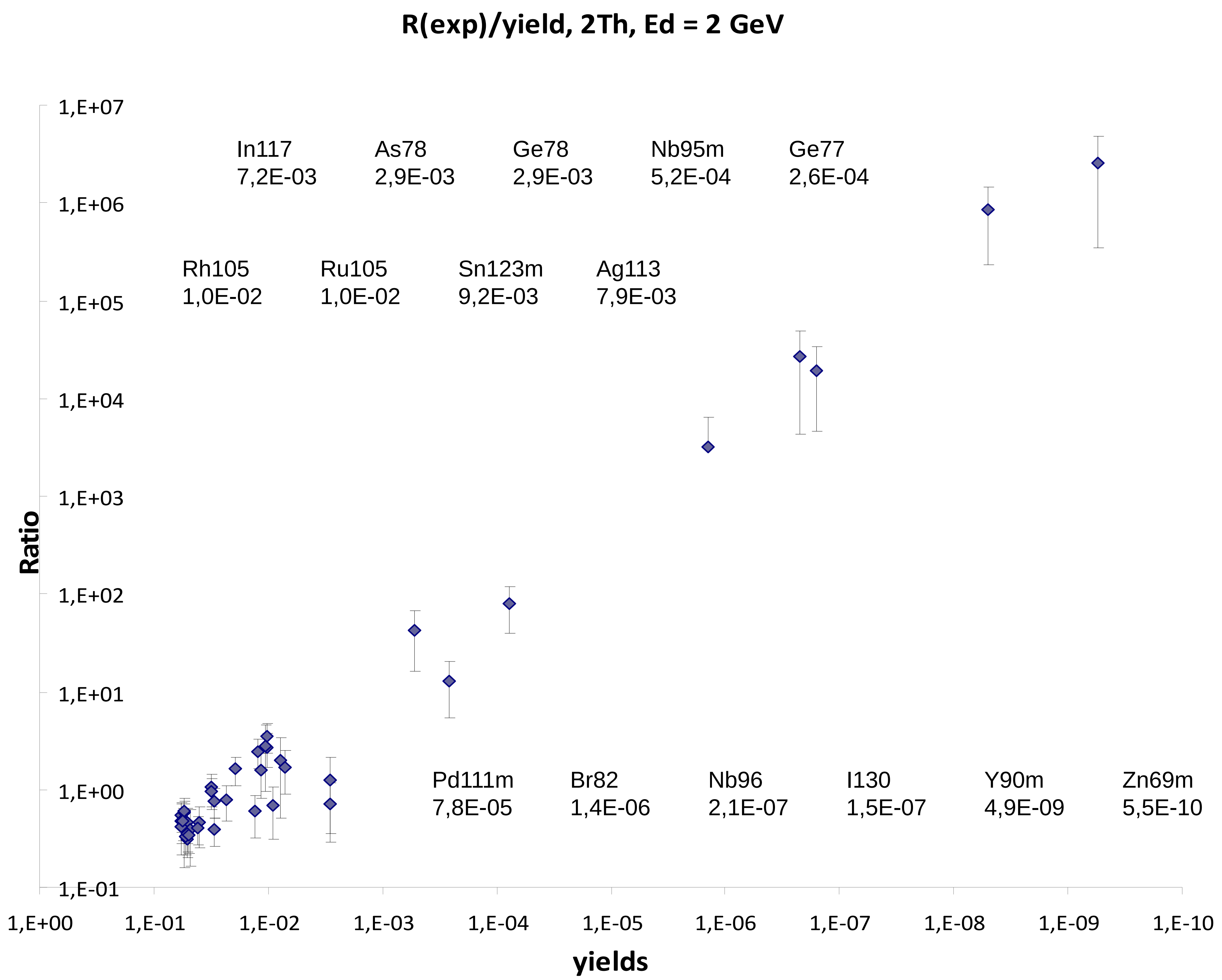
- ***Joint Institute for Nuclear Research, Dubna, Russia***
- ***CPTP «Atomenergomash», Moscow, Russia***
- ***INP, Rez near Praha, Czech Republic***
- ***Gesellschaft for Kernspektrometrie, Germany***
- ***GGS University, New Delhi, India***
- ***School of Physics University of Sydney, Australia***

«Quinta-M» target cross-cut

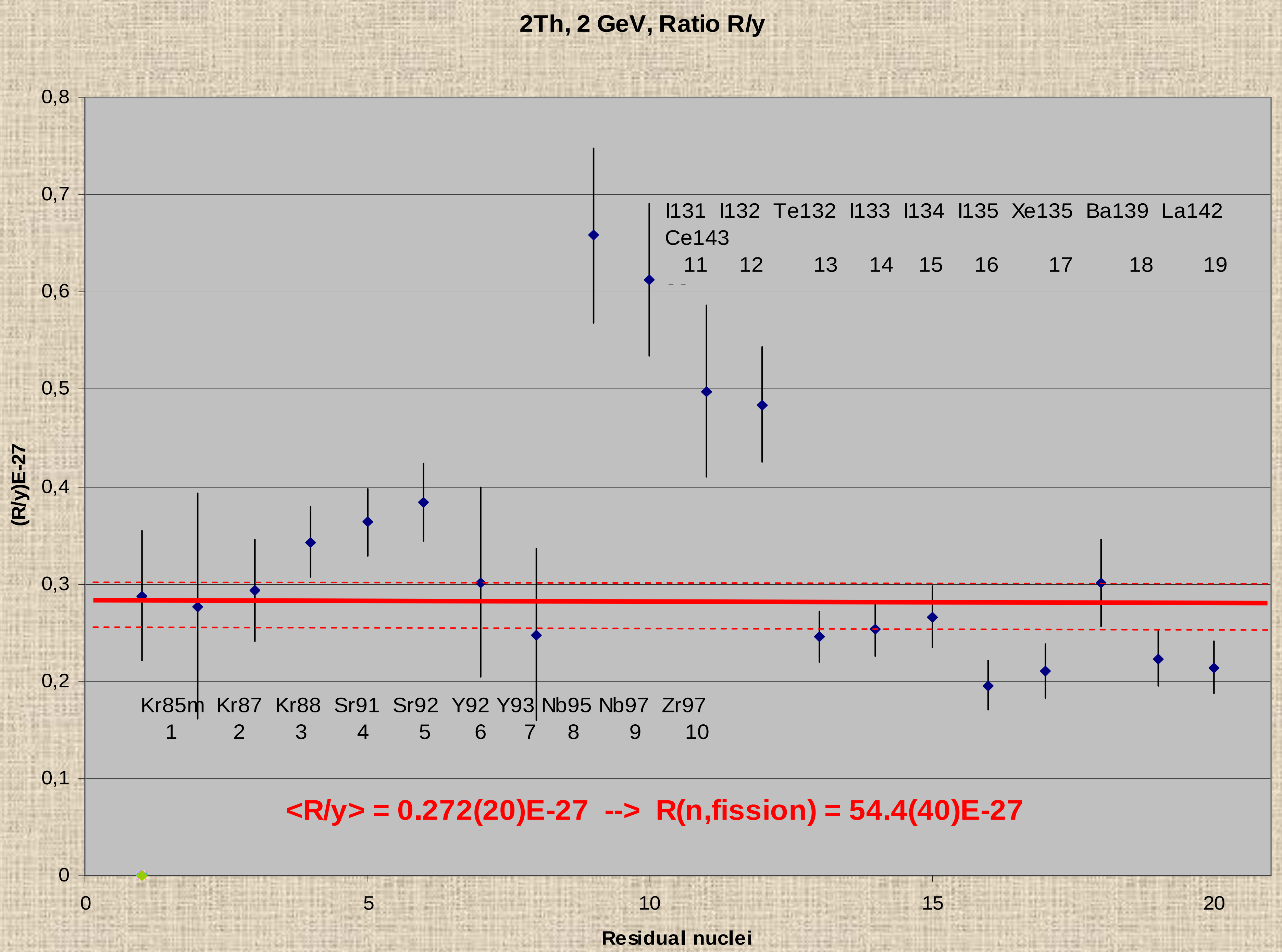



Fission products, 2Th, Ed = 2 GeV
R [x10-27 atoms-1 deuteron-1]
2,5
2
1,5
1
0,5
0
78Ge
78As
85mKr
87Kr
88Kr
91Sr
92Sr
92Y
93Y
95Nb
97NbD
97Zr
99Mo
105Ru
107Rh
112AgD
113Ag
115Cd
117InD
123mSn
128Sb*
131I
132ID
132Te
133I
134I
135I
135Xe
139Ba
142La
143Ce
Nuclide


Spallation products, 2Th, Ed = 2 GeV
R [x10-27 atoms-1 deuteron-1]
Nuclide
0
1
2
3
4
5
6
69mZn
77Ge
82Br
87Y
90mY
93mMo
95mNb
96Nb
105Rh
111mPd
117Sb
118mSb
125Xe
130I
145Eu
183Os
186Ir
193Au
196Tl
200Pb
201Pb
202Bi
203Pb
204Bi
205Bi
206Bi
207Po
209At
210At
224Ac
226Ac
228Pa
230Pa



R(exp)/yield, 2Th, Ed = 2 GeV
Ratio
yields
1,E+07
1,E+06
1,E+05
1,E+04
1,E+03
1,E+02
1,E+01
1,E+00
1,E-01
1,E+00
1,E-01
1,E-02
1,E-03
1,E-04
1,E-05
1,E-06
1,E-07
1,E-08
1,E-09
1,E-10
In117 7,2E-03
As78 2,9E-03
Ge78 2,9E-03
Nb95m 5,2E-04
Ge77 2,6E-04
Rh105 1,0E-02
Ru105 1,0E-02
Sn123m 9,2E-03
Ag113 7,9E-03
Pd111m 7,8E-05
Br82 1,4E-06
Nb96 2,1E-07
I130 1,5E-07
Y90m 4,9E-09
Zn69m 5,5E-10


2Th, 2 GeV, Ratio R/y
(R/y)E-27
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
I131 I132 Te132 I133 I134 I135 Xe135 Ba139 La142 Ce143
11 12 13 14 15 16 17 18 19
Kr85m Kr87 Kr88 Sr91 Sr92 Y92 Y93 Nb95 Nb97 Zr97
1 2 3 4 5 6 7 8 9 10
<R/y> = 0.272(20)E-27 --> R(n,fission) = 54.4(40)E-27
0 5 10 15 20
Residual nuclei

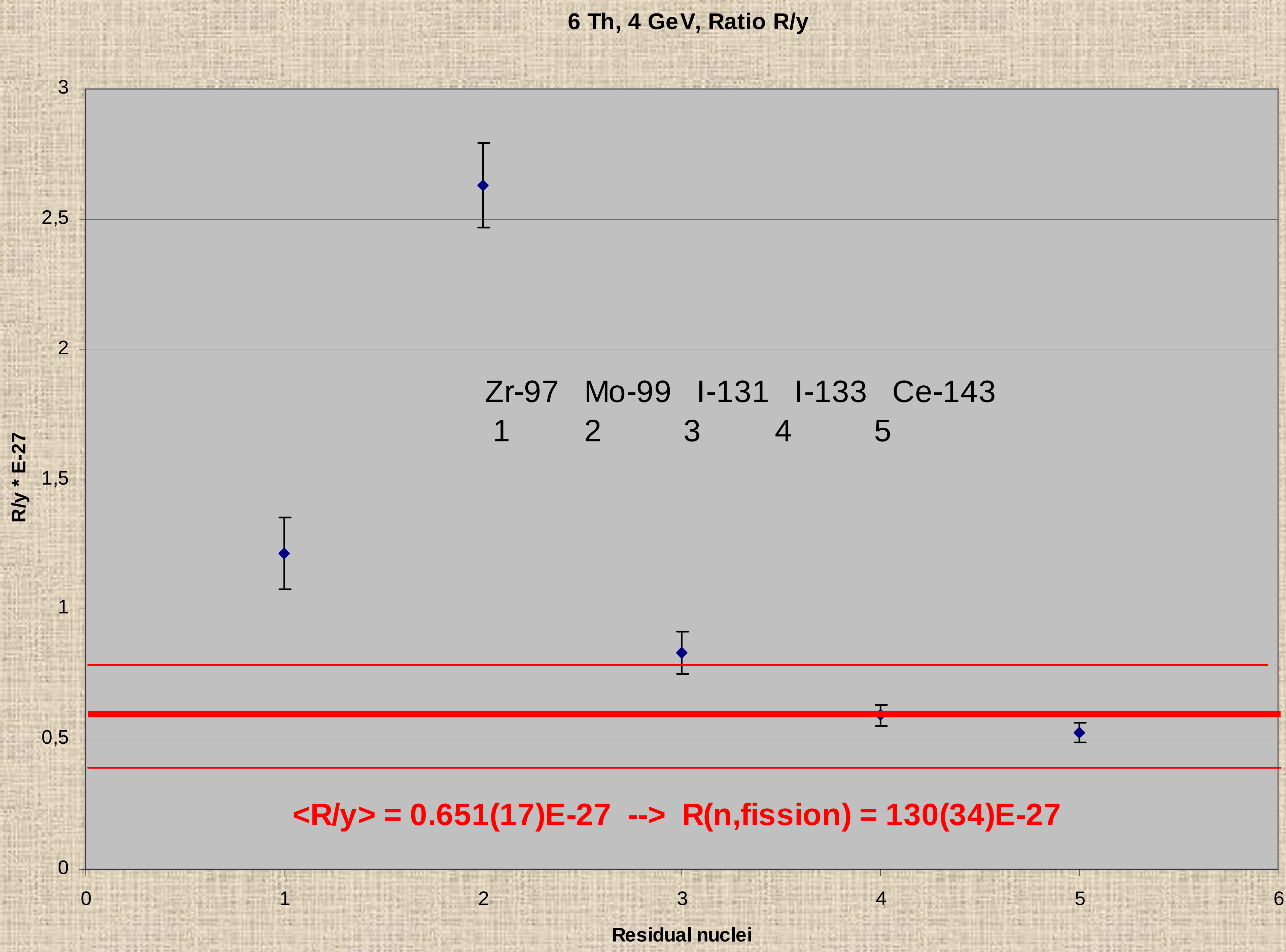
Results, 2Th, Ed = 2 GeV,

Reaction products	**R(exp.) [E-27]**
(n, γ)Pa-233	76.9(39)
(n,p6n)Ac-226	1.13(8)
(n,p8n)Ac-224	0.62(5)
(n,fission)	54.4(20)
(n,spallation)	17.9(25)

6Th - QUINTA - Ed = 4 GeV - Nuclotron-2011

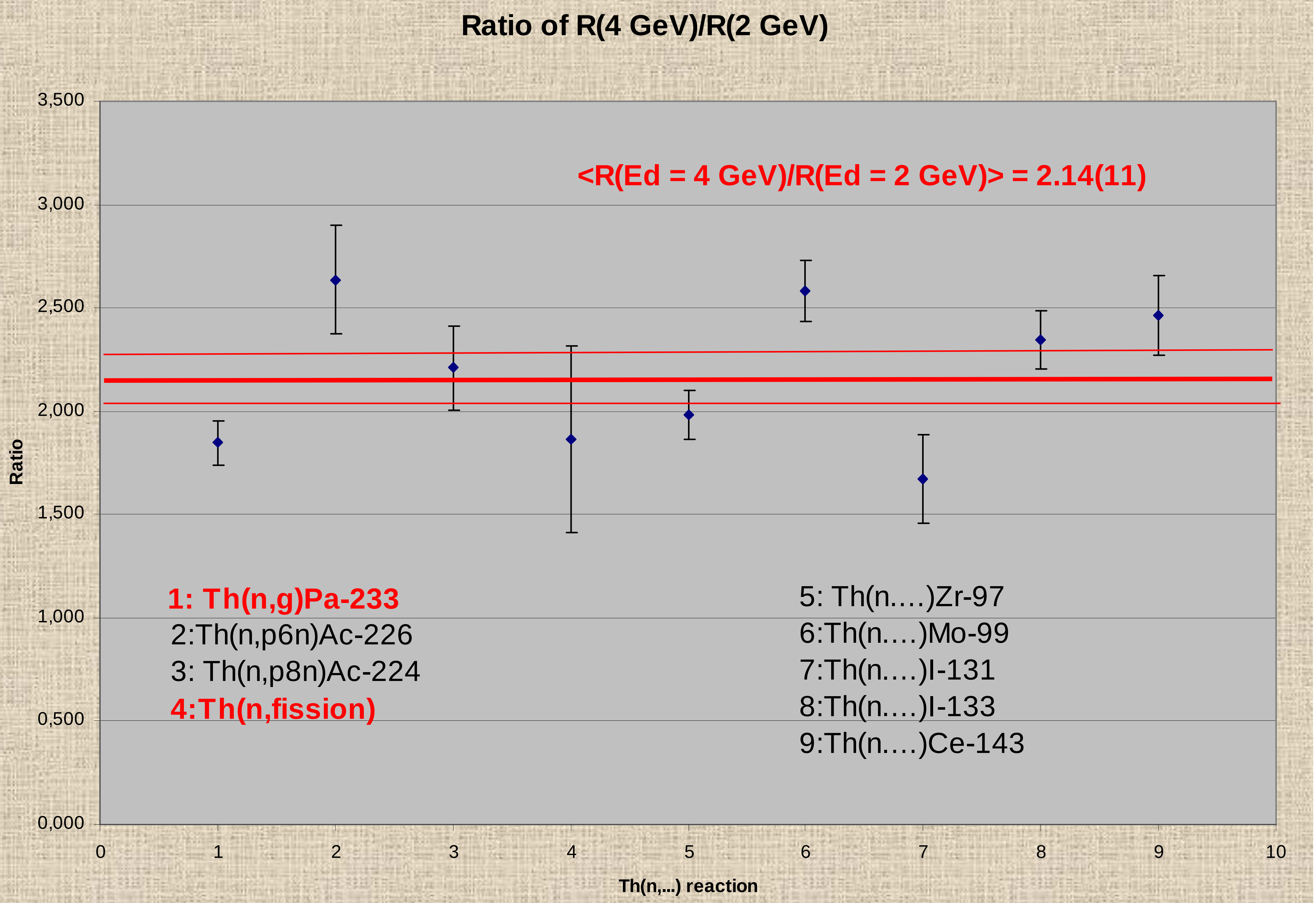
Isotope **Energy [keV]**	**Activity[Bq]** I_g [%]	**$T_{1/2}$(Library)** $T_{1/2}$(Exper.)	**<R>** R	**Number of spectra**
Zr-97		**16.91(5) h**	**3.77(14)E-27**	
743.360	93.0(10)	15.41(28) h	3.77(14)E-27	7-A
Mo-99		**2.747(1) d**	**5.14(6)E-27**	
140.511	89.43(23)	2.65(6)* d	5.14(6)E-27	8-A
Tc-99m		**6.010(10) h**	**1.08(10)E-27**	
140.511	89.43(23)	4.1(19)* h	1.08(10)E-27	2-A
I-131		**8.02(3) d**	**1.92(8)E-27**	
364.489	81.7	12.0(7) d	1.92(8)E-27	8-A
I-133		**20.80(10) h**	**2.44(5)E-27**	
529.872	87.0(17)	21.2(4) h	2.44(5)E-27	9-A
815.772	23.28(19)	-	-	-
1596.210	95.4(14)	-	-	-
Ce-143		**1.377(1) d**	**2.61(5)E-27**	
57.356	11.7(3)	1.1(3)* d	5.9(13)E-27*	6-A
293.266	42.80(13)	1.37(3) d	2.61(5)E-27	8-A

Isotope **Energy [keV]**	**Activity[Bq]** I_g [%]	**$T_{1/2}$(Library)** $T_{1/2}$(Exper.)	**<R>** R	**Number of spectra**
Ac-224		**2.78(17) h**	**1.37(6)E-27**	
131.613	26.9(6)	3.0(5) h	1.35(8)E-27	3-A
215.983	52.3(12)	4.7(9)* h	1.40(10)E-27	2-A
382.300	18	-	-	-
Ac-226		**1.224(5) d**	**2.98(21)E-27**	
158.180	17.5(5)	2.0(5)* d	3.33(15)E-27	4-A
230.370	27.0(10)	1.19(5) d	2.80(8)E-27	8-A
253.730	5.7(4)	19(4) h	3.79(30)E-27	4-A
Th-227		**18.720(20) d**	**3.8(15)E-27**	
50.130	8.0(4)	17(4) d	1.18(16)E-26*	1-C
235.971	12.3(9)	7(4) d	4.12(63)E-27	2-C
256.250	7.0(4)	43(15)* d	2.67(52)E-27	2-C
329.851	2.7(3)	-		-
Th-231		**1.063(1) d**	**5.14(15)E-26**	
25.646	14.5(3)	1.07(4) d	2.48(18)E-25*	8-A
84.216	6.60(30)	1.07(4) d	5.14(15)E-26	8-A
Pa-233		**26.967(2) d**	**1.42(4)E-25**	
300.340	6.62(6)	31.2(12)* d	1.53(6)E-25	2-C
312.170	38.6(4)	26.68(27) d	1.41(3)E-25	5-C
340.810	4.47(4)	23.8(7) d	1.36(5)E-25	3-C

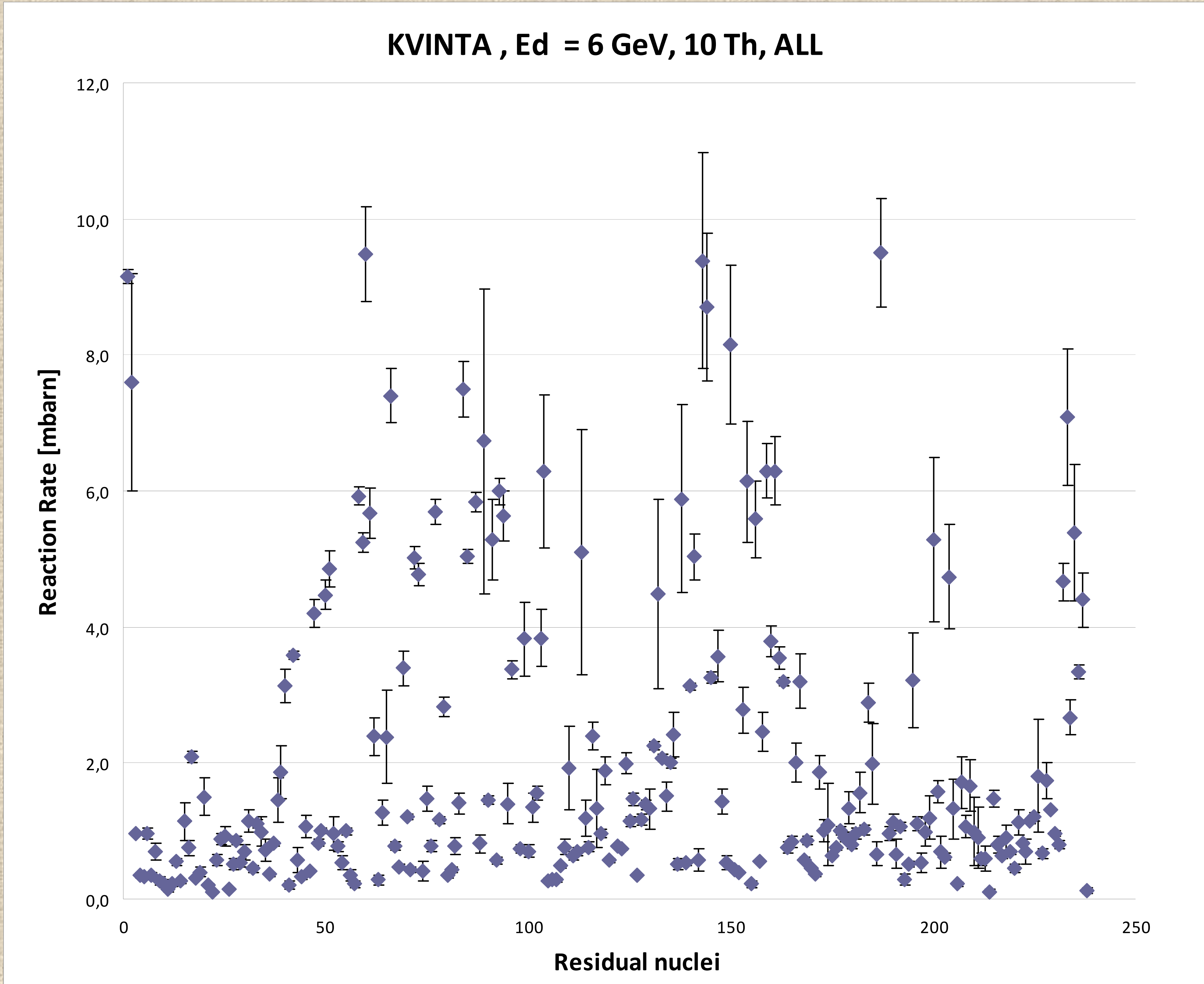

6 Th, 4 GeV, Ratio R/y
R/y * E-27
Residual nuclei
Zr-97 Mo-99 I-131 I-133 Ce-143
1 2 3 4 5
<R/y> = 0.651(17)E-27 --> R(n,fission) = 130(34)E-27
0
0,5
1
1,5
2
2,5
3
0 1 2 3 4 5 6

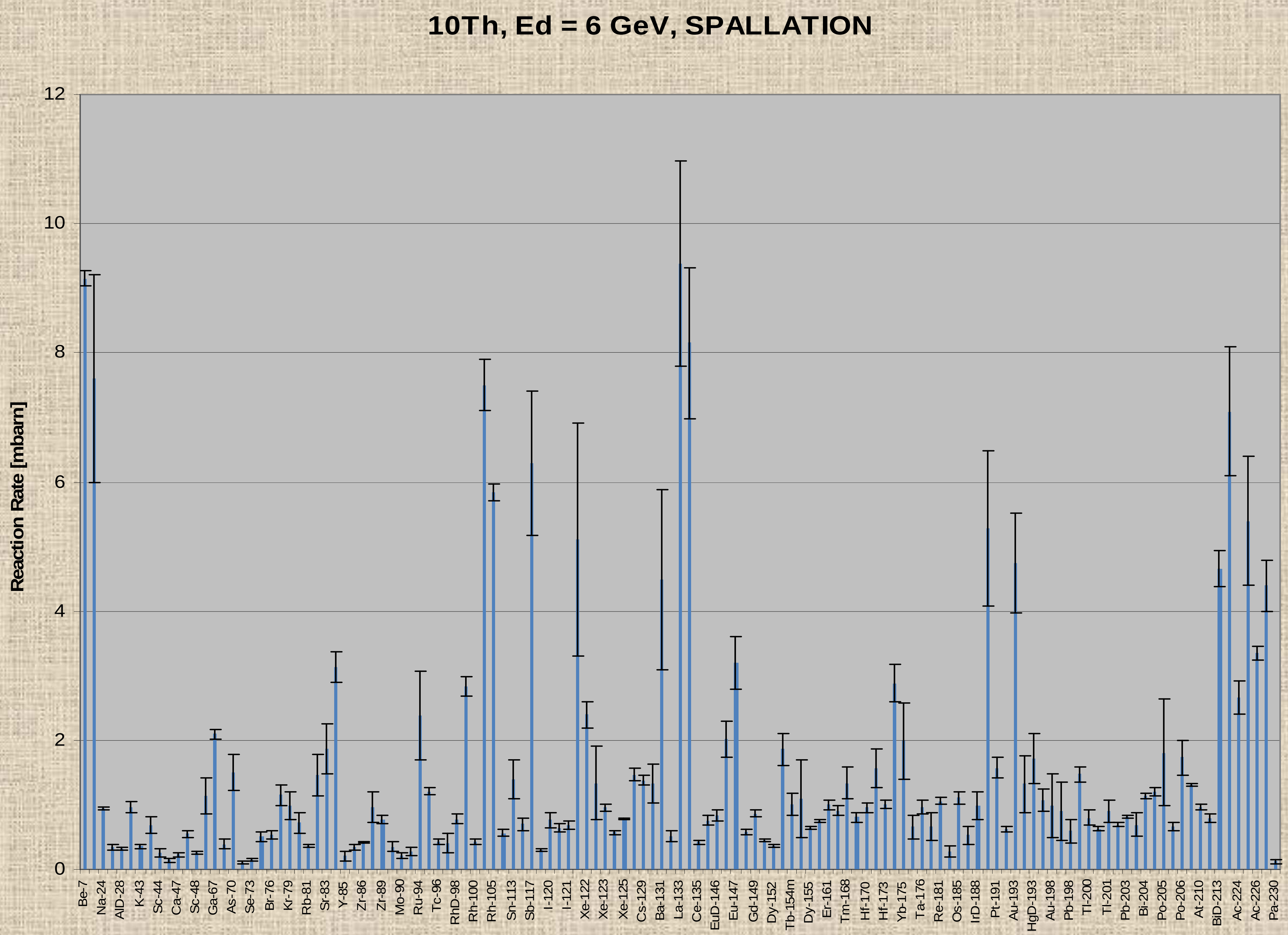
Results 6Th, Ed = 4 GeV, QUINTA
R(exp.) for reactions ^{238}Th (n, …)

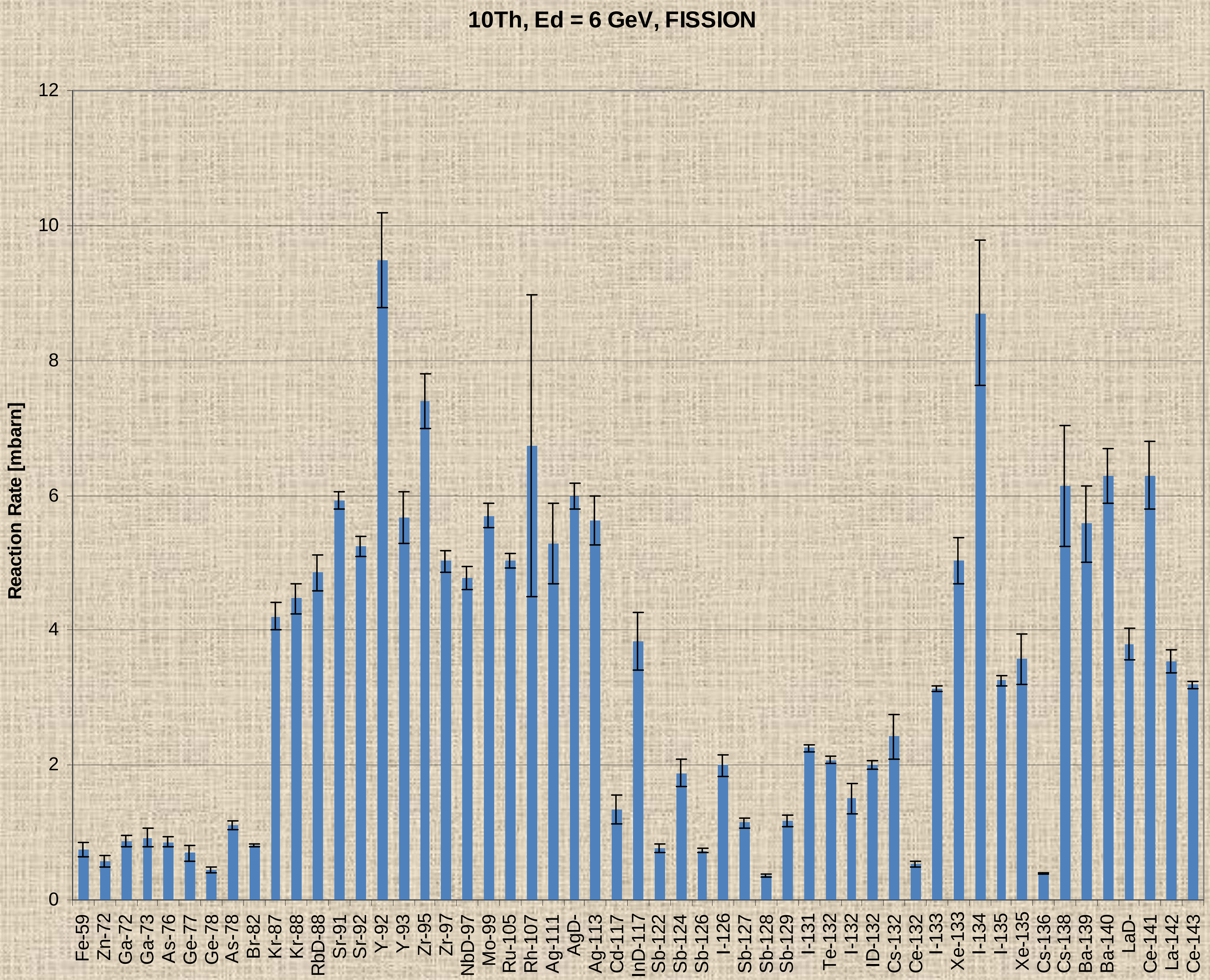
Reaction products	R(exp.)*E+27
(n, γ)Pa-233	142(4)
(n,2n)Th-231	51.4(15)
(n,6n)Th-227	3.5(15)
(n,p6n)Ac-226	2.98(21)
(n,p8n)Ac-224	1.37(6)
(n,fission)	116(12)



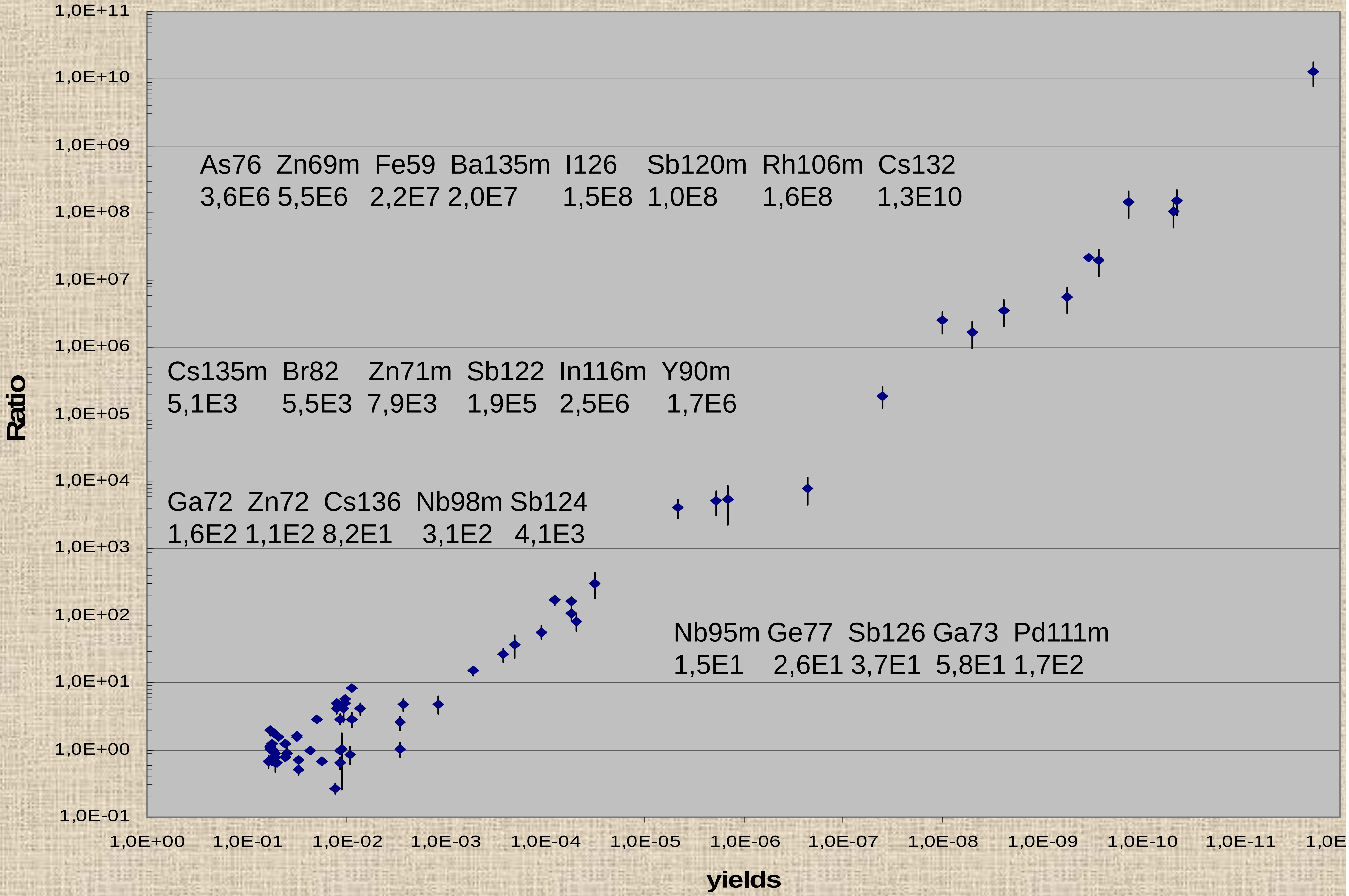
Ratio of R(4 GeV)/R(2 GeV)
<R(Ed = 4 GeV)/R(Ed = 2 GeV)> = 2.14(11)
1: Th(n,g)Pa-233
2:Th(n,p6n)Ac-226
3: Th(n,p8n)Ac-224
4:Th(n,fission)
5: Th(n.…)Zr-97
6:Th(n.…)Mo-99
7:Th(n.…)I-131
8:Th(n.…)I-133
9:Th(n.…)Ce-143
Ratio
3,500
3,000
2,500
2,000
1,500
1,000
0,500
0,000
0
1
2
3
4
5
6
7
8
9
10
Th(n,...) reaction

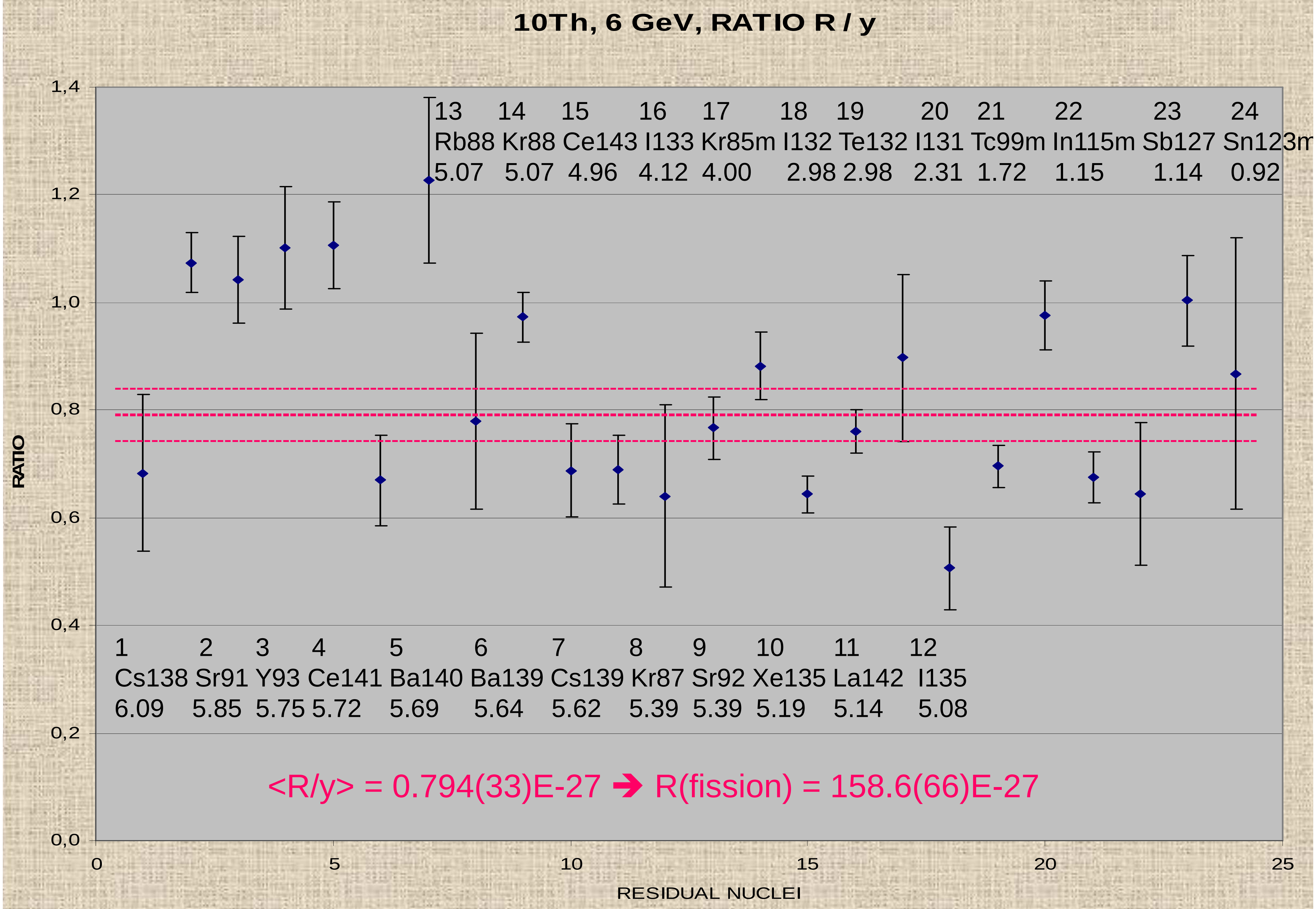

KVINTA , Ed = 6 GeV, 10 Th, ALL
Reaction Rate [mbarn]
Residual nuclei
0,0
2,0
4,0
6,0
8,0
10,0
12,0
0
50
100
150
200
250


10Th, Ed = 6 GeV, SPALLATION
Reaction Rate [mbarn]
0
2
4
6
8
10
12
Be-7
Na-24
AlD-28
K-43
Sc-44
Ca-47
Sc-48
Ga-67
As-70
Se-73
Br-76
Kr-79
Rb-81
Sr-83
Y-85
Zr-86
Zr-89
Mo-90
Ru-94
Tc-96
RhD-98
Rh-100
Rh-105
Sn-113
Sb-117
I-120
I-121
Xe-122
Xe-123
Xe-125
Cs-129
Ba-131
La-133
Ce-135
EuD-146
Eu-147
Gd-149
Dy-152
Tb-154m
Dy-155
Er-161
Tm-168
Hf-170
Hf-173
Yb-175
Ta-176
Re-181
Os-185
IrD-188
Pt-191
Au-193
HgD-193
Au-198
Pb-198
Tl-200
Tl-201
Pb-203
Bi-204
Po-205
Po-206
At-210
BiD-213
Ac-224
Ac-226
Pa-230


10Th, Ed = 6 GeV, FISSION
Reaction Rate [mbarn]
0
2
4
6
8
10
12
Fe-59
Zn-72
Ga-72
Ga-73
As-76
Ge-77
Ge-78
As-78
Br-82
Kr-87
Kr-88
RbD-88
Sr-91
Sr-92
Y-92
Y-93
Zr-95
Zr-97
NbD-97
Mo-99
Ru-105
Rh-107
Ag-111
AgD-
Ag-113
Cd-117
InD-117
Sb-122
Sb-124
Sb-126
I-126
Sb-127
Sb-128
Sb-129
I-131
Te-132
I-132
ID-132
Cs-132
Ce-132
I-133
Xe-133
I-134
I-135
Xe-135
Cs-136
Cs-138
Ba-139
Ba-140
LaD-
Ce-141
La-142
Ce-143

10Th, Ratio R(exp.) / yields, KVINTA, Ed = 6 GeV





10Th, 6 GeV, RATIO R / y
RATIO
RESIDUAL NUCLEI
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0,0
0
5
10
15
20
25
13 Rb88 5.07
14 Kr88 5.07
15 Ce143 4.96
16 I133 4.12
17 Kr85m 4.00
18 I132 2.98
19 Te132 2.98
20 I131 2.31
21 Tc99m 1.72
22 In115m 1.15
23 Sb127 1.14
24 Sn123m 0.92
1 Cs138 6.09
2 Sr91 5.85
3 Y93 5.75
4 Ce141 5.72
5 Ba140 5.69
6 Ba139 5.64
7 Cs139 5.62
8 Kr87 5.39
9 Sr92 5.39
10 Xe135 5.19
11 La142 5.14
12 I135 5.08
<R/y> = 0.794(33)E-27 ➔ R(fission) = 158.6(66)E-27

HART OF THE NUCLIDES 2000

ompiled by

akayoshi HORIGUCHI
epartment of Clinical Radiology, Faculty of Health Sciences,
iroshima International University,
55-36 Gakuendai, Kurose, Kamo-gun, Hiroshima 724-0695, Japan
-mail : t.hori@hs.hirokoku-u.ac.jp

akahiro TACHIBANA and Hiroyuki KOURA
dvanced Research Institute for Science and Engineering,
Vaseda University, 3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555, Japan
-mail : ttachi@mn.waseda.ac.jp
-mail : koura@mn.waseda.ac.jp

un-ichi KATAKURA
Nuclear Data Center, Japan Atomic Energy Research Institute,
Tokai-mura, Ibaraki 319-1195, Japan
E-mail : katakura@ndc.tokai.jaeri.go.jp

7Be independent R

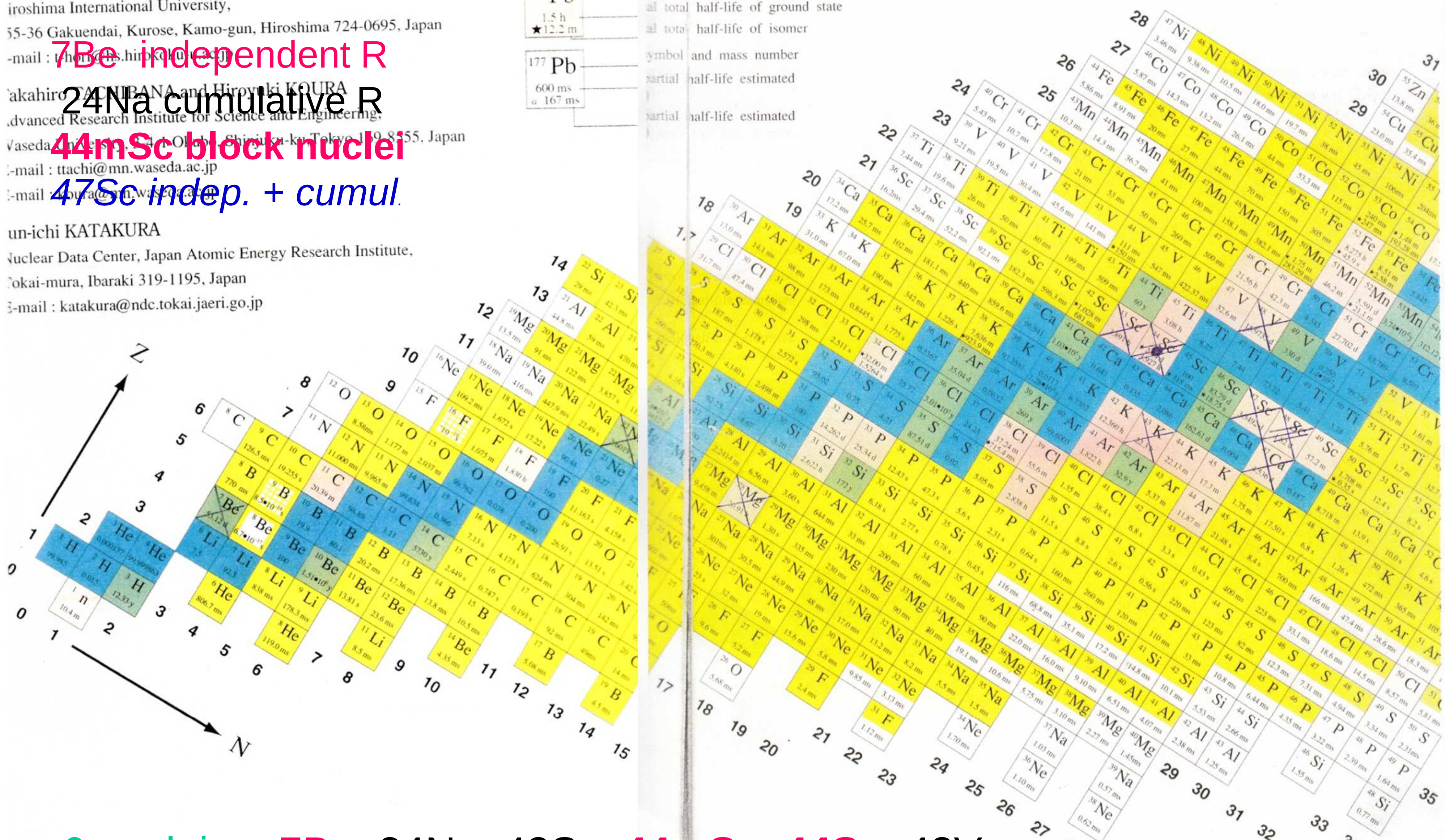
24Na cumulative R

44mSc block nuclei

47Sc indep. + cumul.

Ref.1) T.Tachibana, M.Yamada, Proc. Inc. Conf. on exotic nuclei and atomic masses, Arles, 1995, eds. M. de Saint Simon and O. Sorlin (Editions Frontueres, Gif-sur-Yvette, 1995) p.763. and references therein.

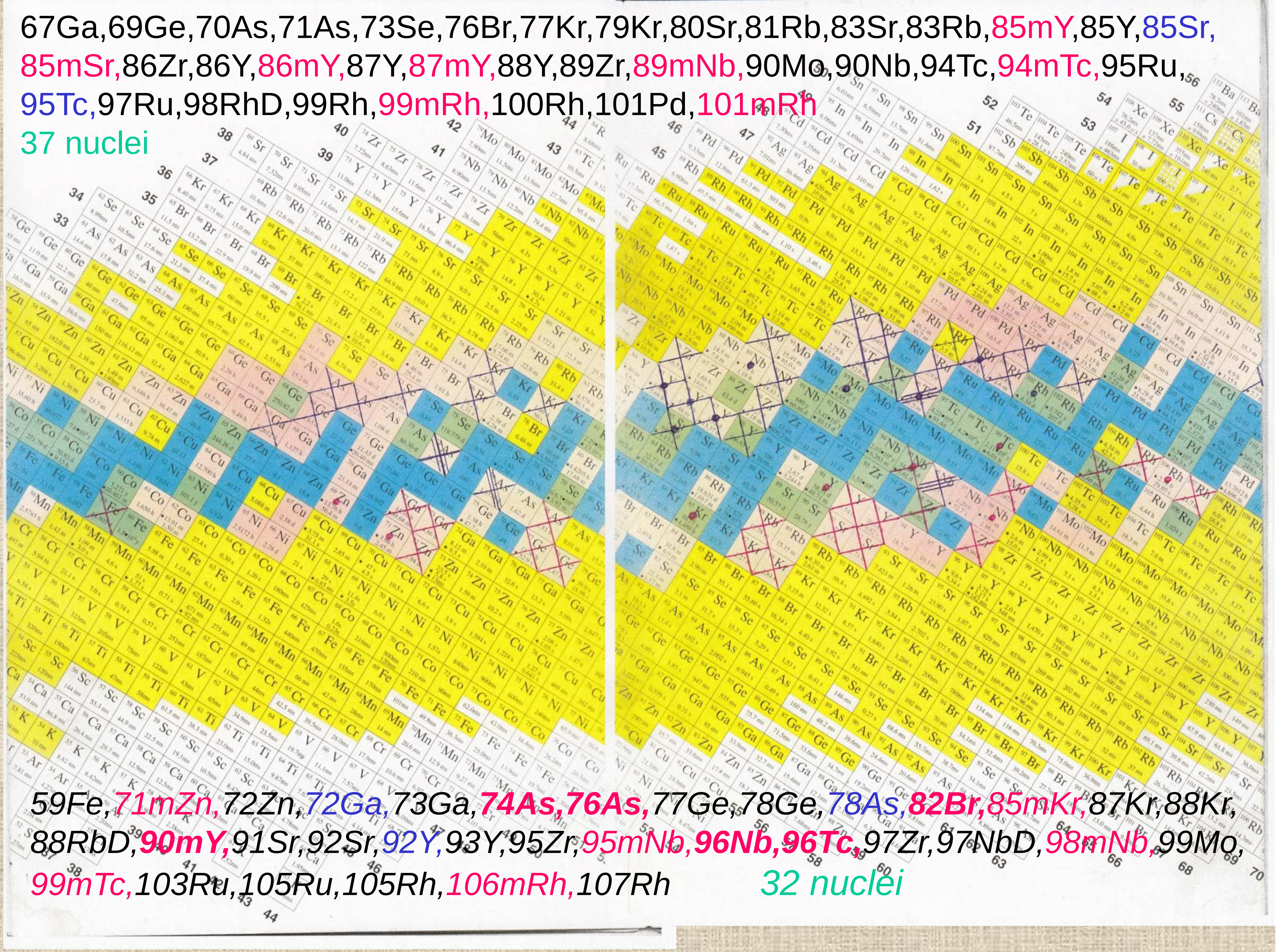
Ref.2) V. E. Viola, Jr. and G. T. Seaborg, J. Inorg. Nucl. Chem. 28 741 (1966) with newly adjusted parameter values.



6 nuclei : 7Be 24Na 43Sc **44mSc** **44Sc** 48V neutron deficient

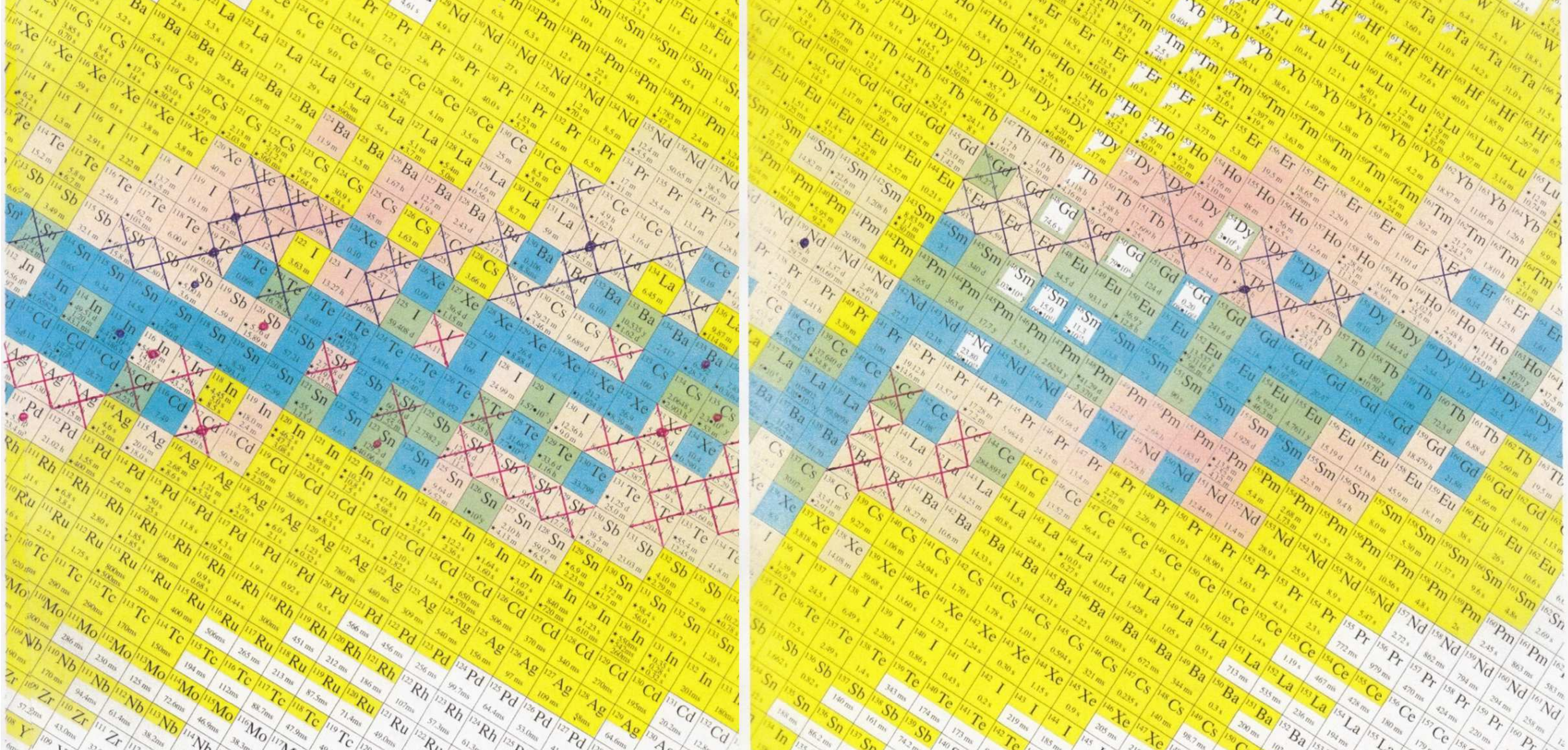
8 nuclei : *22Na 28Mg 28AlD 41Ar 43K 47Ca 47Sc* ***48Sc*** *neutron rich*

67Ga,69Ge,70As,71As,73Se,76Br,77Kr,79Kr,80Sr,81Rb,83Sr,83Rb,85mY,85Y,85Sr,
85mSr,86Zr,86Y,86mY,87Y,87mY,88Y,89Zr,89mNb,90Mo,90Nb,94Tc,94mTc,95Ru,
95Tc,97Ru,98RhD,99Rh,99mRh,100Rh,101Pd,101mRh
37 nuclei



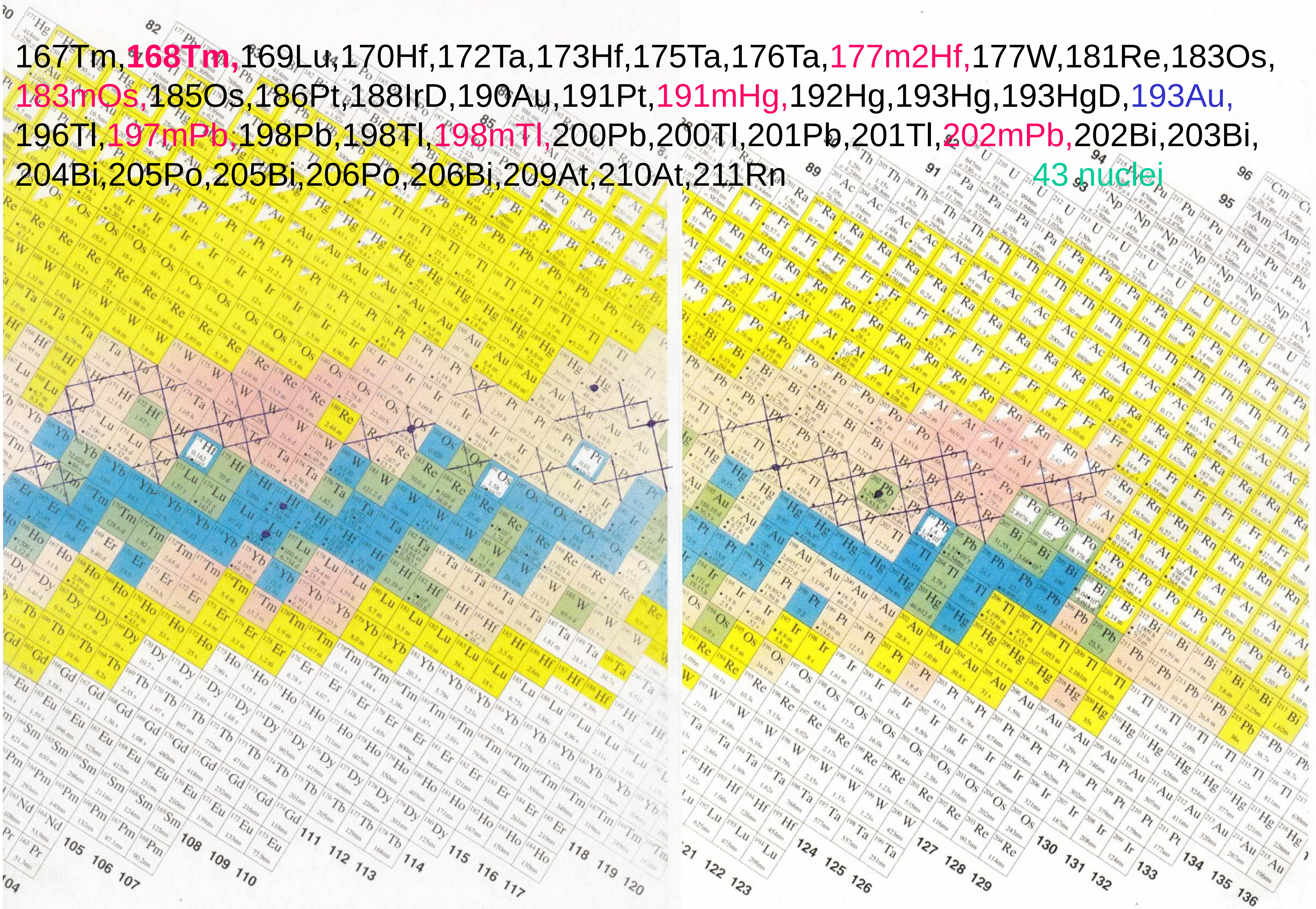
*59Fe,71mZn,72Zn,72Ga,73Ga,**74As,76As,**77Ge,78Ge,78As,**82Br,**85mKr,87Kr,88Kr,*
*88RbD,**90mY,**91Sr,92Sr,92Y,93Y,95Zr,95mNb,**96Nb,96Tc,**97Zr,97NbD,98mNb,99Mo,*
99mTc,103Ru,105Ru,105Rh,106mRh,107Rh 32 nuclei

111In,113Sn,116SbD,117Sb,118mSb,119Te,119mTe,120I,120mI,121I,121Te,122Xe,
123Xe,123Xe,123I,**124I,**125Xe,**126I,**127Cs,129Ba,129Cs,131Ba,**132Cs,**132Ce,132La,
132mLa,133La,135Ce,137mCe,138mPr,139NdD,139mNd,145Eu,146Gd,146EuD,
147Eu,147Gd,149Gd,152Dy,152Tb,**154Tb,154mTb,**155Dy,155Tb,157Dy,161Er,105Ru,
105Rh,106mRh,107Rh 50 nuclei



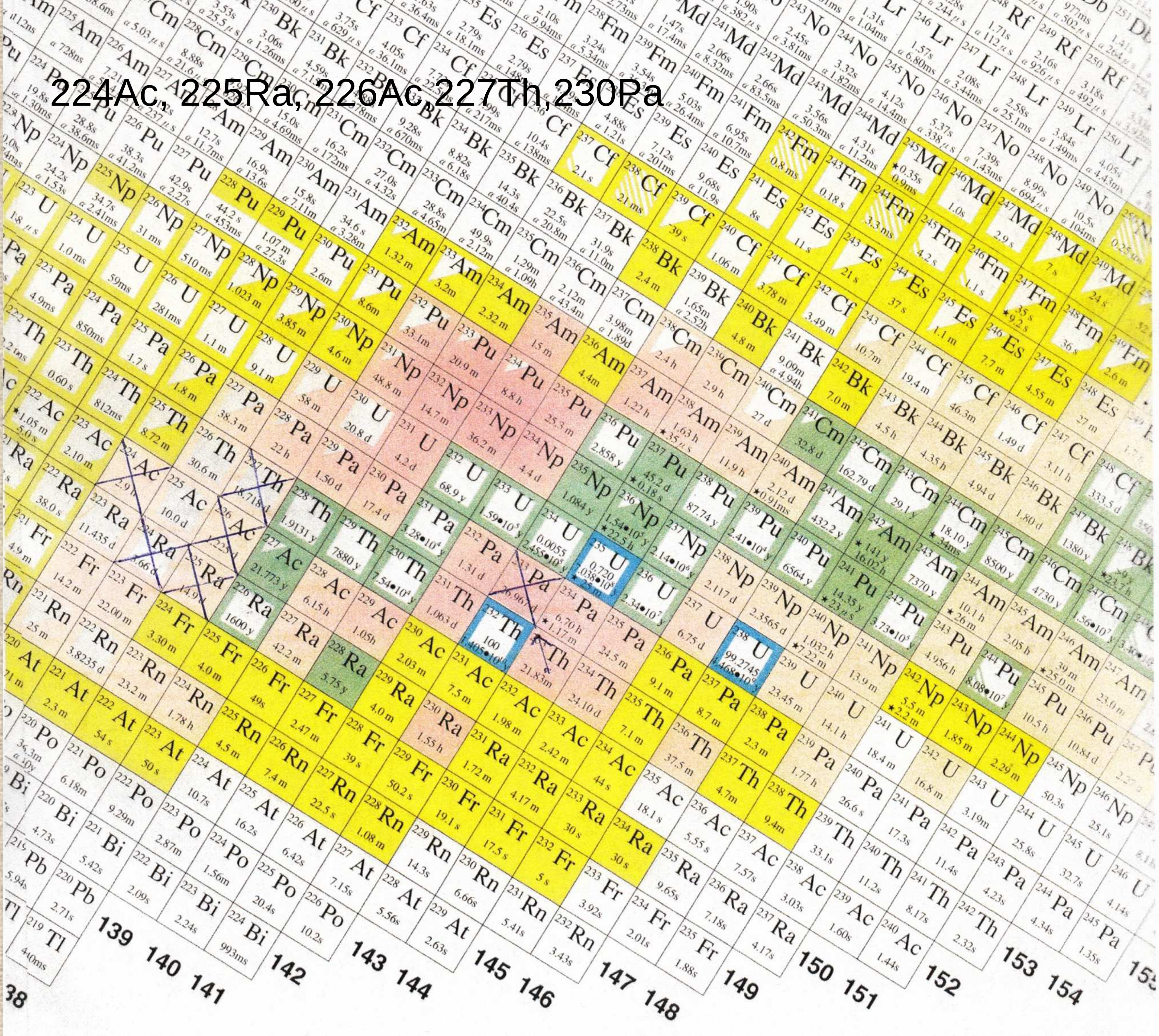
*111mPd,111Ag,112AgD,113Ag,115Cd,115mIn,****116mIn,****117Cd,117mCd,117InD,****120mSb,
122Sb,****123mSn,****124Sb,****126Sb,127Sb,128Sb,129Sb,****130I,****131I,132Te,132I,132ID,133I,
133Xe,133mXe,134I,135I,135Xe,135mCs,135mBa,****136Cs,****138Cs,139Ba,140Ba,140LaD,
142La,143Ce 38 nuclei*

167Tm,168Tm,169Lu,170Hf,172Ta,173Hf,175Ta,176Ta,177m2Hf,177W,181Re,183Os,
183mOs,185Os,186Pt,188IrD,190Au,191Pt,191mHg,192Hg,193Hg,193HgD,193Au,
196Tl,197mPb,198Pb,198Tl,198mTl,200Pb,200Tl,201Pb,201Tl,202mPb,202Bi,203Bi,
204Bi,205Po,205Bi,206Po,206Bi,209At,210At,211Rn 43 nuclei



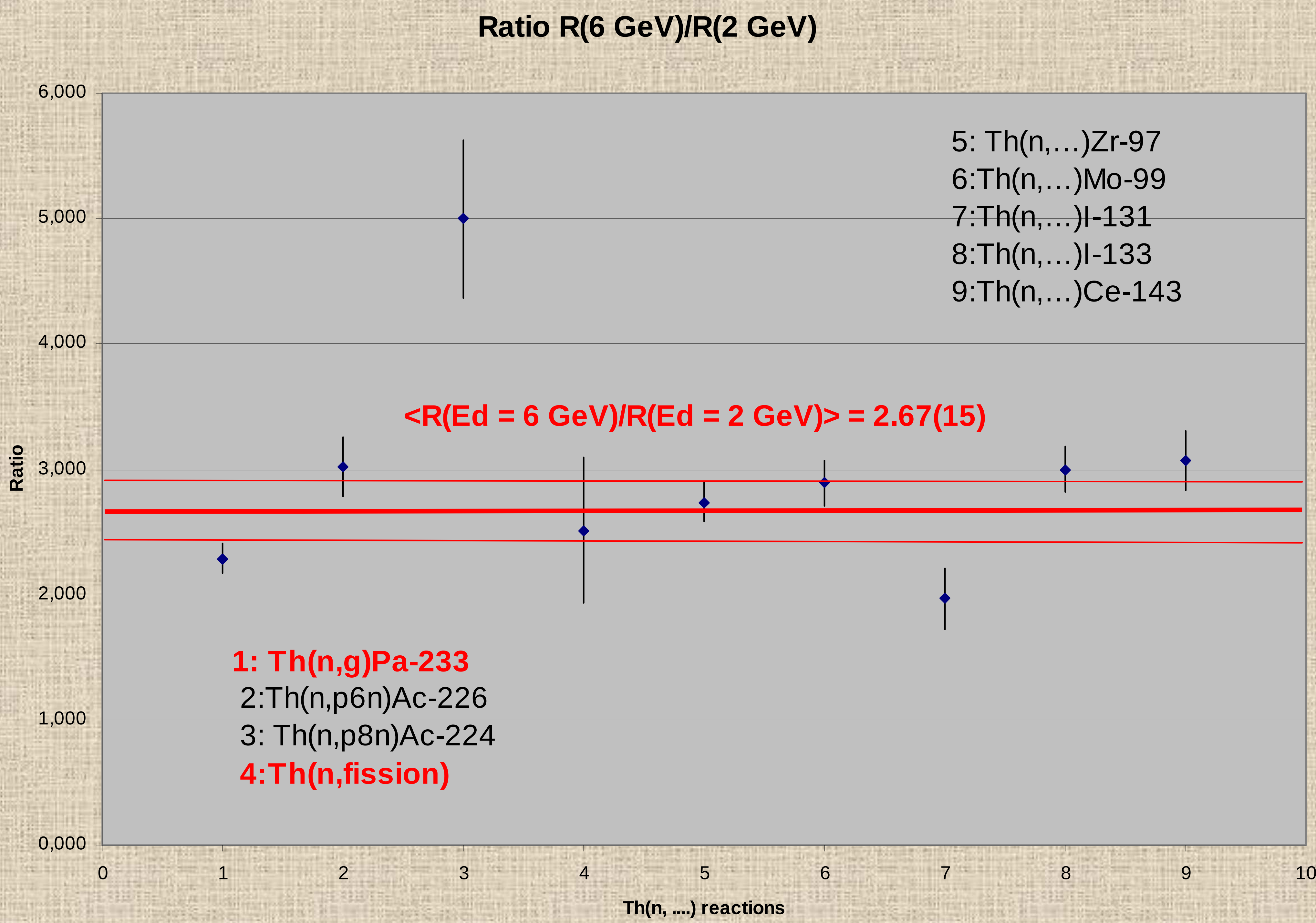
175Yb,185Ta,190mRe,200mAu,200AuD,213BiD,219RnD *7 nuclei*

224Ac, 225Ra, 226Ac,227Th,230Pa

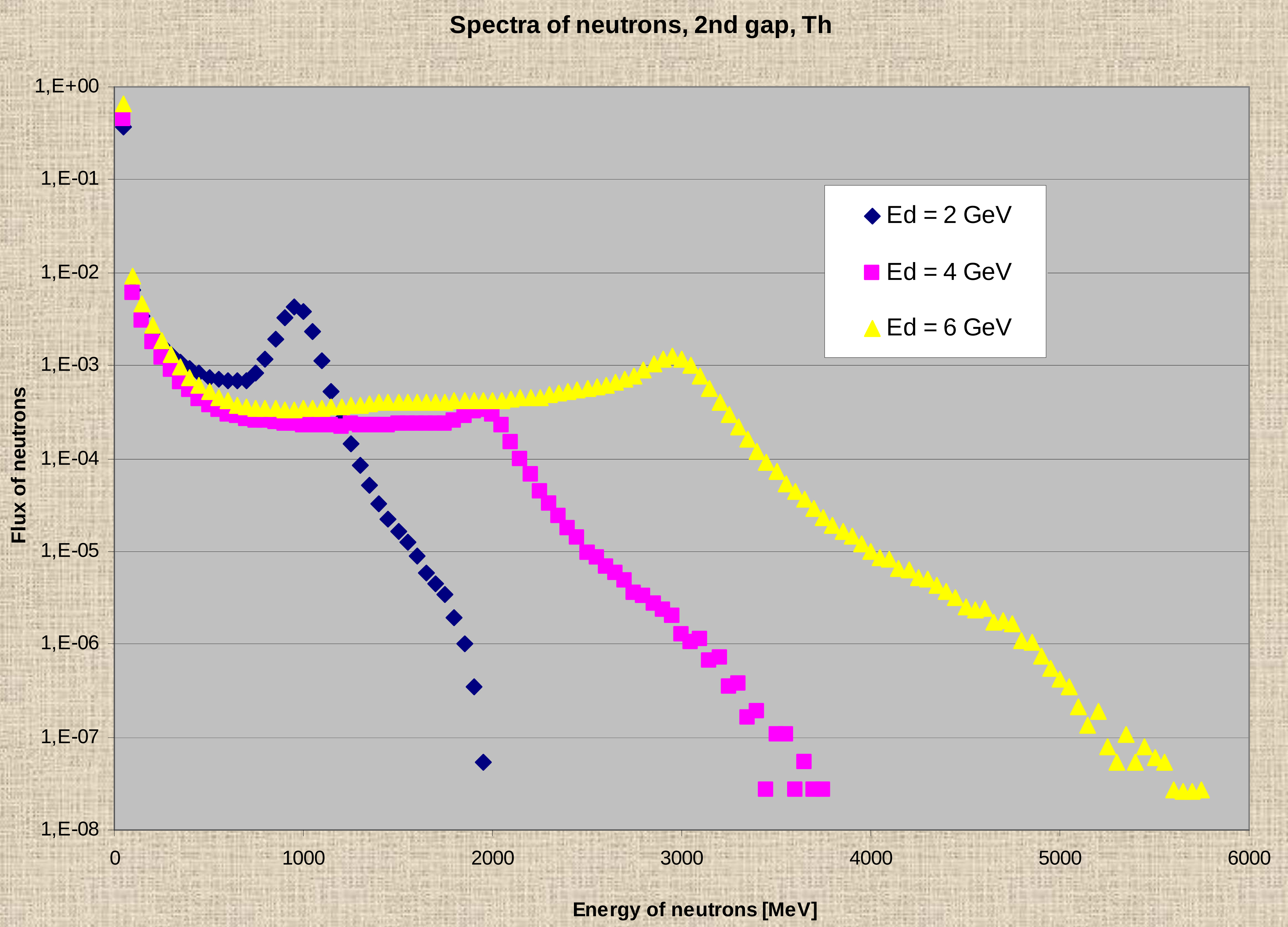


Results 10Th, Ed = 6 GeV, QUINTA
R(exp.) for reactions ^{238}Th (n, …)

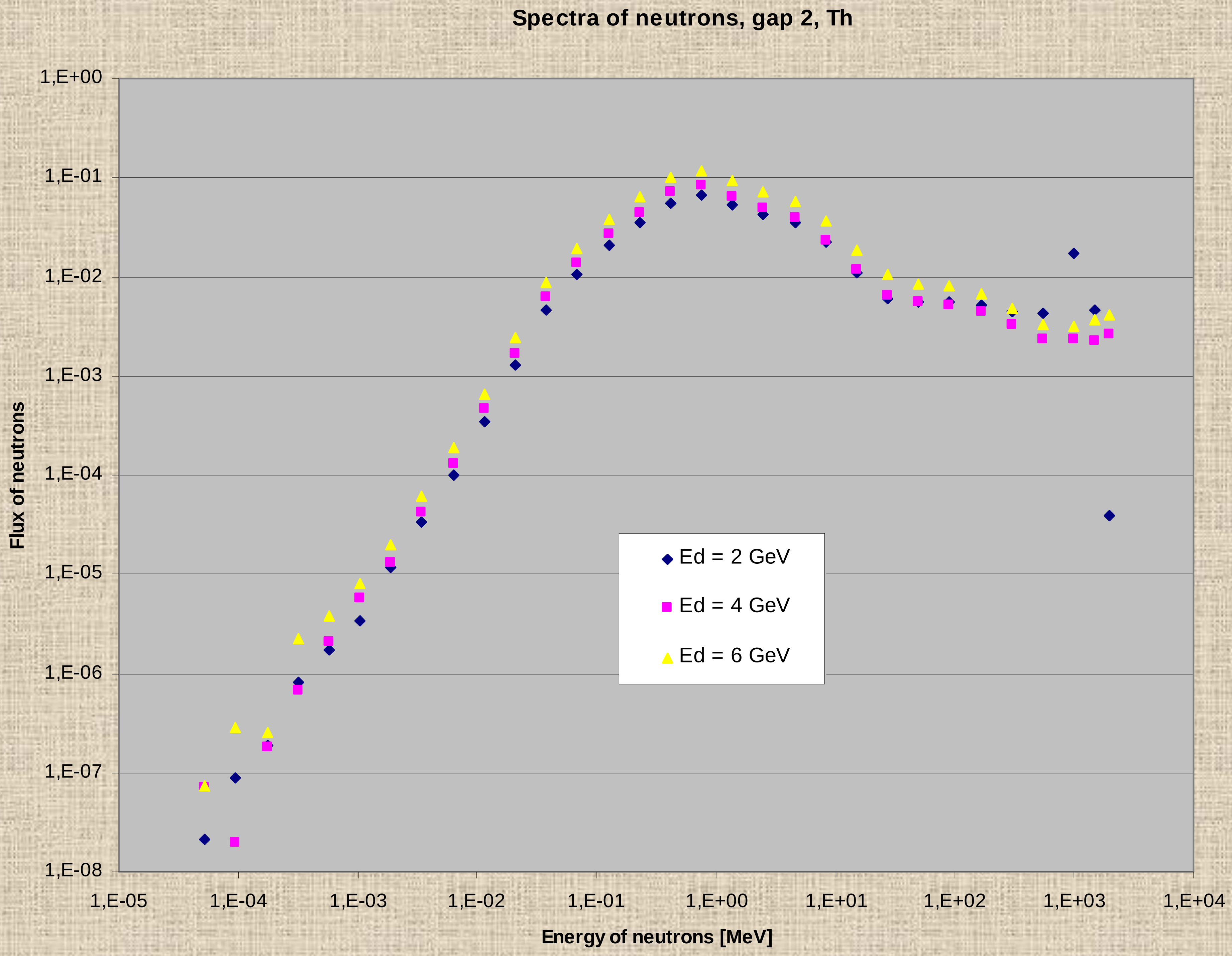
Reaction products	R(exp.)*E+27
(n, γ)Pa-233	176.3(30)
(n,2n)Th-231	71.2(23)
(n,6n)Th-227	4.4(4)
(n,p6n)Ac-226	3.41(11)
(n,p8n)Ac-224	3.1(3)
(n,fission)	158.6(66)
(n,spallation)	194(30)



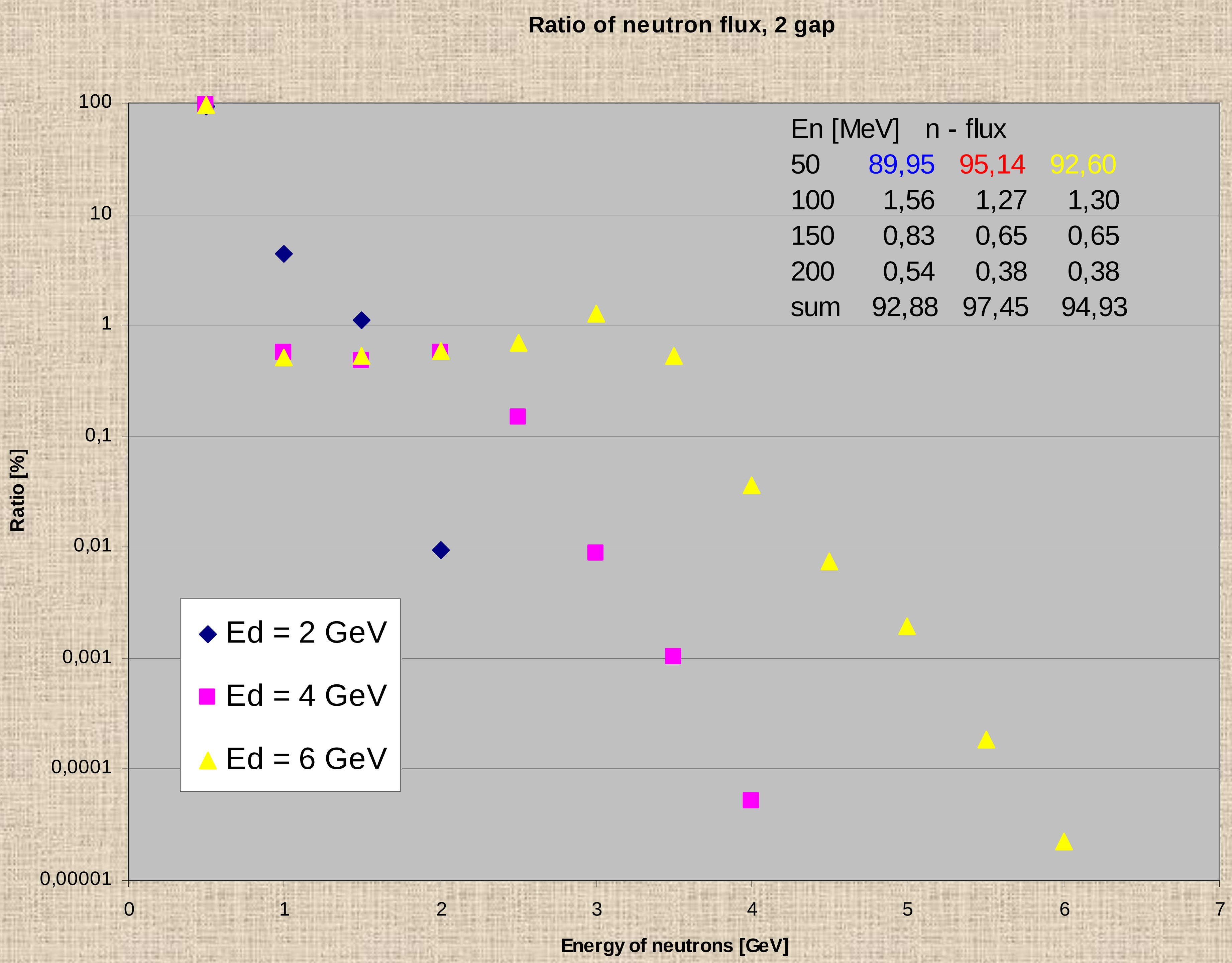
Ratio R(6 GeV)/R(2 GeV)
Ratio
6,000
5,000
4,000
3,000
2,000
1,000
0,000
0
1
2
3
4
5
6
7
8
9
10
Th(n, ...) reactions
5: Th(n,…)Zr-97
6:Th(n,…)Mo-99
7:Th(n,…)I-131
8:Th(n,…)I-133
9:Th(n,…)Ce-143
<R(Ed = 6 GeV)/R(Ed = 2 GeV)> = 2.67(15)
1: Th(n,g)Pa-233
2:Th(n,p6n)Ac-226
3: Th(n,p8n)Ac-224
4:Th(n,fission)



Spectra of neutrons, 2nd gap, Th
Flux of neutrons
1,E+00
1,E-01
1,E-02
1,E-03
1,E-04
1,E-05
1,E-06
1,E-07
1,E-08
0
1000
2000
3000
4000
5000
6000
Energy of neutrons [MeV]
Ed = 2 GeV
Ed = 4 GeV
Ed = 6 GeV



Spectra of neutrons, gap 2, Th
Flux of neutrons
1,E+00
1,E-01
1,E-02
1,E-03
1,E-04
1,E-05
1,E-06
1,E-07
1,E-08
1,E-05
1,E-04
1,E-03
1,E-02
1,E-01
1,E+00
1,E+01
1,E+02
1,E+03
1,E+04
Energy of neutrons [MeV]
Ed = 2 GeV
Ed = 4 GeV
Ed = 6 GeV


Ratio of neutron flux, 2 gap
Ratio [%]
100
10
1
0,1
0,01
0,001
0,0001
0,00001
0
1
2
3
4
5
6
7
Energy of neutrons [GeV]
En [MeV] n - flux
50 89,95 95,14 92,60
100 1,56 1,27 1,30
150 0,83 0,65 0,65
200 0,54 0,38 0,38
sum 92,88 97,45 94,93
Ed = 2 GeV
Ed = 4 GeV
Ed = 6 GeV

	Average energy [MeV]			Flux [h/d.cm^2]		
	n	p	pi	n	p	pi
• Gape 2						
• 2 GeV	106	631	270	4.1E-1	3.1E-2	2.1E-3
• 4 GeV	77	822	470	4.7E-1	1.4E-2	3.8E-3
• 6 GeV	143	1630	729	7.0E-1	3.7E-2	1.0E-2

REACTION RATE R(exp.)[E-27](err.)

Reaction products	Ed = 2 GeV Reza et al.	Ed = 4 GeV Adam et al.	Ed = 6 GeV Adam et al.
Th(n,g)**Pa-233**	76.9(39)	142(4)	176(3)
Th(n,2n)**Th-231**		51.4(15)	71.2(23)
Th(n,6n)**Th-227**		3.8(15)	4.4(4)
Th(n,p6n)**Ac-226**	1.13(8)	2.98(21)	3.41(11)
Th(n,p8n)**Ac-224**	0.62(5)	1.37(6)	3.1(3)
Th(n,**fission**)	**54.4(40)**	**118(10)**	**159(7)**
Th(n,…)**Zr-97**	1.9(9)	3.77(14)	5.2(17)
Th(n,…)**Mo-99**	1.99(11)	5.14(6)	5.75(18)
Th(n,…)**I-131**	1.15(14)	1.92(8)	2.26(6)
Th(n,…)**I-133**	1.04(6)	2.44(5)	3.12(5)
Th(n,…)**Ce-143**	1.06(8)	2.61(5)	3.25(6)
Th(n,**spallation**)	**17.9(25)**	**-**	**194(30)**

Reaction products	Reza et al. Ed = 2 GeV	Adam et al. Ed = 4 GeV	Adam et al. Ed = 6 GeV
	REACTION RATE R(exp.)[E-27](err.)		
	REACTION RATE R(calc.)[E-27]		
Th(n,g)Pa-233	76.9(39)	142(4)	176(3)
	46.3	58.1	83.2
Th(n,2n)Th-231		51.4(15)	71.2(23)
	33.0	35.1	56.8
Th(n,6n)Th-227		3.8(15)	4.4(4)
Th(n,p6n)Ac-226	1.13(8)	2.98(21)	3.41(11)
Th(n,p8n)Ac-224	0.62(5)	1.37(6)	3.1(3)
Th(n,fission)	54.4(40)	118(10)	159(7)
	84.0	89.7	170.9

Conclusions

- **1. $R(n,x,E_d) / E_d \cong$ const., $x = f, \gamma, 2n$**
  E_d from 2 GeV $\rightarrow$ 6 GeV

- **2. $R_{exp}(n,x) / R_{calc}(n,x) = 1.5 \pm 0.5$**
  $x = f, \gamma, 2n$ $E_d = 2, 4,$ and 6 GeV

- **3. R(n,spallation) / R(n,fission)**
  go up with E_d

THANK YOU FOR YOUR ATTENTION!