New cross section measurement for the $^{100}Mo(p,2n)^{99m}Tc$ reaction

Sándor Takács

Institute for Nuclear Research

ATOMKI

Why $^{100}Mo(p,2n)^{99m}Tc$ is interesting ?

- **More than 80% of all diagnostic nuclear procedures uses ^{99m}Tc world wide.**
- **Five nuclear reactors produce ^{99m}Tc.**
- **The world demand is about 6000 Ci/week**
- **Problem with the reactors and planned shutdown**
- **Alternative solution: direct production of ^{99m}Tc**

Accelerator production of ^{99m}Tc

Reactions on Mo

$^{100}Mo(p,2n)^{99m}Tc$

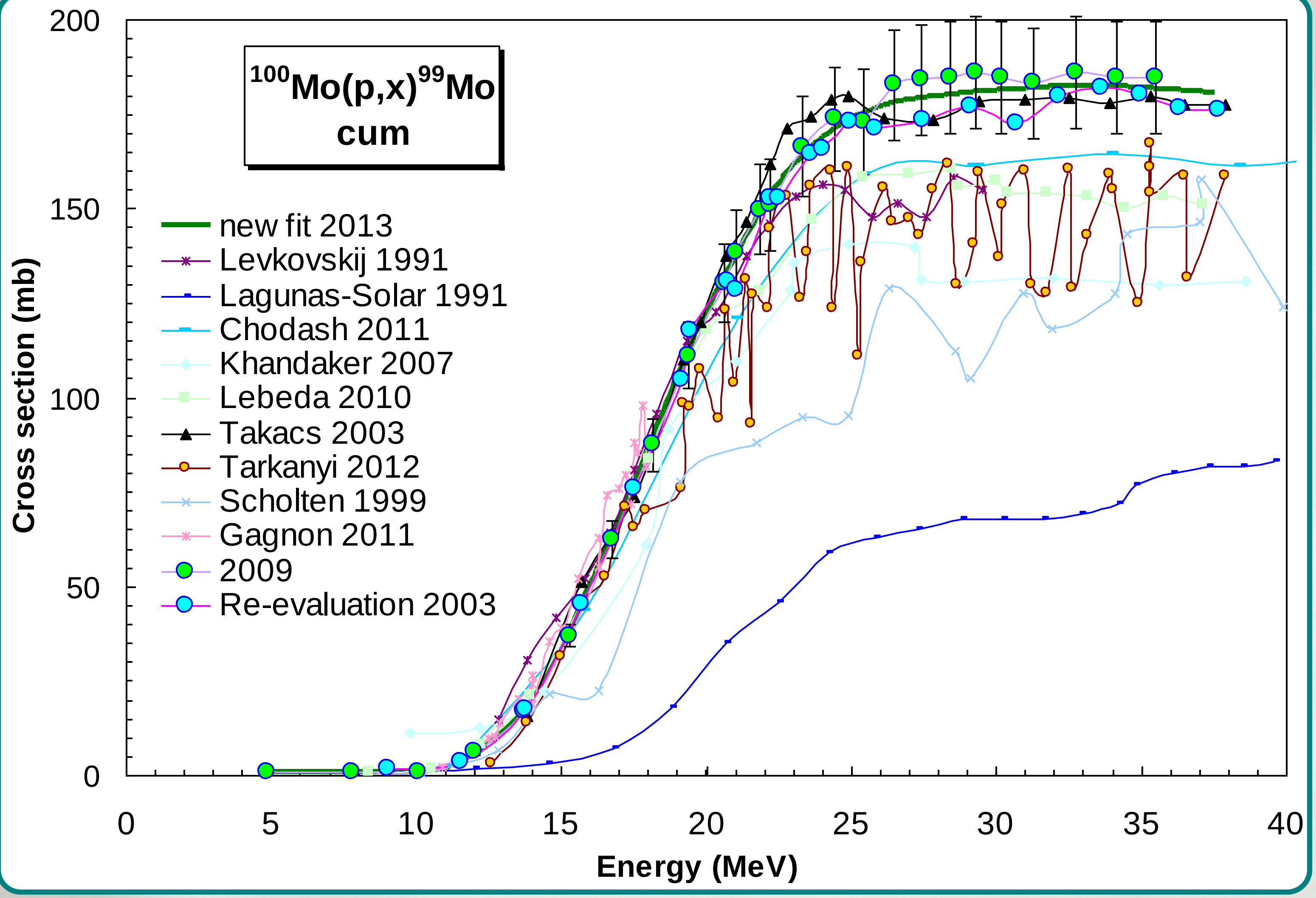
$^{100}Mo(p,x)^{99}Mo \rightarrow {}^{99m}Tc$

$^{100}Mo(n,2n)^{99}Mo \rightarrow {}^{99m}Tc$

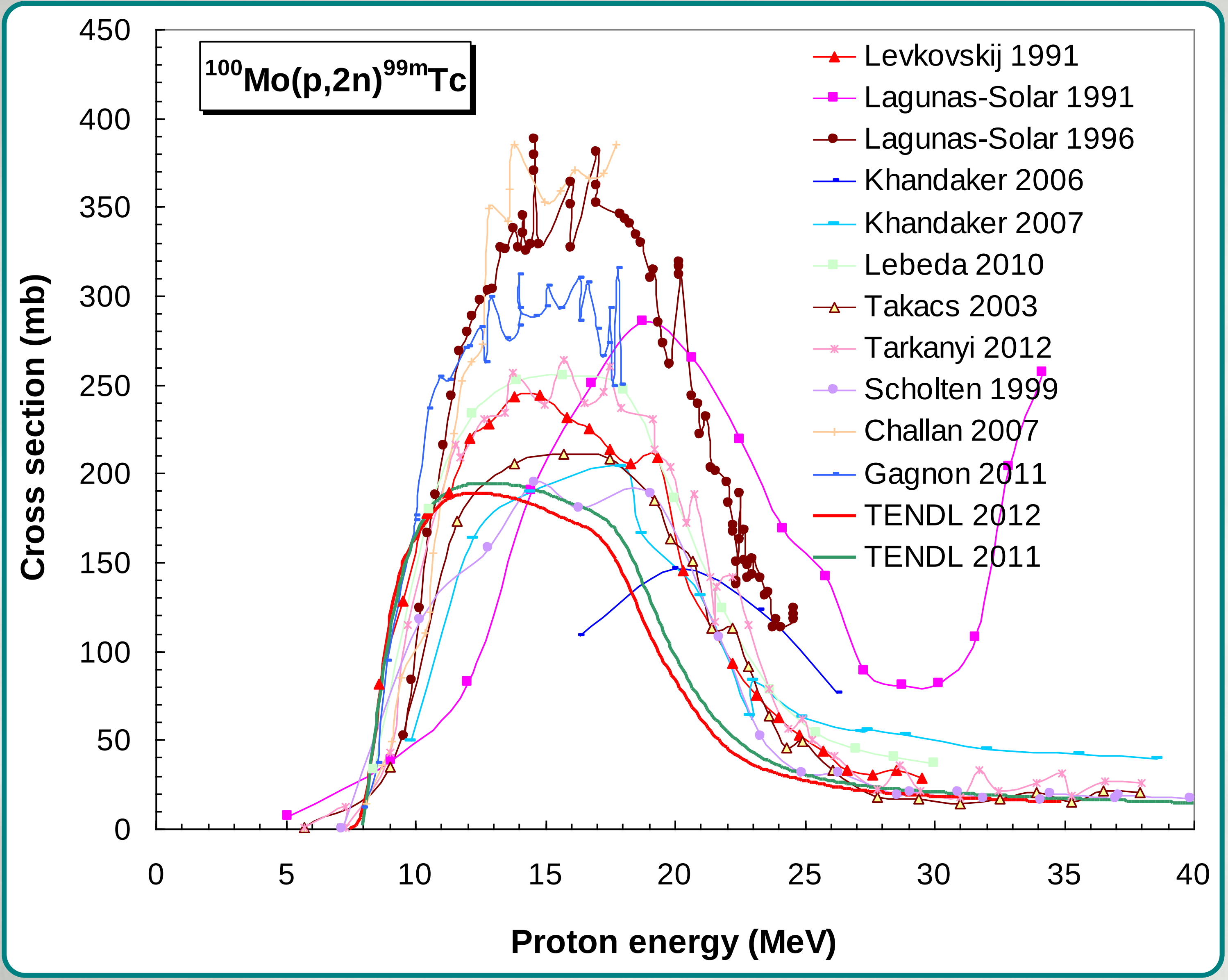
$^{100}Mo(\gamma,n)^{99}Mo \rightarrow {}^{99m}Tc$

$^{98}Mo(n,\gamma)^{99}Mo \rightarrow {}^{99m}Tc$

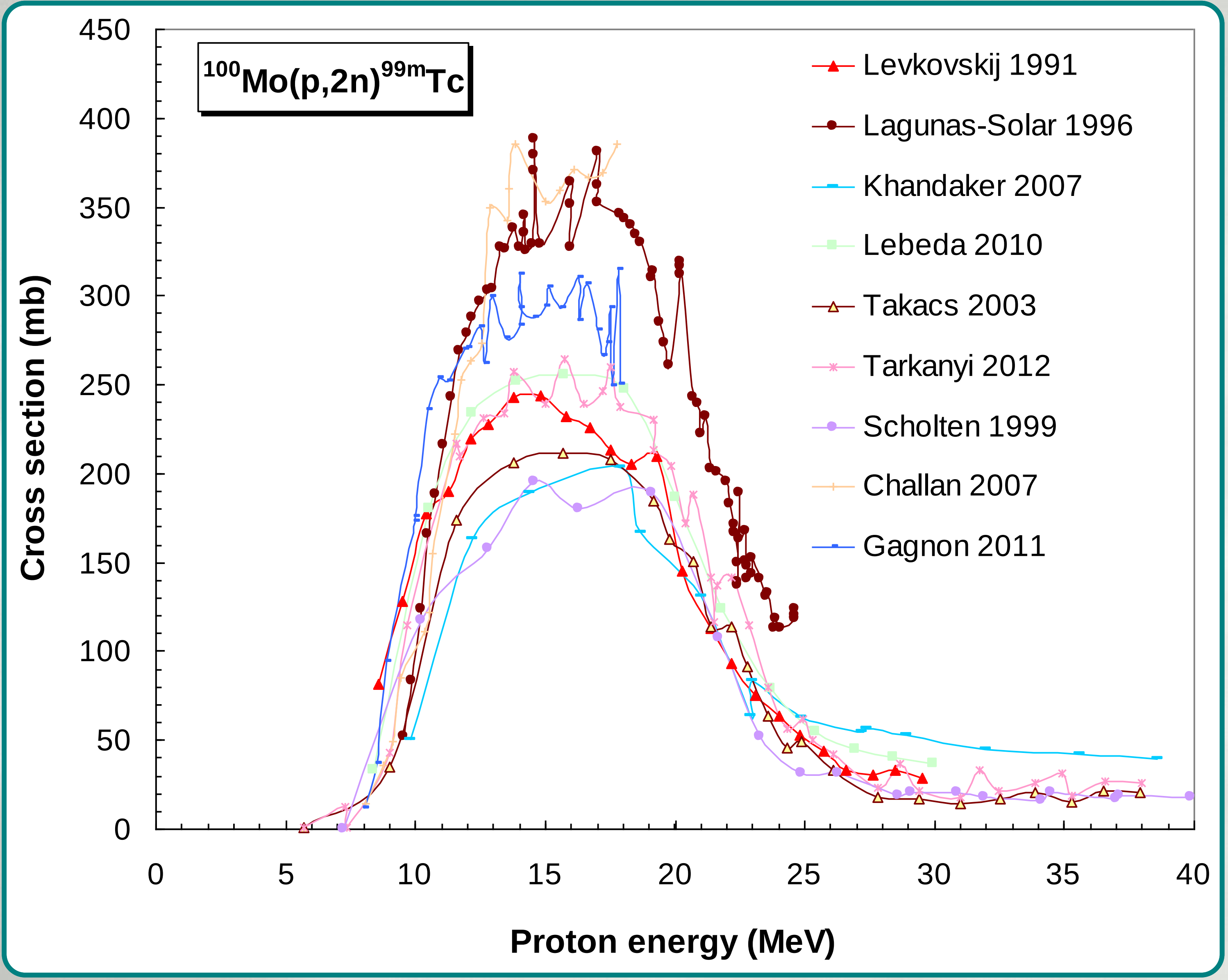
Experimental cross sections of ^{99}Mo



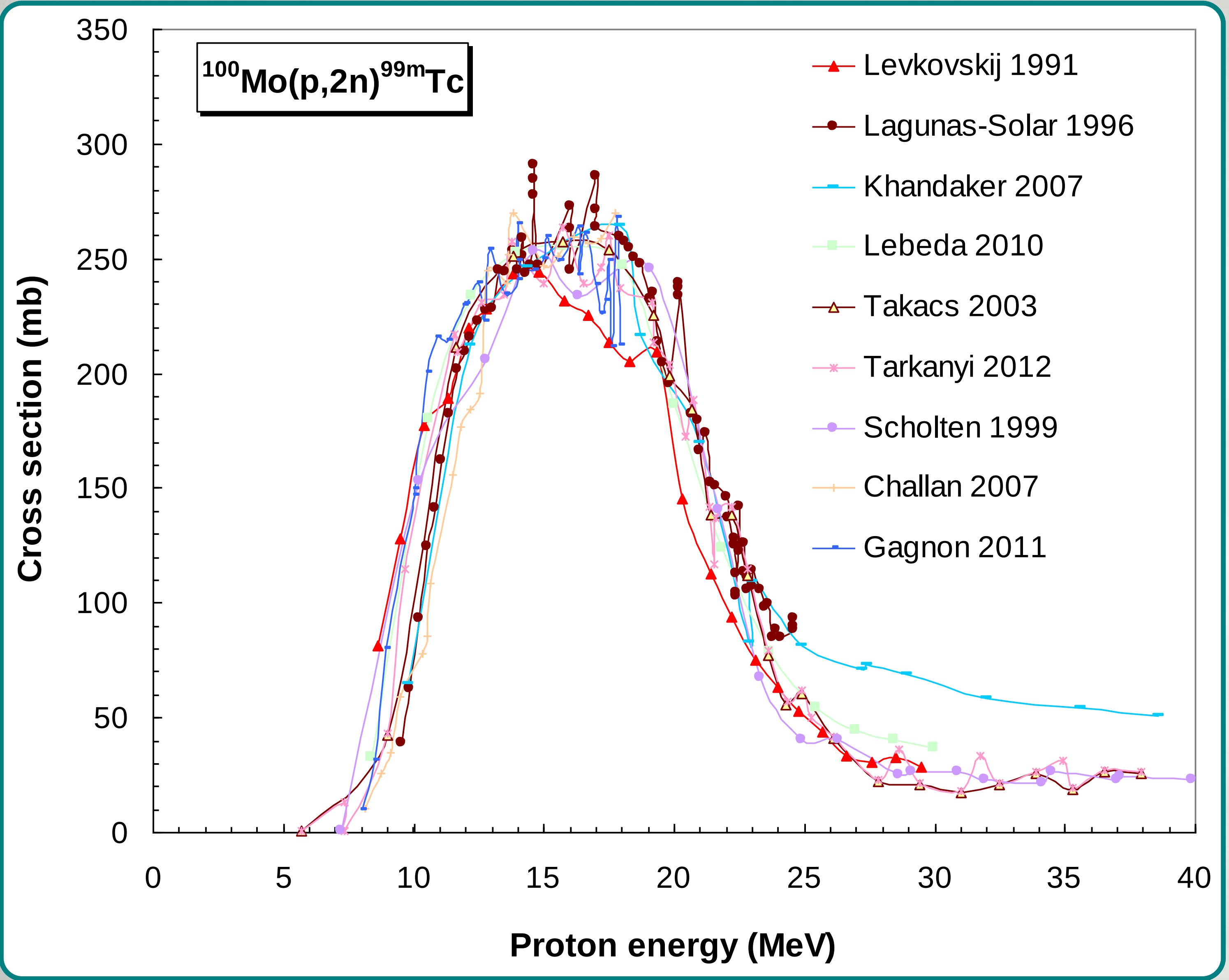
Experimental cross sections of ^{99m}Tc



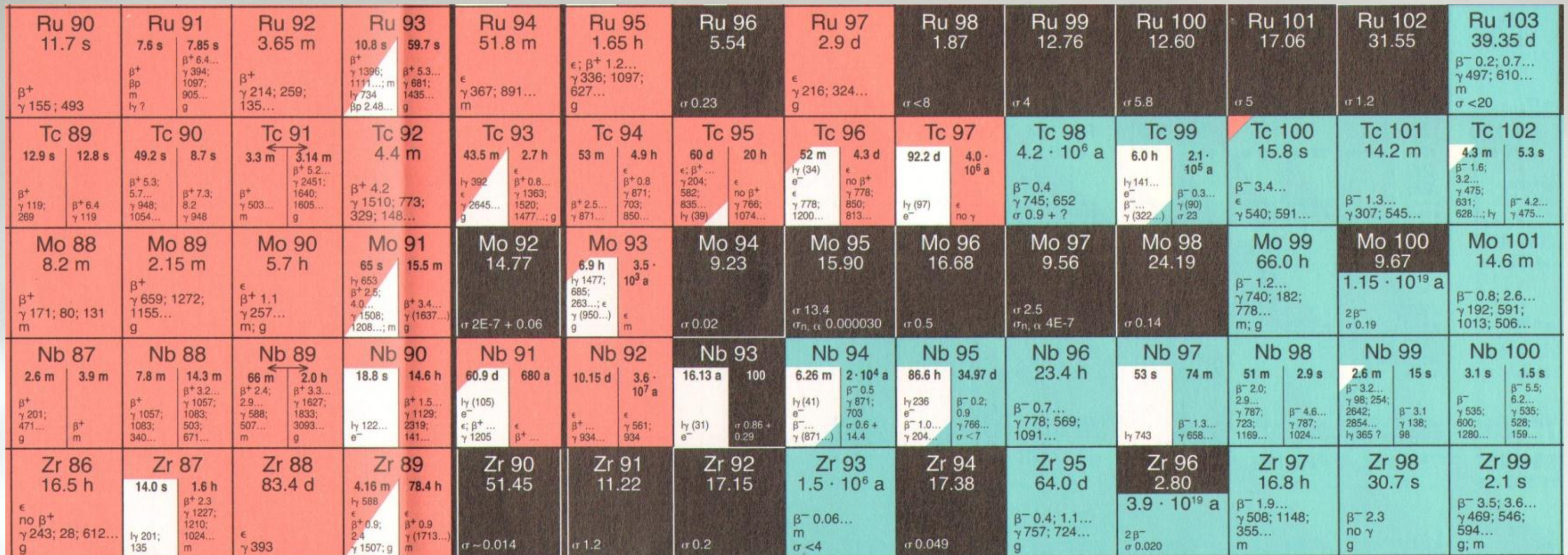
Selected cross sections of ^{99m}Tc



Normalized cross sections of ^{99m}Tc



Accelerator production of ^{99m}Tc



		Q-value MeV	Thrshold MeV
^{99}Mo	$^{100}Mo(p,pn)$	-8.29	8.38
	$^{100}Mo(p,d)$	-6.07	6.13
^{99}Nb	$^{100}Mo(p,2p)$	-11.15	11.26
^{99}Tc	$^{100}Mo(p,2n)$	-7.72	7.79
^{90}Nb	$^{94}Mo(p,\alpha n)$	-8.96	9.05
	$^{92}Mo(p,^{3}He)$	-11.79	11.92
^{90}Mo	$^{92}Mo(p,t)$	-14.30	14.45

Systematic error sources

- beam current measurement or charge integration

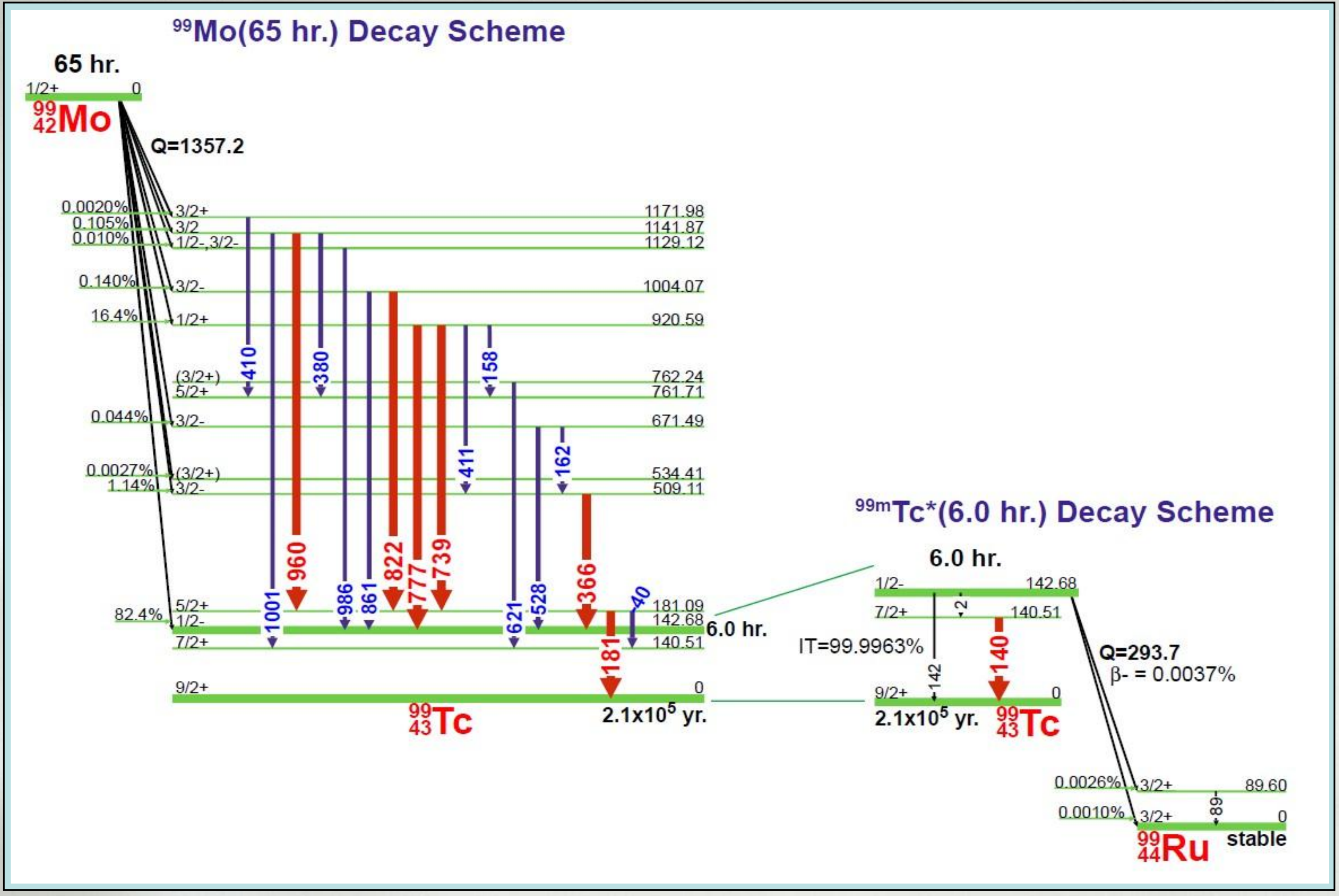
  (Faraday-cup, black current, secondary electrons, electron suppression)

- detector efficiency calibration

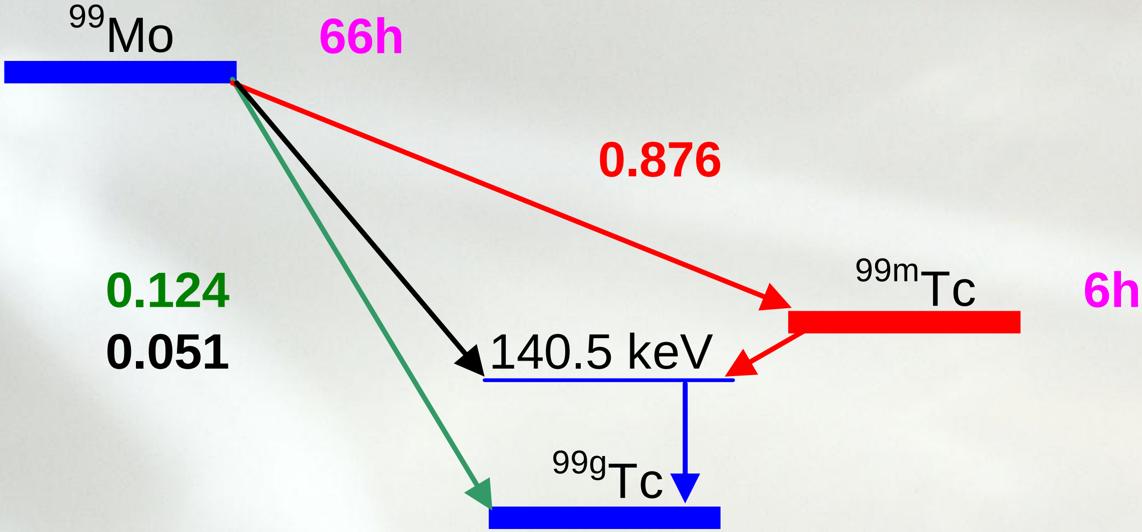
  (140 keV is the most problematic part of the efficiency curve)

- target thickness measurement
- use of out dated decay data
- problematic peak area determination and data evaluation

Decay of ^{99}Mo



Contribution to 140.5 keV gamma-line



Gammas

0.896	**in equilibrium**
0.885	**just 99mTc**
0.0472	**prompt**

Intensity of the 140.5 keV gamma-line

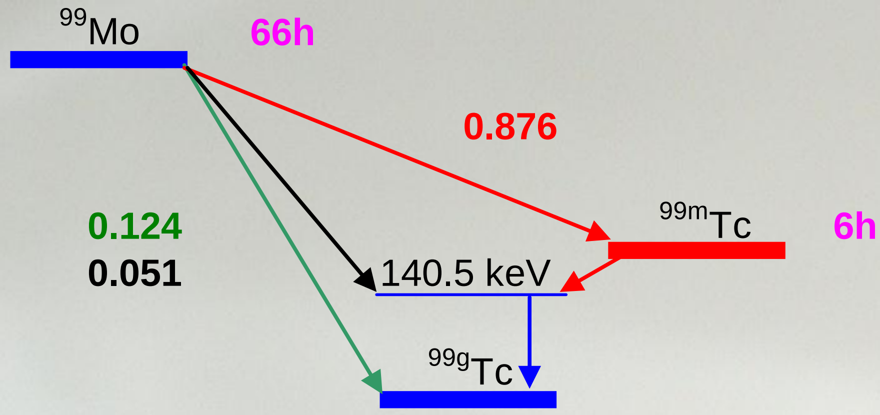
40.58323 *17*	1.06 % *4*	4.32E-4 *15*
158.782 *15*	0.0191 % *8*	3.04E-5 *13*
162.370 *15*	0.0120 % *6*	1.95E-5 *10*
181.068 *8*	6.14 % *12*	0.01112 *23*
242.29 *8*	0.0026 % *5*	6.2E-6 *12*
249.03 *3*	0.0039 % *5*	9.8E-6 *12*
366.421 *15*	1.204 % *22*	0.00441 *8*
380.13 *8*	0.0105 % *9*	4.0E-5 *3*
391.7 *4* ?	0.0032 % *6*	1.25E-5 *24*
410.27 *10*	0.0020 % *4*	8.0E-6 *15*
411.491 *15*	0.0147 % *6*	6.1E-5 *3*
457.60 *3*	0.0082 % *6*	3.8E-5 *3*
469.63 *7*	0.0027 % *5*	1.27E-5 *23*
528.788 *15*	0.058 % *3*	3.05E-4 *14*
537.79 *15*	0.0033 % *6*	1.8E-5 *3*
580.51 *7*	0.0032 % *5*	1.9E-5 *3*
620.03 *4*	0.0023 % *9*	1.4E-5 *5*
621.771 *24*	0.018 % *4*	1.14E-4 *23*
689.6 *9*	4.3E-4 % *18*	3.0E-6 *13*
739.500 *17*	12.26 % *22*	0.0907 *16*
761.77 *8*	4.0E-4 % *4*	3.1E-6 *3*
777.921 *20*	4.30 % *8*	0.0335 *6*

NuDat

	Energy keV	Photons per 100 disint.
$\gamma_{2,1}$(Tc)	2,1726 (4)	7.10^{-9}
$\gamma_{3,1}$(Tc)	40,58323 (17)	1,022 (27)
$\gamma_{1,0}$(Tc)	140,511 (1)	89,6 (17)
$\gamma_{2,0}$(Tc)	142,675 (25)	0,0211 (17)
$\gamma_{9,7}$(Tc)	158,782 (15)	0,0145 (9)
$\gamma_{6,4}$(Tc)	162,370 (15)	0,0114 (6)
$\gamma_{3,0}$(Tc)	181,068 (8)	6,01 (11)
$\gamma_{10,7}$(Tc)	242,29 (8)	0,0014 (3)
$\gamma_{9,6}$(Tc)	249,03 (3)	0,0035 (4)
$\gamma_{4,2}$(Tc)	366,421 (15)	1,194 (23)
$\gamma_{13,7}$(Tc)	380,13 (8)	0,0091 (5)
$\gamma_{5,2}$(Tc)	391,7 (4)	0,0025 (6)
$\gamma_{14,7}$(Tc)	410,27 (10)	0,0016 (4)
$\gamma_{9,4}$(Tc)	411,491 (15)	0,0161 (12)
$\gamma_{12,6}$(Tc)	457,60 (3)	0,0074 (6)
$\gamma_{13,6}$(Tc)	469,63 (7)	0,0027 (5)
$\gamma_{6,2}$(Tc)	528,788 (15)	0,0541 (19)
$\gamma_{11,5}$(Tc)	537,79 (15)	0,0015 (5)
$\gamma_{7,3}$(Tc)	580,51 (5)	0,0036 (4)
$\gamma_{8,3}$(Tc)	581,30 (12)	0,00010 (5)
$\gamma_{12,4}$(Tc)	620,03 (5)	0,0024 (6)
$\gamma_{8,1}$(Tc)	621,773 (24)	0,0262 (10)
$\gamma_{15,4}$(Tc)	689,6 (9)	0,00042 (18)
$\gamma_{9,3}$(Tc)	739,500 (17)	12,12 (15)

Monographie BIPM-5

Contribution to 140.5 keV gamma-line



Gammas

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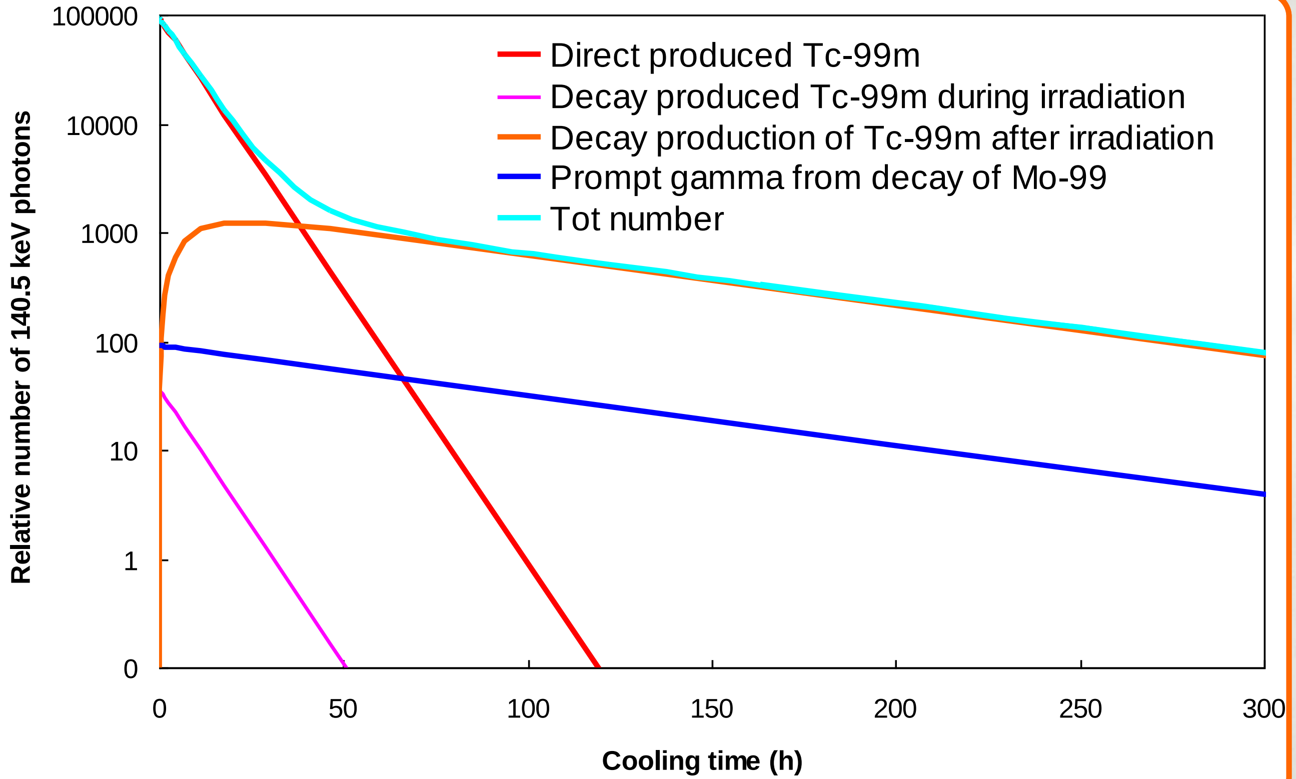


Contribution to 140.5 keV gamma-line

t_b bombarding time, t_c cooling time, t_m measuring time
(number of decay during measuring time)

$$\Delta N(direct)_D = N_t N_b \sigma_2 \left(1-e^{-\lambda_2 t_b}\right)\frac{1}{\lambda_2} e^{-\lambda_2 t_c}\left(1-e^{-\lambda_2 t_m}\right)$$

$$\Delta N(decay)_1 = \frac{f N_t N_b \sigma_1}{(\lambda_1-\lambda_2)}\left[\lambda_1\left(1-e^{-\lambda_2 t_b}\right)-\lambda_2\left(1-e^{-\lambda_1 t_b}\right)\right]\frac{1}{\lambda_2} e^{-\lambda_2 t_c}\left(1-e^{-\lambda_2 t_m}\right)$$

$$\Delta N(decay)_2 = \frac{f N_t N_b \sigma_1}{(\lambda_1-\lambda_2)}\left(1-e^{-\lambda_1 t_b}\right)\left[e^{-\lambda_2 t_c}\left(1-e^{-\lambda_2 t_m}\right)-\frac{\lambda_2}{\lambda_1} e^{-\lambda_1 t_c}\left(1-e^{-\lambda_1 t_m}\right)\right]$$

$$\Delta N(direct)_M = g N_t N_b \sigma_1 \left(1-e^{-\lambda_1 t_b}\right)\frac{1}{\lambda_1} e^{-\lambda_1 t_c}\left(1-e^{-\lambda_1 t_m}\right)$$

$$\frac{T_\gamma}{\varepsilon_d \varepsilon_\gamma} = \Delta N(direct)_D + \Delta N(decay)_1 + \Delta N(decay)_2 + p\Delta N(direct)_M$$

Composition of the stack

		E(in)	E(out)	E(mean)	dx[um]	X[mg/cm2]	dE	
mo	1	**16.00**	15.79	**15.90**	**11.80**	12.06	1	0.25
mo	2	15.79	15.58	**15.69**	**11.80**	12.06	2	0.25
ti	1	15.58	15.46	**15.52**	**12.05**	5.47	3	0.26
mo	3	15.46	15.25	**15.36**	**11.80**	12.06	4	0.26
mo	4	15.25	15.03	**15.14**	**11.80**	12.06	5	0.27
ti	2	15.03	14.91	**14.97**	**12.05**	5.47	6	0.27
mo	5	14.91	14.69	**14.80**	**11.80**	12.06	7	0.27
mo	6	14.69	14.47	**14.58**	**11.80**	12.06	8	0.28
ti	3	14.47	14.34	**14.40**	**12.05**	5.47	9	0.28
mo	7	14.34	14.12	**14.23**	**11.80**	12.06	10	0.29
mo	8	14.12	13.89	**14.00**	**11.80**	12.06	11	0.29
ti	4	13.89	13.76	**13.82**	**12.05**	5.47	12	0.29
mo	9	13.76	13.52	**13.64**	**11.80**	12.06	13	0.30
mo	10	13.52	13.29	**13.41**	**11.80**	12.06	14	0.30
ti	5	13.29	13.15	**13.22**	**12.05**	5.47	15	0.31
mo	11	13.15	12.91	**13.03**	**11.80**	12.06	16	0.31
mo	12	12.91	12.67	**12.79**	**11.80**	12.06	17	0.32
ti	6	12.67	12.53	**12.60**	**12.05**	5.47	18	0.32
mo	13	12.53	12.28	**12.40**	**11.80**	12.06	19	0.33
mo	14	12.28	12.03	**12.15**	**11.80**	12.06	20	0.33
ti	7	12.03	11.88	**11.95**	**12.05**	5.47	21	0.34
mo	15	11.88	11.62	**11.75**	**11.80**	12.06	22	0.34
mo	16	11.62	11.36	**11.49**	**11.80**	12.06	23	0.35
ti	8	11.36	11.21	**11.28**	**12.05**	5.47	24	0.35
mo	17	11.21	10.94	**11.07**	**11.80**	12.06	25	0.36
mo	18	10.94	10.66	**10.80**	**11.80**	12.06	26	0.36
ti	9	10.66	10.50	**10.58**	**12.05**	5.47	27	0.37
mo	19	10.50	10.22	**10.36**	**11.80**	12.06	28	0.37
mo	20	10.22	9.93	**10.07**	**11.80**	12.06	29	0.38
ti	10	9.93	9.76	**9.85**	**12.05**	5.47	30	0.38
mo	21	9.76	9.46	**9.61**	**11.80**	12.06	31	0.39
mo	22	9.46	9.16	**9.31**	**11.80**	12.06	32	0.40
ti	11	9.16	8.98	**9.07**	**12.05**	5.47	33	0.40
mo	23	8.98	8.66	**8.82**	**11.80**	12.06	34	0.41
mo	24	8.66	8.34	**8.50**	**11.80**	12.06	35	0.41
ti	12	8.34	8.15	**8.24**	**12.05**	5.47	36	0.42
mo	25	8.15	7.80	**7.98**	**11.80**	12.06	37	0.43
mo	26	7.80	7.45	**7.63**	**11.80**	12.06	38	0.43
ti	13	7.45	7.25	**7.35**	**12.05**	5.47	39	0.44
mo	27	7.25	6.88	**7.06**	**11.80**	12.06	40	0.45
mo	28	6.88	6.49	**6.68**	**11.80**	12.06	41	0.45
ti	14	6.49	6.26	**6.37**	**12.05**	5.47	42	0.46
ti	15	6.26	6.02	**6.14**	**12.05**	5.47	43	0.47
ti	16	6.02	5.78	**5.90**	**12.05**	5.47	44	0.47
ti	17	5.78	5.53	**5.66**	**12.05**	5.47	45	0.48
ti	18	5.53	5.27	**5.40**	**12.05**	5.47	46	0.49
ti	19	5.27	5.01	**5.14**	**12.05**	5.47	47	0.50
ti	20	5.01	4.73	**4.87**	**12.05**	5.47	48	0.50
ti	21	4.73	4.44	**4.58**	**12.05**	5.47	49	0.51

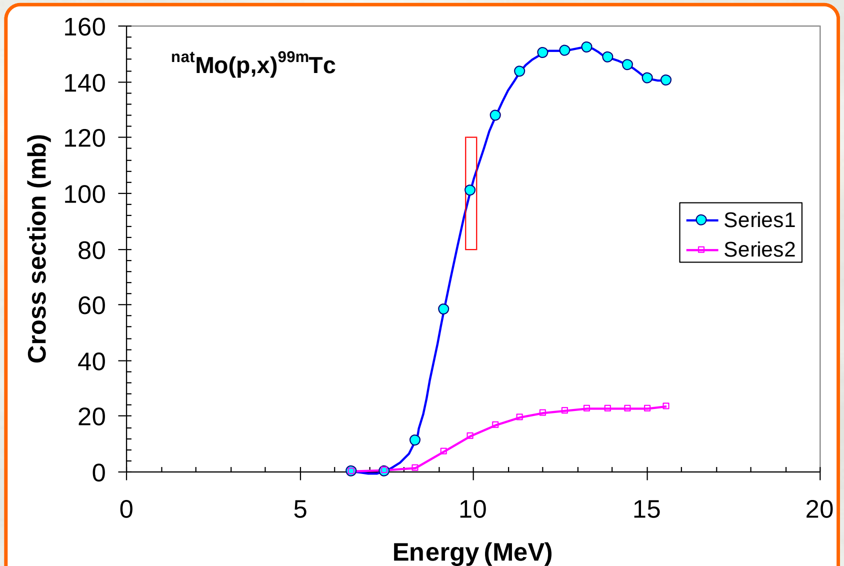
Bombarding energy: ~16MeV

Irradiation time: 1.8 hours

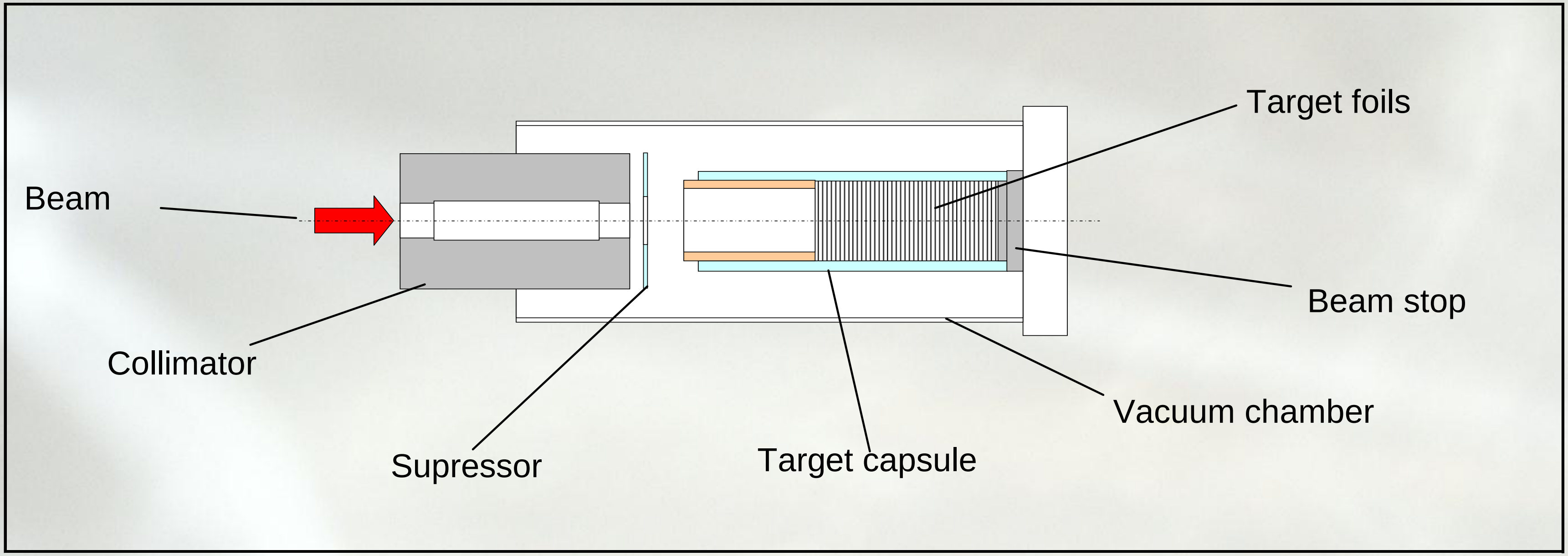
Beam current: 116 nA

Mo foil thickness: 11.8 micron

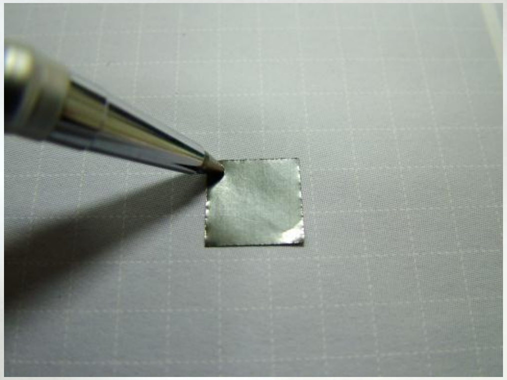
Ti foil thickness: 12.05 micron

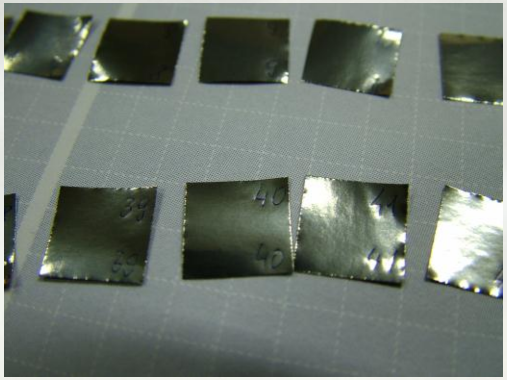


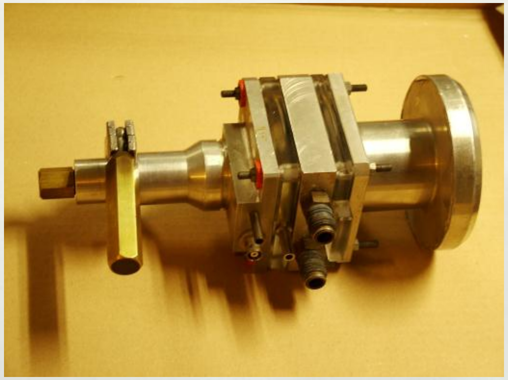
Irradiation arrangement



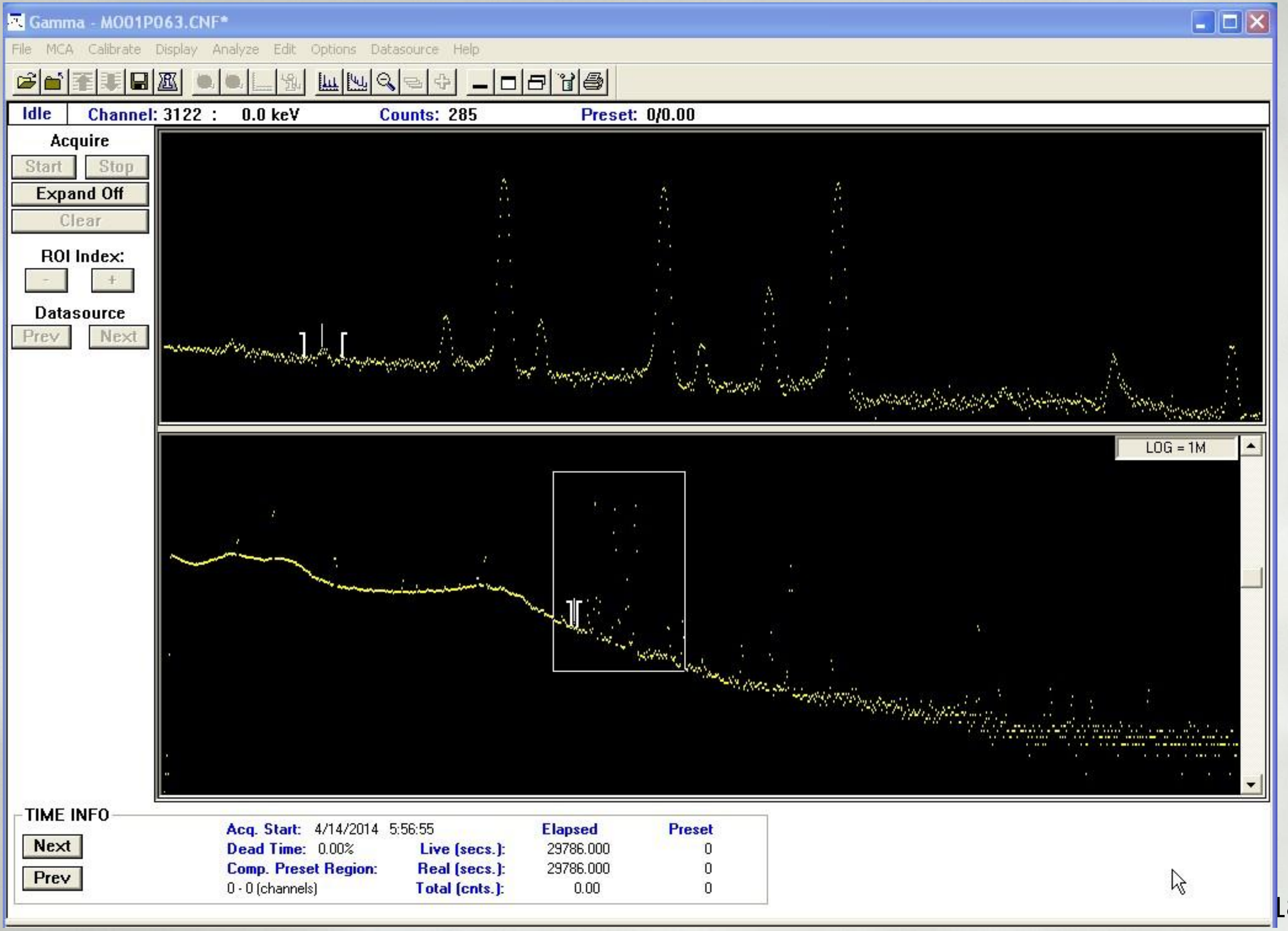
Target preparation



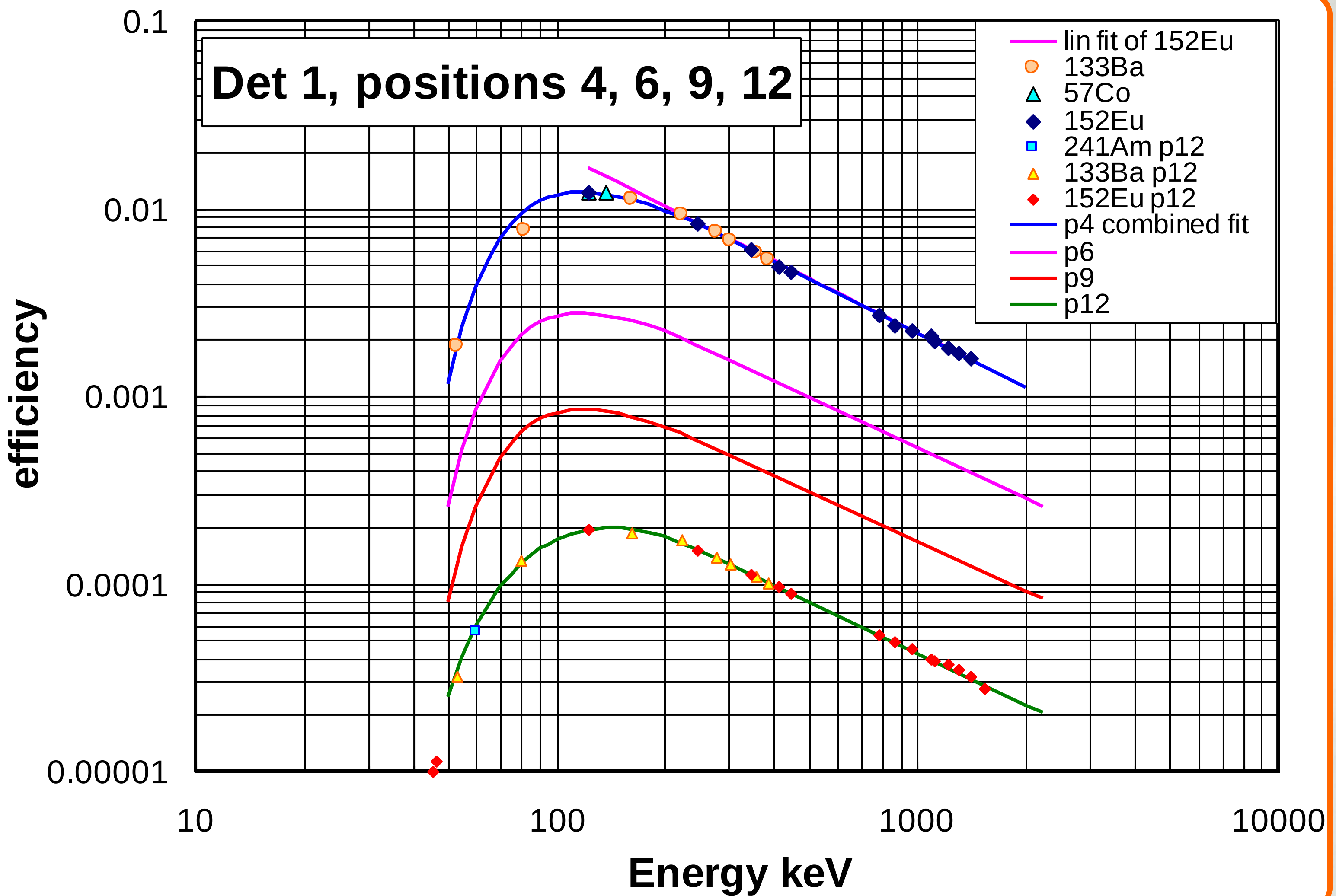




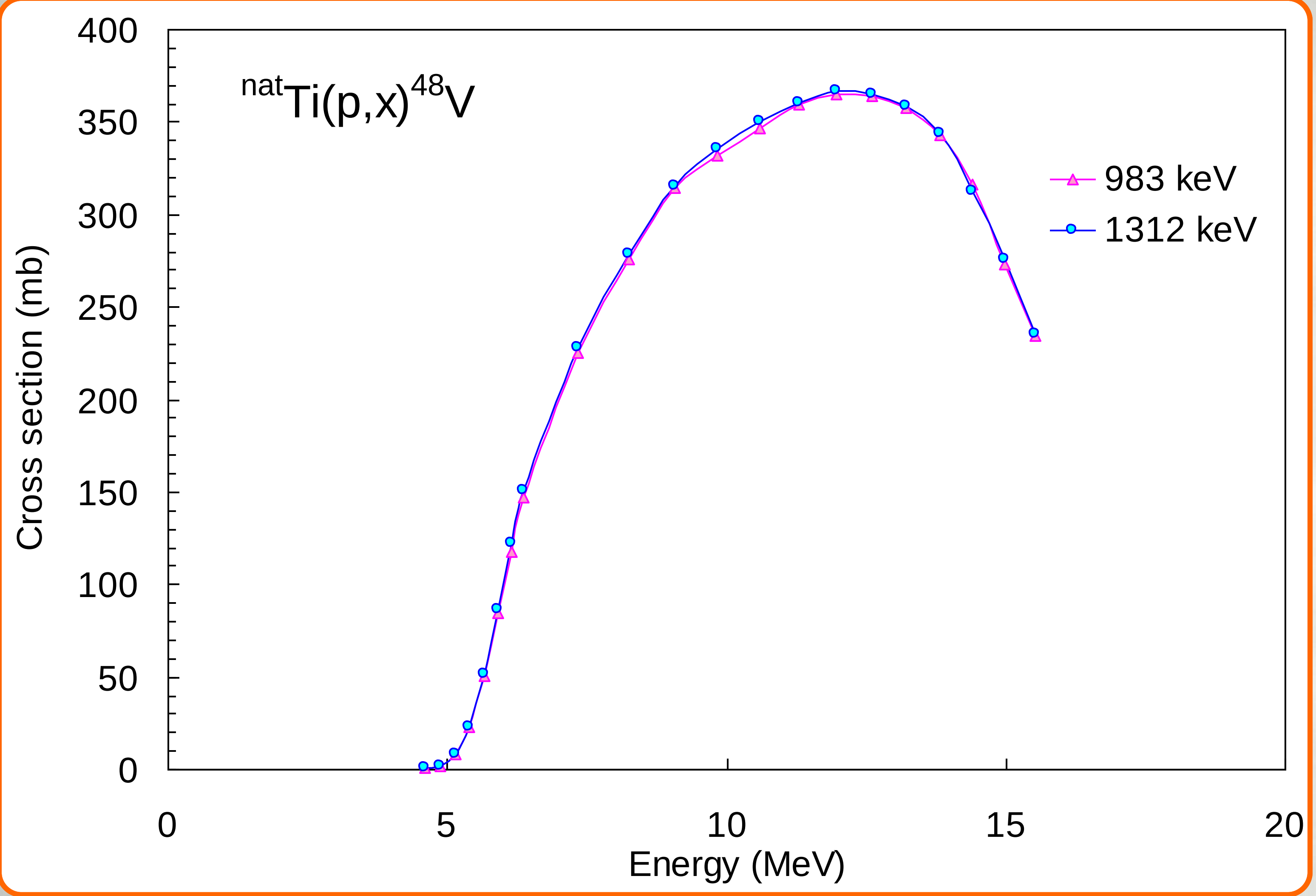
Gamma spectrum of a Mo foil



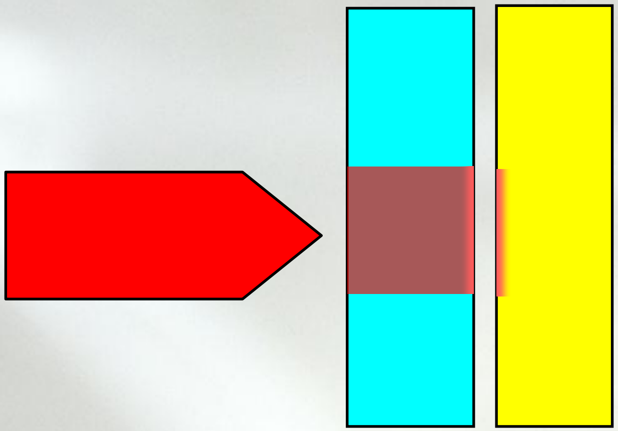
Detector calibration

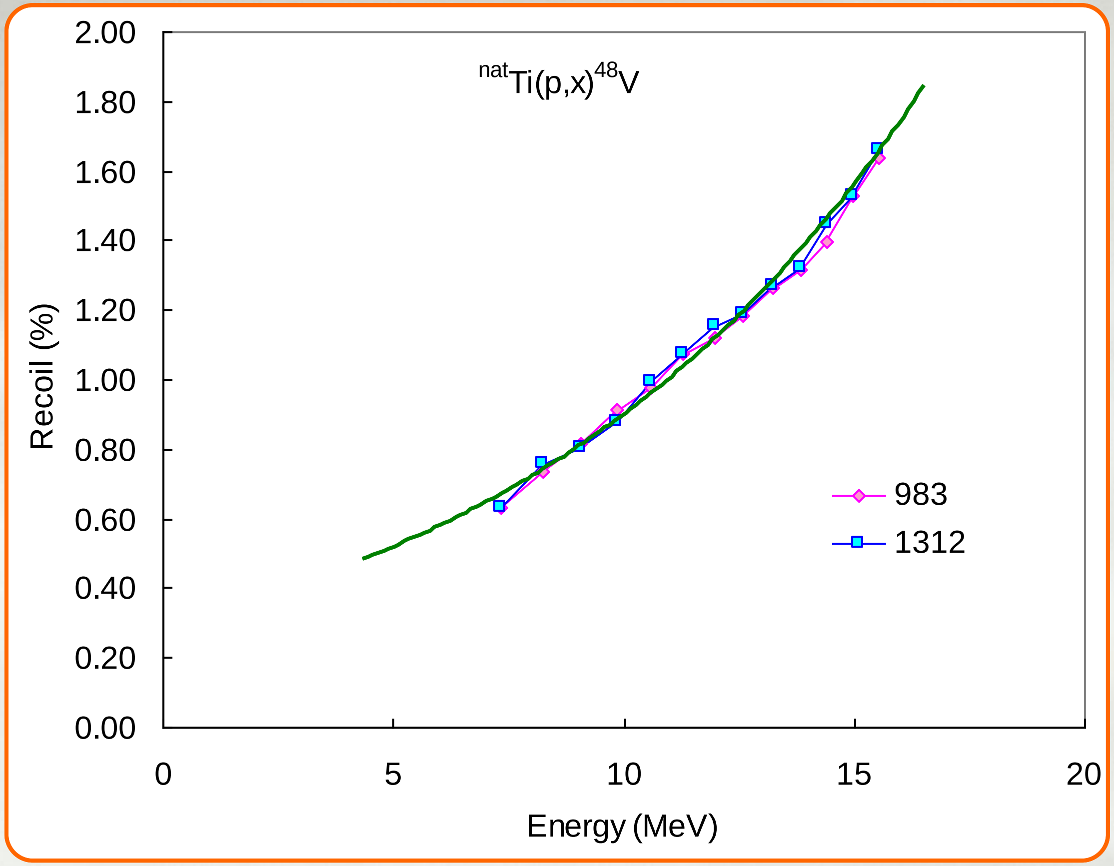


Beam monitoring

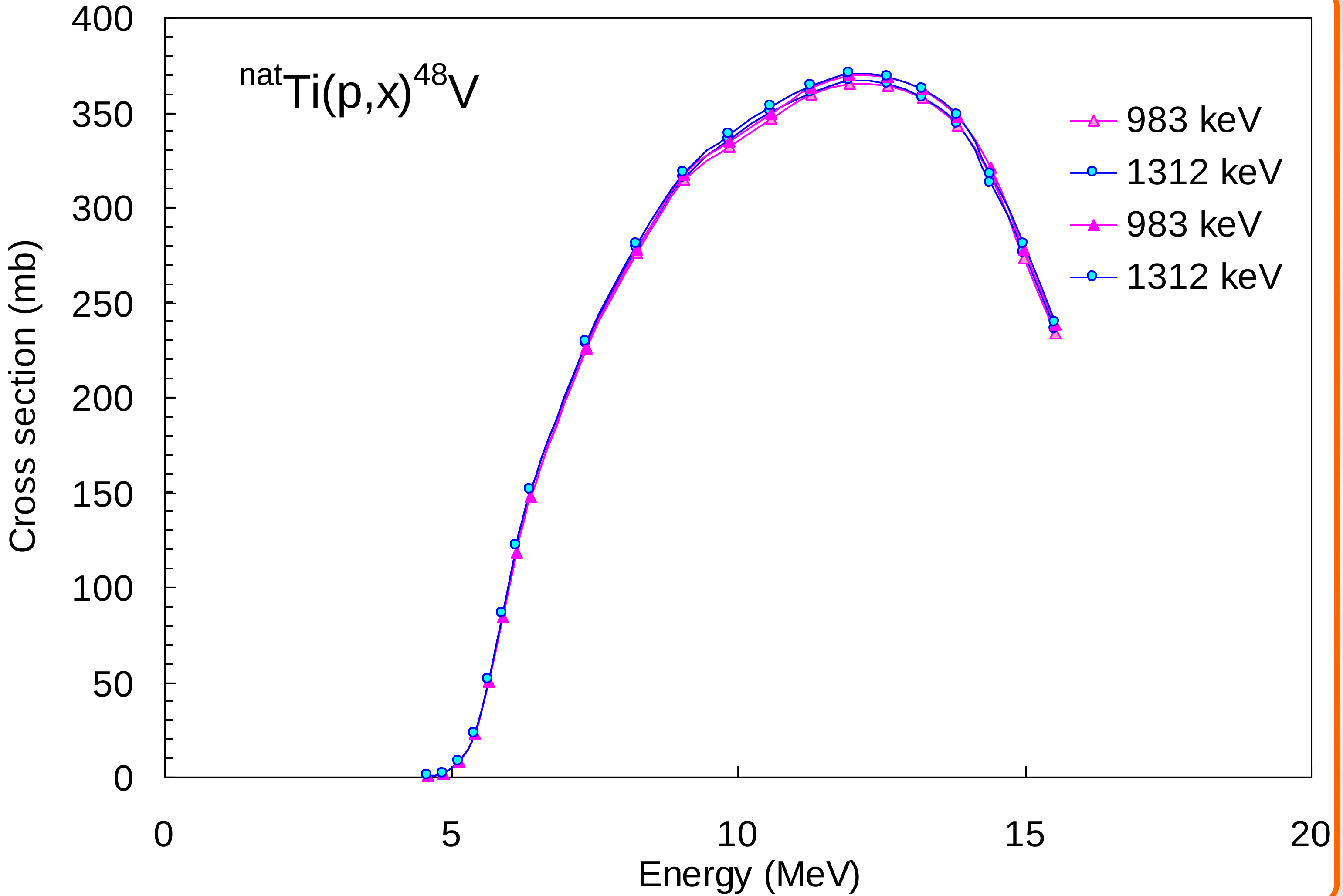


Recoil correction

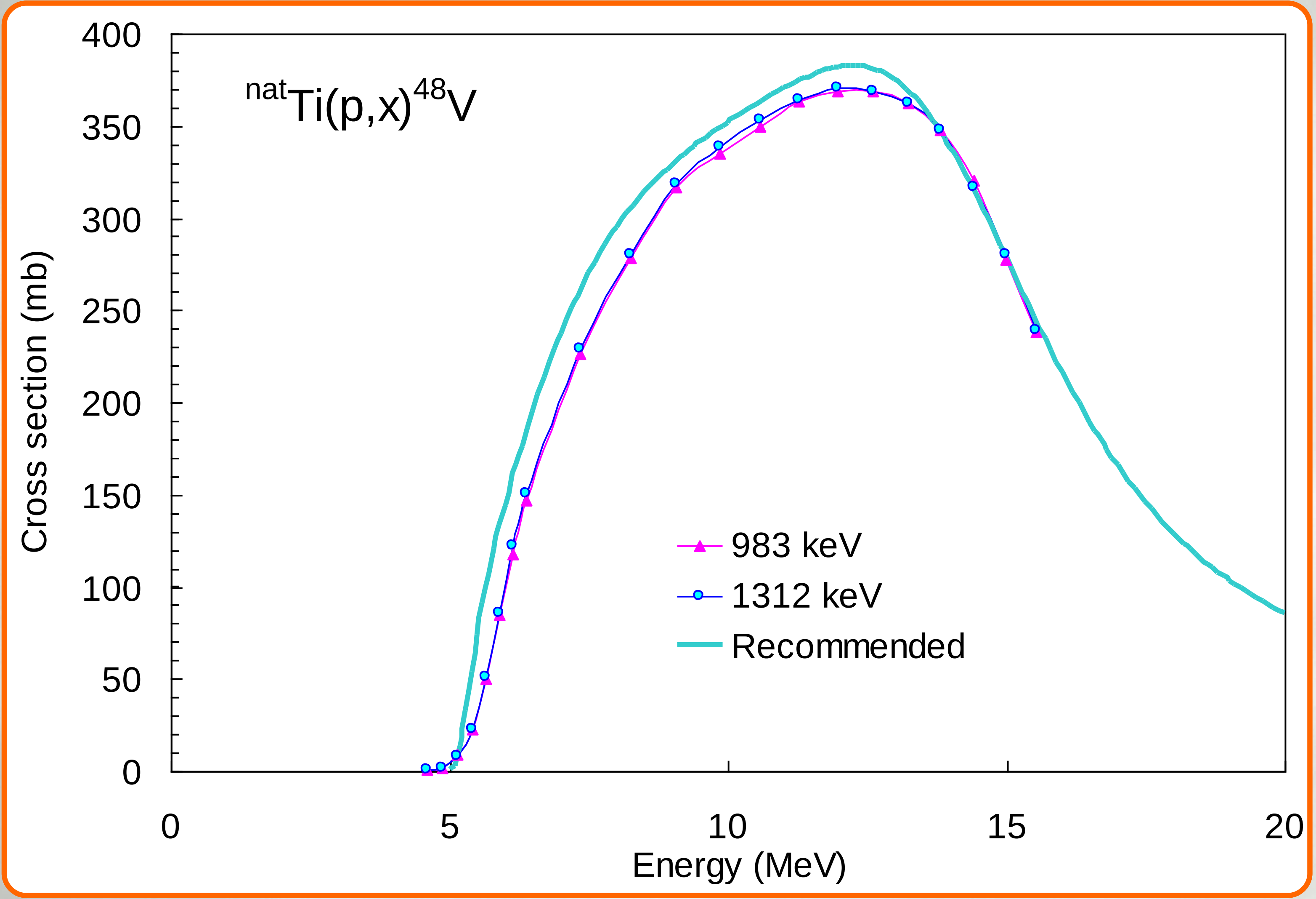




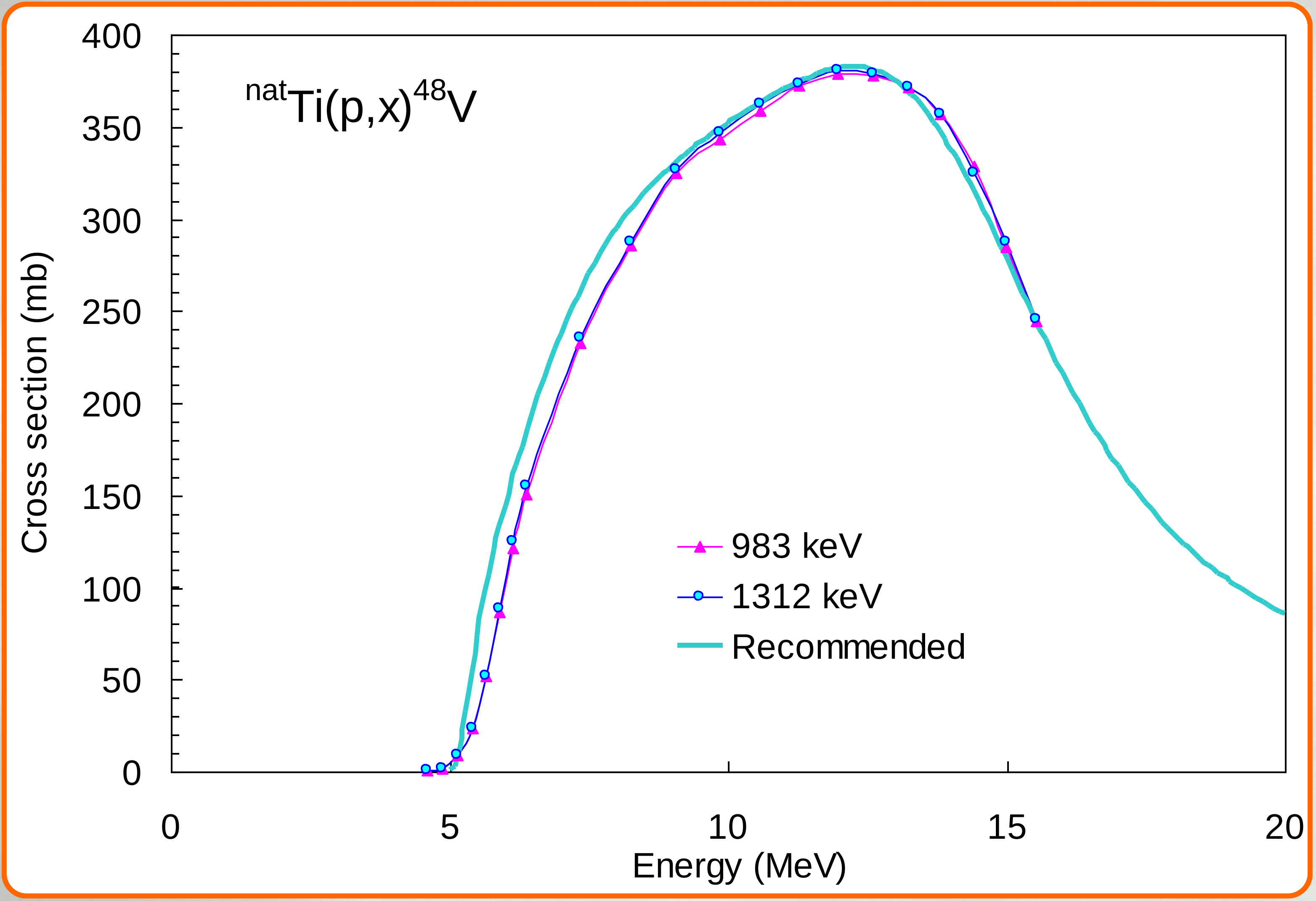
Recoil correction



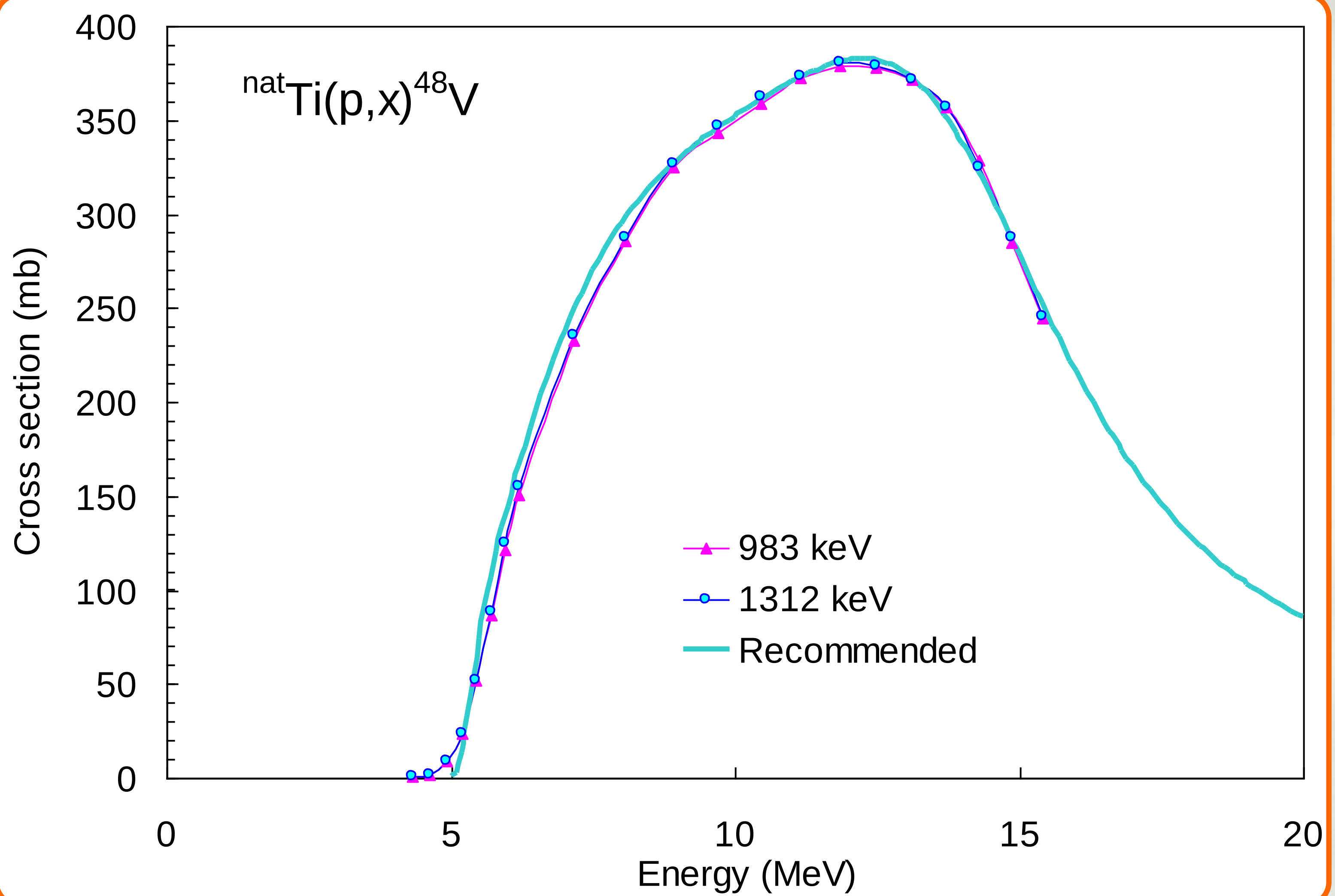
Recoil corrected



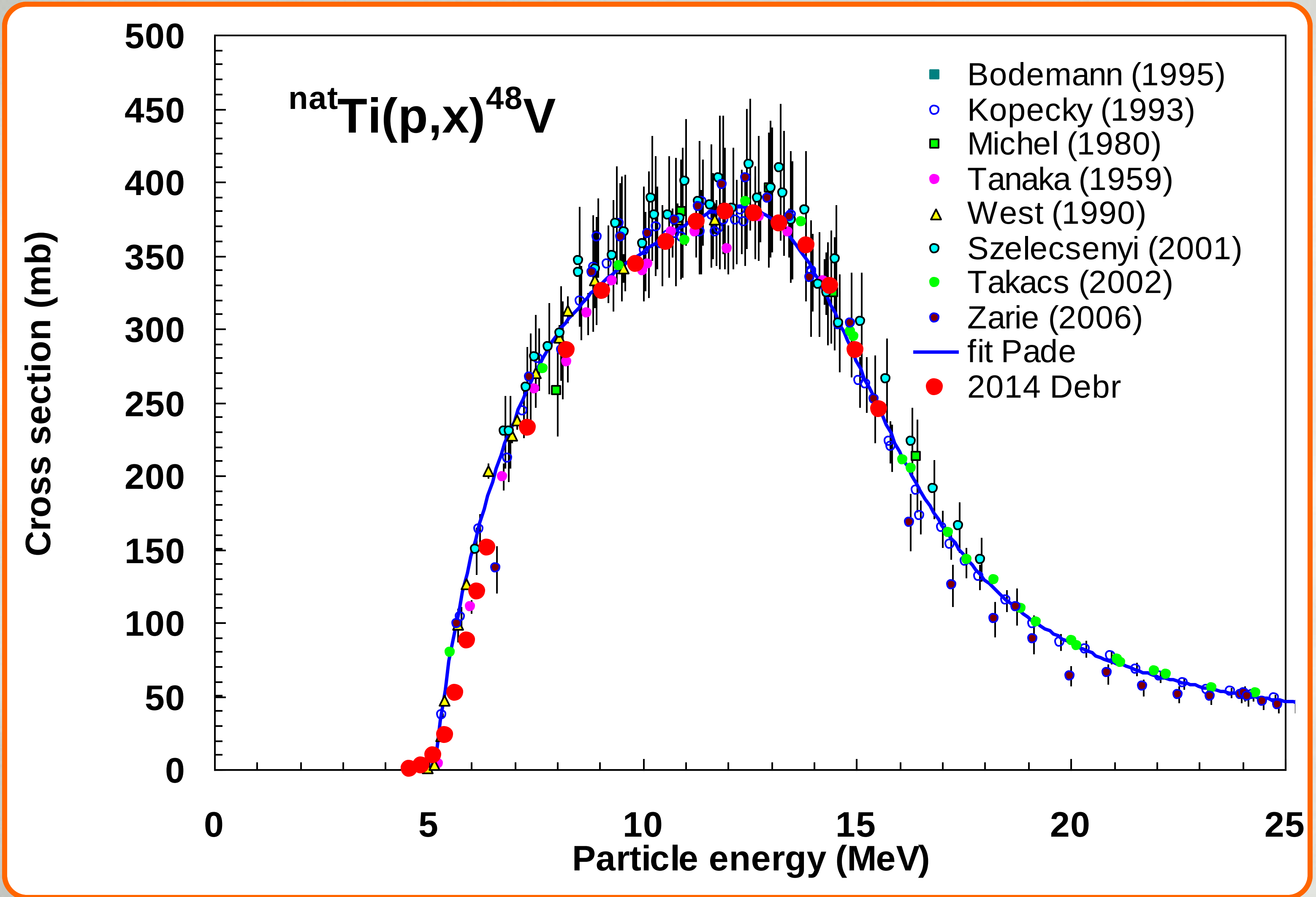
Intensity corrected
-2.5 %



Energy corrected
-100 keV



Recommended cross section

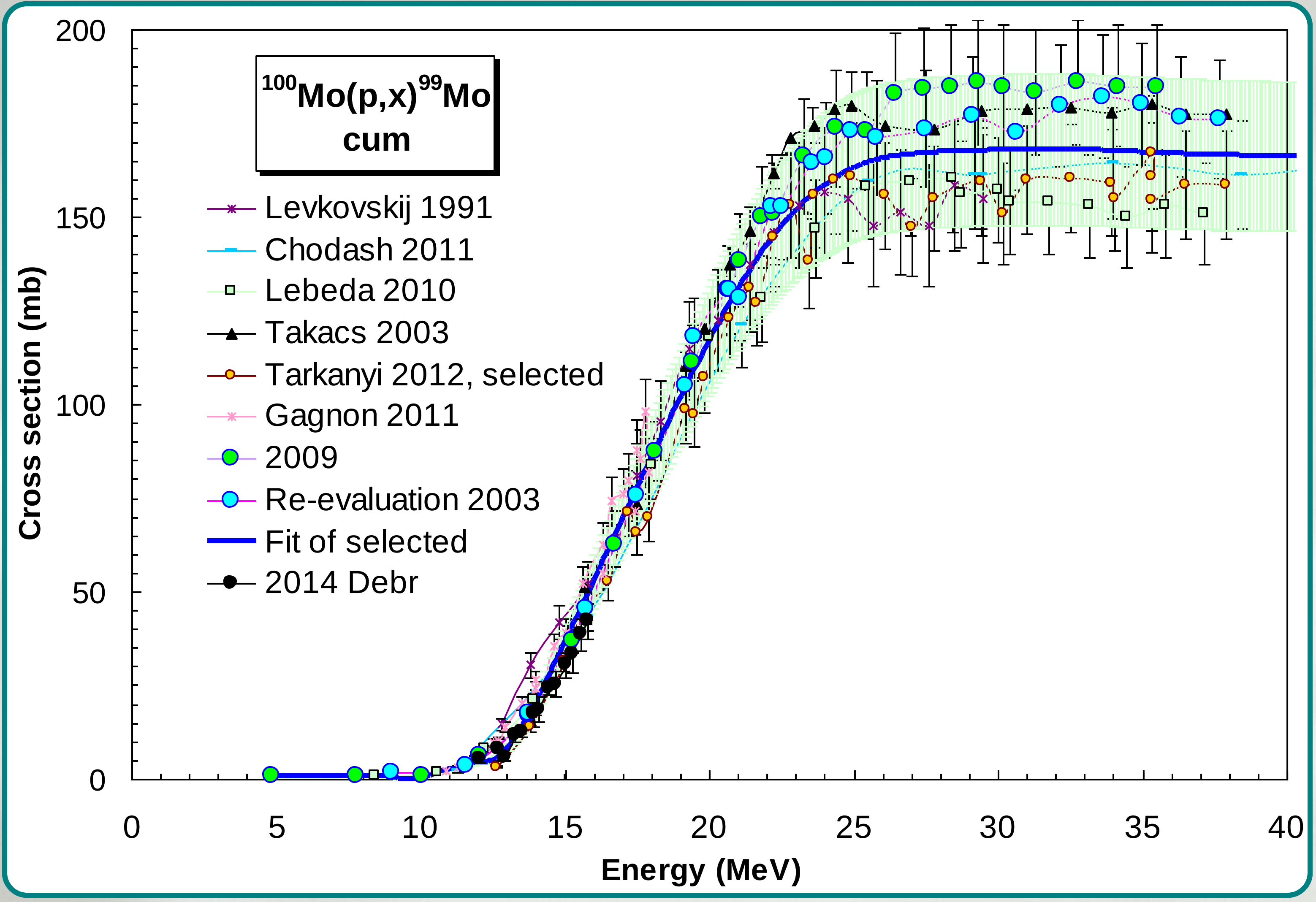


Origin of the 140.5 keV gammas for $^{100}Mo(p,x)^{99}Mo$ reaction

Spectrum name	cooling time (h)	Direct prod D %	Decay prod.1 %	Decay prod.2 %	Prompt M %
Mo02p063	171	0	0	94.8	5.2
Mo04p063	187	0	0	94.8	5.2
Mo06p063	213	0	0	94.8	5.2
Mo08p063	236	0	0	94.8	5.2
Mo10p063	245	0	0	94.8	5.2
Mo12p063	262	0	0	94.8	5.2
Mo14p063	269	0	0	94.8	5.2

Spectrum name	cooling time (h)	**Energy MeV**	**140.5 keV equiblibrium**	181 keV	739 keV
Mo02p063	171	**15.6**	**3.5**	3.1	3.5
Mo04p063	187	**15.0**	**2.9**	2.9	2.3
Mo06p063	213	**14.5**	**2.2**	2.3	2.2
Mo08p063	236	**13.9**	**1.6**	1.9	1.6
Mo10p063	245	**13.3**	**1.1**	1.9	1.3
Mo12p063	262	**12.7**	**0.8**	0.5	0.3
Mo14p063	269	**12.0**	**0.6**	0.0	0.0

Results

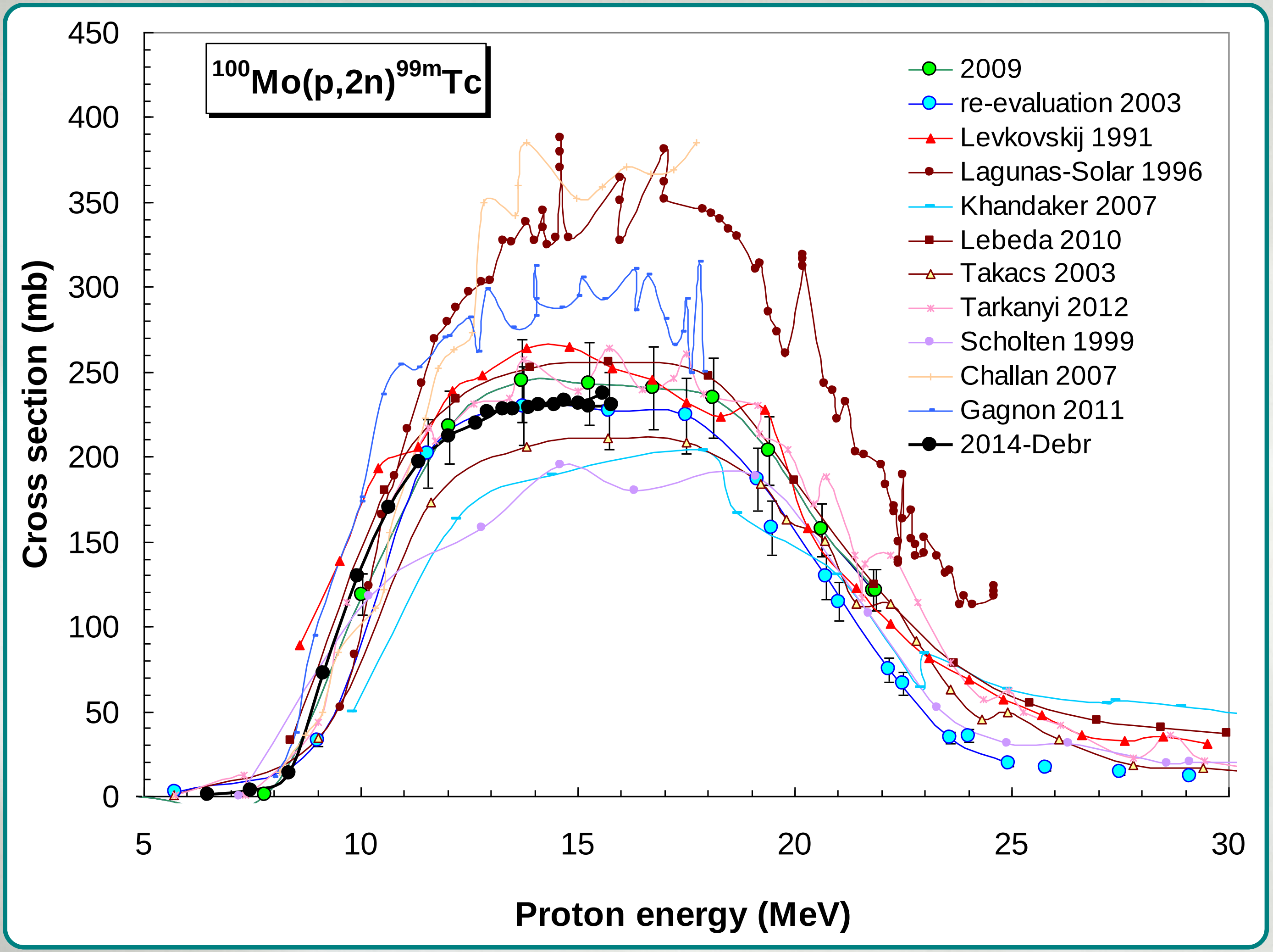


$^{100}Mo(p,x)^{99}Mo$ cum
Levkovskij 1991
Chodash 2011
Lebeda 2010
Takacs 2003
Tarkanyi 2012, selected
Gagnon 2011
2009
Re-evaluation 2003
Fit of selected
2014 Debr
Cross section (mb)
Energy (MeV)
0
50
100
150
200
0
5
10
15
20
25
30
35
40

Origin of the 140.5 keV gammas

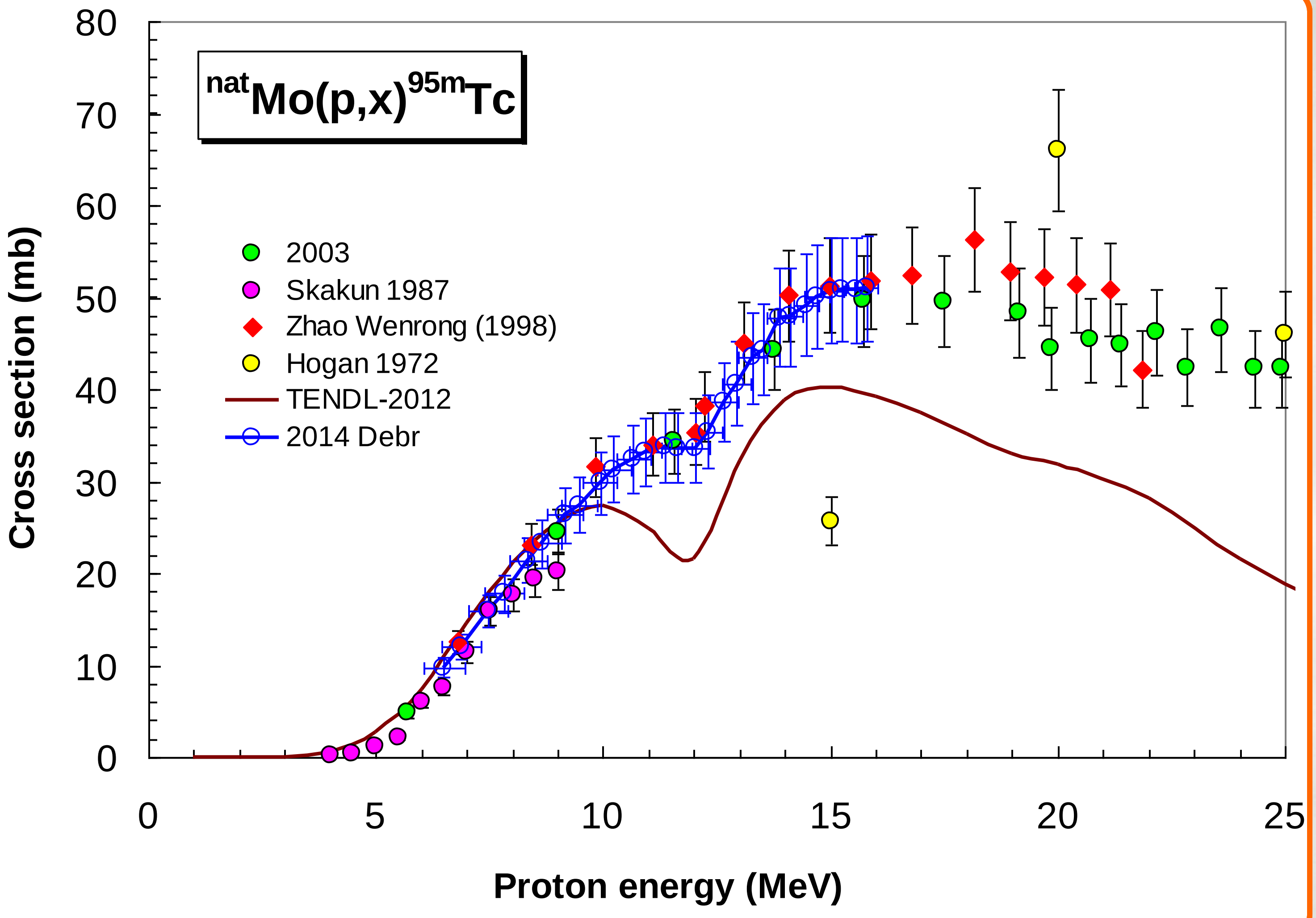
Spectrum name	cooling time (h)	Direct prod D %	Decay prod.1 %	Decay prod.2 %	Prompt M %
Mo01p121	6.6	98.1	0.1	1.6	0.2
Mo02p121	4.7	98.8	0.1	0.9	0.1
Mo03p121	7.1	98.3	0.1	1.5	0.2
Mo04p121	4.3	99.0	0.1	0.8	0.1
Mo05p121	7.4	98.6	0.1	1.2	0.1
Mo06p121	4.0	99.3	0.1	0.6	0.1
Mo07p121	7.7	98.9	0.1	0.9	0.1
Mo08p121	3.7	99.5	0.1	0.4	0.1
Mo09p121	8.1	99.1	0.0	0.7	0.1
Mo10p121	3.5	99.8	0.0	0.2	0.0
Mo11p121	8.6	99.2	0.0	0.7	0.1
Mo12p121	3.2	99.7	0.0	0.2	0.0
Mo14p121	2.9	99.9	0.0	0.0	0.0
Mo16p121	2.6	100.0	0.0	0.0	0.0
Mo18p121	2.3	100.0	0.0	0.0	0.0
Mo20p121	2.0	100.0	0.0	0.0	0.0
Mo22p121	1.7	100.0	0.0	0.0	0.0
Mo24p121	1.4	100.0	0.0	0.0	0.0
Mo26p121	1.2	100.0	0.0	0.0	0.0
Mo28p121	0.9	100.0	0.0	0.0	0.0

Results

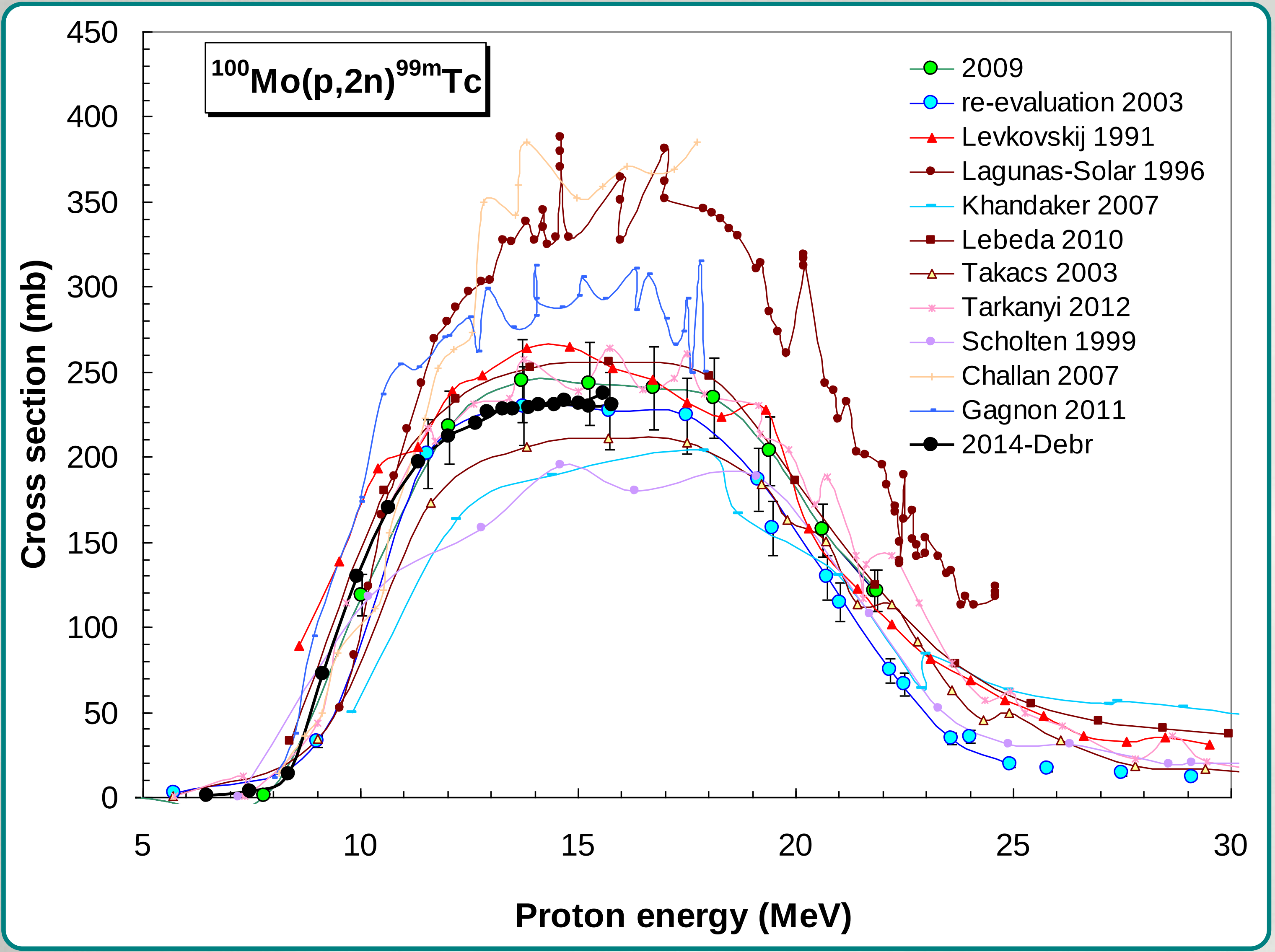


$^{100}Mo(p,2n)^{99m}Tc$
2009
re-evaluation 2003
Levkovskij 1991
Lagunas-Solar 1996
Khandaker 2007
Lebeda 2010
Takacs 2003
Tarkanyi 2012
Scholten 1999
Challan 2007
Gagnon 2011
2014-Debr
Cross section (mb)
Proton energy (MeV)
0
50
100
150
200
250
300
350
400
450
5
10
15
20
25
30

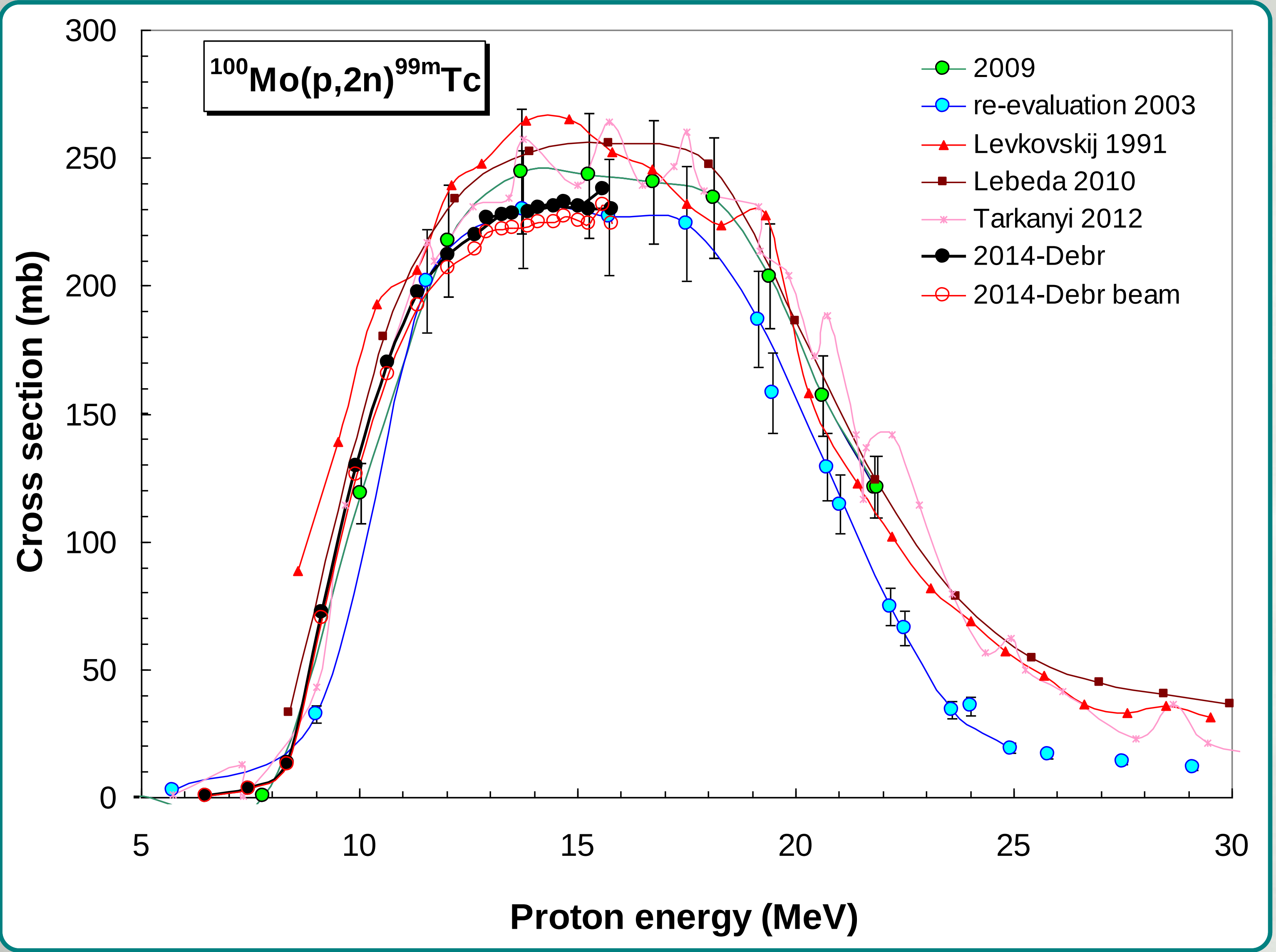
Results Cross Check



Conclusion and Summary



Conclusion and Summary



Thank you for Your attention