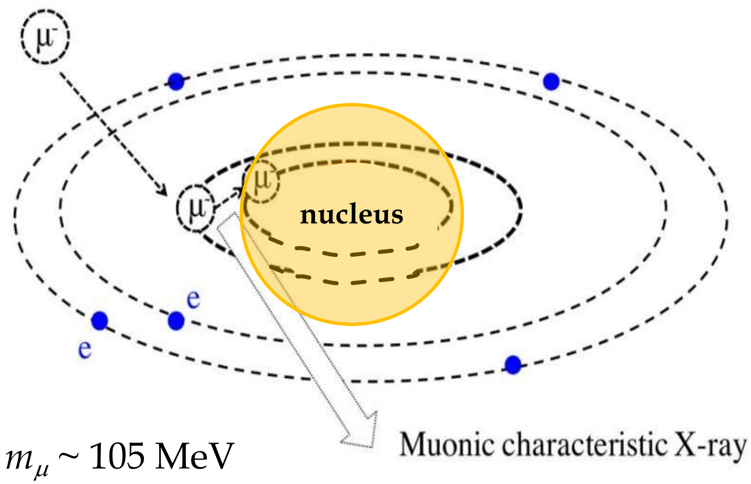
General OMC4DBD collaboration meeting, 22 – 24th May 2023

Ordinary Muon Capture (OMC)



$$\mu^- \rightarrow e^- + \nu_e + \nu_\mu \qquad \tau_{dec} = 2.2\mu s$$

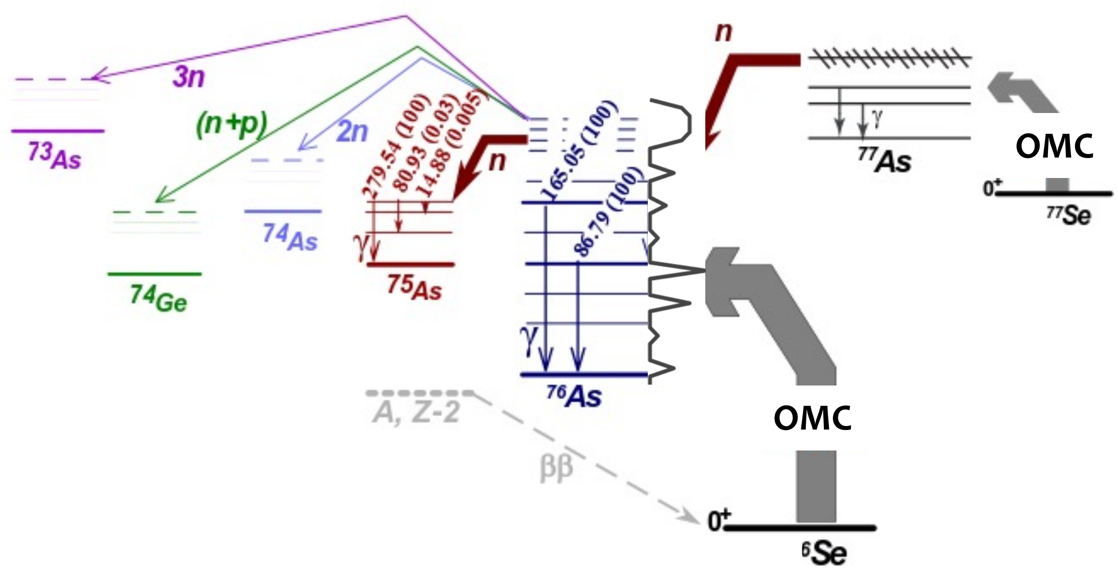
$$(A, Z) + \mu^- \rightarrow (A, Z\text{-}1)^* + \nu_\mu$$

$$\rightarrow (A, Z\text{-}1) + \gamma$$

$$\rightarrow (A\text{-}1, Z\text{-}1) + \gamma + n$$

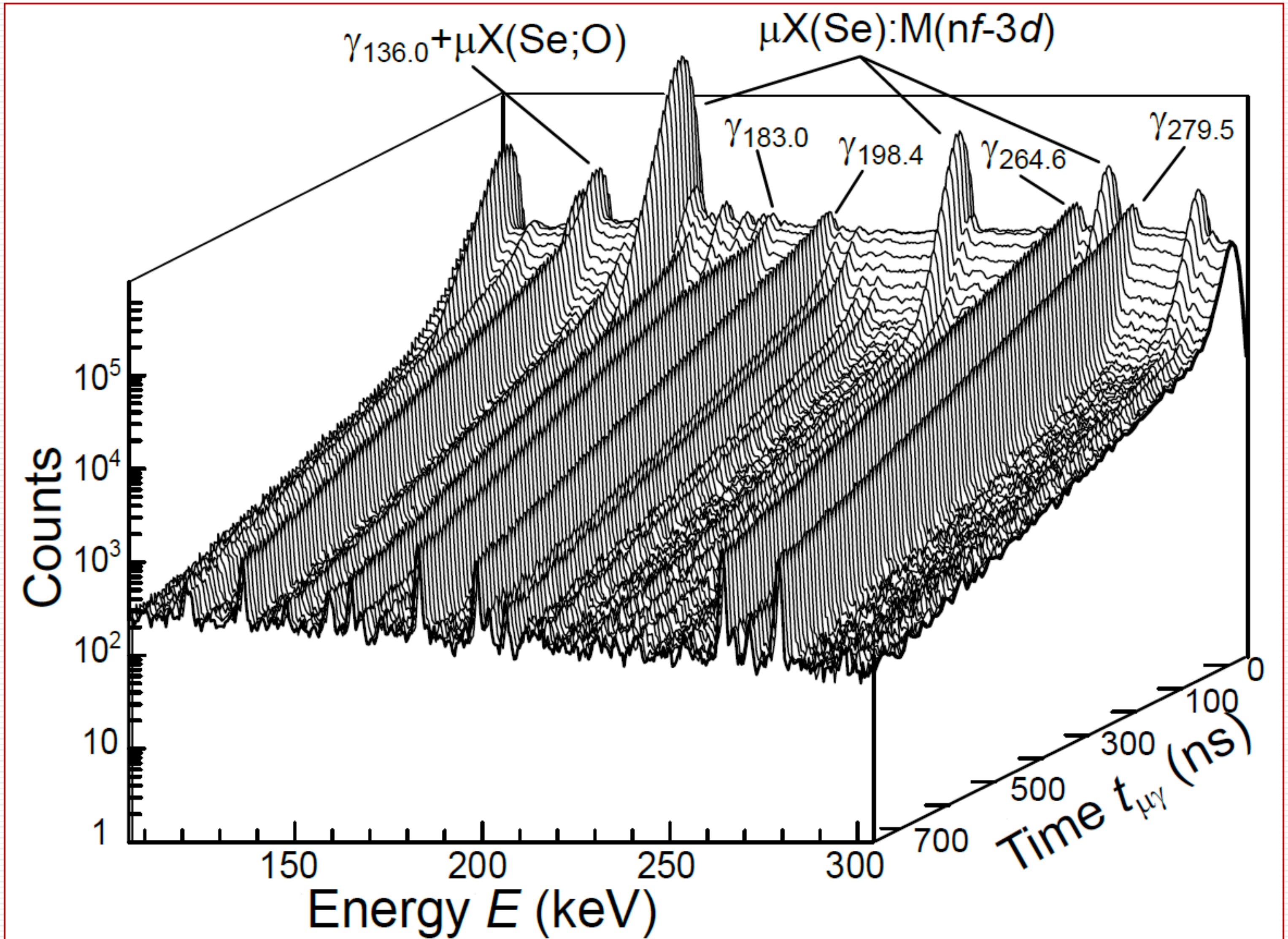
$$\rightarrow (A\text{-}2, Z\text{-}1) + \gamma + 2n$$

$$\rightarrow (A\text{-}1, Z\text{-}2) + \gamma + n + p$$



- Muonic cascades (our by-product)
- High momentum transfer (up to 100 MeV) -- High-lying states population
- **Right leg testing for DBD calculations (coupling to charge exchange reactions)**
- g_a – suppression probing -- via capture rates calculations (+ other methods)
- Angular correlations in OMC (Doppler shape of γ-lines)

(E, t) distribution of the correlated events following μ-capture in ^{76}Se target



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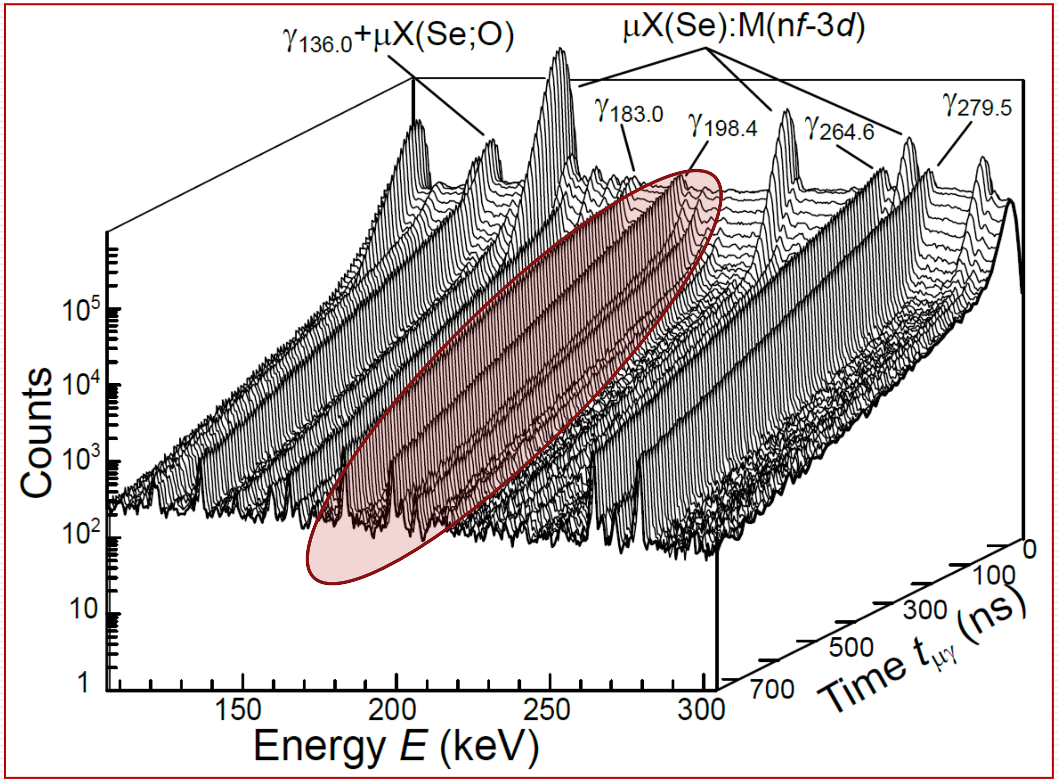
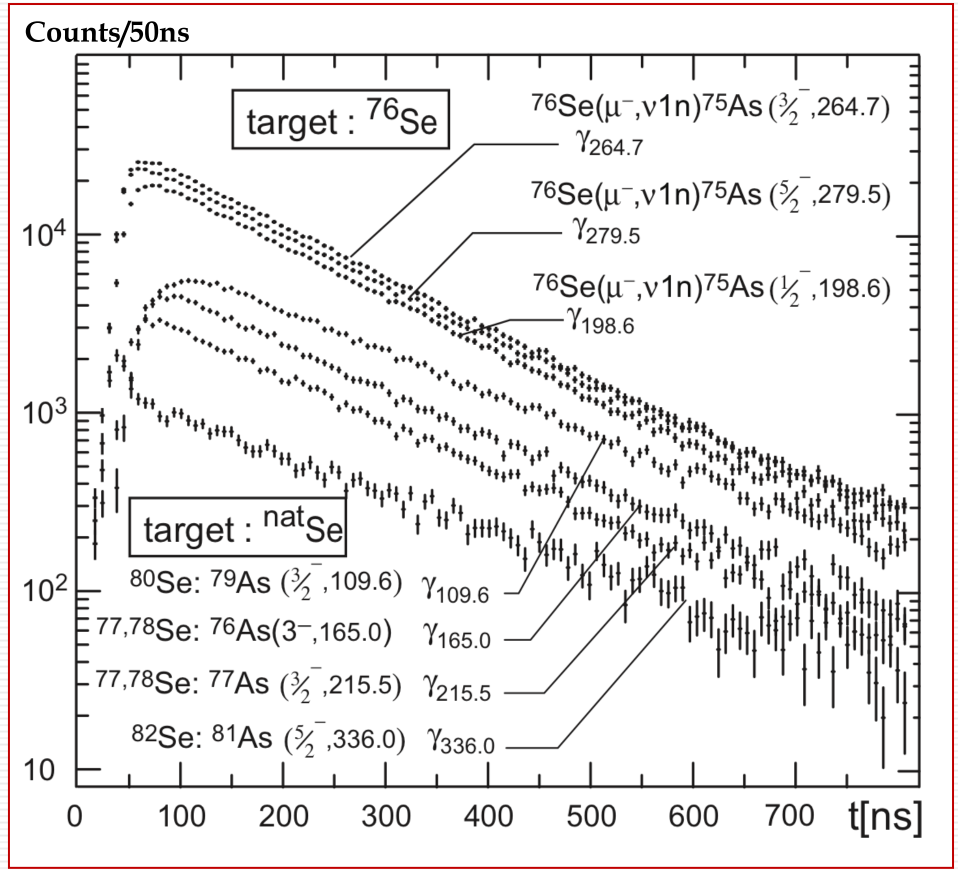
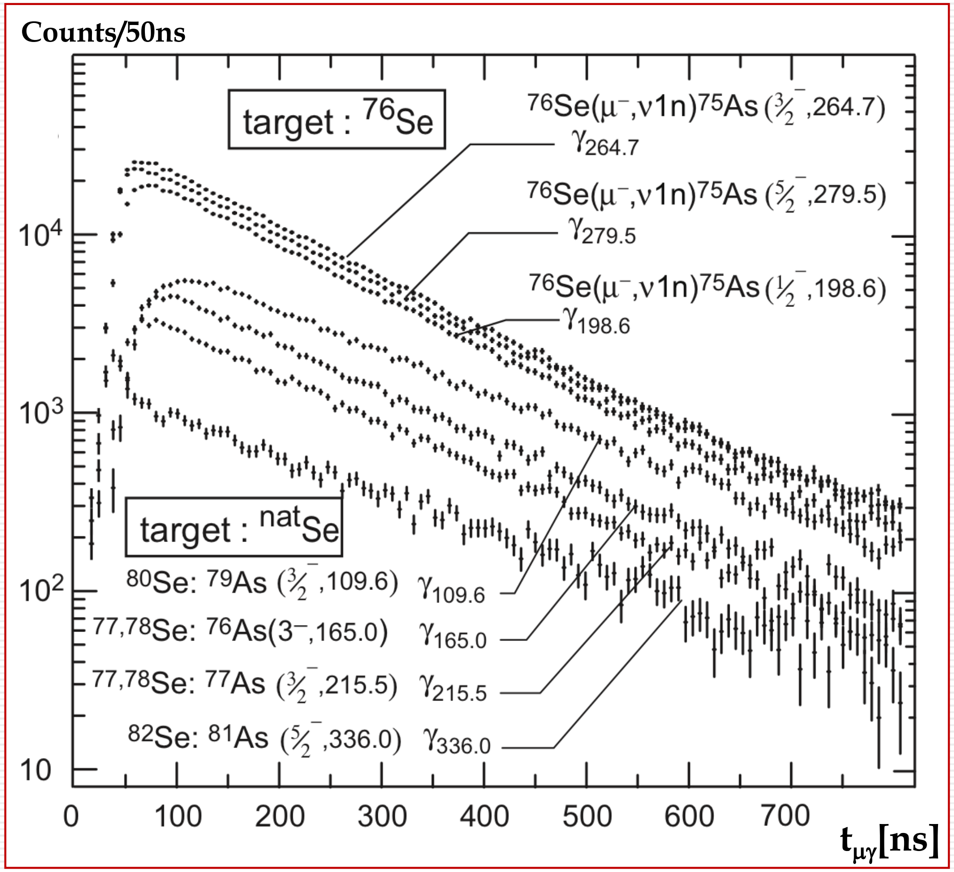




Time evolution of the intensities of the strongest γ-lines following OMC in ^{76}Se (top) и ^{nat}Se (bottom).

Total μ-capture rates in different isotopes of Se



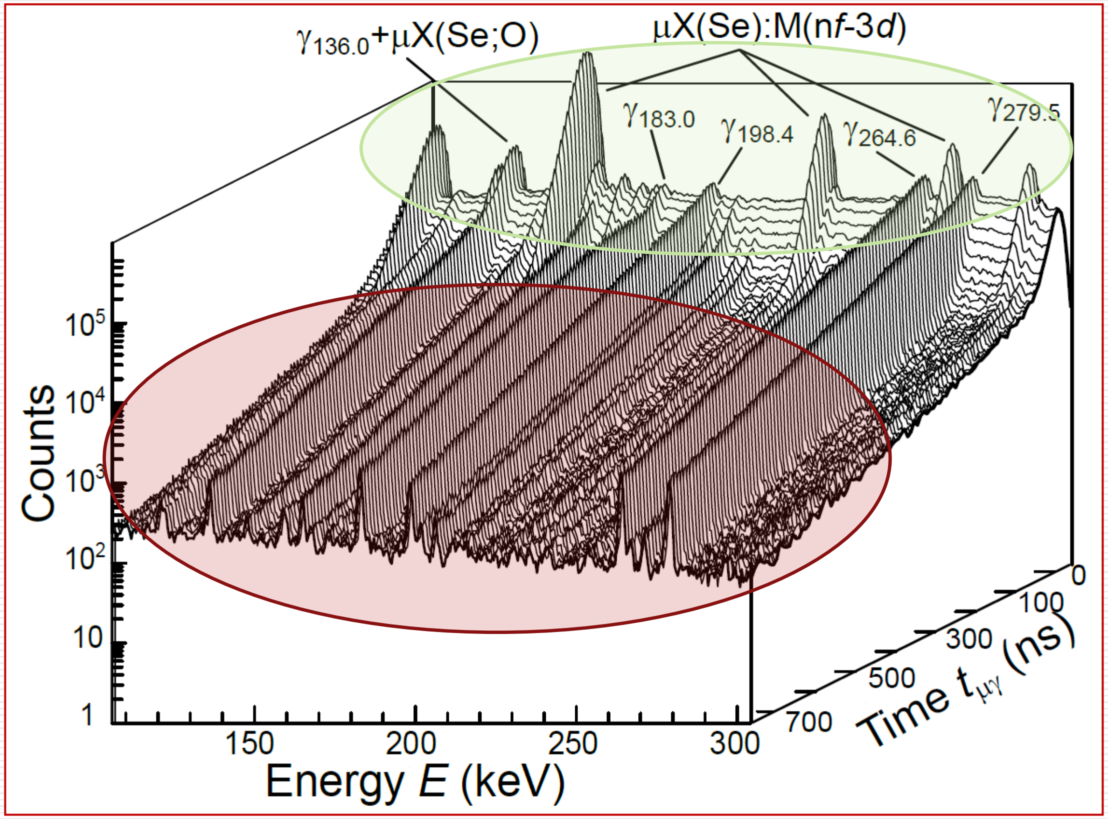
Time evolution of the intensities of the strongest γ-lines following OMC in ^{76}Se (top) и ^{nat}Se (bottom) (A.

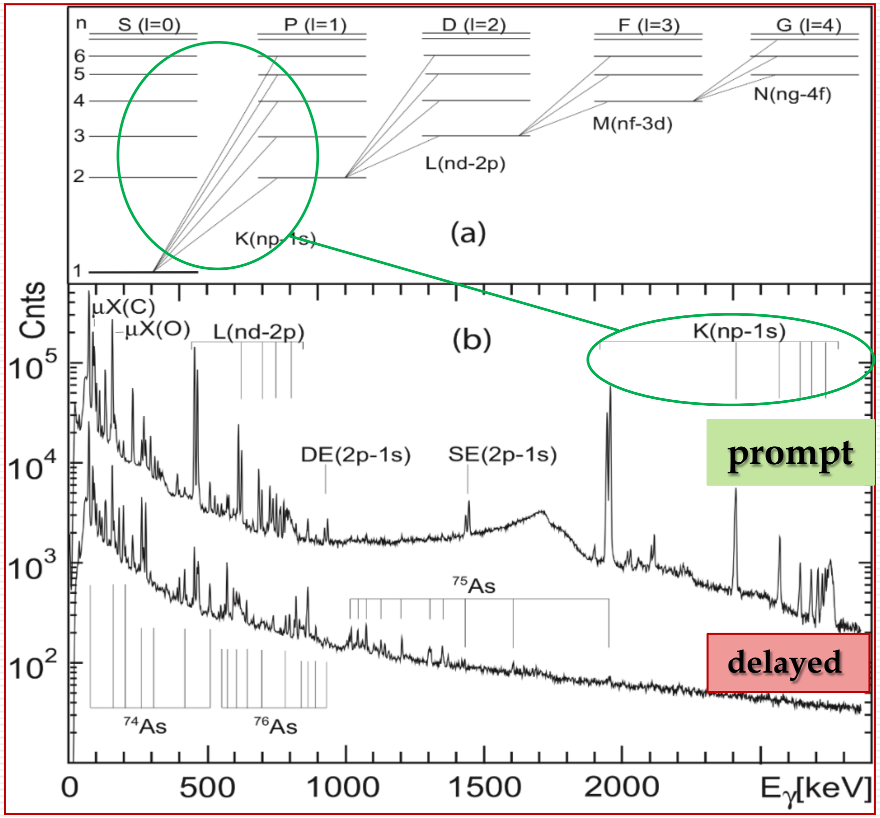
Target	Daugh. Nuclei	E_i^{γ} [keV]	τ [ns]	$\langle\lambda_{cap}\rangle$ [10^6 c^{-1}]
^{76}Se (A	^{75}As	198.6	148.4(7)	
		279.5	148.6(5)	
			<148.48(10)>	**6.300(4)**
^{nat}Se (A				
$^{(77)}$Se	^{76}As	164.7	**163.5(20)**	**5.68(7)**
$^{(78)}$Se	^{77}As	215.5	**165.9(19)**	**5.59(7)**
$^{(80)}$Se	^{79}As	109.7	**185.5(27)**	**4.96(7)**
$^{(82)}$Se	^{81}As	336.0	**208.2(68)**	**4.37(14)**
^{nat}Se (B			**163.5(10)**	**5.681(37)**

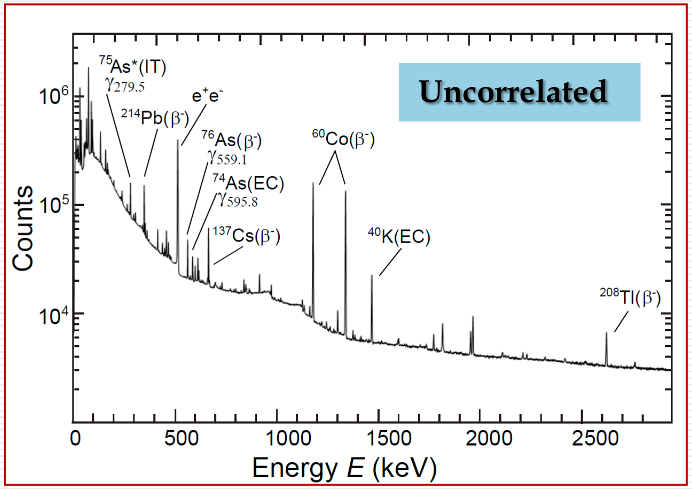
A) D. Zinatulina, V. Egorov et al. // Phys. Rev. C 99(2019)024327

B) T. Suzuki, D.F. Measday // Phys. Rev. C 35(1987)2212

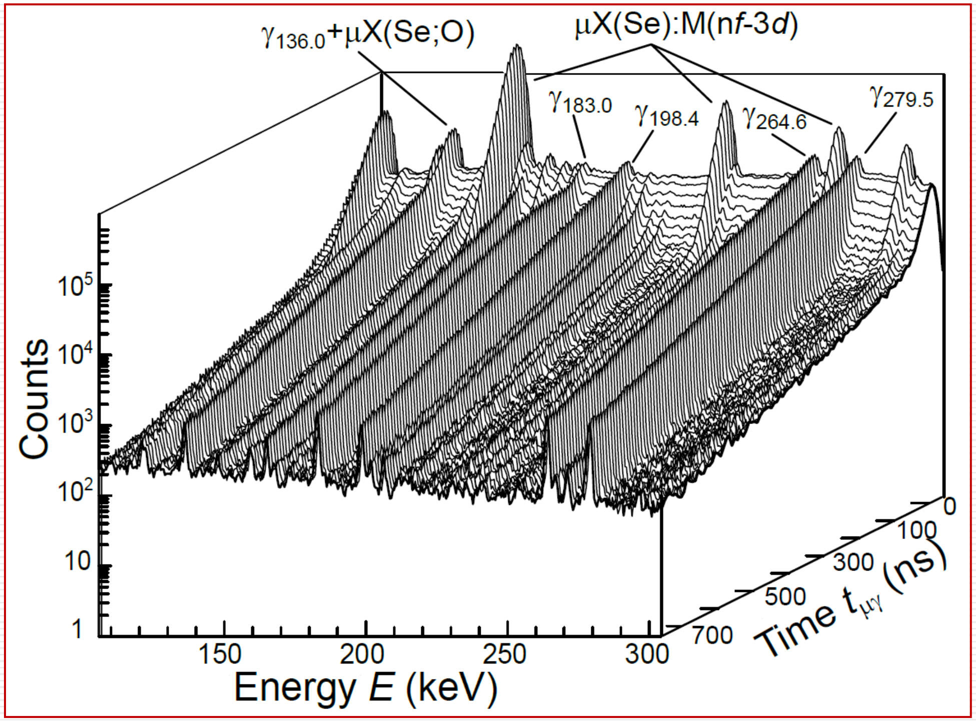
Energy spectra in OMC

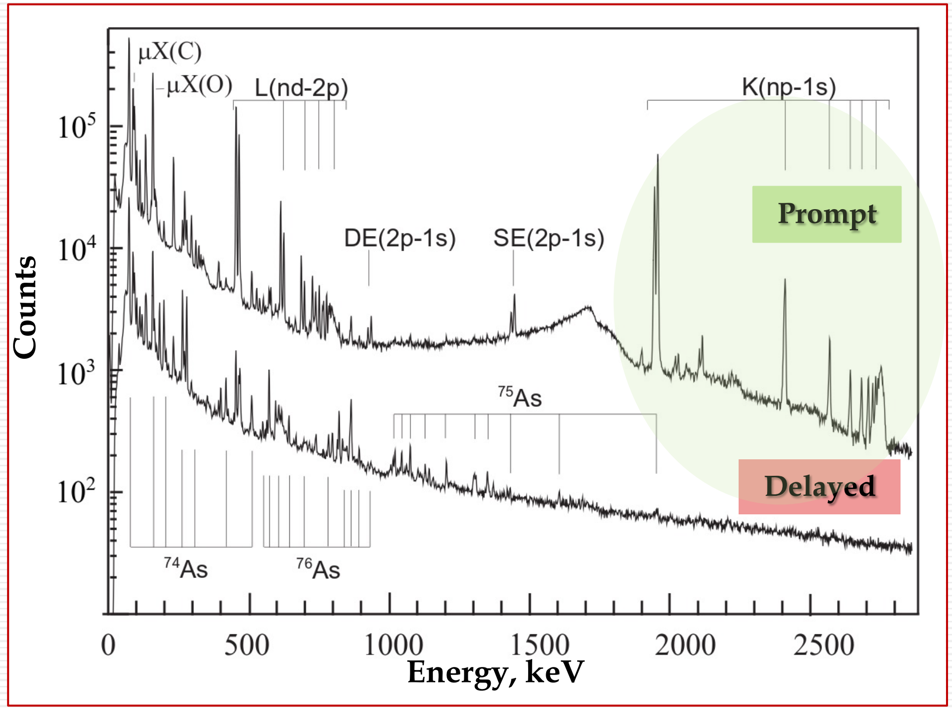




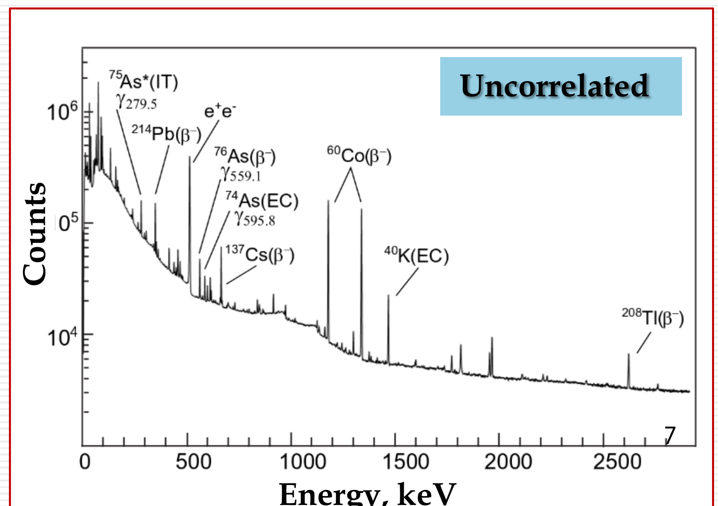


Energy spectra in OMC

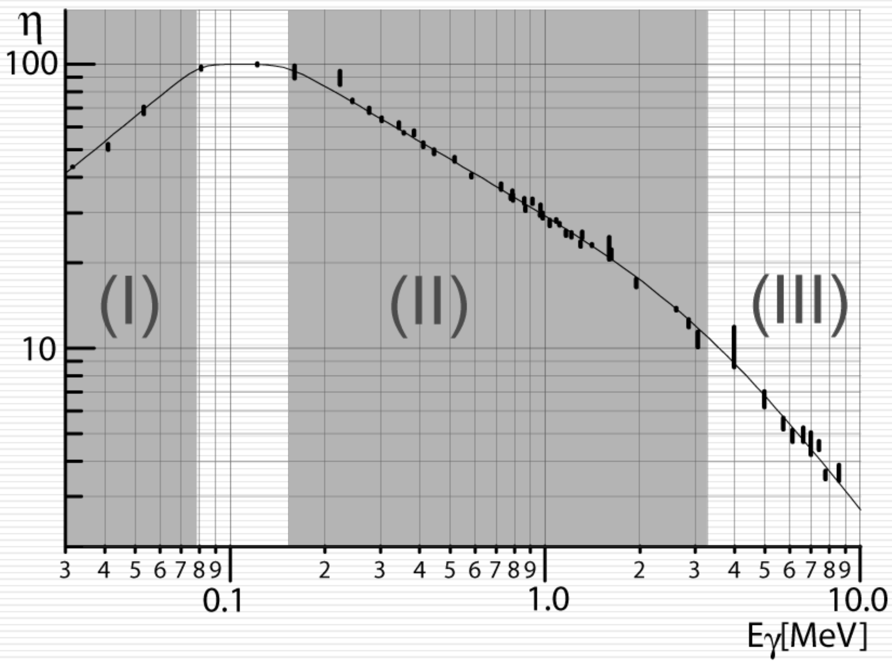


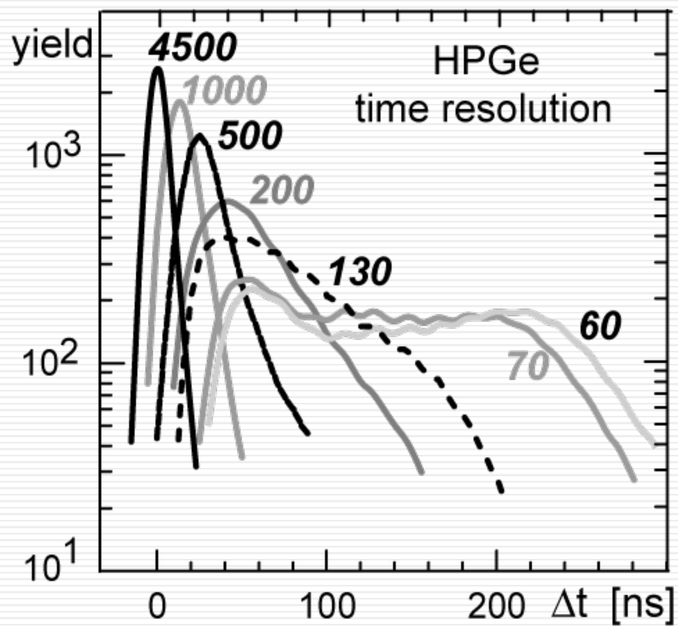


- $t_{\mu\gamma}$ = 0-50 ns: μX-cascades (**Prompt** spectra) – normalization, identification, composition of the surrounded materials and target itself;
- $t_{\mu\gamma}$ = 50-700 ns: γ-radiation following OMC (**Delayed** spectra) – partial μ-capture rates – strength function of the right side;
- T >> $t_{\mu\gamma}$: background radiation (**Uncorrelated** spectra) – calibration of the det-s, identification, yields of short-lived RI during exposure



Detector efficiencies and timing

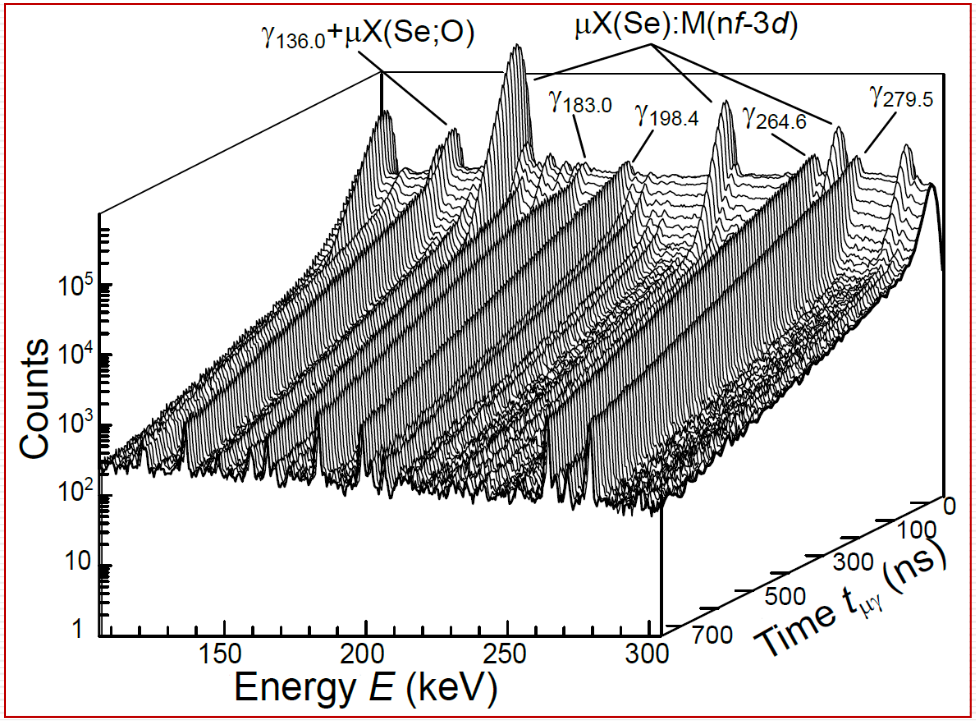


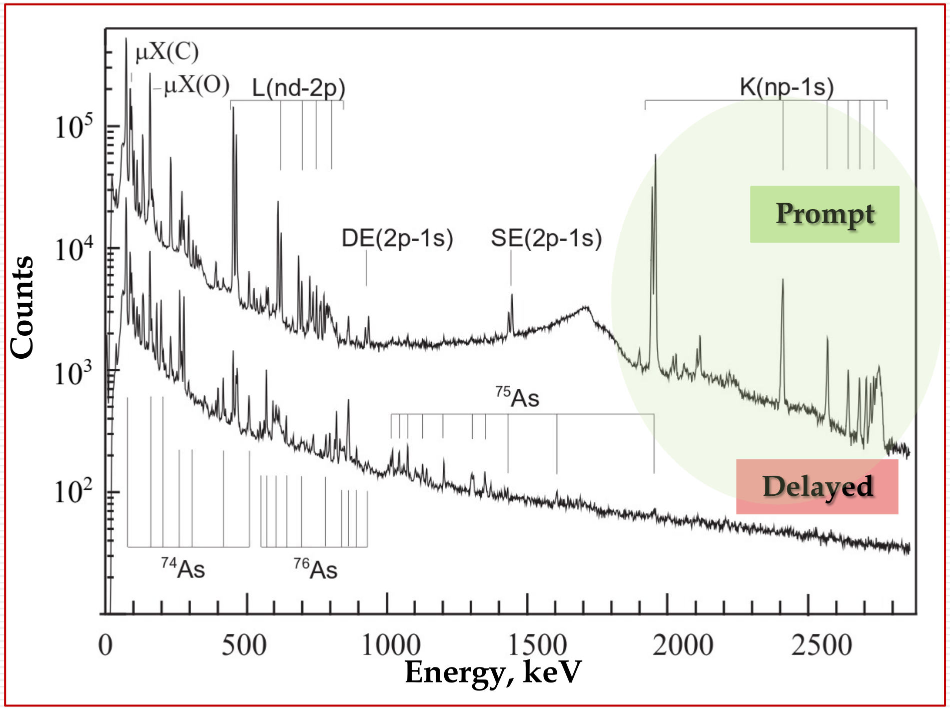


high γ's from
^{35}Cl(n,γ), ^{56}Fe(n,γ),^{28}Si(n,γ)
and
μX-rays from Au, Cd, Sm

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

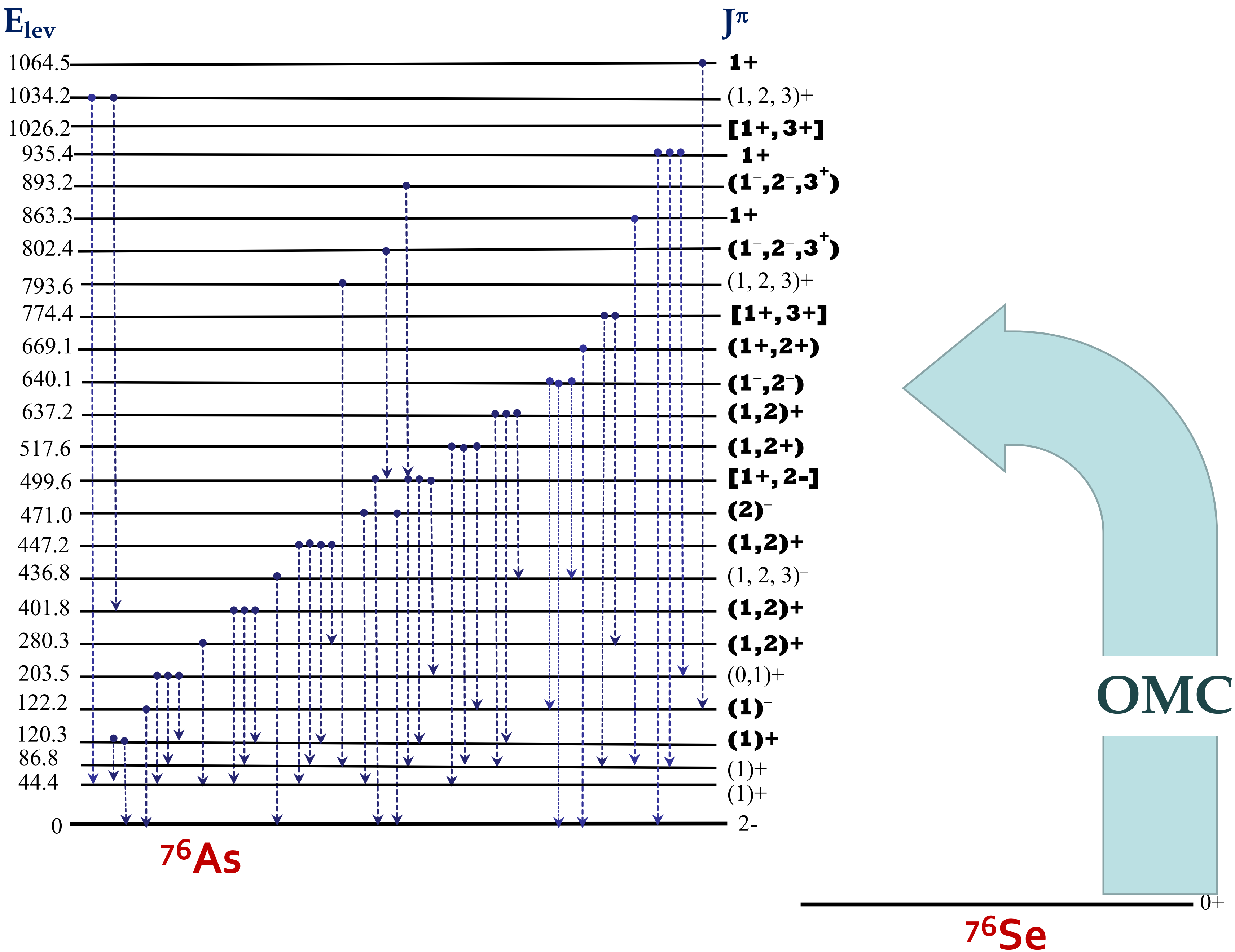
What do we need for the extraction partial caprates for OMC?



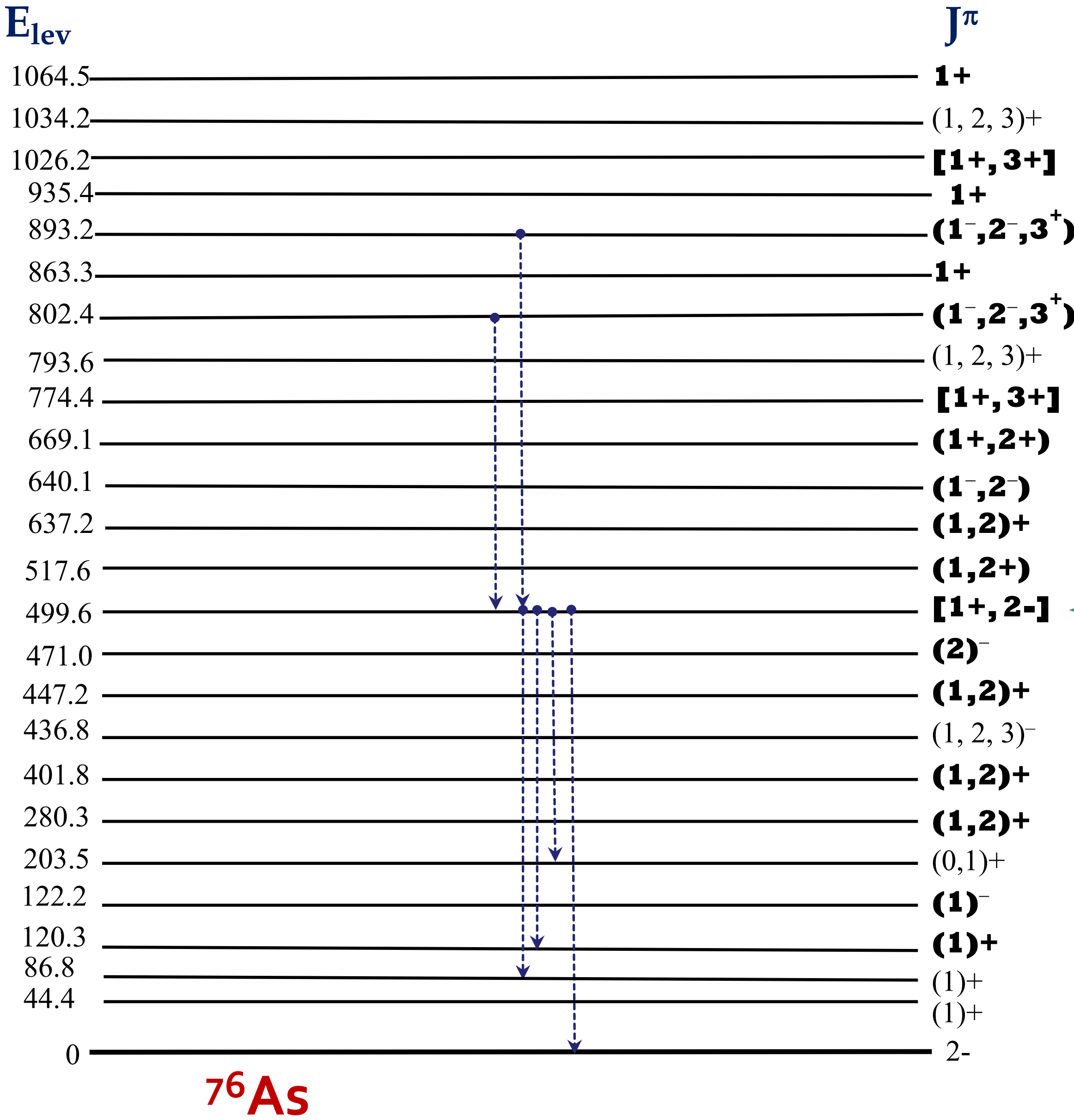


- Cascade of the muonic X-rays
- Efficiency
- Total capture rates
- Good identification of the gammas
- Time window for the **delayed** spectra

Partial μ-capture probabilities to ^{76}As



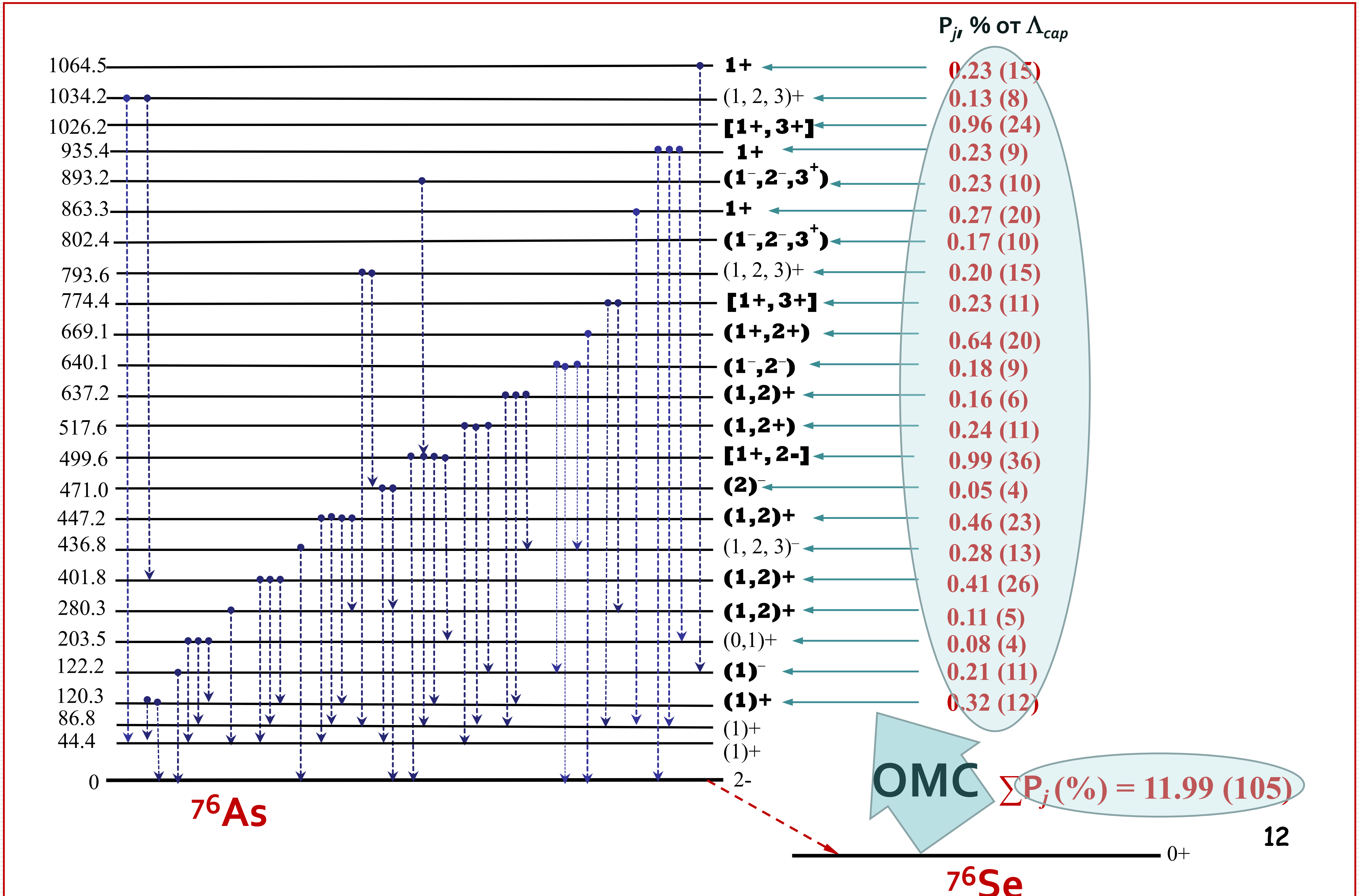
Partial μ-capture probabilities to ^{76}As



$$Y_j^{\mu} = \frac{\sum I_{i\downarrow}^{\gamma} - \sum I_i^{\gamma\downarrow}}{\varepsilon \sum_n I(K_n)}$$

$$P_j^{\mu}[\%] = \frac{\lambda_{part}}{\lambda_{cap}} \cdot 100\% = \frac{Y_j^{\mu} \lambda_{tot}}{\lambda_{cap}} \cdot 100\%$$

Partial μ-capture probabilities to ^{76}As



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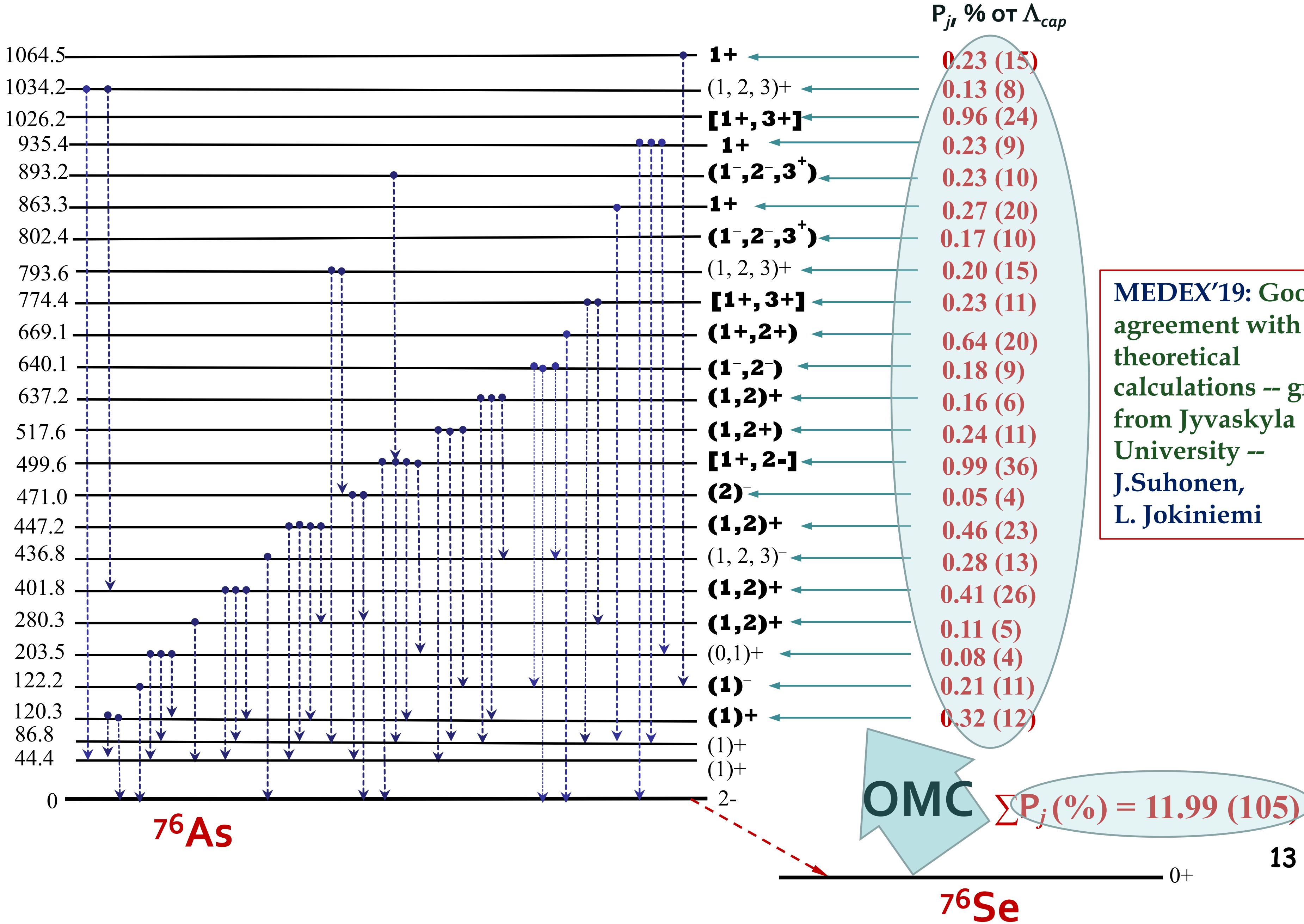
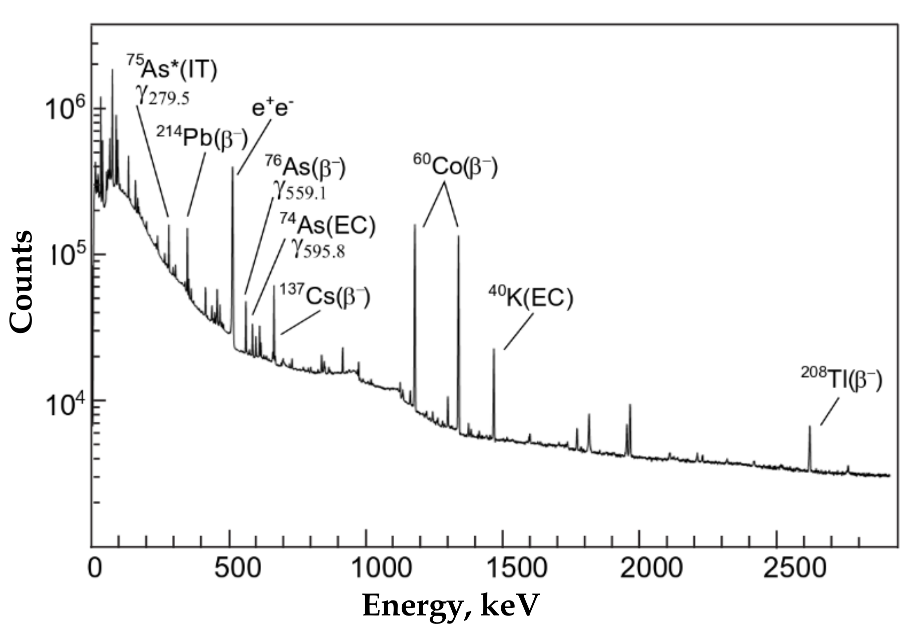


MEDEX'19: Good agreement with theoretical calculations -- group from Jyvaskyla University -- J.Suhonen, L. Jokiniemi

Results measured with U-spectra in ^{76}Se

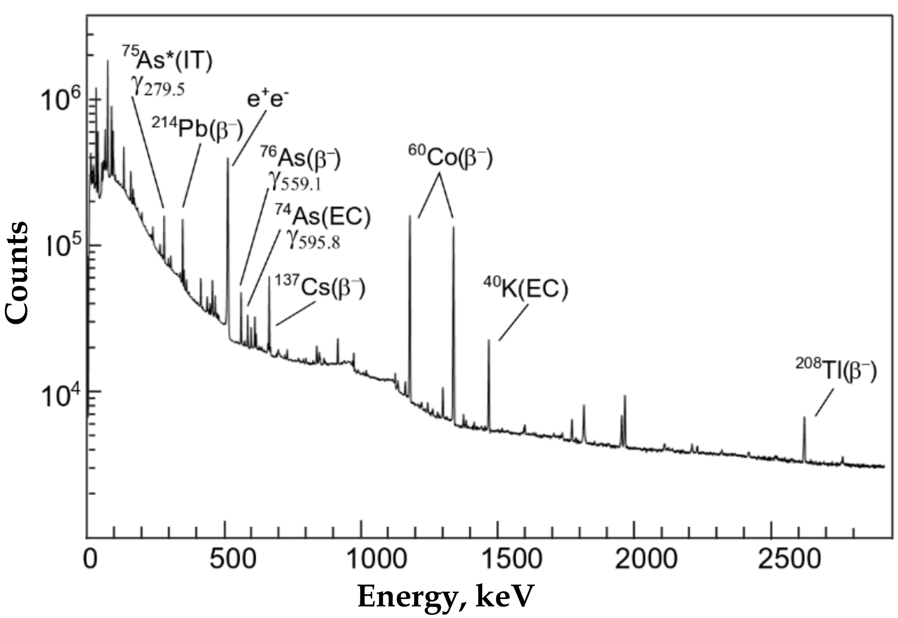


Isotope	Type of decay	$T_{1/2}$	Λ_{cap} (xn yp) [10^6 c^{-1}]	P_{cap} [%]
^{76}As	β^-	26.3 h	1.45(11)	13.65(255)
^{75m}As	IT	17.6 μs	1.80(31)	6.5(11)
^{75}As	stable		Not measured	
^{74}As	β^-, EC	17.8 d	1.1(2)	17.5(32)
^{73}As	EC	80.3 d	Not measured	
^{72}As	β^+	26 h	0.15(3)	2.4(5)
^{71}As	β^+	65.3 h	0.061(18)	0.96(28)
^{75m}Ge	IT	48 s	0.047(13)	0.75(21)
^{75}Ge	β^-	82.8 min	0.054(2)	0.86(3)
^{71m}Ge	IT	20 μs	0.020(3)	0.32(5)
^{74}Ga	β^-	8.1 min	0.026(6)	0.40(9)
^{72}Ga	β^-	14.1 h	0.026(7)	0.40(11)
				$\sum$=43.7(43)

Background radiation (**Uncorrelated** spectra) –

- calibration of the det-s,
- identification,
- yields of short-lived RI during exposure

Results measured with U-spectra in ^{76}Se



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Background radiation (**Uncorrelated** spectra) –

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- yields of short-lived RI during exposure

Back Slides

Ordinary muon capture studies for the matrix elements in $\beta\beta$ decay

D. Zinatulina,[1] V. Brudanin,[1] V. Egorov,[1] C. Petitjean,[2] M. Shirchenko,[1] J. Suhonen,[3] and I. Yutlandov[1]

[1] *Joint Institute for Nuclear Research, 141980 Dubna, Russia*
[2] *Paul Scherrer Institute, 5232 Villigen, Switzerland*
[3] *Department of Physics, University of Jyväskylä, PO Box 35, FIN-40351 Jyväskylä, Finland*

(Dated: October 16, 2018)

Precise measurement of γ-rays following ordinary (non-radiative) capture of negative muons by natural Se, Kr, Cd and Sm, as well as isotopically enriched ^{48}Ti, ^{76}Se, ^{82}Kr, ^{106}Cd and ^{150}Sm targets was performed by means of HPGe detectors. Energy and time distributions were investigated and total life time of negative muon in different isotopes was deduced. Detailed analysis of γ-lines intensity allows to extract relative yield of several daughter nuclei and partial rates of (μ,ν) capture to numerous excited levels of the ^{48}Sc, ^{76}As, ^{82}Br, ^{106}Ag and ^{150}Tc isotopes which are considered to be virtual states of an intermediate odd-odd nucleus in 2β-decay of ^{48}Ca, ^{76}Ge, ^{82}Se, ^{106}Cd and ^{150}Nd, respectively. These rates are important as an experimental input for the theoretical calculation of the nuclear matrix elements of 2β-decay.

PACS numbers: 23.40.-s, 23.40.Hc, 27.40.+z, 27.50.+e, 27.60.+j, 27.70.+q

I. INTRODUCTION

At the moment the neutrinoless $\beta\beta$ ($0\nu\beta\beta$) decay of atomic nuclei is the only practical means of accessing the Majorana nature of the neutrino. In order to occur the decay requires the violation of lepton-number conservation and non-zero neutrino mass. Due to the importance of the related beyond-the-standard-model physics it is of interest to study the nuclei involved by both experimental and theoretical means. Large experimental collaborations have been established in order to measure the $0\nu\beta\beta$ half-lives in the presently running and future underground experiments. The connection between the (possibly) measured half-lives and the fundamental observables, like the electron neutrino mass, is provided by the nuclear matrix elements (NMEs) [1].

Nuclear models aimed at the description of the NMEs of $0\nu\beta\beta$ decays have traditionally been tested in connection with the two-neutrino $\beta\beta$ ($2\nu\beta\beta$) decays [1, 2] and β decays [3]. In [4] it was proposed that the ordinary muon capture (OMC) could be used for this purpose, as well. The $2\nu\beta\beta$ and β decays are low-momentum exchange processes ($q \sim$ few MeV), whereas both $0\nu\beta\beta$ and OMC are high-momentum exchange processes ($q \sim 100$ MeV). In this way the $0\nu\beta\beta$ and OMC are similar processes and possess similar features: they are able to excite high-lying nuclear states with multipolarities J^π higher than $J^\pi = 1^+$. The $0\nu\beta\beta$ decay proceeds between the 0^+ ground states of parent and daughter even-even nuclei through virtual states of the intermediate odd-odd nucleus. These same virtual states can be accessed by the OMC from either the daughter nucleus (electron-emitting

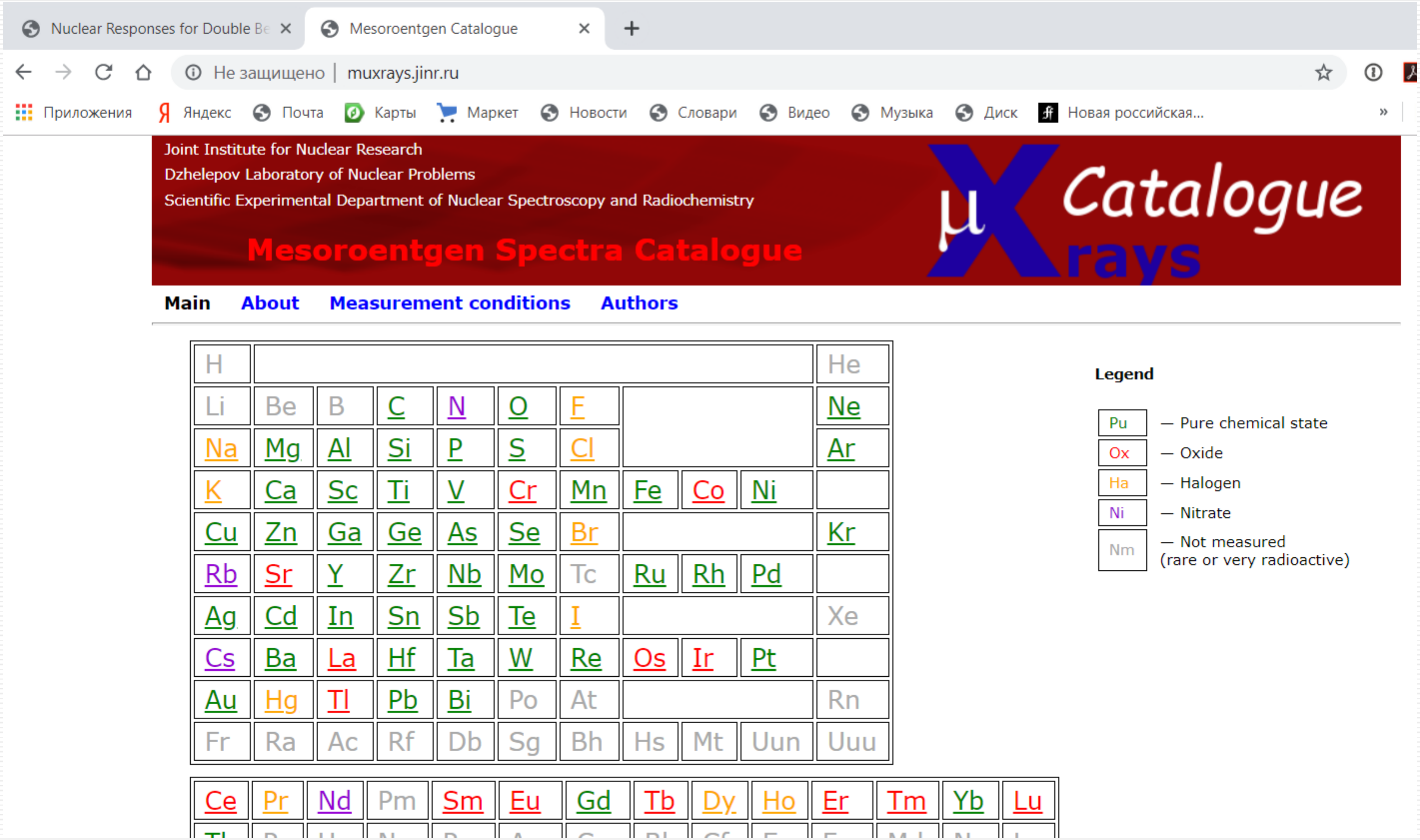
the processes stemming, e.g., from the neutrino potential generated by the propagator of the virtual Majorana neutrino in the $0\nu\beta\beta$ decay [5]. Despite this difference the OMC can effectively probe the nuclear wave functions relevant for the $0\nu\beta\beta$ decay, as shown for the light nuclei in the shell-model framework in [6].

For the medium-heavy and heavy open-shell nuclei the shell-model framework is unfeasible due to computational limitations. For these nuclei the model framework of the quasiparticle random-phase approximation (QRPA [7] is a good choice. In particular, the proton-neutron version of the QRPA (pnQRPA) can access the virtual intermediate states of the $0\nu\beta\beta$ decays [1]. A particular problem pestering the pnQRPA approach is the uncertainty associated with one of its key parameters, the particle-particle interaction strength $g_{\rm pp}$. This parameter is used to introduce a phenomenological overall scaling of the particle-particle part of proton-neutron interaction [8]. It is not clear how this scaling should be done for the $0\nu\beta\beta$ decays since there is no experimental data for transitions from either the $0\nu\beta\beta$ mother or daughter nuclei to the multipole $J^\pi \neq 1^+, 2^-$ intermediate states (the 1^+ and partly 2^- states can be probed by the (p,n) and (n,p) charge-exchange reactions [9]). In this case the only viable method to access this "$g_{\rm pp}$ problem" is the OMC [10]. By using experimental data on OMC to individual intermediate J^π states one can access the value of $g_{\rm pp}$ for each multipole separately and at the same time study the consistency of these values by comparison with the measured OMC rates for a wider palette of nuclear states.

In order to give an experimental input to 2β NME cal-

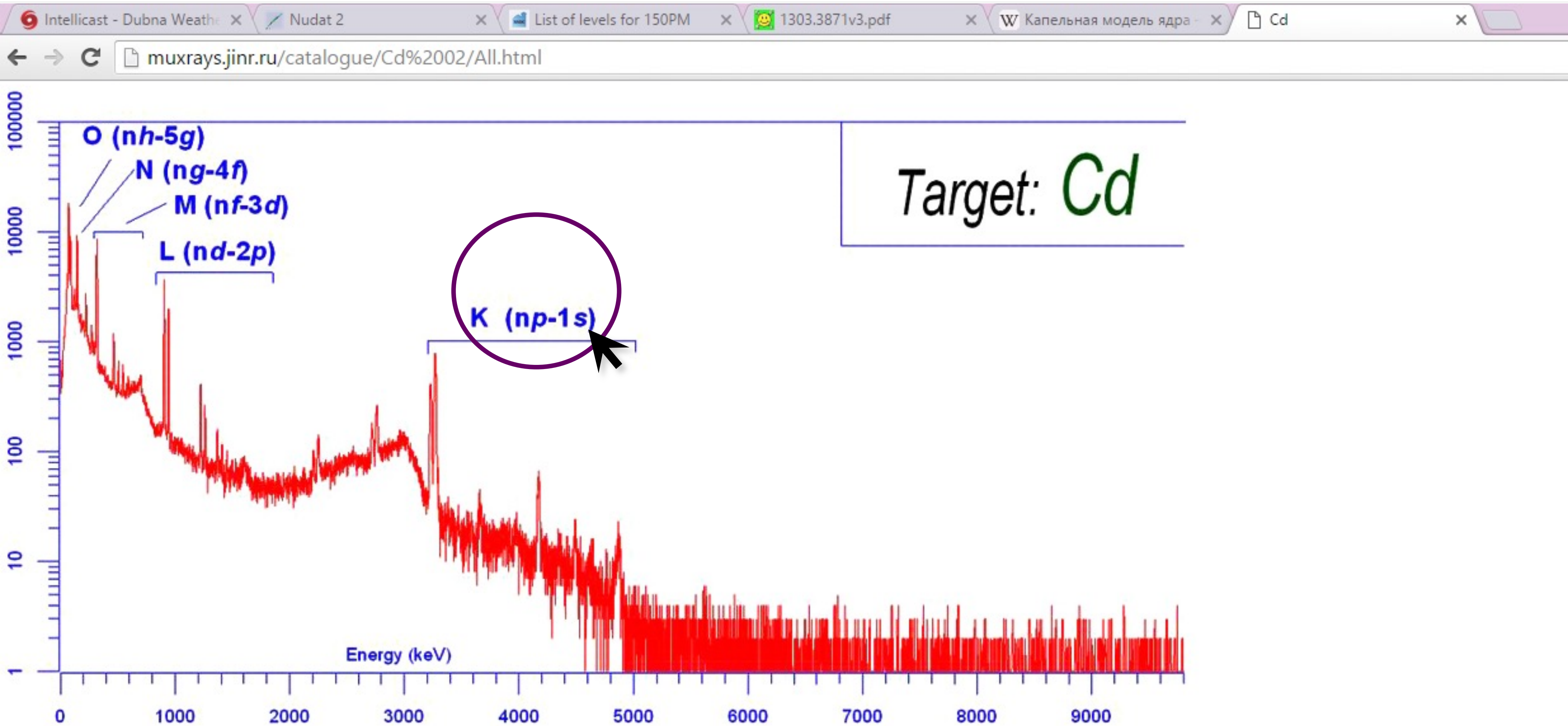
arXiv: 1803.10960v2

URL: http://muxrays.jinr.ru/



Измерено более 75 химических элементов, PSI, μE1 и μE4

Total μX-ray spectrum of Cd



Мишень: ^{48}Ti

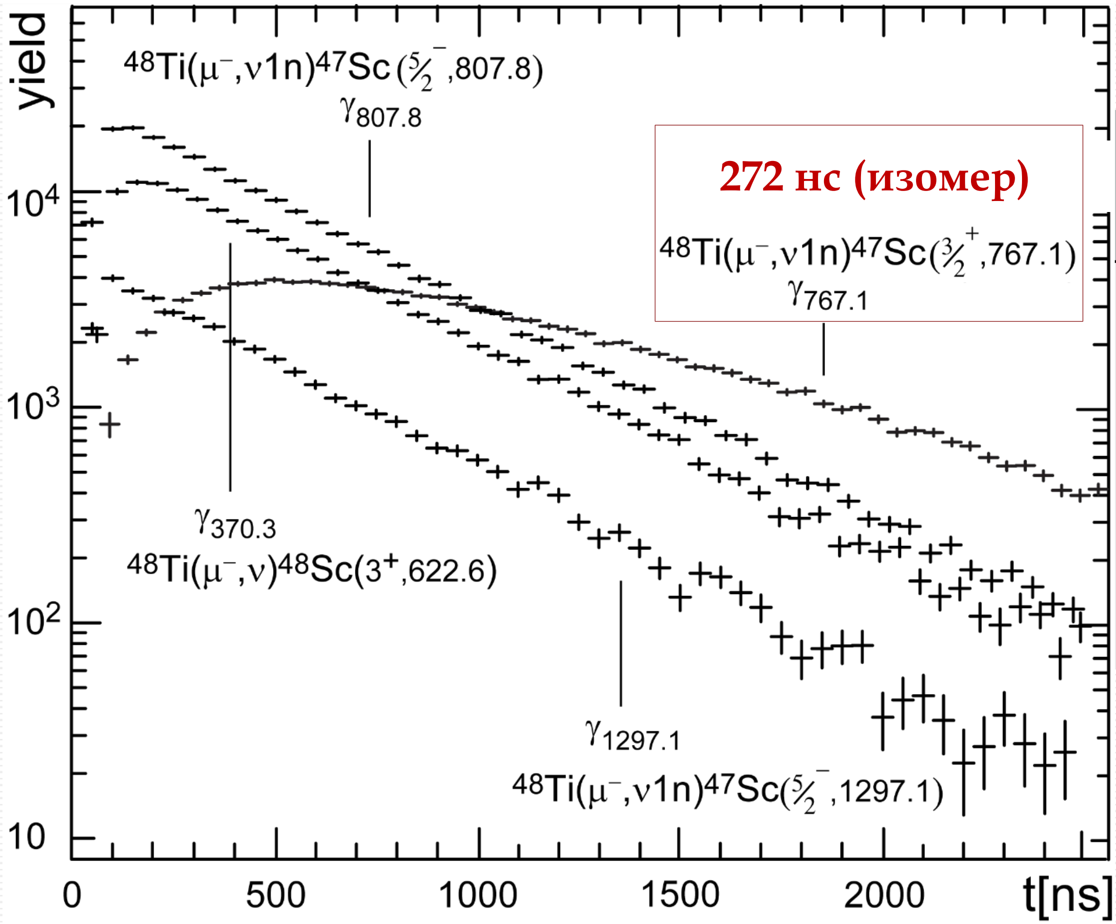
Год исследования: 2002

Обогащение: 95.8%

Состав: TiO_2 порошок

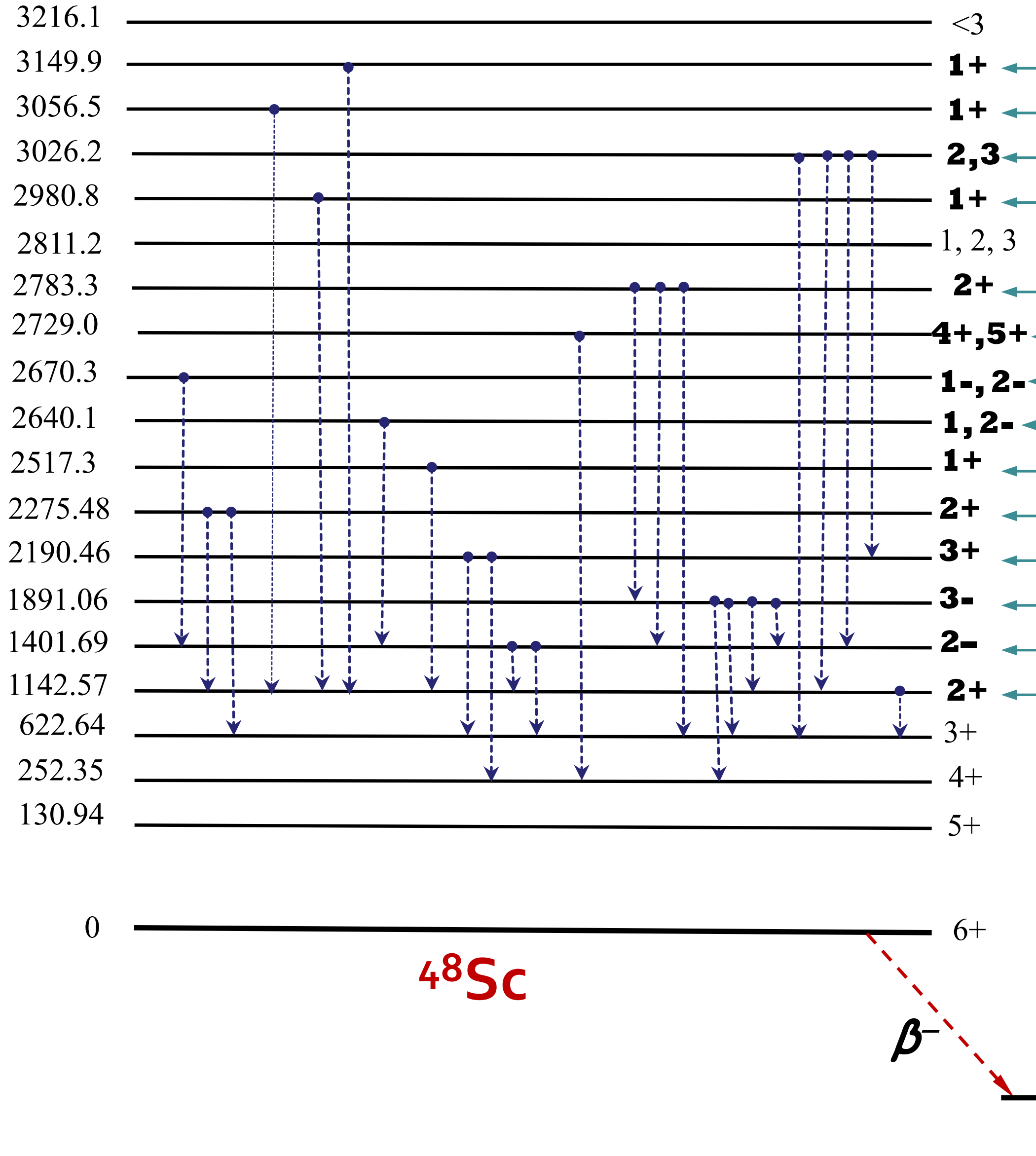
Количество: 1.0 г

Полные скорости μ-захвата в ^{48}Ti

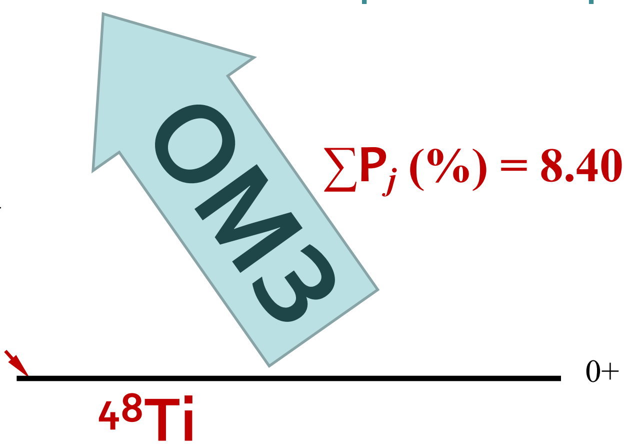


Мишень	Доч. ядро	E_i^γ [кэВ]	τ [нс]	<Λ_{cap}> [10^6 с$^{-1}$]
^{48}Ti	^{48}Sc	370.3	363.8(26)	
	^{47}Sc	807.8	359.7(28)	
		1297.1	358.0(40)	
	^{47m}Sc	767.1	358(10) [+272 нс]	
			<361.1(24)>	2.323(15)

Парциальные вероятности μ-захвата ^{48}Sc



Уровень	J^π	P_j, % от Λ_{cap}	P_j, *относит.*	J.Suhonen et al.
3216.1	<3			
3149.9	1+	0.14 (8)	0.118	0.011
3056.5	1+	0.45 (24)	0.379	0.102
3026.2	2,3	1.175 (717)	0.991	
2980.8	1+	0.53 (29)	0.447	0.128
2811.2	1, 2, 3			
2783.3	2+	0.47 (33)	0.397	
2729.0	4+,5+	0.19 (8)	0.160	
2670.3	1-, 2-	0.19 (6)	0.160	0.080
2640.1	1, 2-	1.056 (328)	0.891	
2517.3	1+	0.52 (23)	0.439	0.050
2275.48	2+	0.71 (42)	0.599	0.195
2190.46	3+	0.55 (32)	0.464	
1891.06	3-	0.11 (6)	0.093	
1401.69	2-	1.136 (707)	0.959	1.000
1142.57	2+	1.185 (677)	1.000	
622.64	3+			
252.35	4+			
130.94	5+			
0	6+			



$\sum P_j\,(\%) = 8.40\ (157)$