Ordinary muon capture (OMC) studies by means of γ-spectroscopy

Joint Institute for Nuclear Research, DUBNA

D.R. Zinatulina

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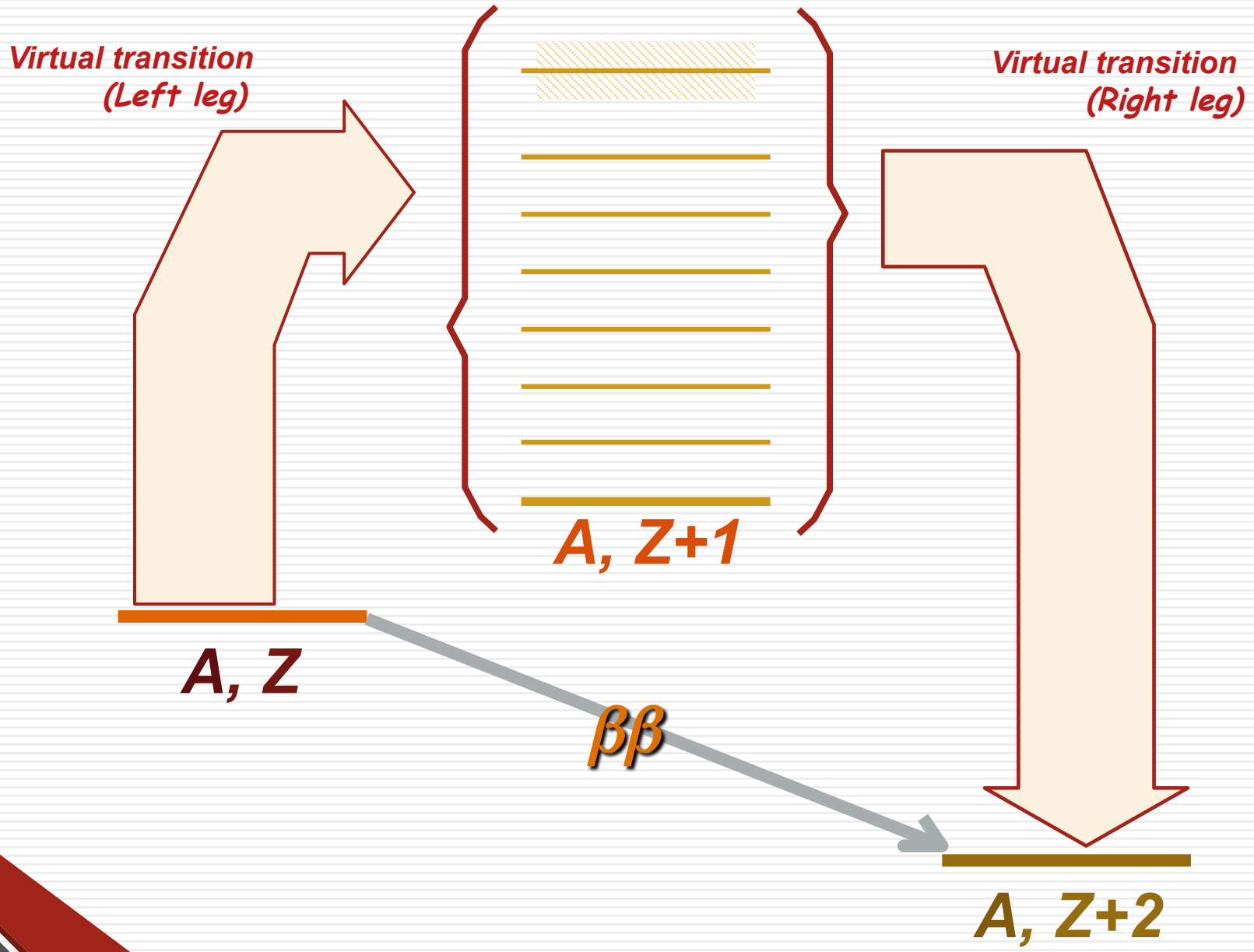
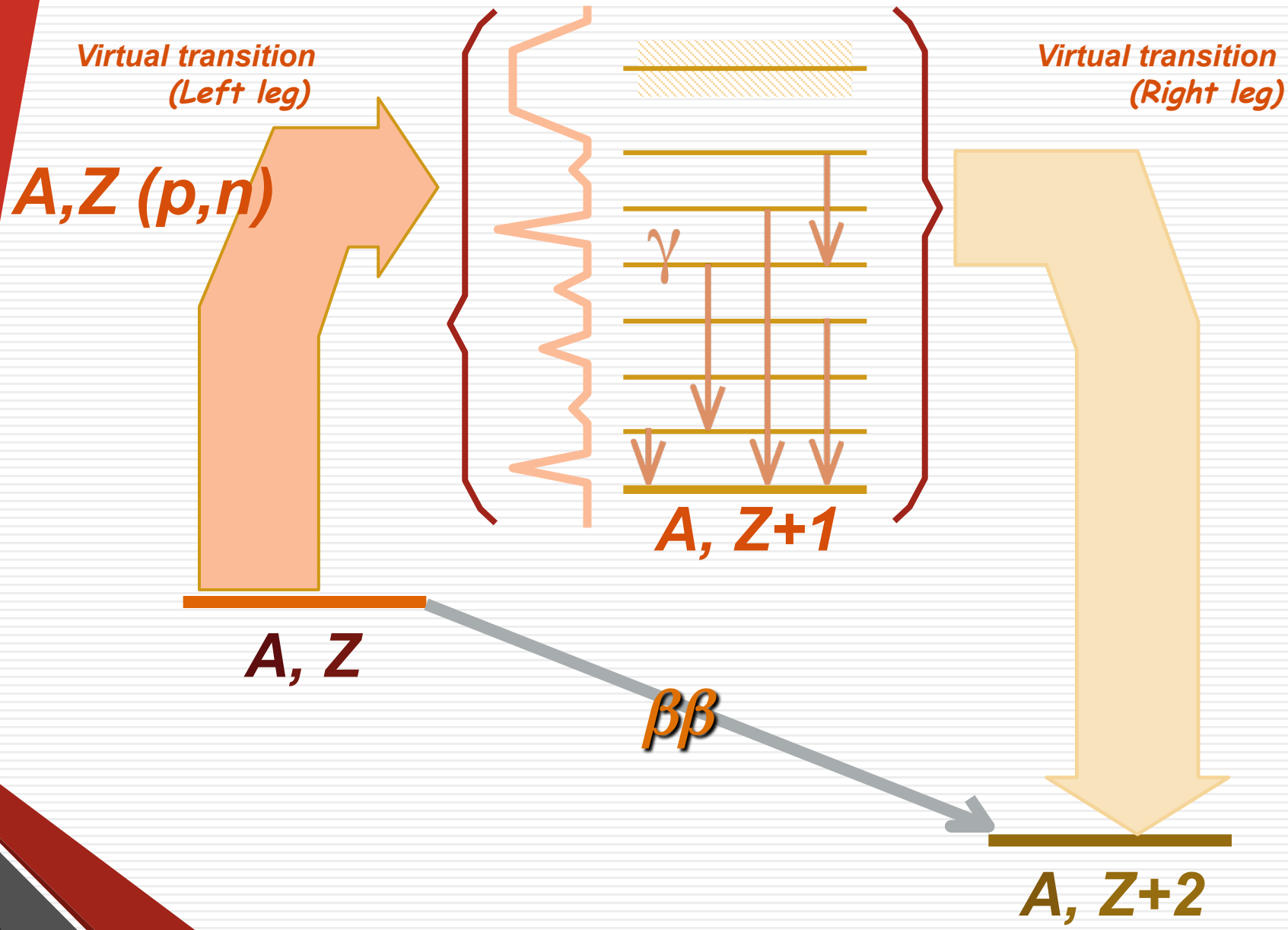
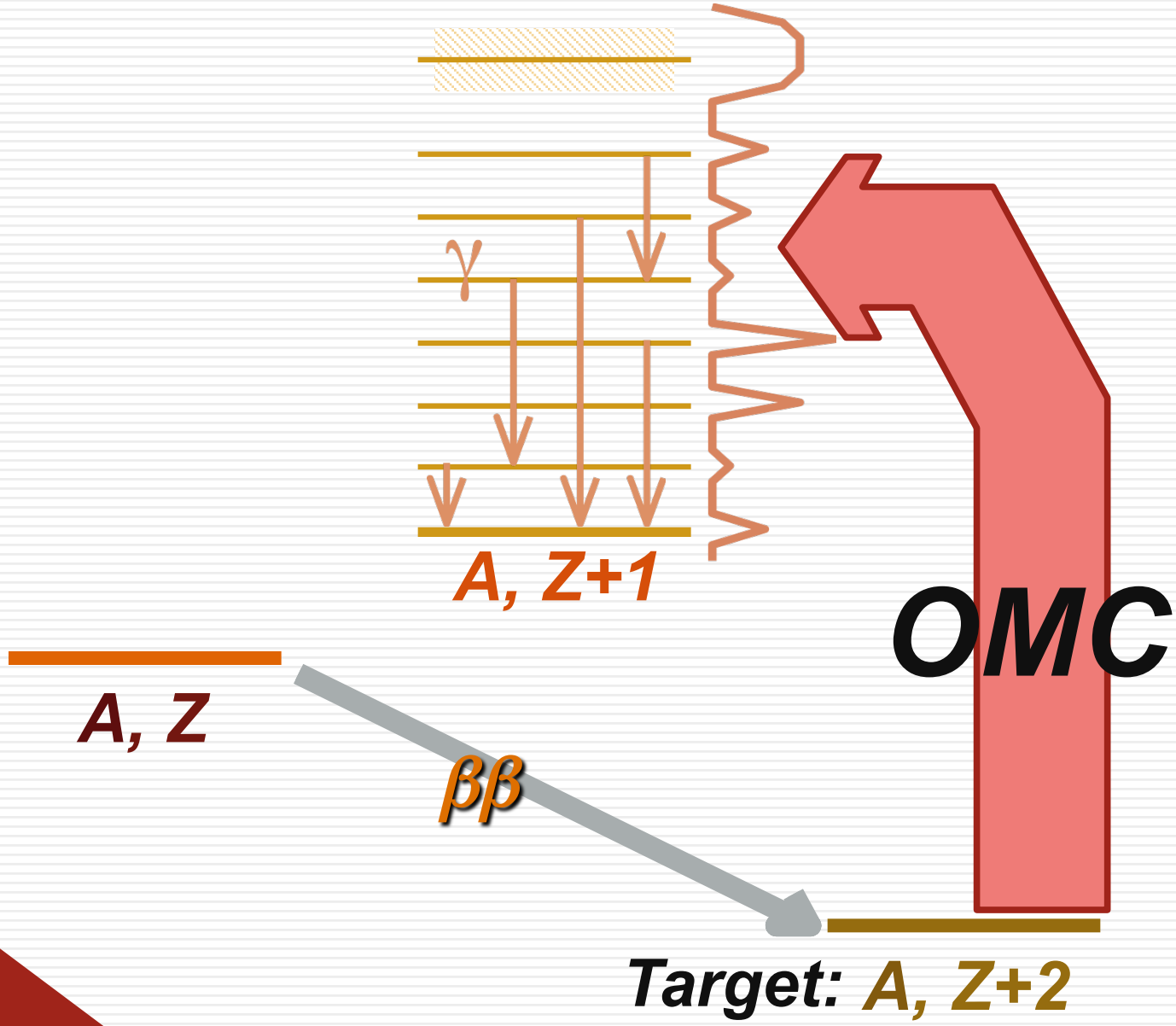
MEDEX'17, Prague

Main goal:

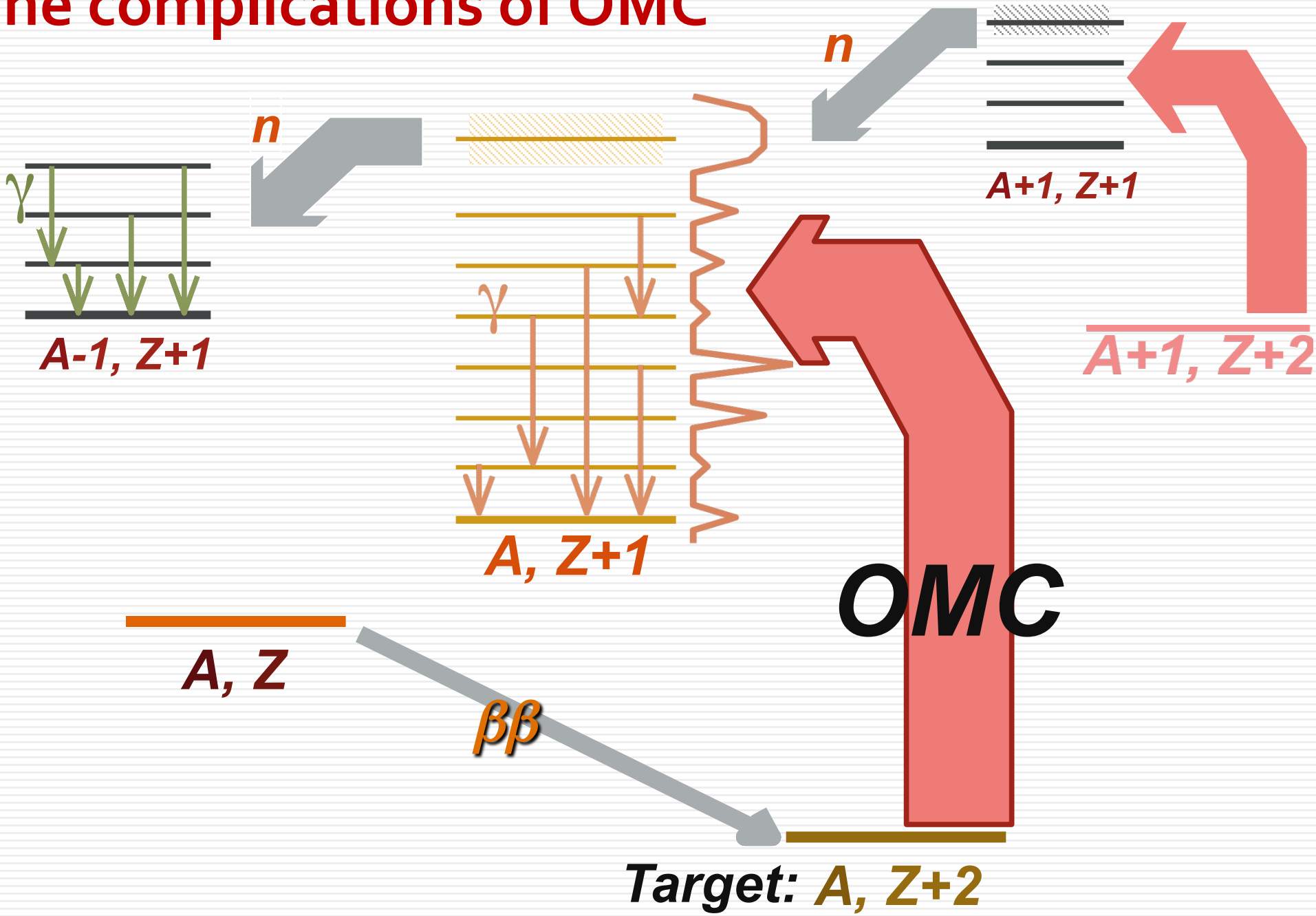
$$\left(T_{1/2}^{0\nu}\right)^{-1} = \left(\frac{\langle m_\nu \rangle}{m_e}\right)^2 \times F_{0\nu} \times \left|NME_{0\nu}\right|^2$$


Virtual transition
(Left leg)
Virtual transition
(Right leg)
A, Z+1
A, Z
ββ
A, Z+2


Virtual transition
(Left leg)
A,Z (p,n)
γ
A, Z+1
Virtual transition
(Right leg)
A, Z
ββ
A, Z+2

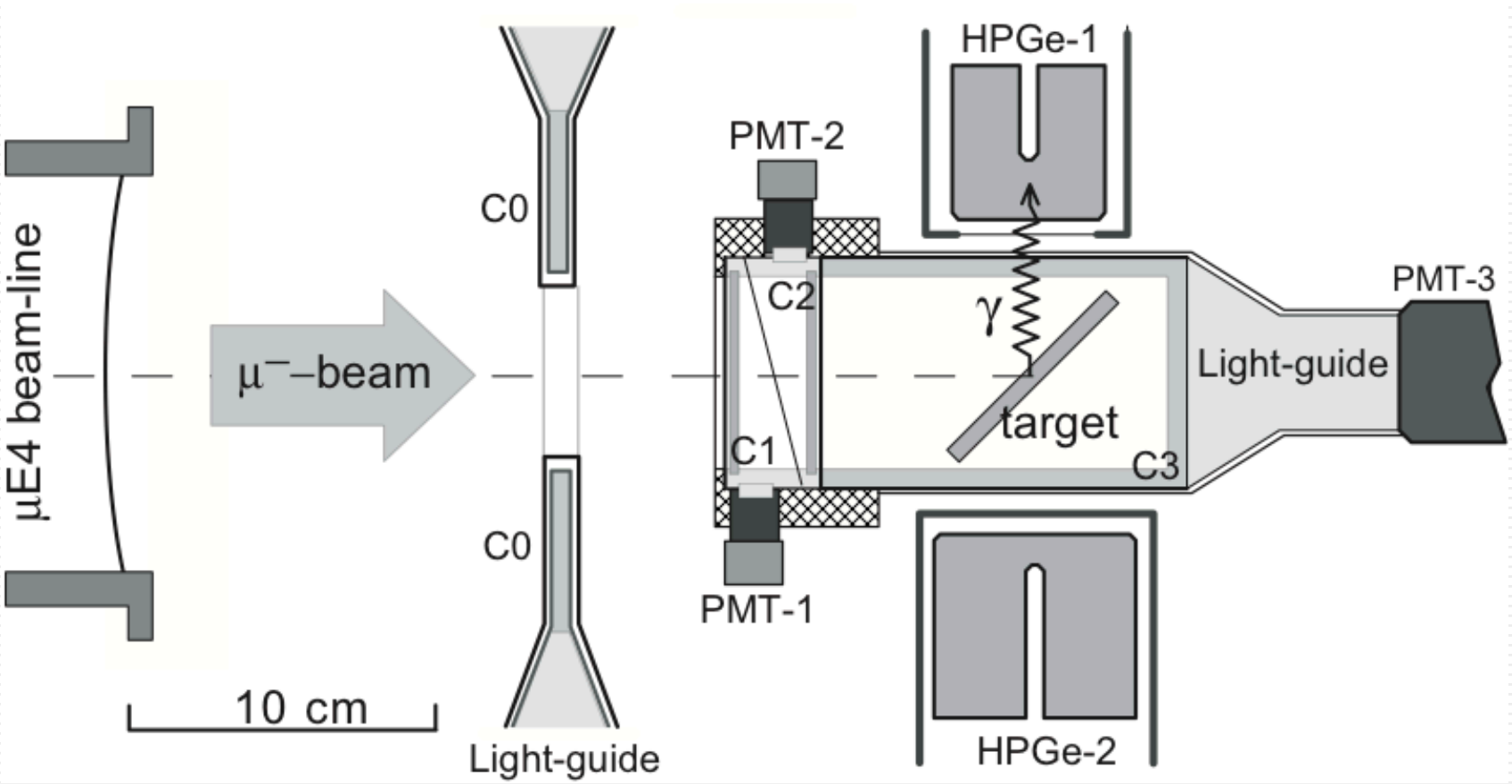

γ
A, Z+1
OMC
A, Z
ββ
Target: A, Z+2

The complications of OMC



2β-decay	2β-experiments	OMC target	Status
^{76}Ge	GerdaI/II, Majorana Demonstrator, LEGEND (R&D)	^{76}Se	2004
^{48}Ca	TGV, NEMO3, Candles III	^{48}Ti	2002
^{106}Cd	TGV	^{106}Cd	2004
^{82}Se	NEMO3, SuperNEMO, Lucifer(R&D)	^{82}Kr	2006
^{100}Mo	NEMO3, AMoRE(R&D), LUMINEU(R&D)	^{100}Ru	—
^{116}Cd	NEMO3, Cobra	^{116}Sn	2002
^{150}Nd	SuperNEMO, DCBA(R&D)	^{150}Sm	2002, 2006
^{136}Xe	EXO200, nEXO(R&D), Kamland-Zen, NEXT	^{136}Ba	–
^{130}Te	Cuore 0/Cuore, SNO+	^{130}Xe	–

Measurement set-up

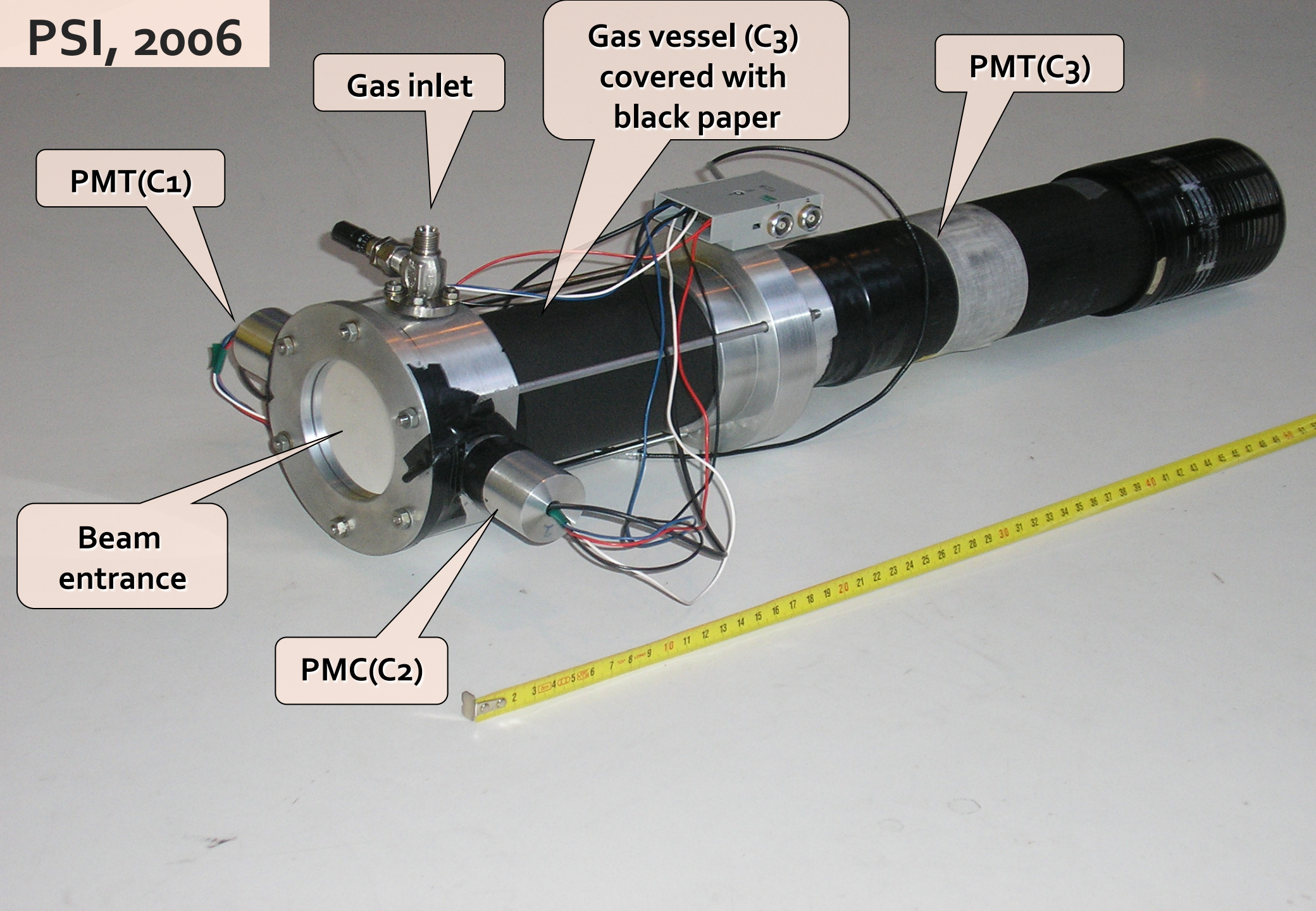


$$\mu_{stop} = \overline{C0} \wedge C1 \wedge C2 \wedge \overline{C3}$$

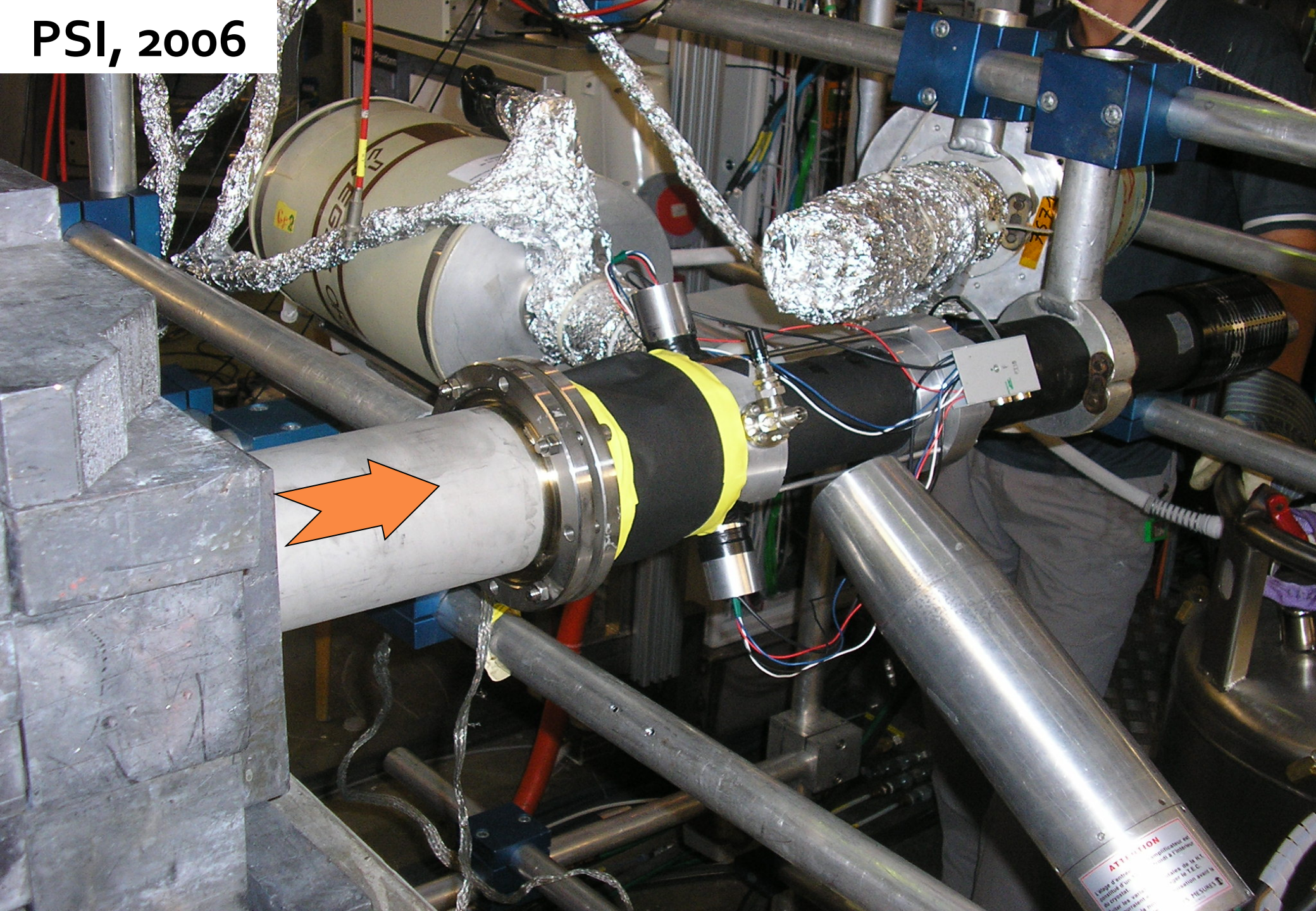
Number of μ-stop = (8 – 25) x 10^3 with 20 – 30 MeV/c


Ge4
Ge2
Ge3
C2
Jupiter
MISE EN PRESSION

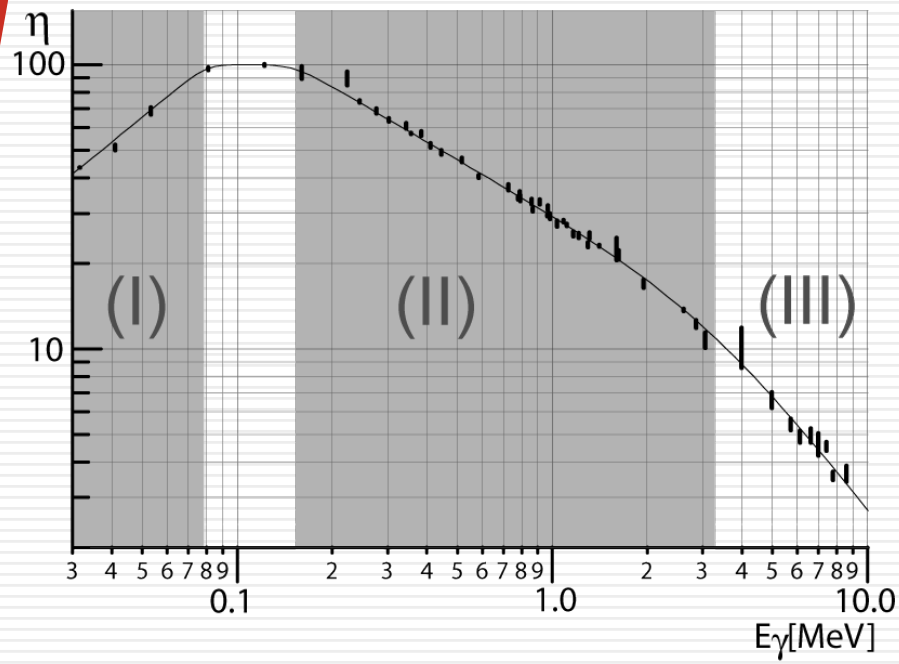
PSI, 2006

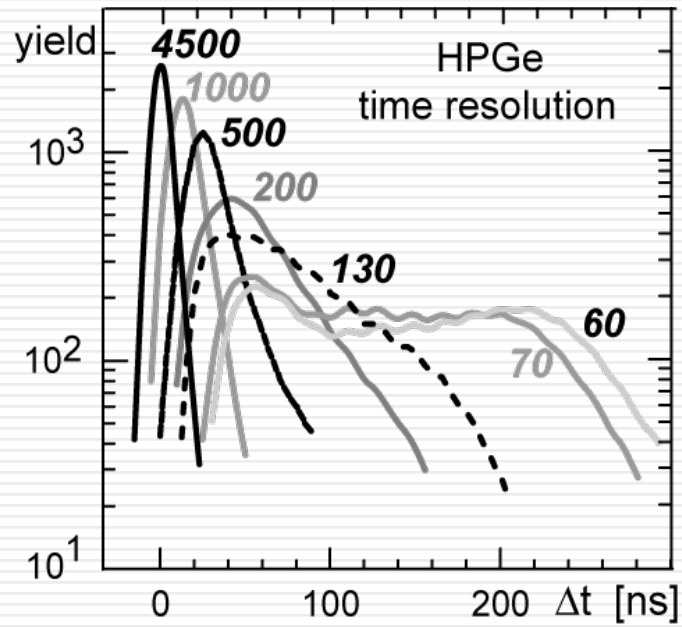

Gas inlet
Gas vessel (C3) covered with black paper
PMT(C3)
PMT(C1)
Beam entrance
PMC(C2)

PSI, 2006



Detector efficiencies and timing



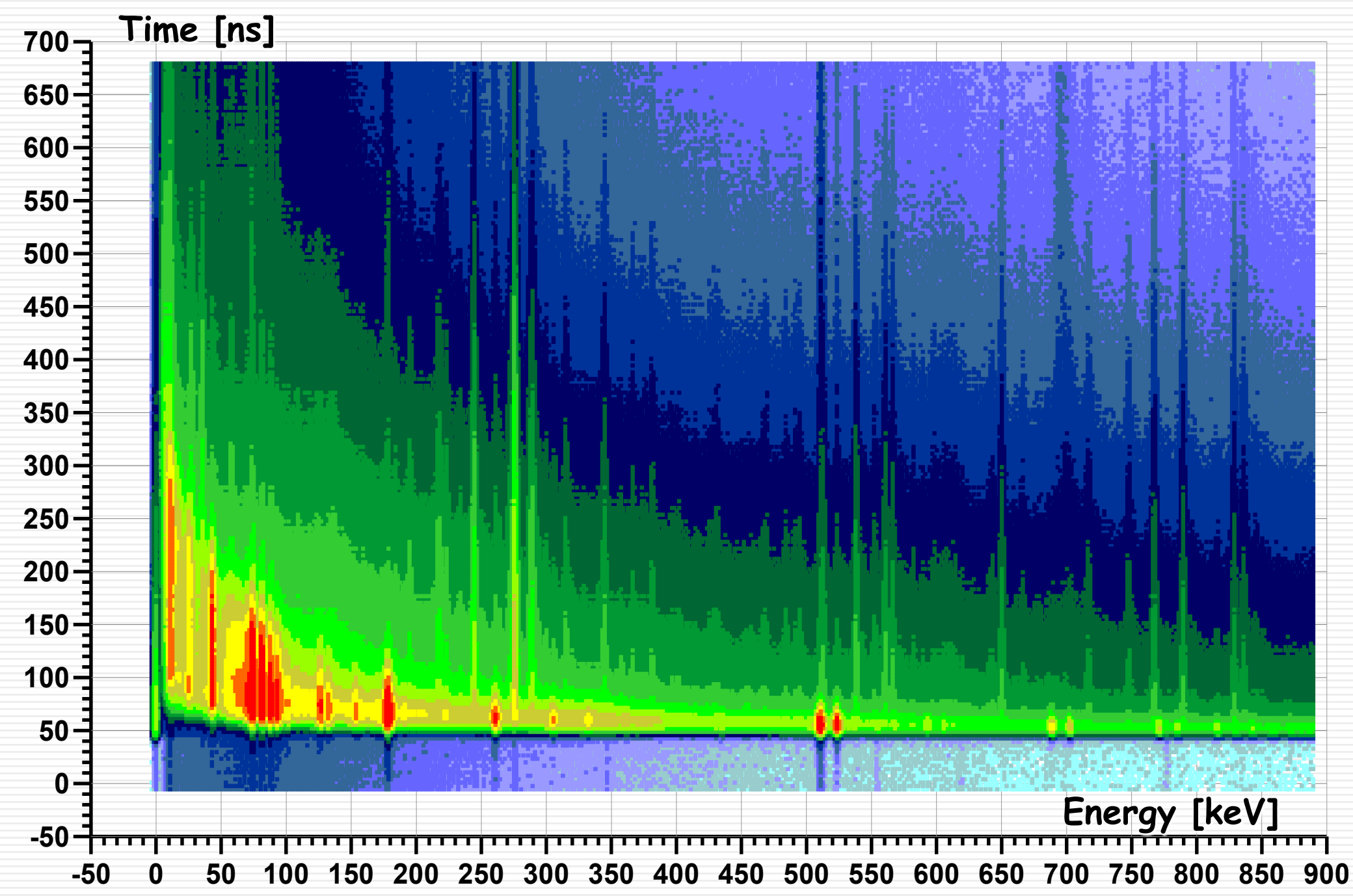


high γ's from
^{35}Cl(n,γ), ^{56}Fe(n,γ),^{28}Si(n,γ)
and
μX-rays from Au, Cd, Sm

timing deterioration due co-axial geometry of HPGe
time lag due to incomplete charge collection

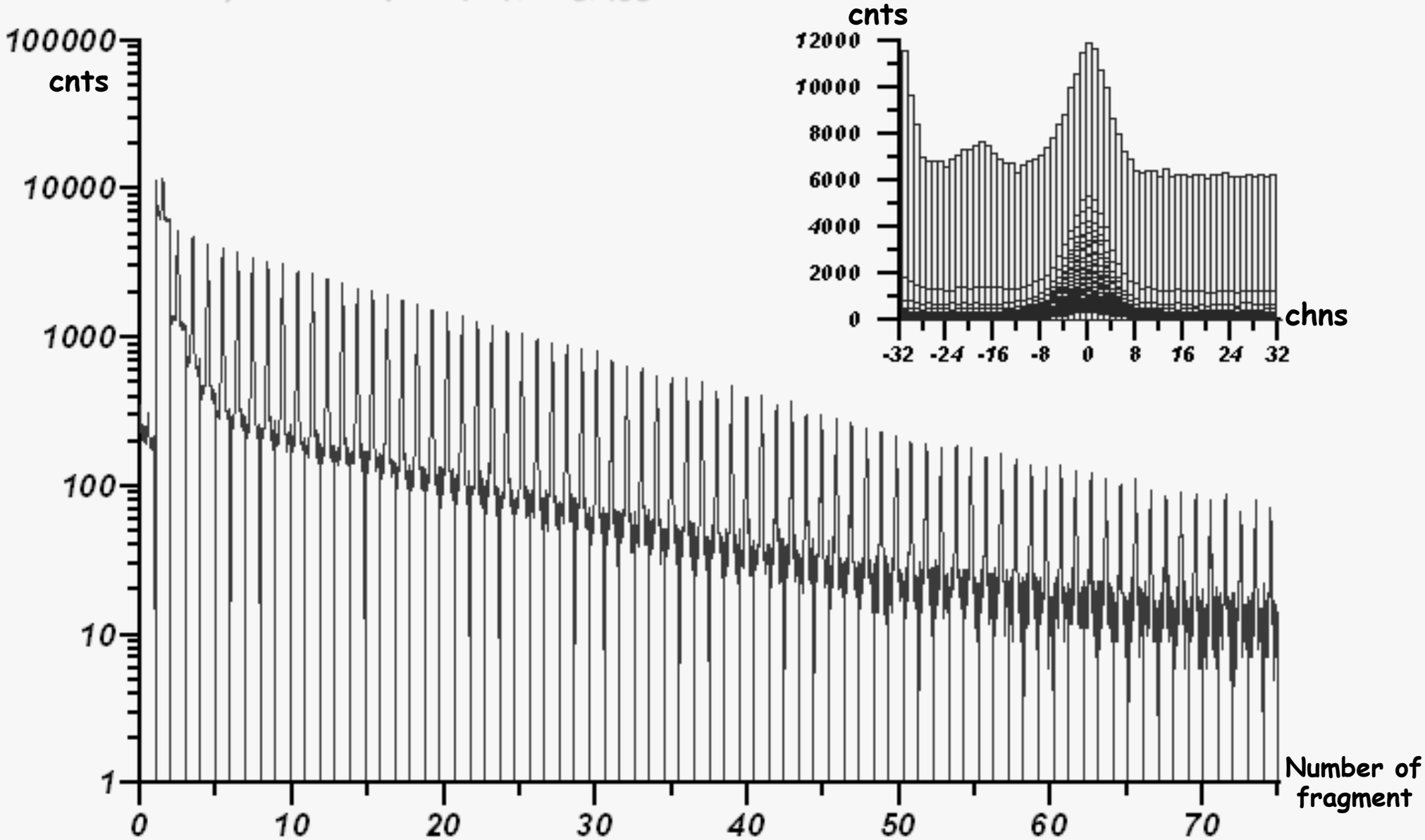
What do we observe and what can we get from the data?:

- Correlated events which could be sorted by time or by energy:
  A. Sorted by energy: Total capture rates;
  B. Sorted by time from 20-50 ns: Cascade of muonic X-rays (**prompt** spectra) – normalization, identification, composition of around materials and target, enrichment by isotopic shifts;
  C. Sorted by time from 50-700 ns: Nuclear γ-rays following μ-capture (**delayed** spectra) – partial capture rates, doppler shape of gamma lines can obtain angular correlation (n, ν), energy of high excited GDR state;
- (Background) radiation not connected directly to muons (**uncorrelated** spectra)
  A. Yield of different isotopes from β-decay.

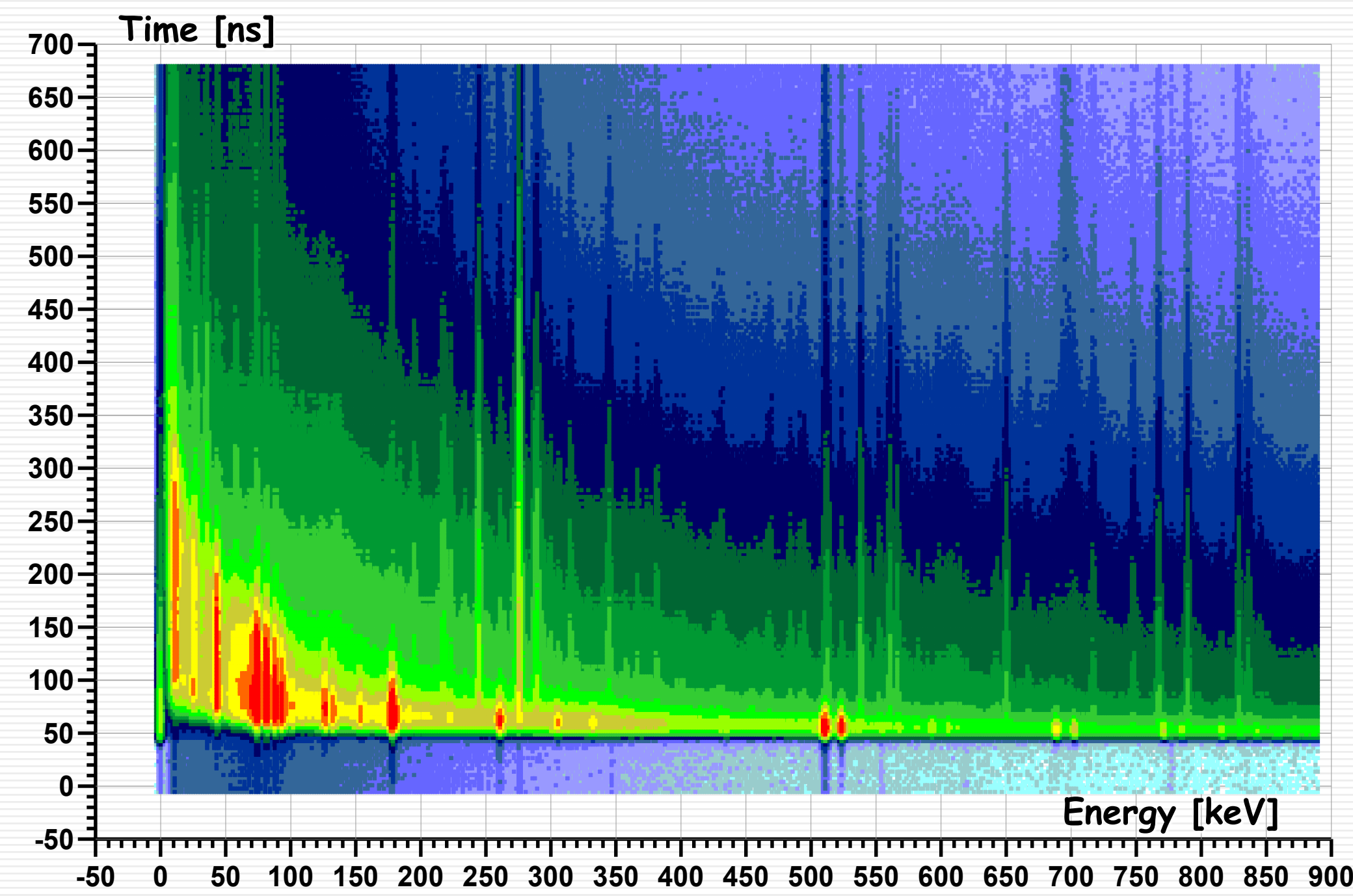

Time [ns]
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
Energy [keV]
-50
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900

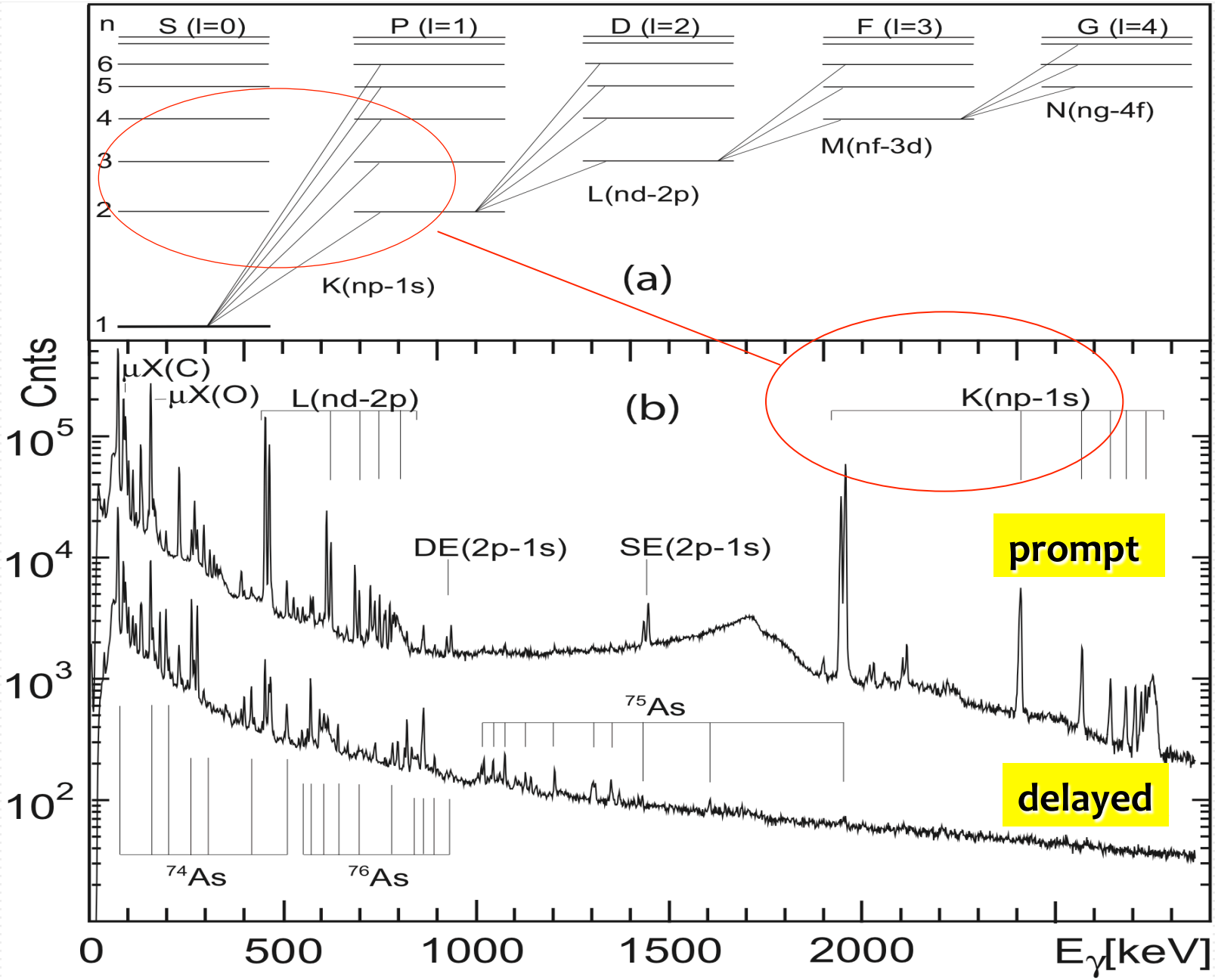
Time evolution (method)

H.O.U. Fynbo et. al.,NPA724(2003)493

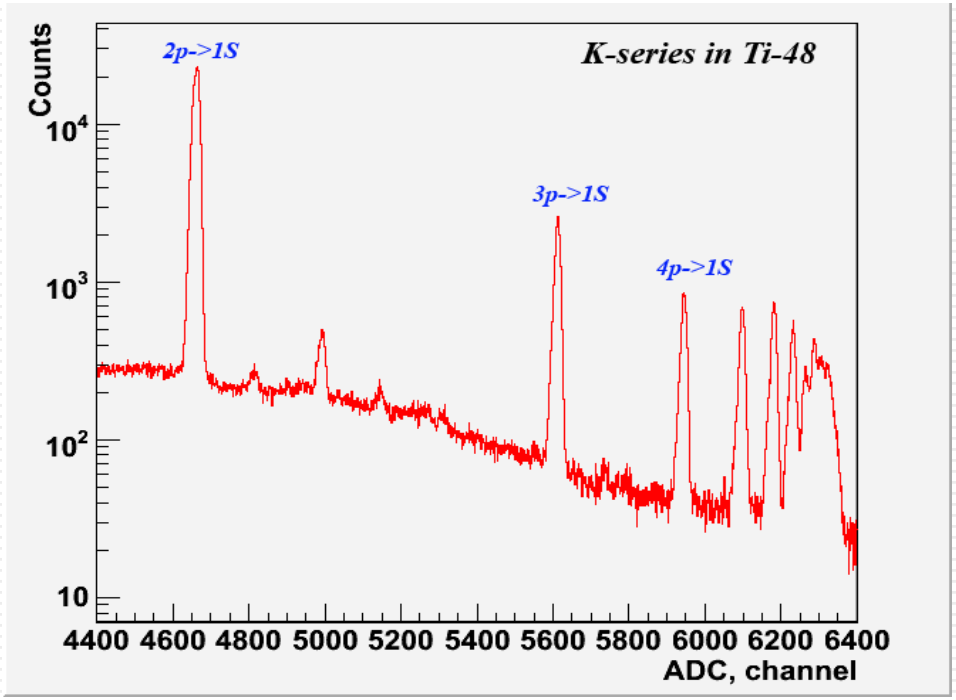


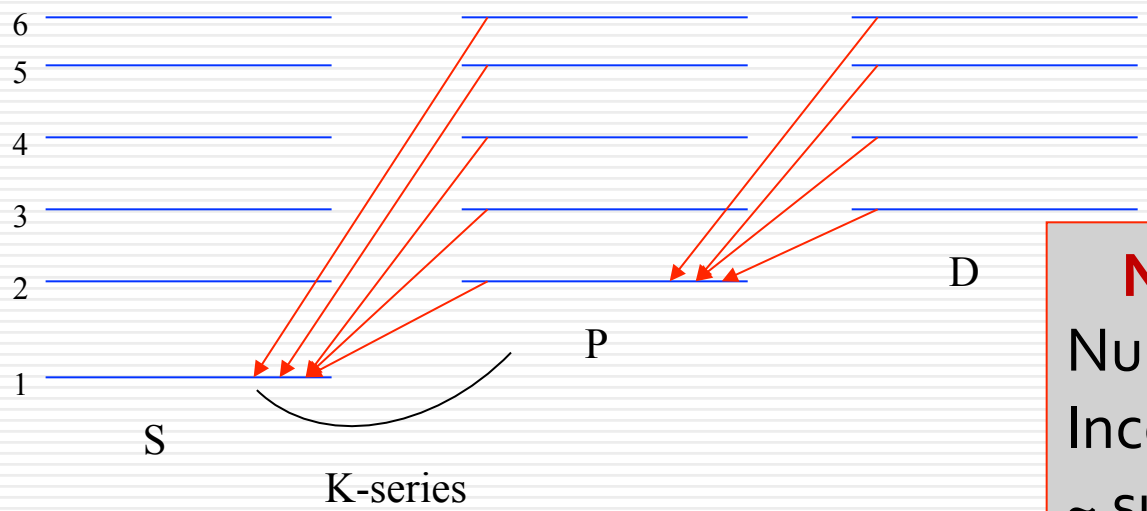
The fragment number (each fragment corresponds to 10 ns time period)


Time [ns]
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
Energy [keV]
-50
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900


n
S (l=0)
P (l=1)
D (l=2)
F (l=3)
G (l=4)
6
5
4
3
2
1
N(ng-4f)
M(nf-3d)
L(nd-2p)
K(np-1s)
(a)
Cnts
μX(C)
μX(O)
L(nd-2p)
(b)
K(np-1s)
DE(2p-1s)
SE(2p-1s)
prompt
75As
delayed
74As
76As
10^5
10^4
10^3
10^2
0
500
1000
1500
2000
Eγ[keV]

Muonic-X-rays





Normalization:
Number of Incoming muons ~ ~ sum of KX-lines

Link: *muxrays.jinr.ru*

Chrome Файл Изменить Посмотреть История Закладки Пользователи Окно Справка 98 % Пн 23:05

Входящие - d.zinatulina@gma | Mesoroentgen Catalogue | Fe_K.png (991×494) | C_K.png (962×498) | Как снять скриншот в Mac

muxrays.jinr.ru

Joint Institute for Nuclear Research
Dzhelepov Laboratory of Nuclear Problems
Scientific Experimental Department of Nuclear Spectroscopy and Radiochemistry

Mesoroentgen Spectra Catalogue

μ X Catalogue rays

Main **About** **Measurement conditions** **Authors**

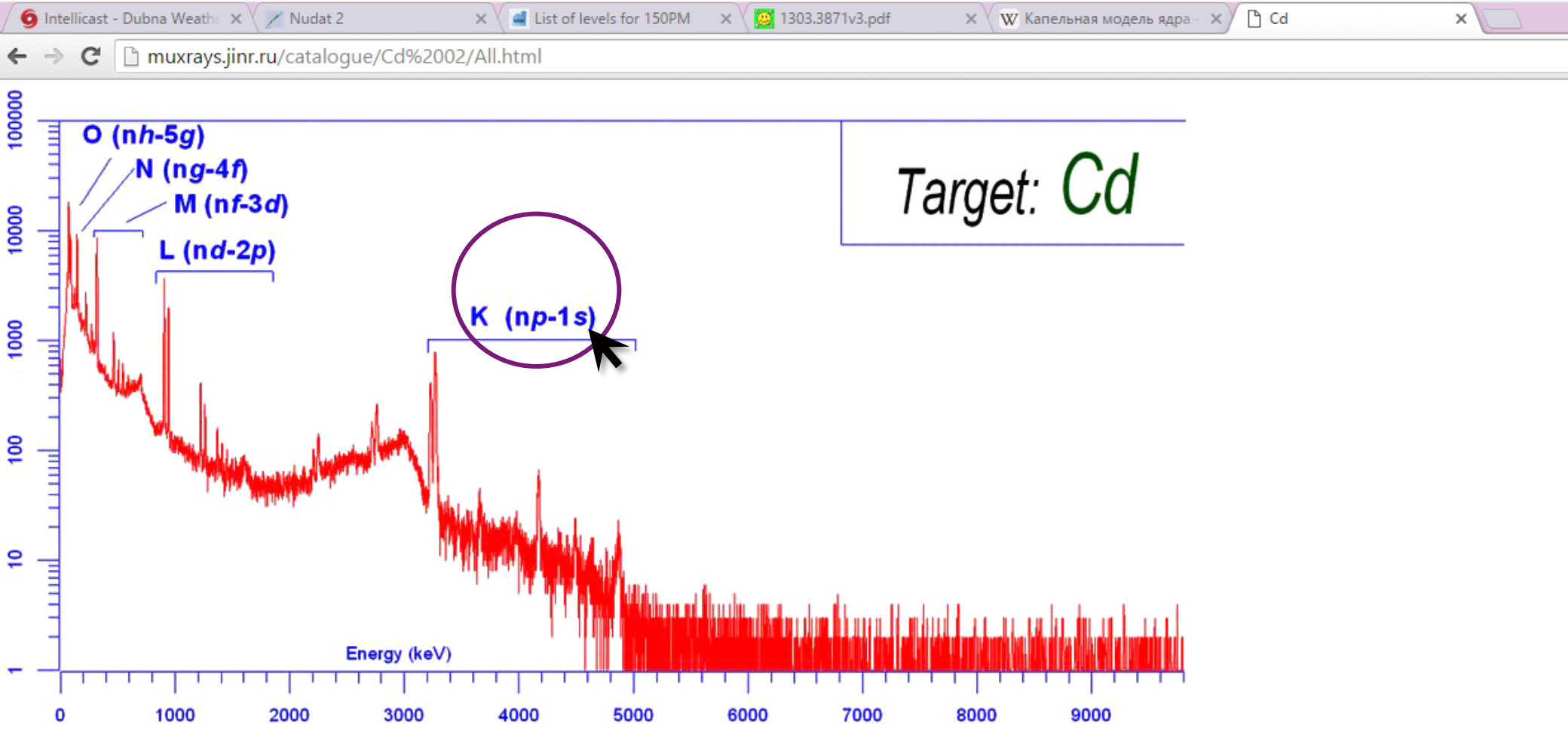
H										He
Li	Be	B	C	N	O	F				Ne
Na	Mg	Al	Si	P	S	Cl				Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	
Cu	Zn	Ga	Ge	As	Se	Br				Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	
Ag	Cd	In	Sn	Sb	Te	I				Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	
Au	Hg	Tl	Pb	Bi	Po	At				Rn
Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu

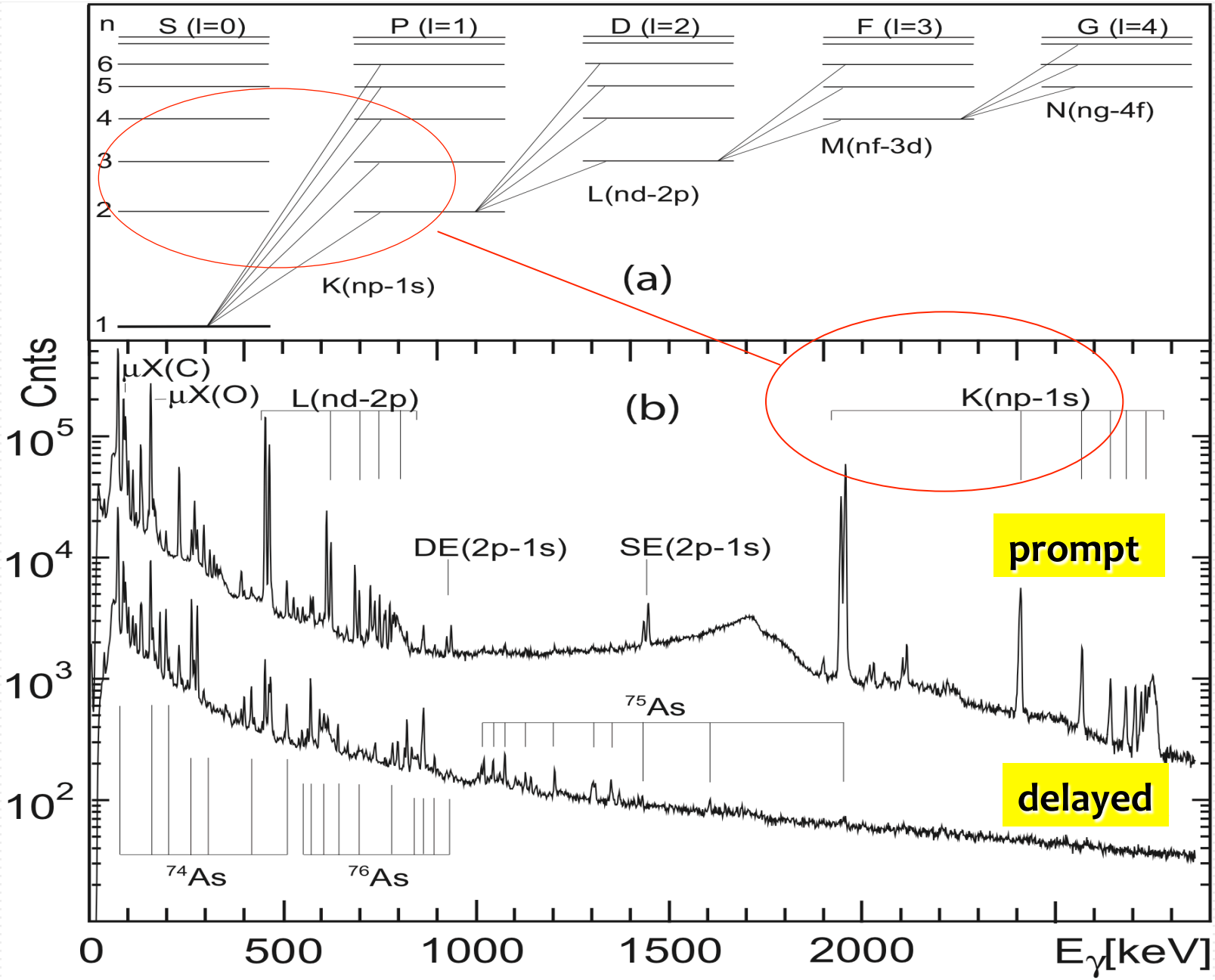
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Legend

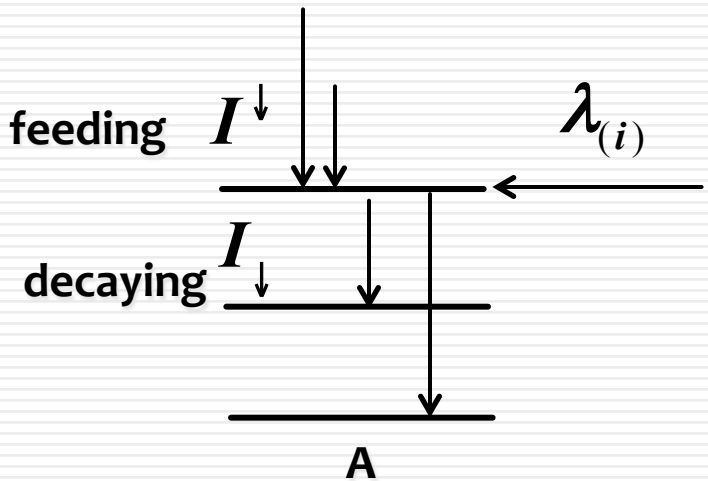
- Pu — Pure chemical state
- Ox — Oxide
- Ha — Halogen
- Ni — Nitrate
- Nm — Not measured (rare or very radioactive)

Total μX-ray spectrum of Cd




n
S (l=0)
P (l=1)
D (l=2)
F (l=3)
G (l=4)
6
5
4
3
2
1
N(ng-4f)
M(nf-3d)
L(nd-2p)
K(np-1s)
(a)
Cnts
μX(C)
μX(O)
L(nd-2p)
(b)
K(np-1s)
DE(2p-1s)
SE(2p-1s)
prompt
75As
delayed
74As
76As
10^5
10^4
10^3
10^2
0
500
1000
1500
2000
Eγ[keV]

Extraction of the partial rates



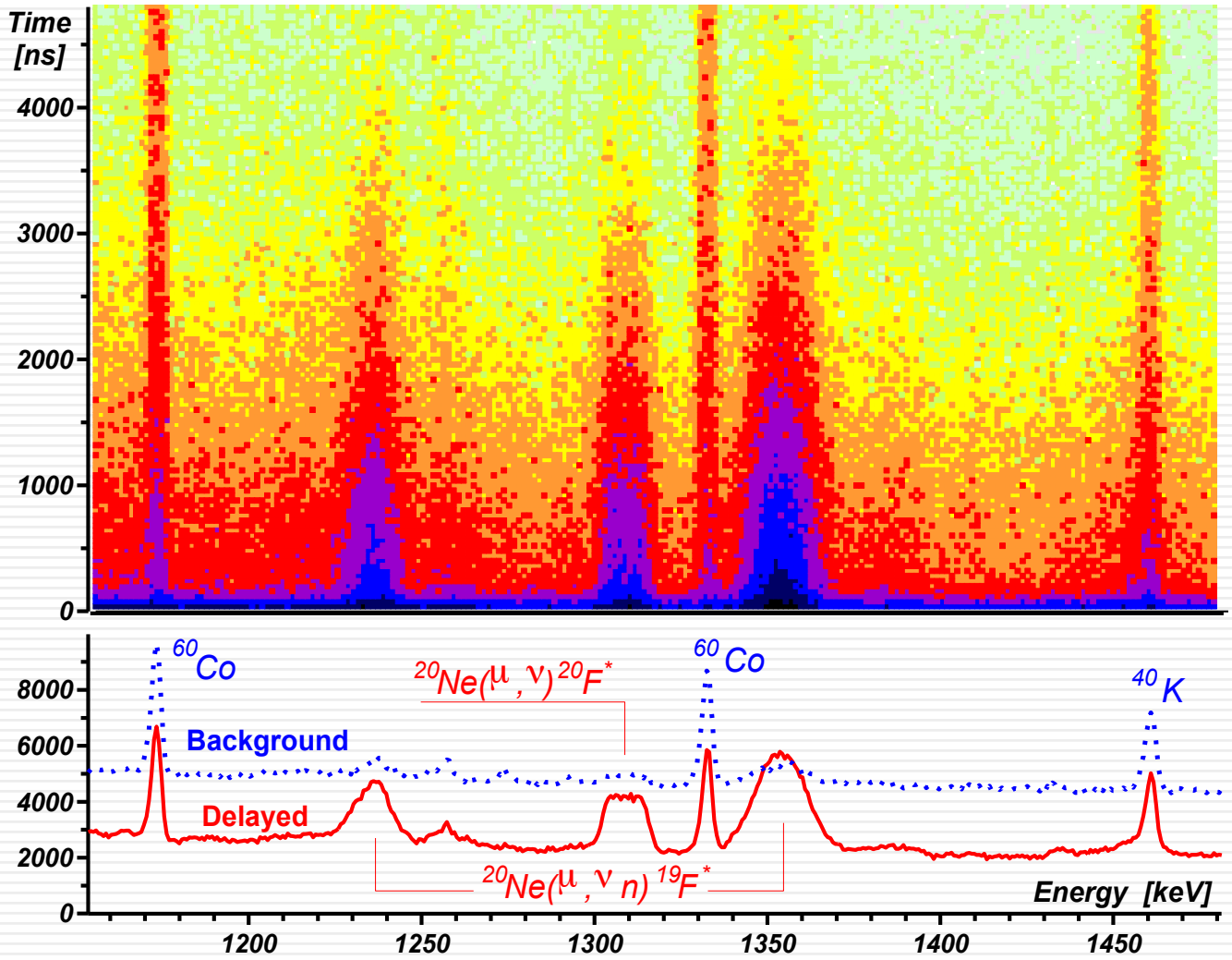
$$\lambda_{(i)} = \frac{\sum I_{\downarrow} - \sum I^{\downarrow}}{\varepsilon \sum I(nK)}$$

detailed balance

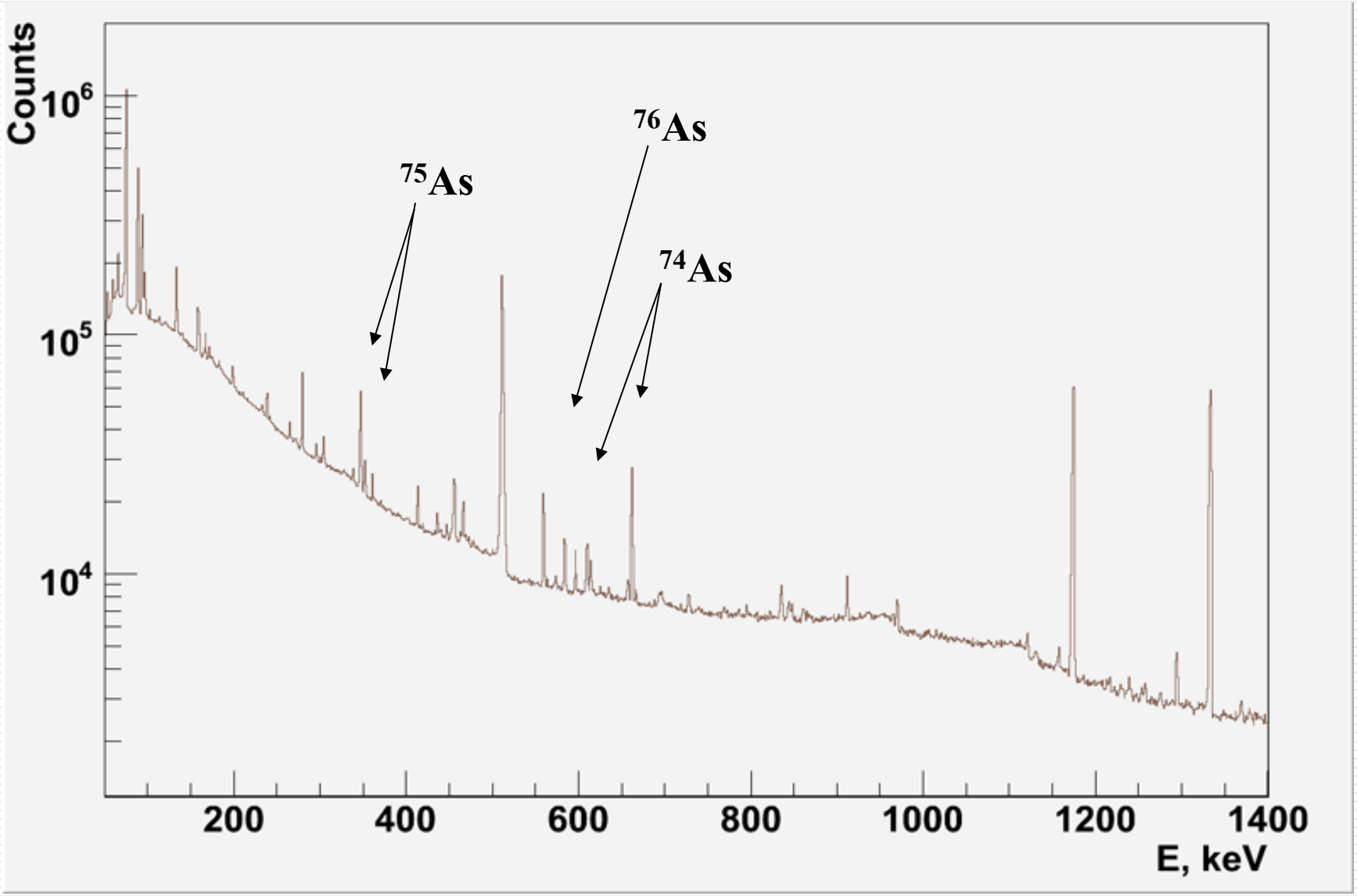
$$\lambda_{cap} = \lambda_{total} - Q\lambda_{decay} \qquad Q \rightarrow \text{Huff-factor}$$

$$\lambda_{(i)}[\%] = \frac{\lambda_{(i)}}{\lambda_{cap}}$$

Angular correlations with ν in OMC (Doppler shape of γ-lines)



Uncorrelated spectrum measured with ^{76}Se target



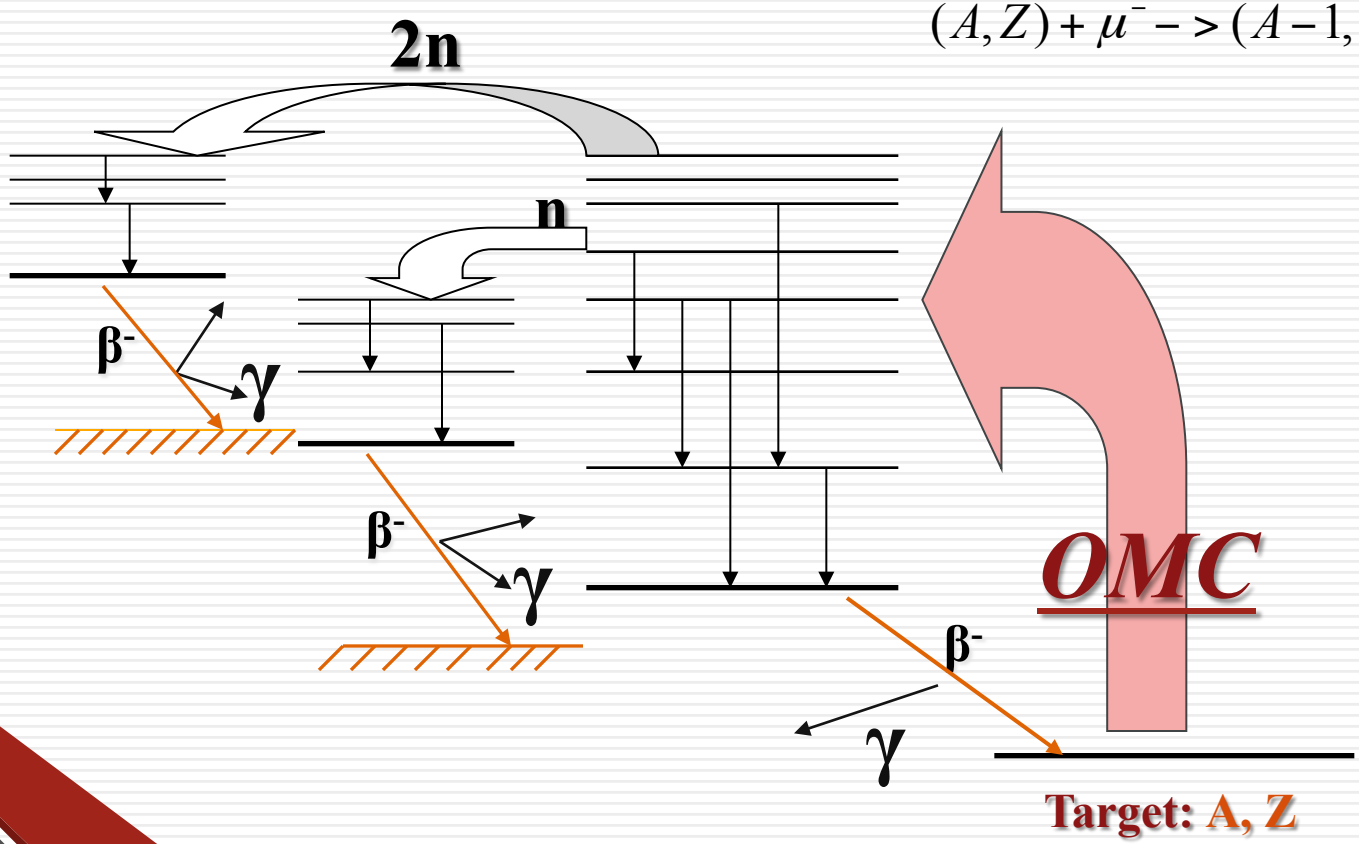
Yield of different isotopes from β-decay

$$(A,Z)+\mu^- -> (A,Z-1)+\nu$$

$$(A,Z)+\mu^- -> (A-1,Z-1)+{}^1_0n+\nu$$

$$(A,Z)+\mu^- -> (A-2,Z-1)+2{}^1_0n+\nu$$

$$(A,Z)+\mu^- -> (A-1,Z-2)+{}^1_1p+\nu$$



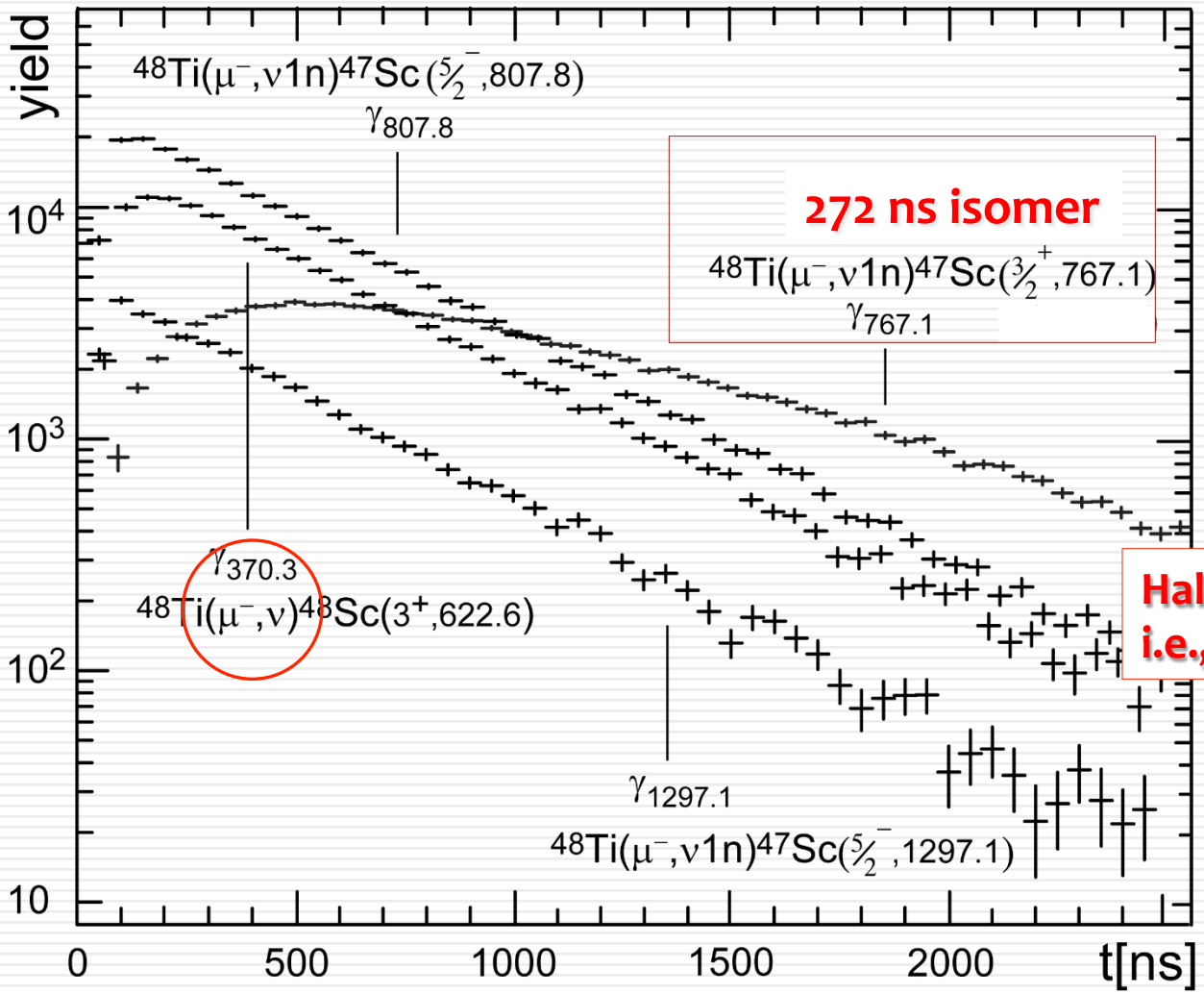
Target: ^{48}Ti

Enrichment: 95.8%

Composition: TiO_2 powder

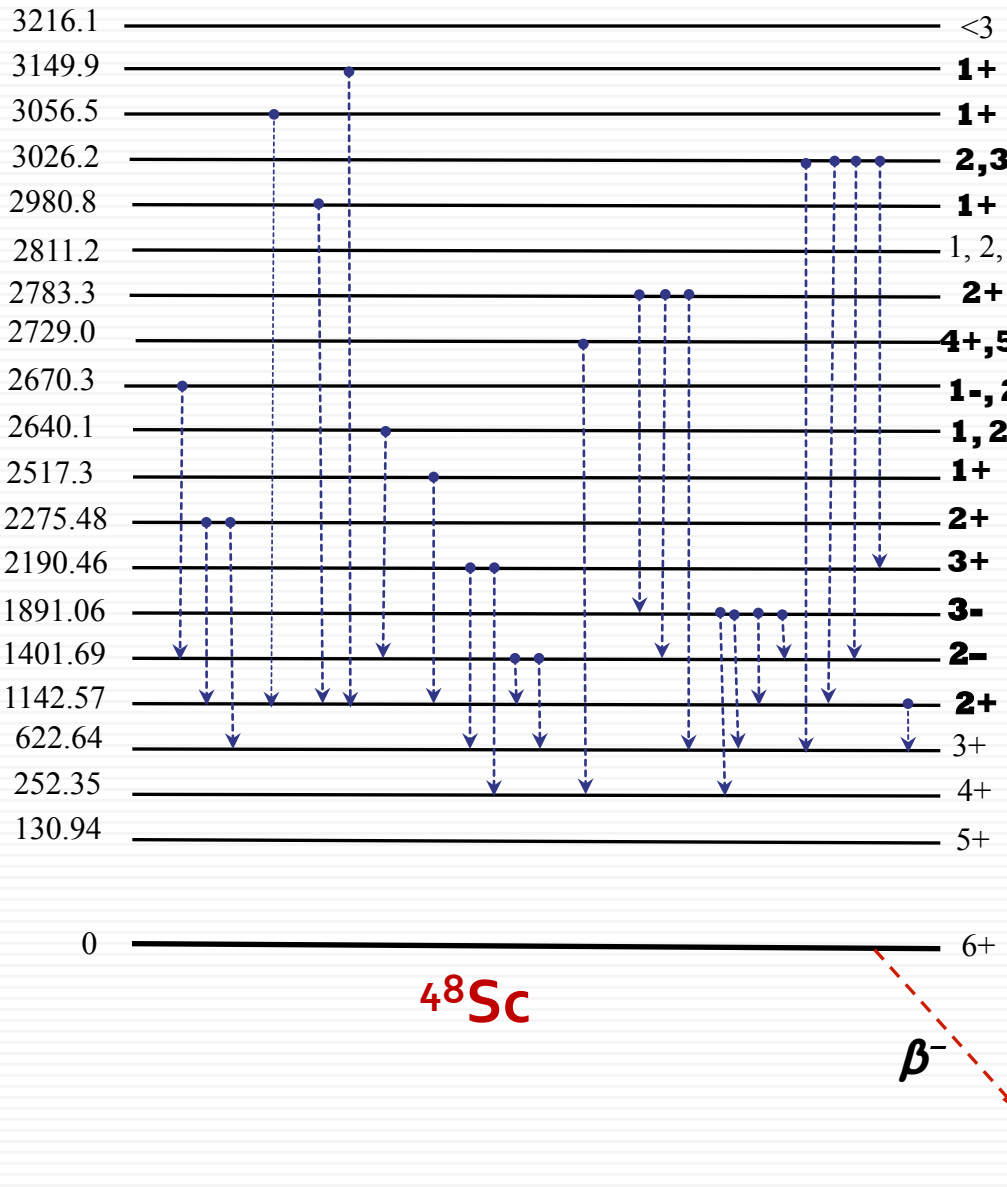
Quantity: 1.0 g

Total μ-capture rates on ^{48}Ti



Half-life: 361.1 ns
i.e., λ_{cap} = 2.32 μs^{-1}

Partial rates results of the ^{48}Sc



J.Suhonen
Czech.JP,V56(2006)5

Λ_{par}, % of Λ_{cap}	Λ_{par}, relative	
0.14 (8)		
0.45 (24)	0.396	0.102
1.175 (717)		
0.53 (29)	0.466	0.128
0.47 (33)		
0.19 (8)		
0.19 (6)	0.167	0.001
1.064 (628)	0.936	0.007
0.52 (23)	0.46	0.05
0.71 (42)		
0.55 (32)		
0.11 (6)		
1.136 (707)	1.000	1.000
1.185 (677)	1.043	0.011

OMC

$\sum\Lambda_{par}(\%) = 8.40\ (157)$

Targets: ^{76}Se , ^{nat}Se

^{76}Se

Enrichment: 92.4%

Composition: Se granules

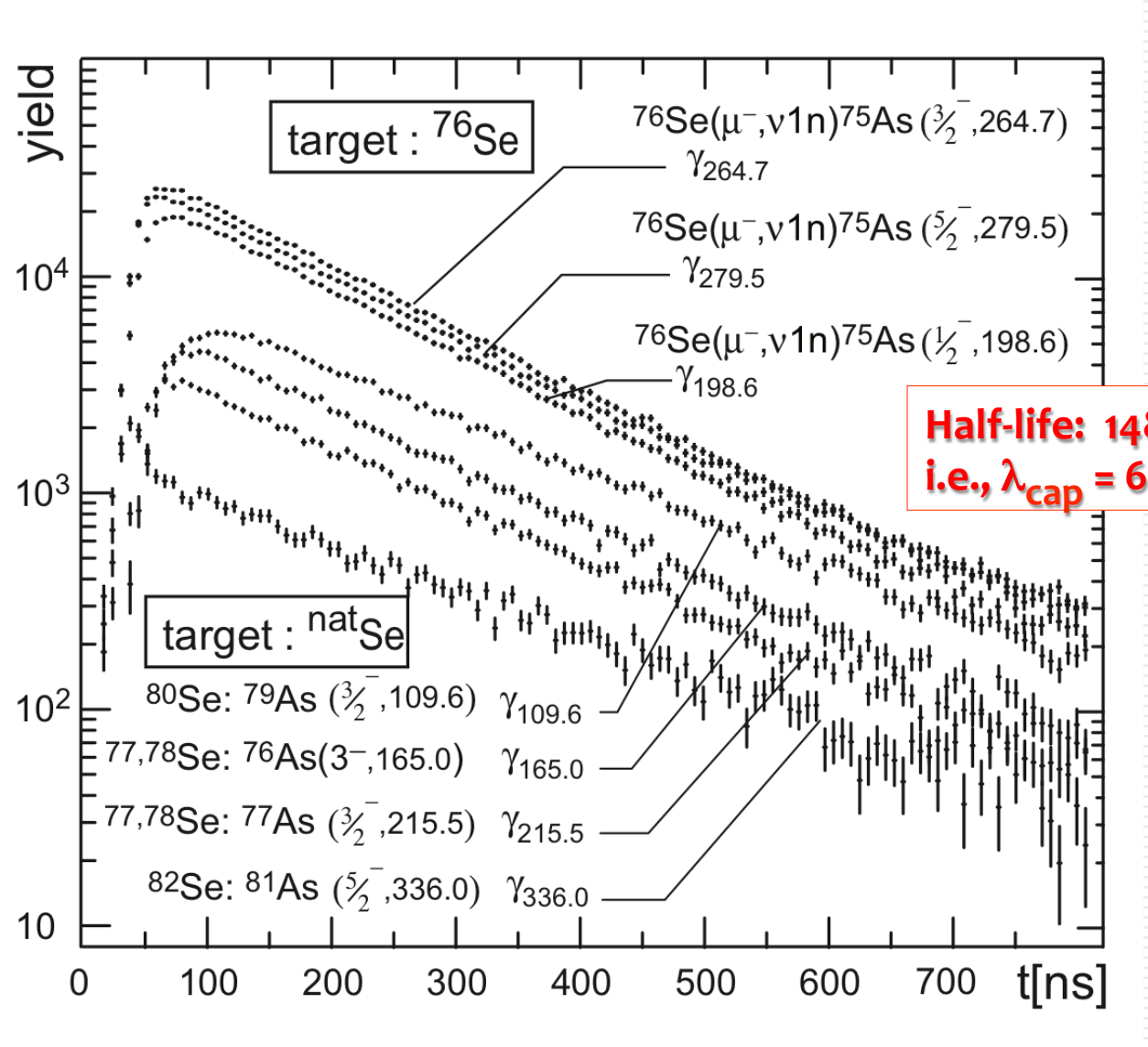
Quantity: 5.0 g

^{nat}Se

Composition: Se granules

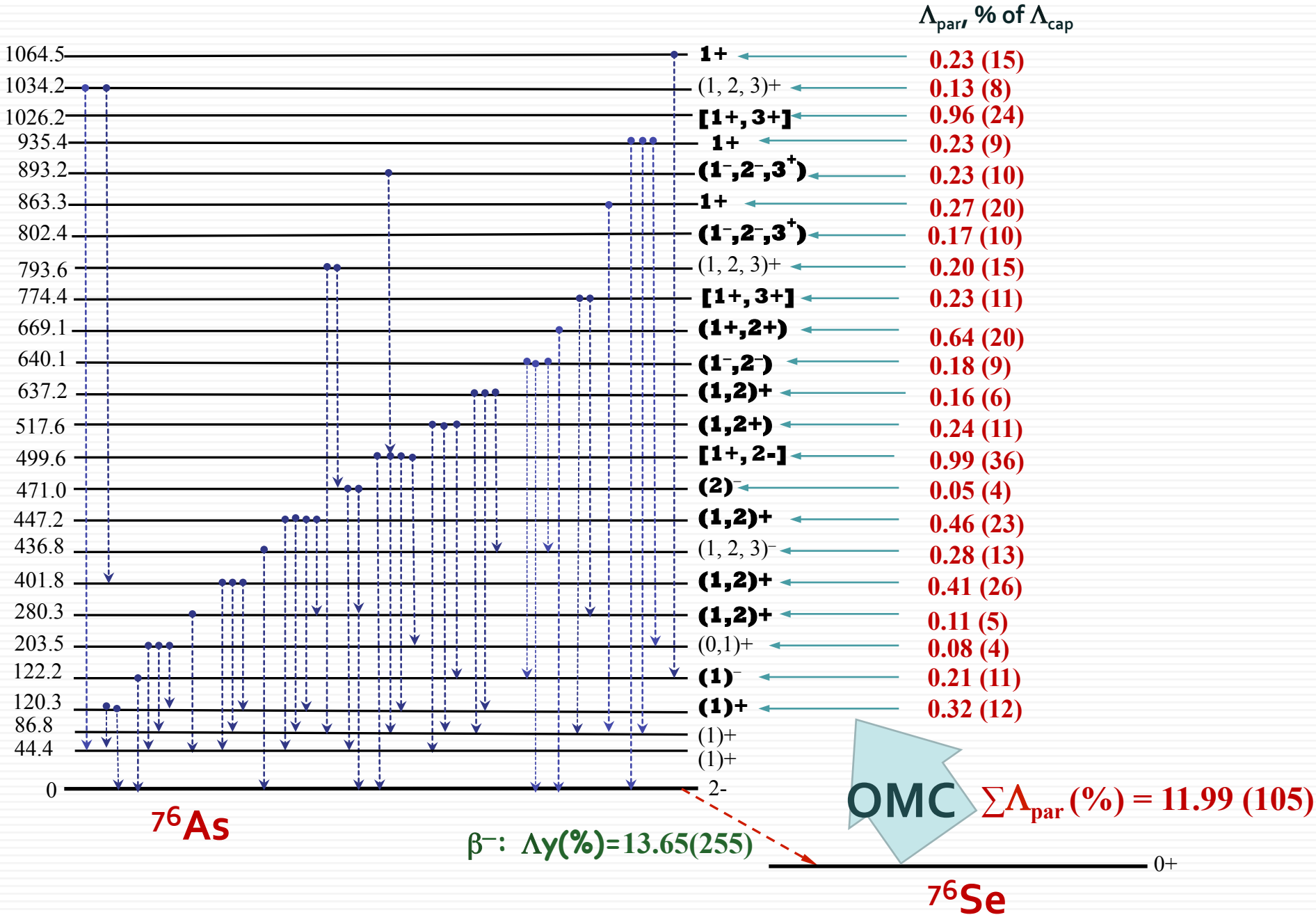
Quantity: 5.0 g

Total μ-capture rates on Se isotopes



Half-life: 148.48 ns
i.e., λ_{cap} = 6.3 μs^{-1}

Partial rates results of the ^{76}As



Targets: ^{106}Cd, ^{nat}Cd

^{106}Cd

Enrichment: 63.0%

Composition: Cd metal foil

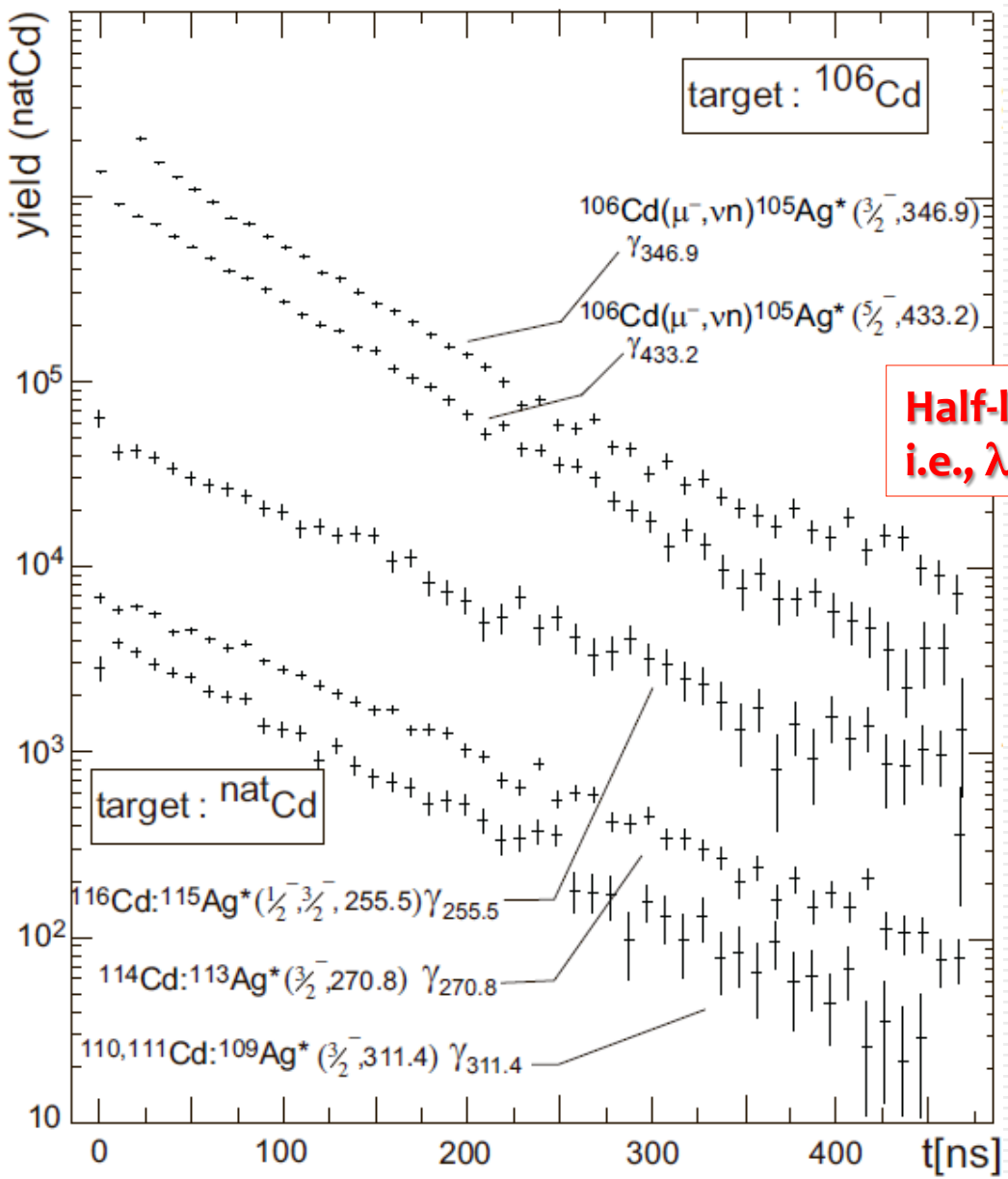
Quantity: 5.0 g

^{nat}Cd

Composition: Cd metal foil

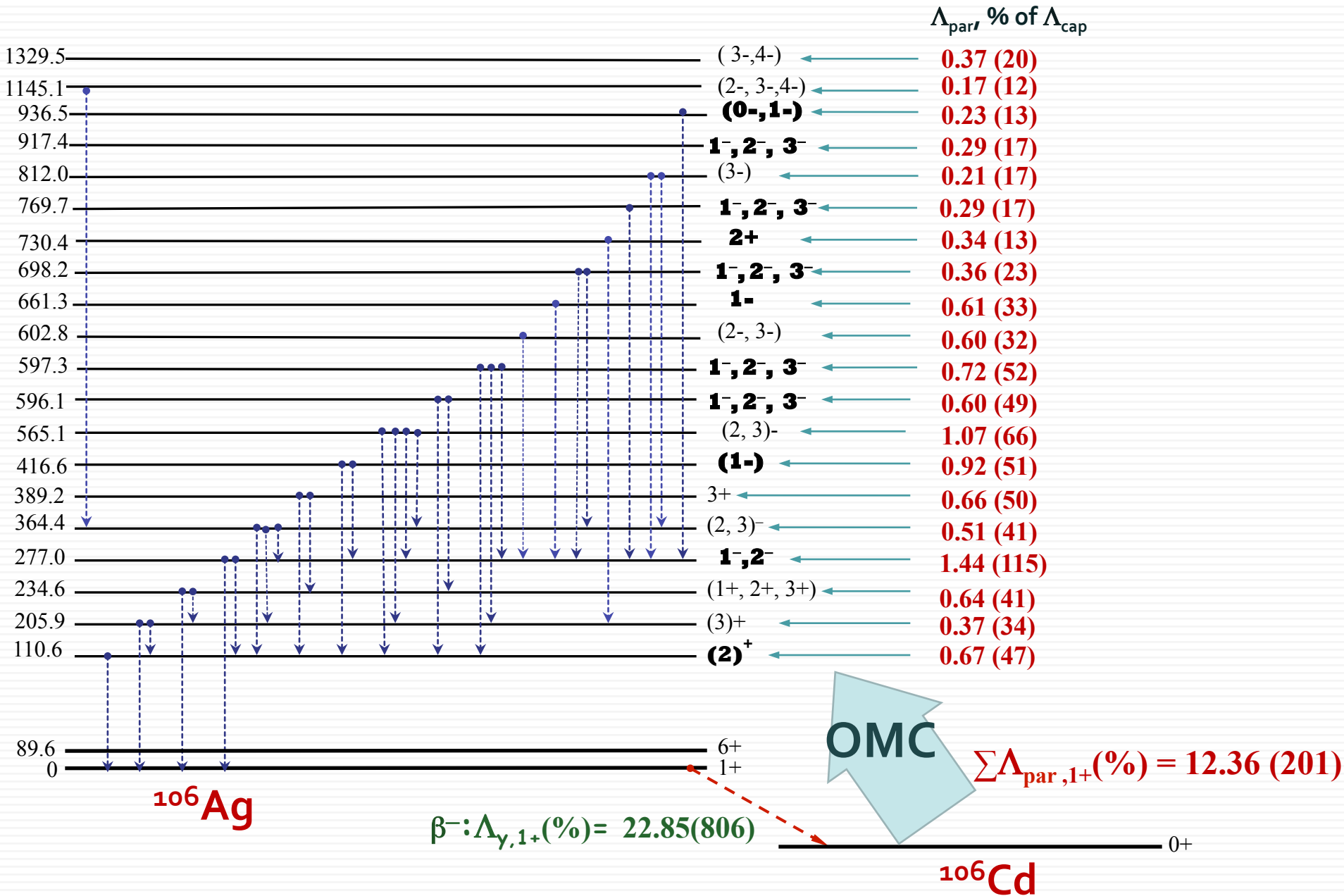
Quantity: 5.0 g

Total μ-capture rates on Cd isotopes



Half-life: 72.97 ns
i.e., λ_{cap} = 13.28 μs^{-1}

Partial rates results of the ^{106}Ag



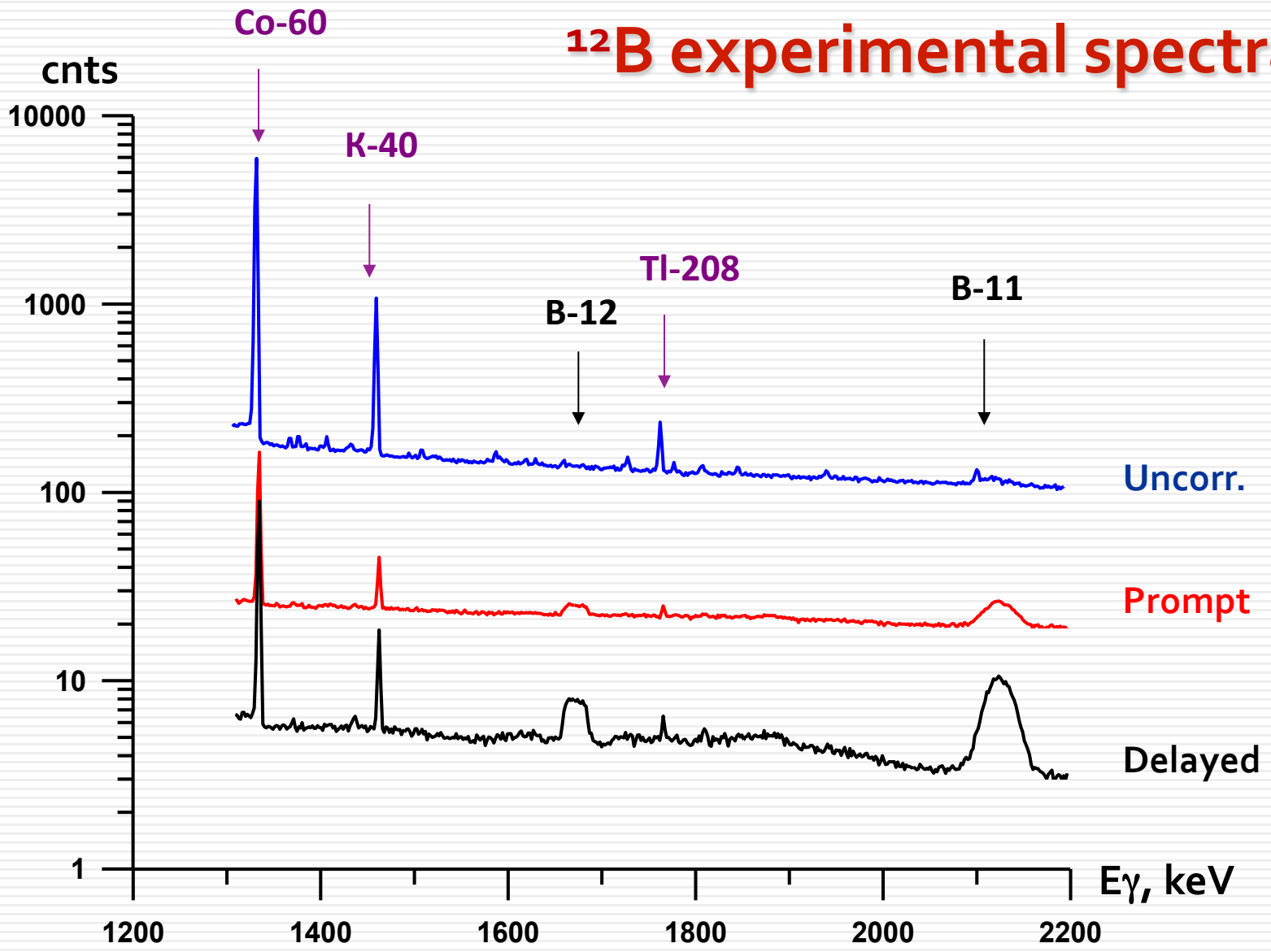
Target: ^{12}C

Year: 2006

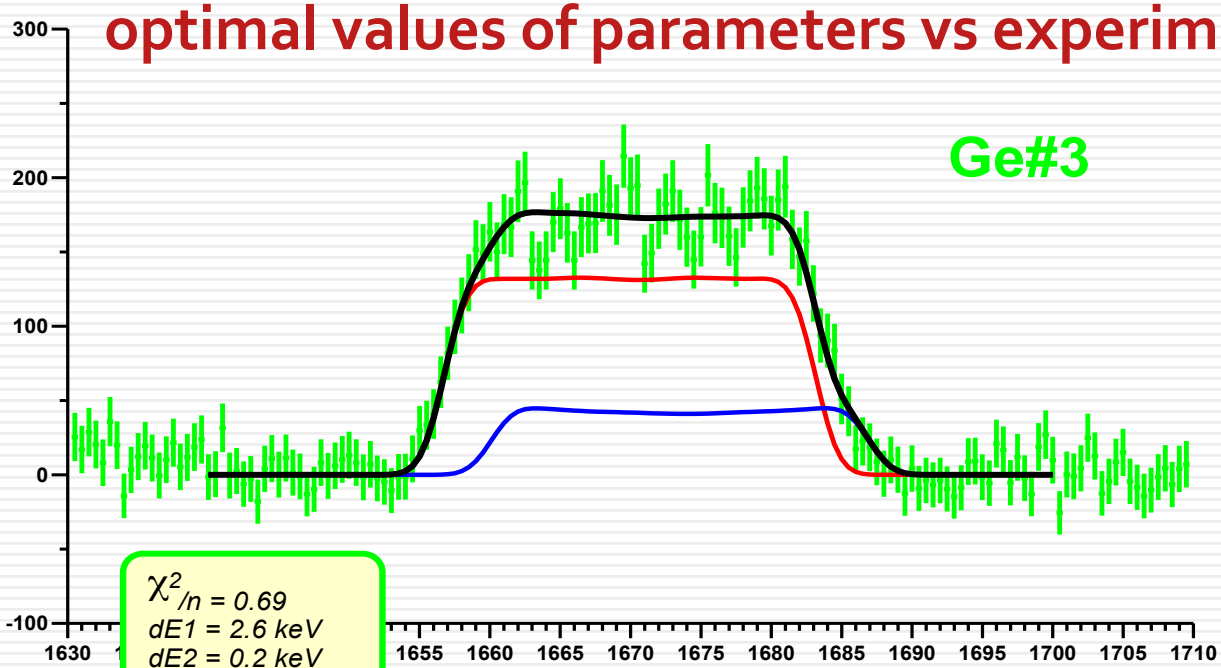
Composition: C_4H_{10} (gas)

Quantity: 1.0 l (1 atm.)

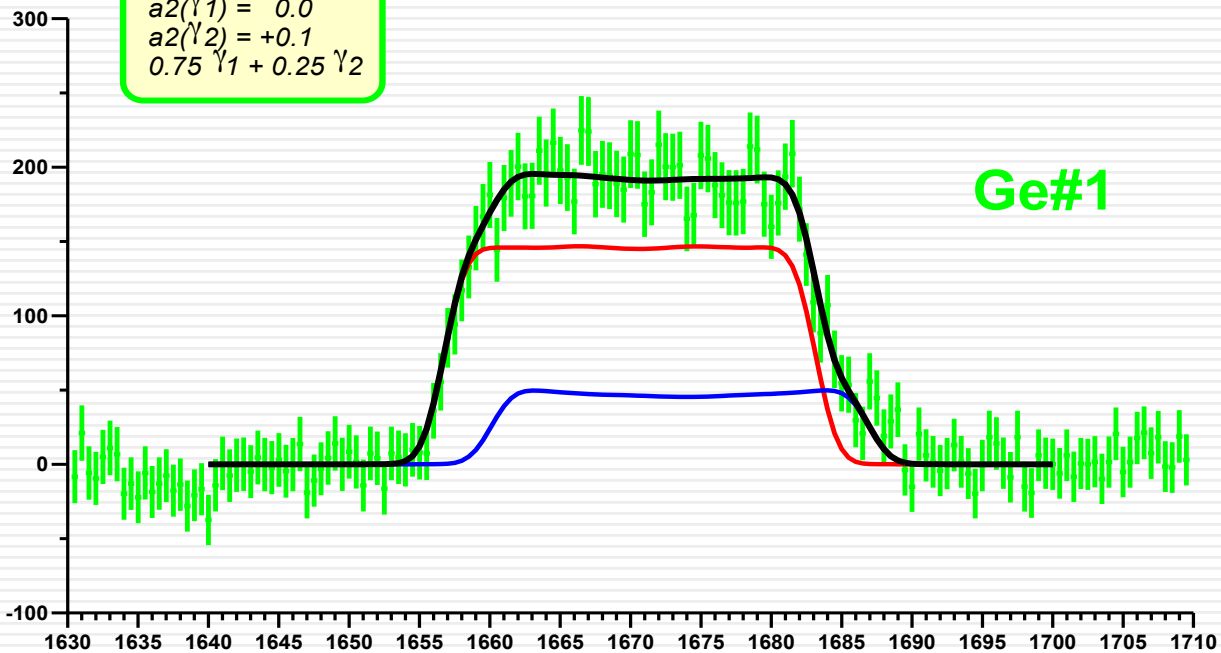
^{12}B experimental spectra



Comparison of fitted spectral lines and doublets with optimal values of parameters vs experimental results

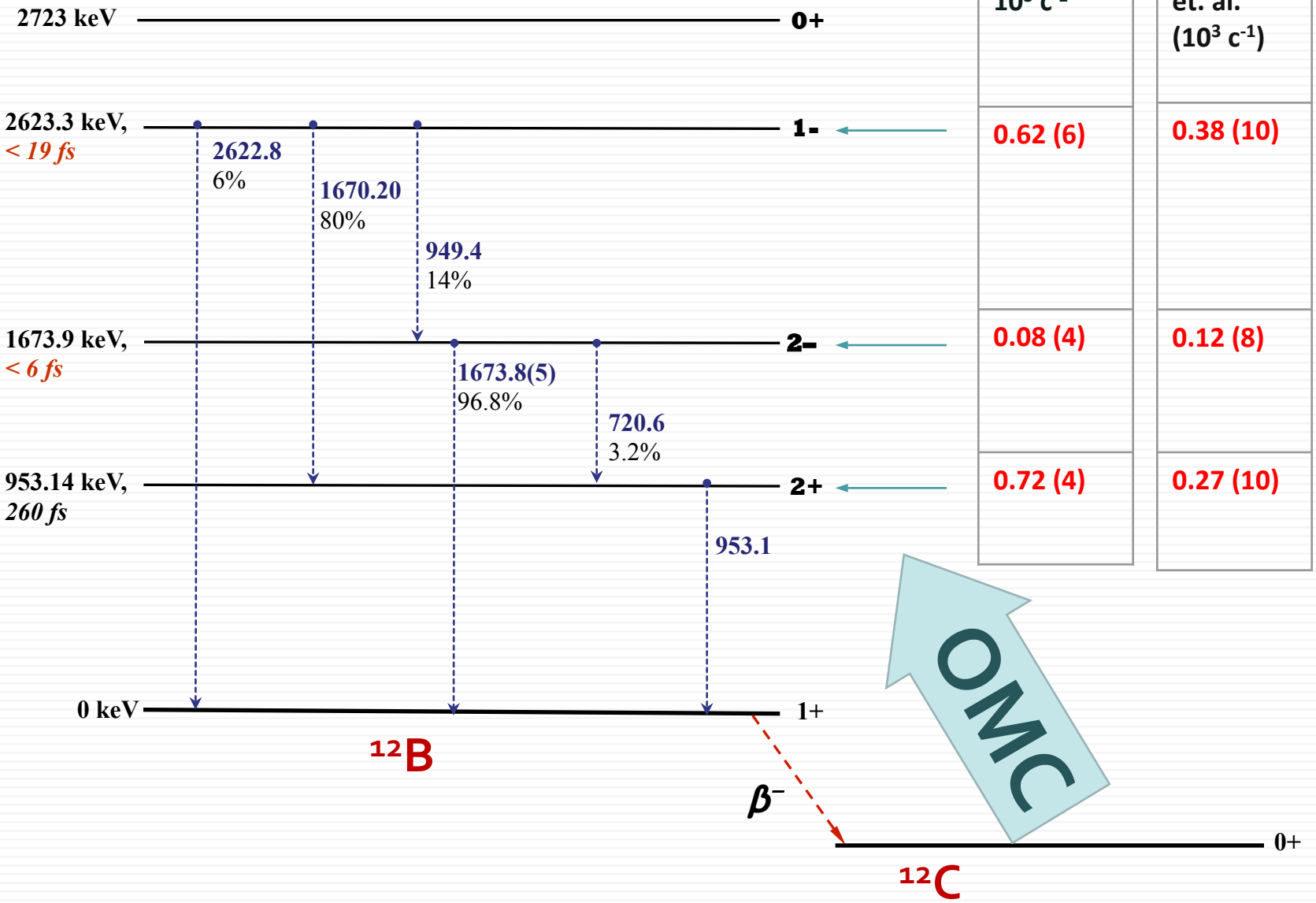


$\chi^2/n = 0.69$
$dE1 = 2.6$ keV
$dE2 = 0.2$ keV
$a2(\gamma 1) = 0.0$
$a2(\gamma 2) = +0.1$
$0.75\ \gamma 1 + 0.25\ \gamma 2$



Eγ, keV τ, fs	Eγ, keV (after fit) τ, fs (after fit)
1667.54 τ < 70 *fs*	1670.14(20) τ < 19 *fs*
1673.52 τ < 50 *fs*	1673.8(5) τ < 6 *fs*

Level scheme of the ^{12}B bound states



Λ_{par}, 10^3 c^{-1}	Roesch et. al. (10^3 c^{-1})	Giffon et. al. (10^3 c^{-1})
0.62 (6)	0.38 (10)	1.08 (13)
0.08 (4)	0.12 (8)	0.06 (20)
0.72 (4)	0.27 (10)	0

Conclusion and further plans:

- **OMC** can provide important information about the high-q component of the weak nuclear response, i.e. it is relevant for the neutrinoless double beta decay (here in particular the 2- and 1+ states)

- **^{48}Ti, ^{76}Se, ^{106}Cd and ^{12}C (and ^{82}Kr, ^{150}Sm) have been studied in μ-capture by our group**
  A. Total capture rates were measured;
  B. Normalization to μX-rays (total intensity of the μX(Z)-ray *K-series* gives the number of muons stopped exactly in the target with specific Z), identification were done (as a result – by product – muxrays.jinr.ru for around 75 elements)
  C. Partial capture rates were extracted, as for ^{12}B the correct values of energies and levels life-times were found by fit with χ^2 function;
  D. Yield of ^{76}Se and ^{106}Cd from β-decay have been measured.

- **All results about μ-capture experiments with different isotopes (^{48}Ti, ^{76}Se, ^{106}Cd, ^{150}Sm and ^{82}Kr) are in preparation.**

- **Collaborative work with J.Suhonen (compare results more precisely)**
- **Join to H. Ejiri's group for further μ-capture experiments.**

Thank you for your attention!