Proposal for BVR 51

OMC4DBD: ordinary muon capture as a probe of properties of double beta decay processes

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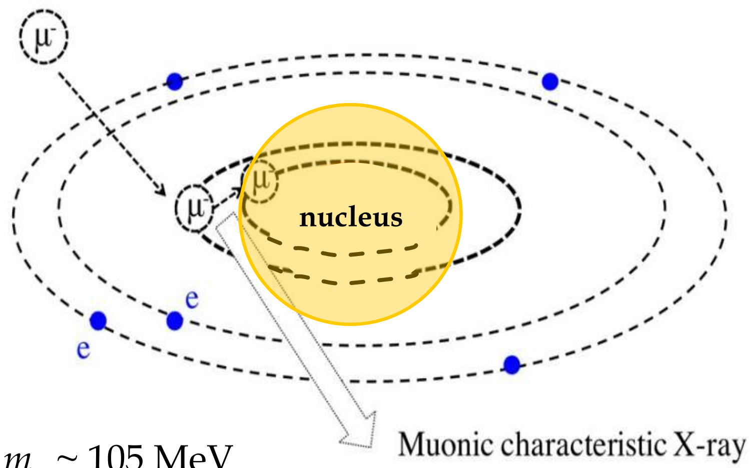
Daniya Zinatulina **Open Users Meeting BV51, 28.02.2020**

Overview:

- **Ordinary muon capture (OMC)**
- **Motivation**
  - Nuclear Matrix Elements (NME) for double beta-decay (DBD) processes;
  - g_A suppression;
  - OMC for astroneutrinos;
- **Targets**
- **Measurement principle**
  - Short history;
  - Experimental method and comparison with theoretical calculations;
  - First results (2019);
  - Proposed measurements (detection system, DAQ, rates);
- **Beam request**
- **Conclusion**

Ordinary Muon Capture (OMC)



$m_\mu \sim 105$ MeV

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

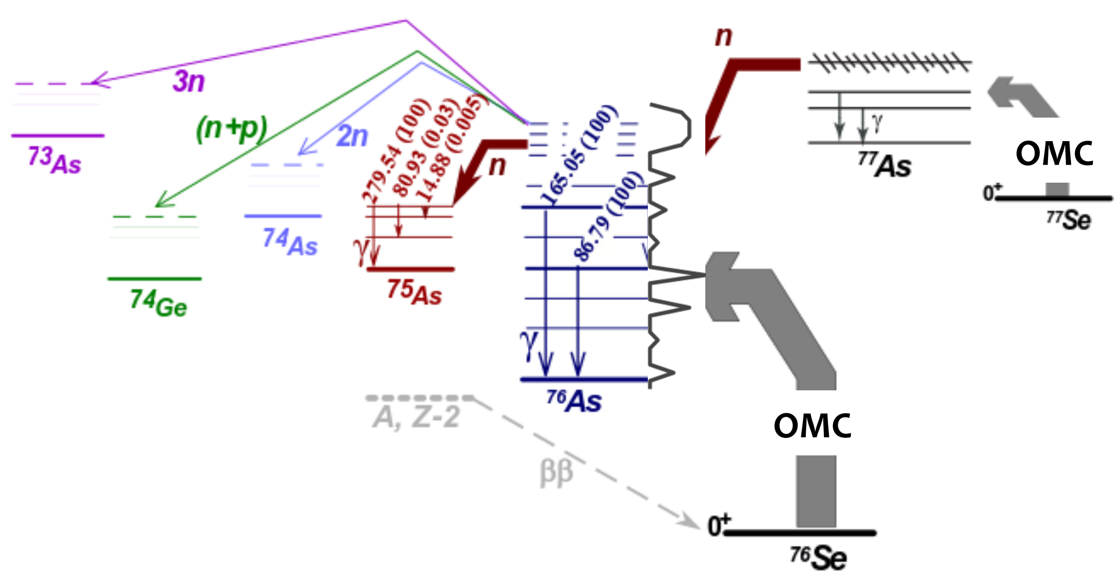
$(A, Z) + \mu^- \rightarrow (A, Z\text{-}1)^* + \nu_\mu$

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

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

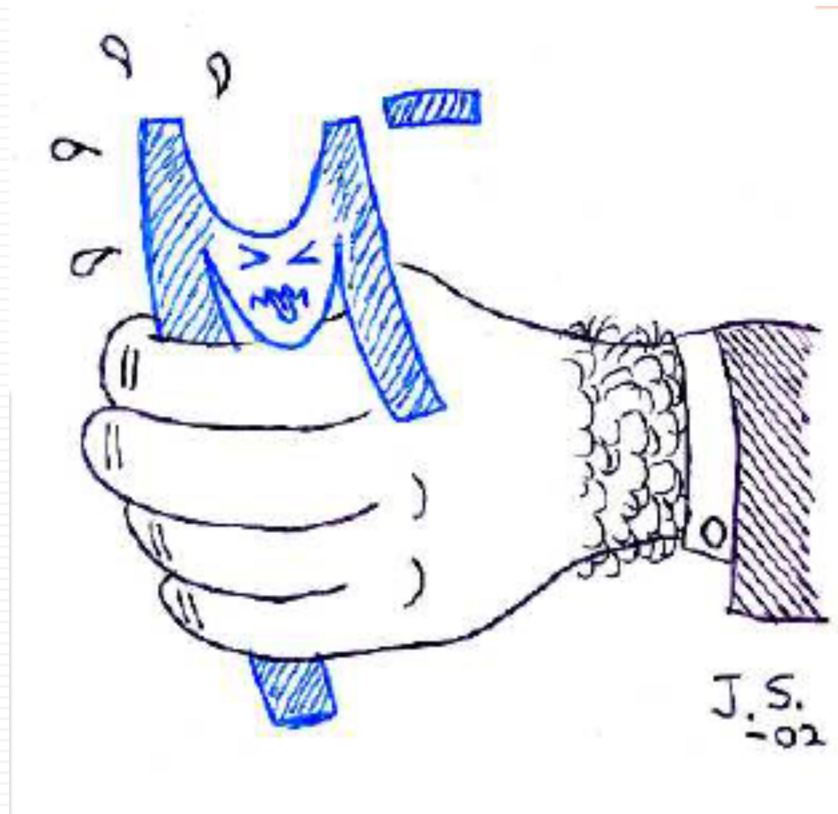
$\rightarrow (A\text{-}2, Z\text{-}1) + \gamma + 2n$

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



- Muonic cascades (muxrays.jinr.ru)
- High momentum transfer (up to 100 MeV) -- High-lying states population
- γ-radiation following OMC in targets
- Yields of short-lived RI during exposure

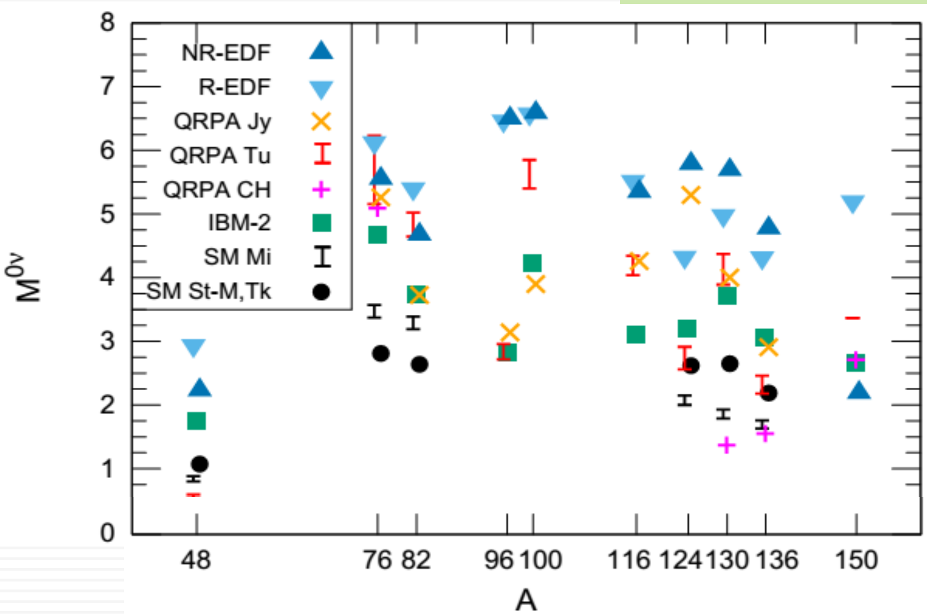
Motivation

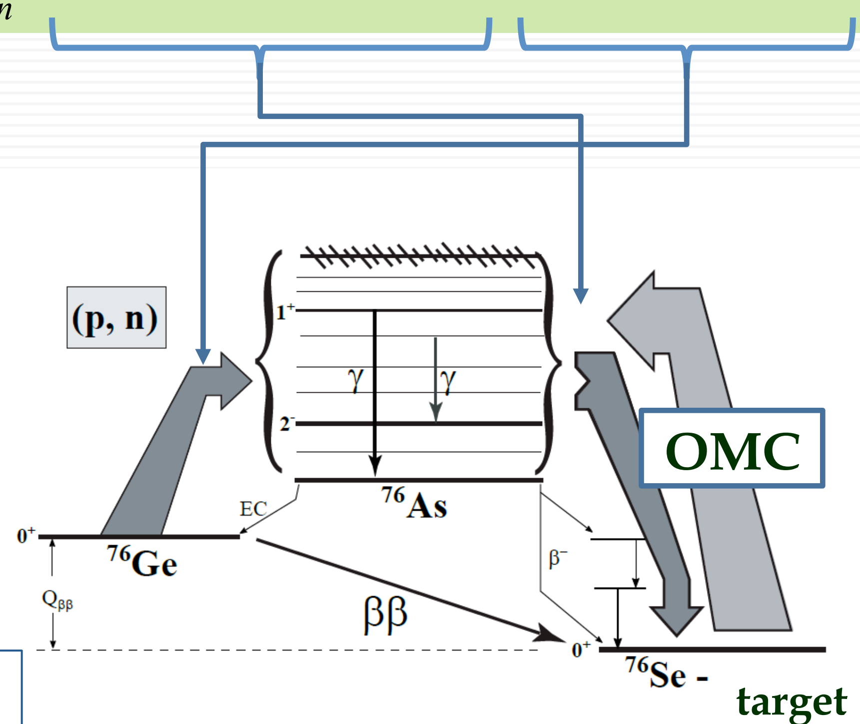


Experimental input for DBD NME calculations

$$\frac{1}{T_{1/2}^{0\nu}} \propto \underbrace{\left|\sum_i U_{ei}^2 m_i\right|^2}_{\langle m_{\beta\beta}\rangle} G^{0\nu} \underbrace{\left|\langle A, Z+2 | S | A, Z\rangle\right|^2}_{M^{0\nu}}$$

$$\langle A, Z+2 | S | A, Z\rangle \propto \sum_n \langle Z+2 | \hat{H} | Z+1, n\rangle \langle Z+1, n | \hat{H} | Z\rangle$$





APPEC-2019, Recommendation 6: *The computation of nuclear matrix elements is challenging and currently is affected by an uncertainty which is typically quantified in a factor of 2-3… An enhanced effort is required and a stronger interactions between the particle physics and nuclear community would be highly beneficial. Dedicated experiments may be required.*

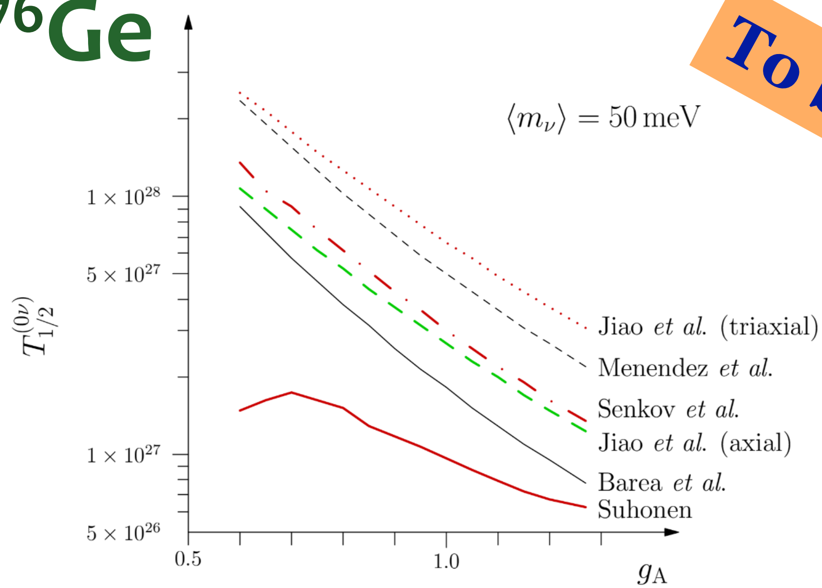
g_A – suppression probing -- via capture rates calculations

To be, or not to be, that is the quenching…

$$|\mathrm{NME}_{0\nu}|^2 \cong \left|M^{0\nu}_{GTGT}\right|^2 = \left(g_{a,0\nu}\right)^4 \left|\Sigma_{J^\pi}\left(\langle 0_f^+|O^{0\nu}_{GTGT}|0_i^+\rangle\right)\right|^2$$

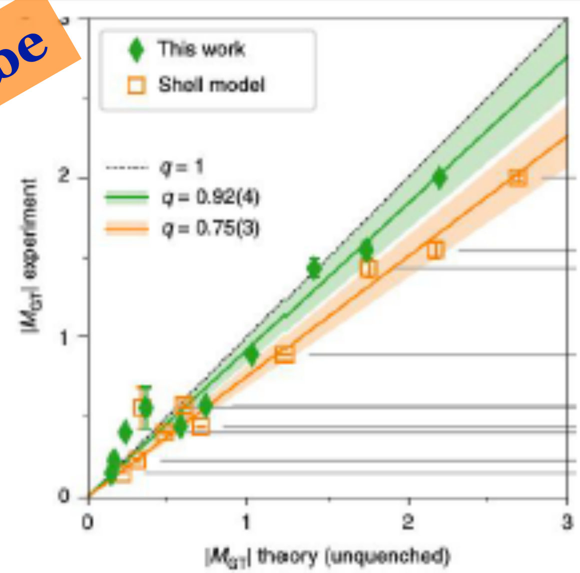
^{76}Ge

To be



Jiao et al.: Phys.Rev. C **96** (2017)054310 (GCM+ISM)
Menendez et al.:Nucl. Phys. A818 (2009) 139 (ISM)
Senkov et al.:Phys. Rev. C **93** (2016) 044334 (ISM)
Barea et al.: Phys.Rev. C **91** (2015)034304 (IBM-2)
Suhonen: Phys.Rev. C **96** (2017)055501 (pnQRPA)

or not to be

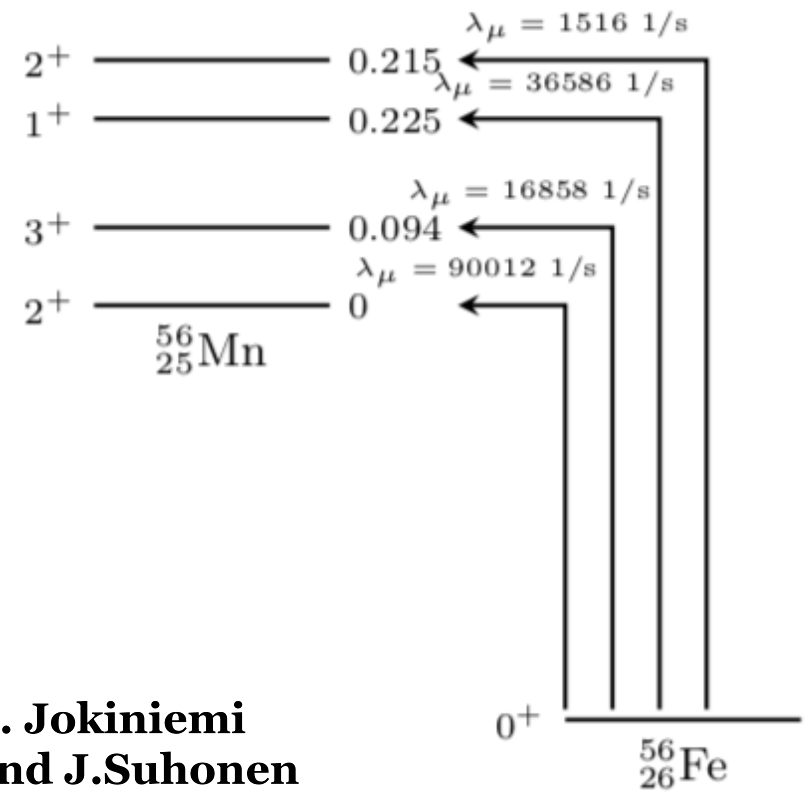


Gysbers et al. Nature Phys. 15 428 (2019)

Ab initio calculations including meson-exchange currents do not need any "quenching"

Testing shell model calculations (^{56}Fe, ^{24}Mg, ^{32}S)

- The level scheme of light nuclei is very well known
- Experiment vs. theory
- Optimization for DBD candidates
- Testing g_A quenching

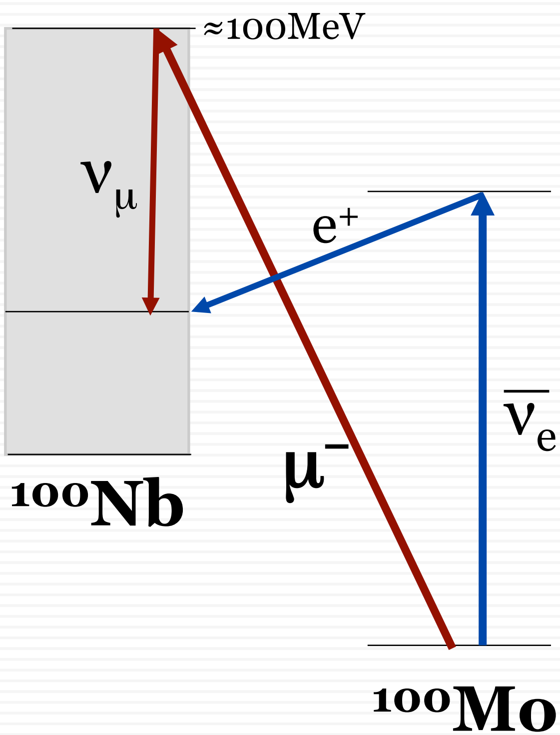


L. Jokiniemi and J.Suhonen

$$\lambda_\mu \approx C(q_i) \sum_{\kappa u} |g_V M_V(\kappa, u) + g_A M_A(\kappa, u) + g_P M_P(\kappa, u)|^2$$

Astrophysics with ^{100}Mo

- Astro neutrino (including solar and supernovae neutrino study) observation provides evidences for neutrino matter oscillation, nuclear fusion reaction in sun and as tools for probing the supernovae (SN) explosion process
- It was proposed to measure SN antineutrinos on ^{100}Mo (MOON) [1, 2]
- OMC in ^{100}Mo will give experimental input for theoretical calculations of this process



^{100}Mo($\bar{\nu}_e$, e^+)^{100}Nb (SN)

^{100}Mo(μ^-, e^+)^{100}Nb (OMC)

[1] H.Ejiri, J.Suhonen, K.Zuber. // Phys. Rep 797 (2019) 1 – 102

[2] H.Ejiri, J.Engel, N. Kudomi // PLB 530 (2002) 27-32

Targets:

- The present project is extended to DBD nuclei in the atomic mass number region between 70 to 140;

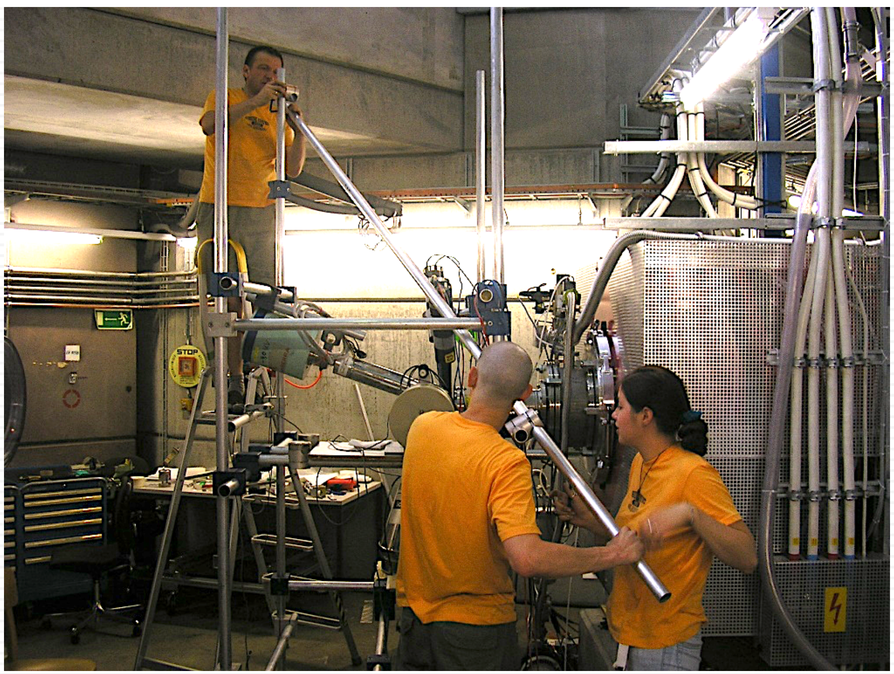
Target	Enrichment	Main purpose	Year
^{136}Ba	95.27 %	Partial cap.rates for NME for DBD	2020
^{nat}Ba	--	Identification for enriched Ba	2020
^{100}Mo	99.8 %	Astroneutrinos	2020 - 2021
^{96}Mo	99.78 %	Partial cap.rates for NME for DBD	2021
^{nat}Mo	--	Identification for enriched Mo	2021
^{76}Se	99.7 %	Partial cap.rates for NME for DBD	2020 - 2021
^{40}Ca	99.81 %	g_A testing with SM	2022
^{56}Fe	99.9 %	g_A testing with SM	2022
^{32}S	99.95 %	g_A testing with SM	2022

Measurement principle


PSI 1998
AC/MC

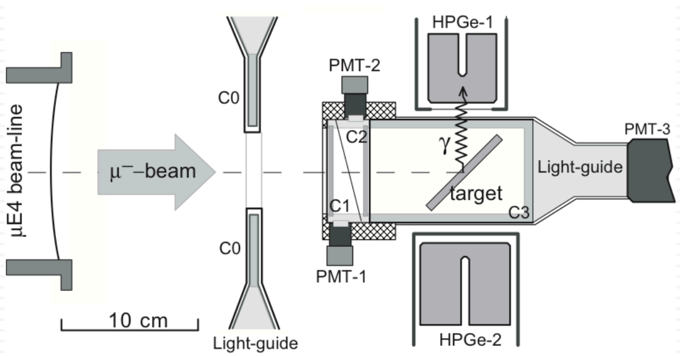
PSI 2006

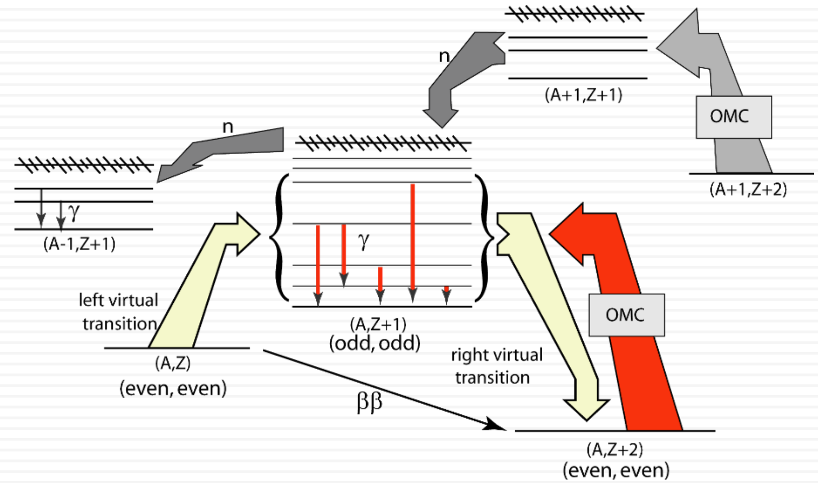
OMC



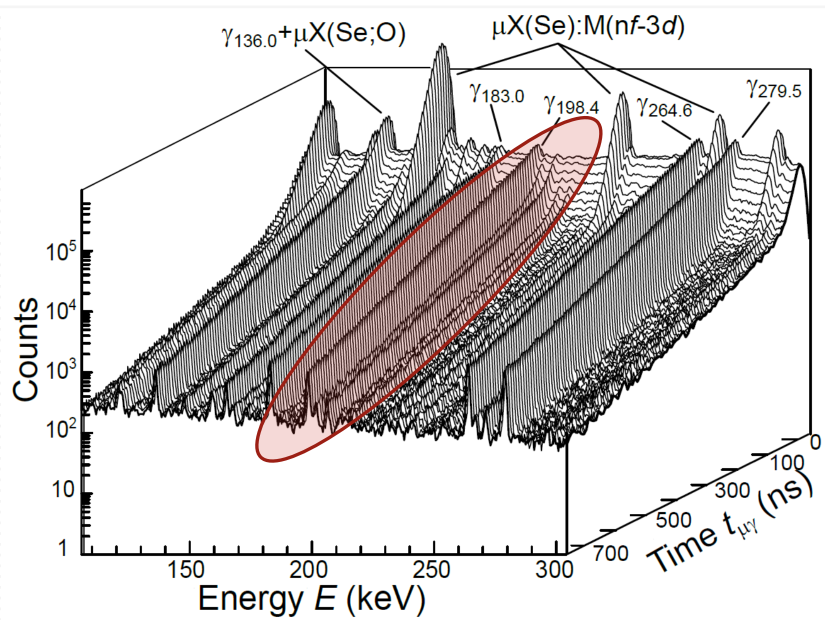
2β-decay	2β-experiments	OMC target	Status
^{76}Ge	GerdaI/II, Majorana Demonstrator, LEGEND	^{76}Se	2004 (PSI)
^{48}Ca	TGV, NEMO3, Candles III	^{48}Ti	2002 (PSI)
^{106}Cd	TGV	^{106}Cd	2004 (PSI)
^{82}Se	NEMO3, SuperNEMO, Lucifer(R&D)	^{82}Kr	2019 (PSI)
^{100}Mo	NEMO3, AMoRE(R&D), LUMINEU(R&D), CUPID-0 Mo	^{100}Ru	--
^{116}Cd	NEMO3, Cobra	^{116}Sn	--
^{150}Nd	SuperNEMO, DCBA(R&D)	^{150}Sm	2006 (PSI)
^{136}Xe	nEXO, KamLAND2-Zen, NEXT, DARWIN, PandaX-III	^{136}Ba	2020 (PSI)
^{130}Te	Cuore 0/Cuore, SNO+	^{130}Xe	2019 (PSI)

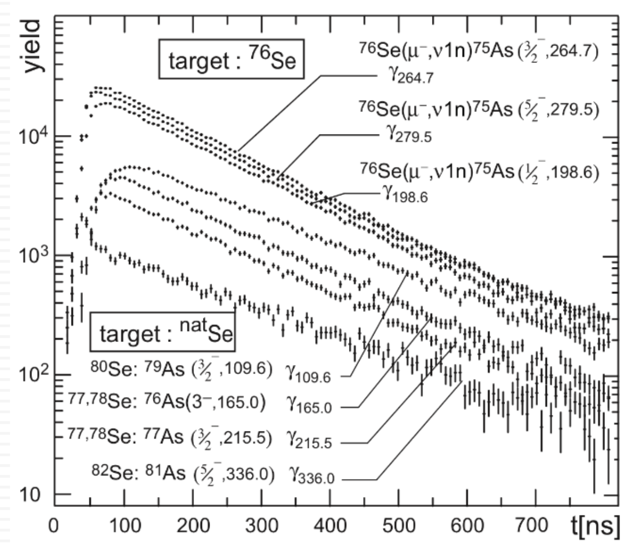
Experimental method of OMC





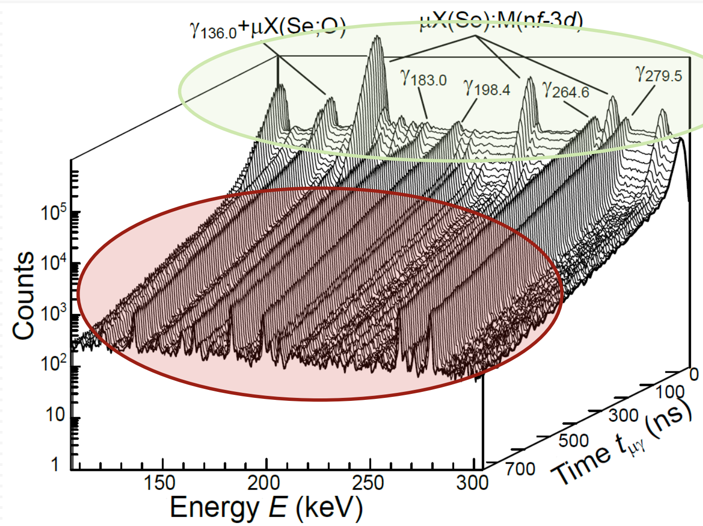
Number of μ-stop = (8 – 25) x 10³ with 20 – 30 MeV/c

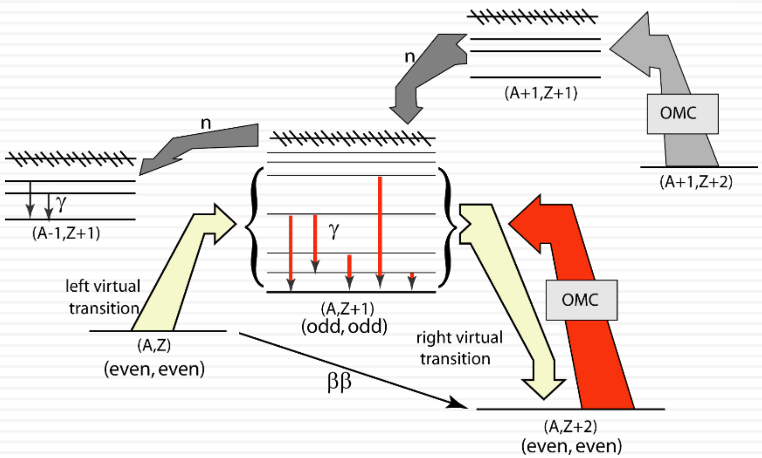


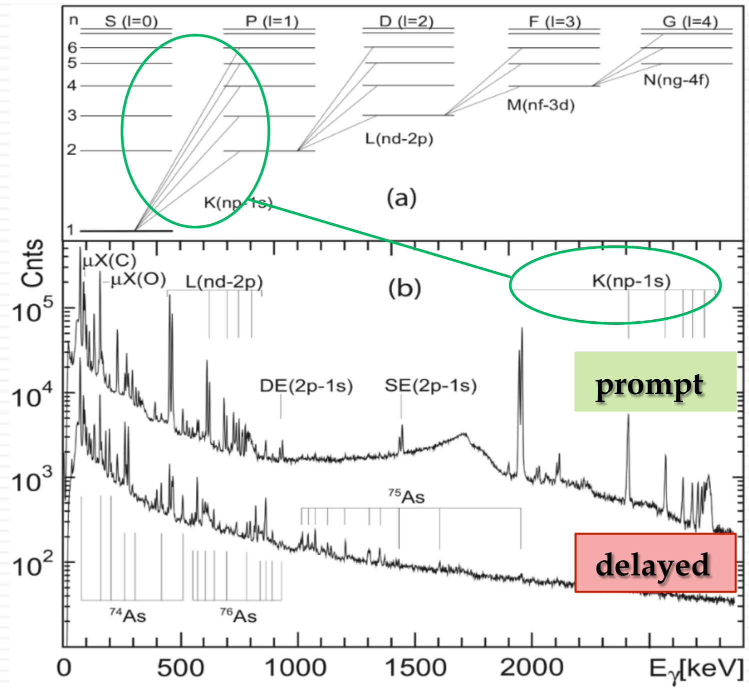


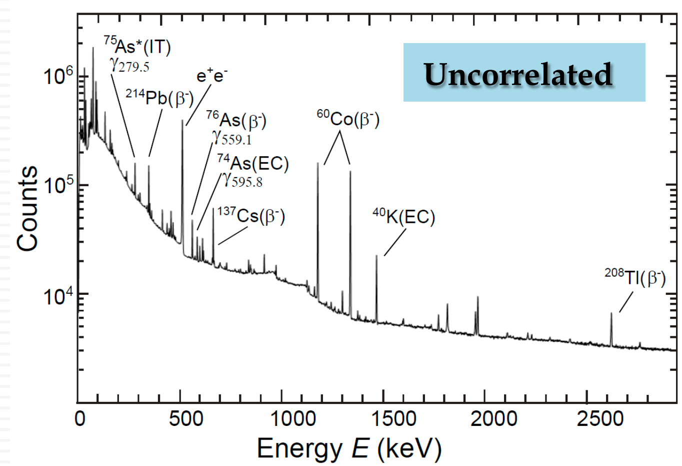
D. Zinatulina, V. Egorov et al. // Phys. Rev. C 99(2019)024327

Experimental method of OMC



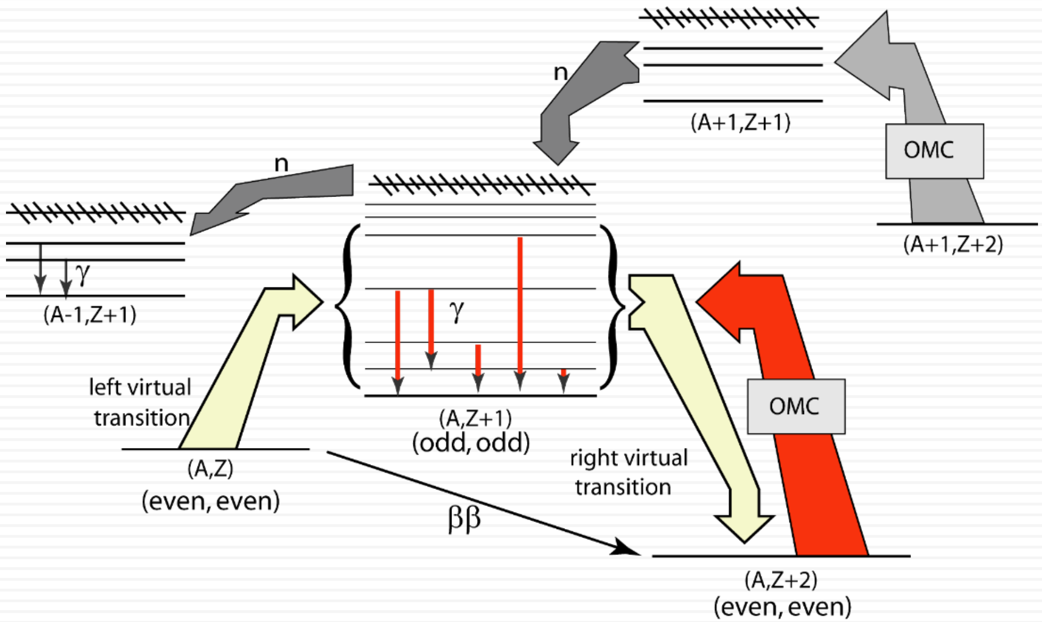






All results have been published in 9 different journals also the main article with methods is - >
D. Zinatulina, V. Egorov et al. // Phys. Rev. C 99(2019)024327

Comparison experimental OMC results with theoretical calculations



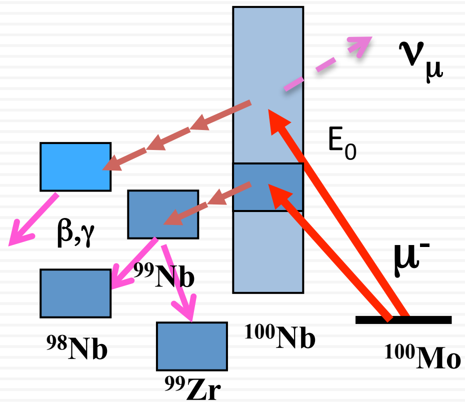
OMC in ^{76}Se

J^π	OMC rate (1/s) Exp.(A	pnQRPA (B
0^+	5120	414
1^+	218 240	236 595
1^-	31 360	28 991
2^+	120 960	114 016
2^-	145 920 + g.s.	177 802
3^+	60 160	55 355
3^-	53 120	34 836
4^+	-	2797
4^-	30 080	23 897

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

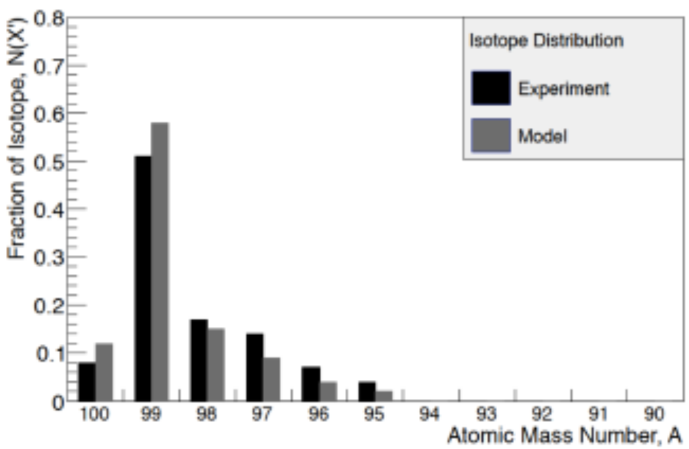
B) L. Jokiniemi, J. Suhonen // Phys. Rev. C 100 (2019) 014619

Comparison experimental OMC results with theoretical calculations

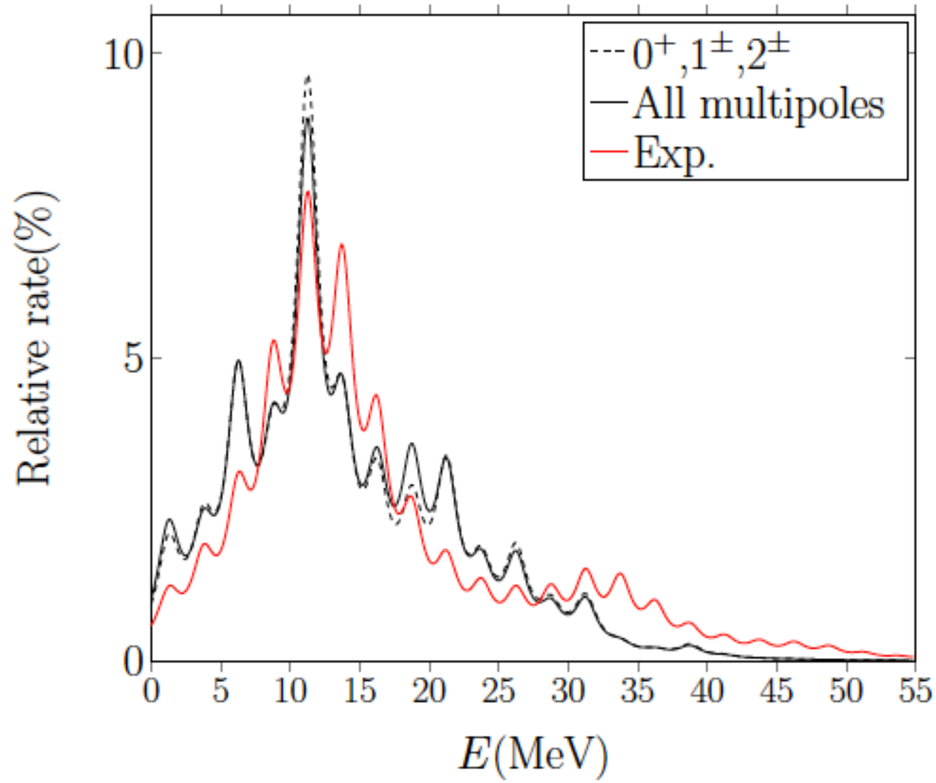


OMC in ^{100}Mo

Calculation by proton and neutron emission model provides initial capture strength ^{100}Nb after muon capture



Population of RI $^{100-x}$Nb isotopes after muon capture on ^{100}Mo.

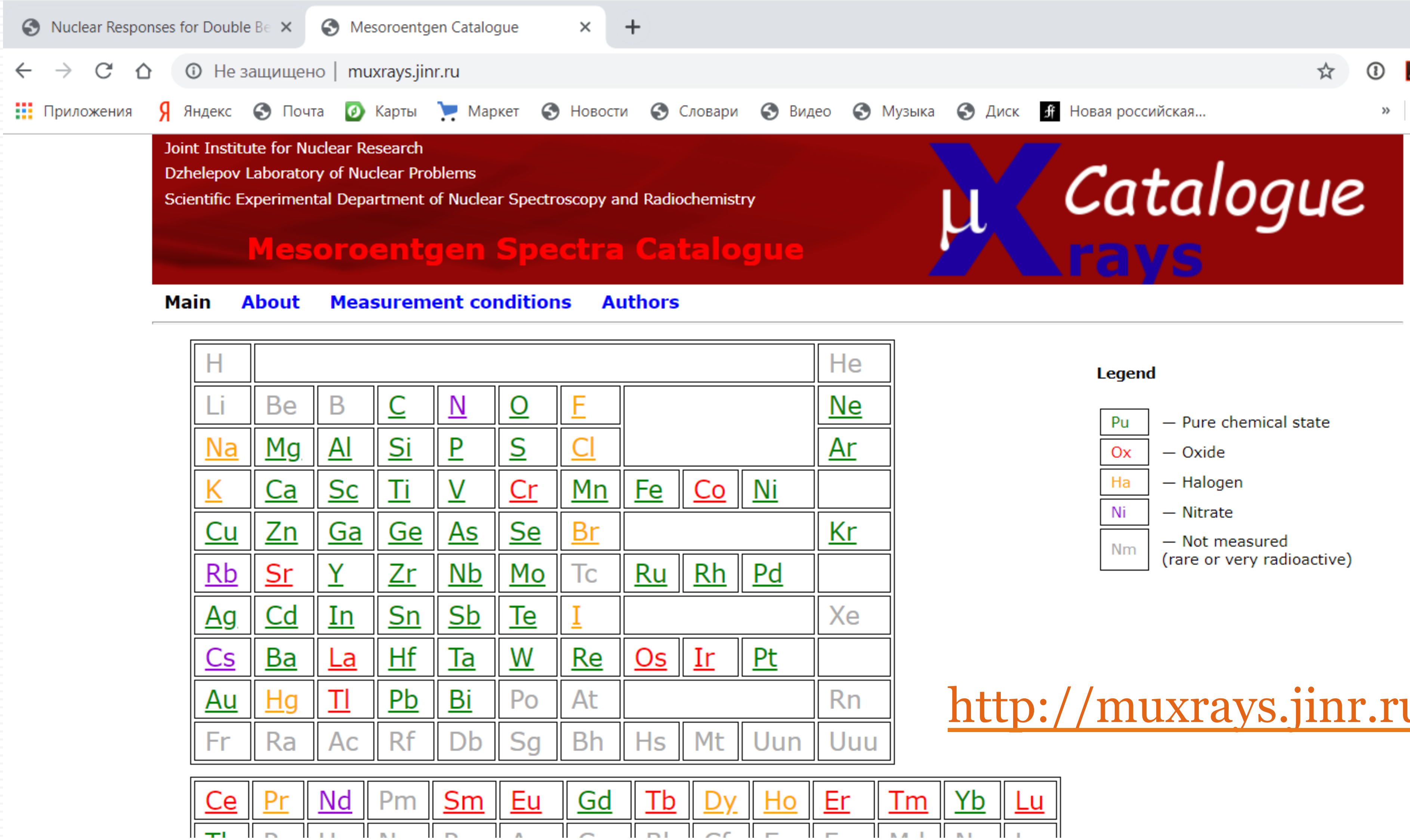


Comparison of the measured and computed relative OMC capture rates for the OMC on ^{100}Mo. Two theoretical distributions are shown, the total one and the one containing the main contributing multipolarities.

Distribution of initial strength can provide the final nuclei isotope population (**PRC 97(2018) 014617 (J-PARC 2014)**)

L. Jokiniemi, J. Suhonen, H. Ejiri, and I.H. Hashim, Phys. Lett. B 794 (2019) 143

Muonic X-rays Catalogue



http://muxrays.jinr.ru/

More than 75 chemical elements, PSI, μE1 и μE4

μX collaboration and JINR group

Addendum to proposal R-16-01.1 ("Muon capture on double beta decay nuclei of ^{130}Xe, ^{82}Kr and ^{24}Mg to study neutrino nuclear responses")

A. Adamczak[1], A. Antognini[2,3], N. Berger[4], T. Cocolios[5], R. Dressler[2], C. Du¨llmann[4], R. Eichler[2], P. Indelicato[6], K. Jungmann[7], K. Kirch[2,3], A. Knecht[2], J. Krauth[4], J. Nuber[2], A. Papa[2], R. Pohl[4], M. Pospelov[8,9], E. Rapisarda[2], D. Renisch[4], P. Reiter[10], N. Ritjoho[2,3], S. Roccia[11], N. Severijns[5], A. Skawran[2,3], S. Vogiatzi[2], F. Wauters[4], and L. Willmann[7]

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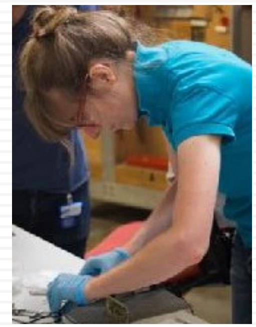
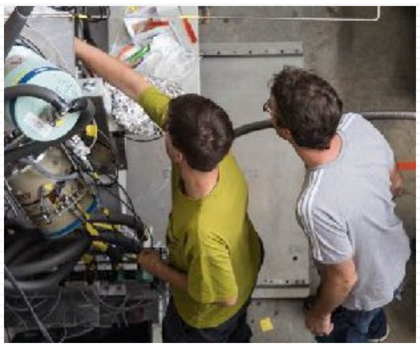
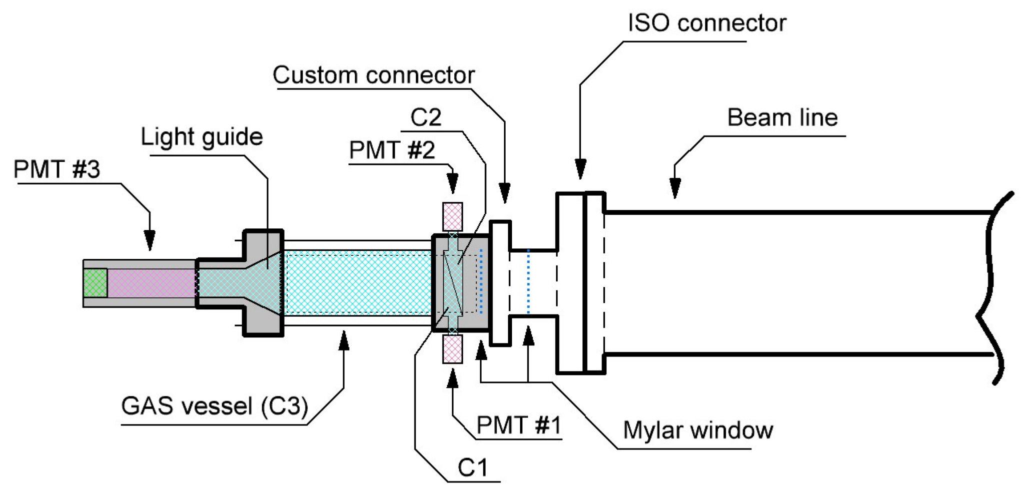
[2]Paul Scherrer Institut, Villigen, Switzerland
[3]ETH Zu¨rich, Switzerland [4]University of Mainz, Germany [5]KU Leuven, Belgium
[6]LKB Paris, France
[7]University of Groningen, The Netherlands
[8]University of Victoria, Canada
[9]Perimeter Institute, Waterloo, Canada
[10]Institut fu¨r Kernphysik, Universita¨t zu Ko¨ln, Germany
[11]CSNSM, Universit´e Paris Sud, CNRS/IN2P3, Orsay Campus, France

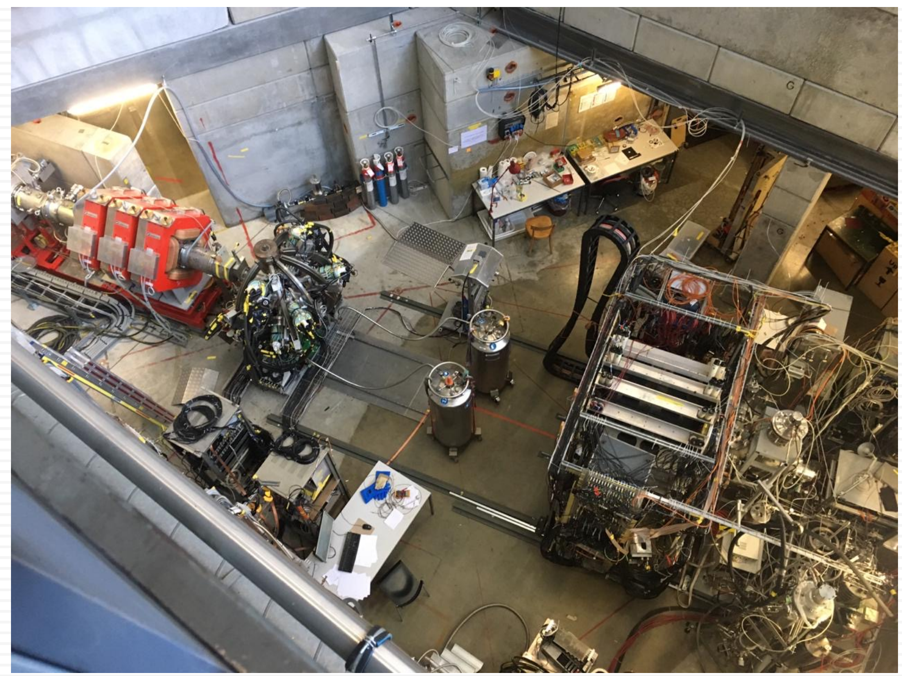




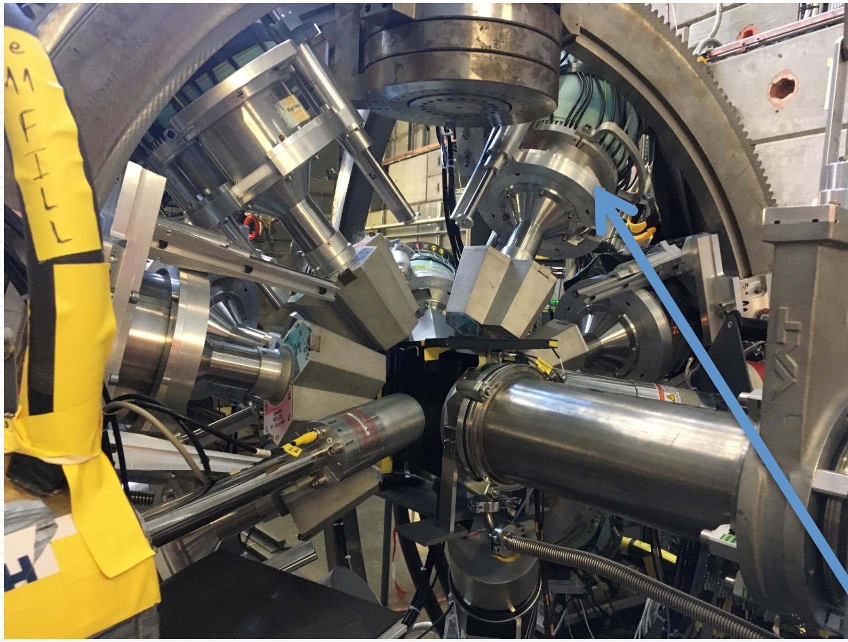

First measurements in 2019

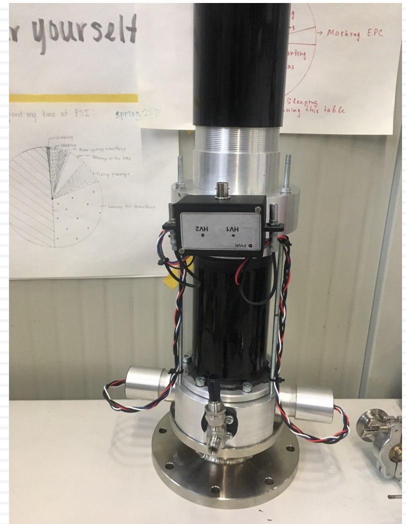


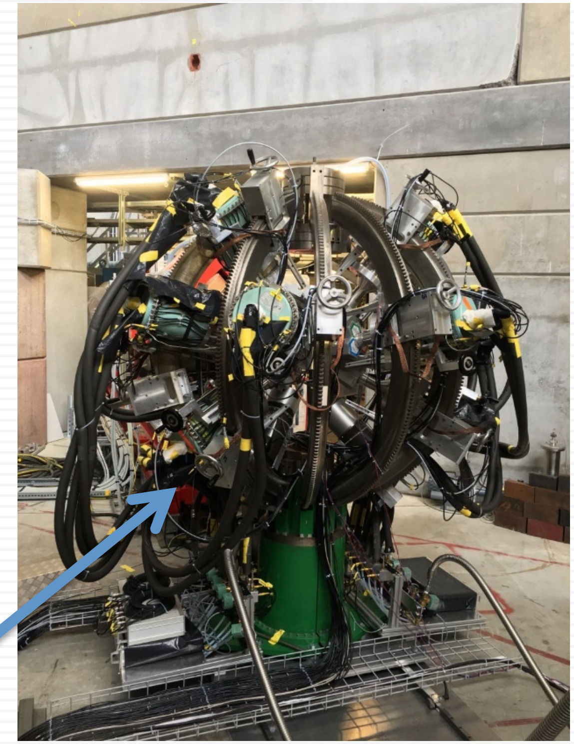


0ν2β-decay	0ν2β-Exper-ts	OMC targets	Quant-ty
^{82}Se	NEMO3, SuperNEMO, Lucifer(R&D)	^{82}Kr (99.9%)	1 l (1.7 atm.)
^{130}Te	Cuore 0/Cuore, SNO+	^{130}Xe (99.9%)	1 l (1.7 atm.)
---	Testing shell model for NME	^{24}Mg (99.85%)	2 g

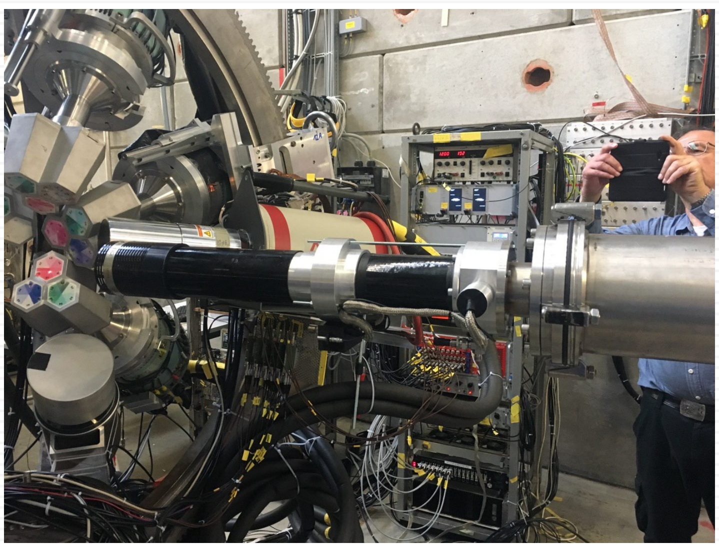
First measurements in 2019

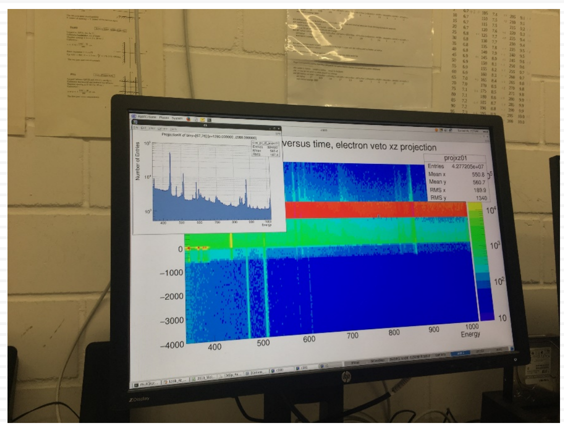






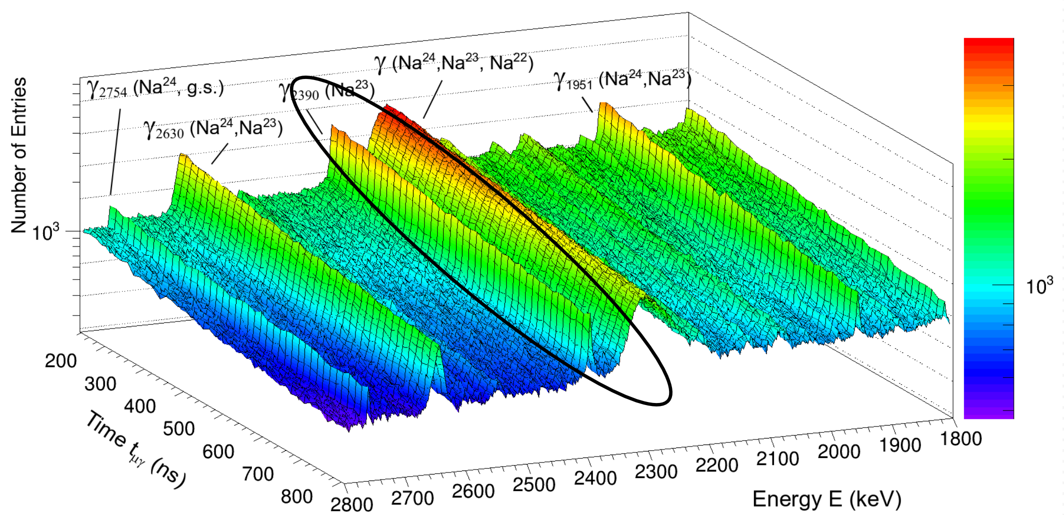
«Miniball» HPGe detectors array

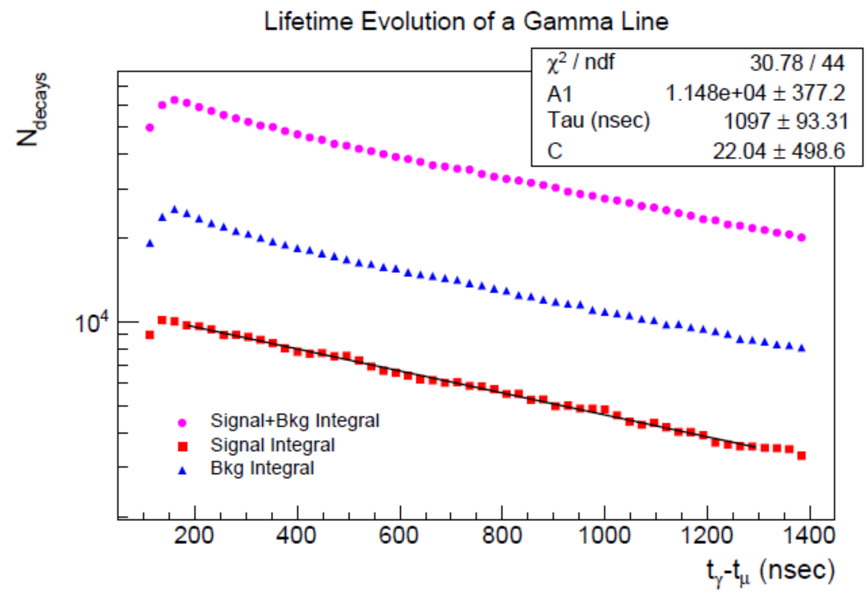




DAQ: 3 digitizers@250 MHz
MIDAS DAQ
MIDAS slow control
Online analysis
Data backup

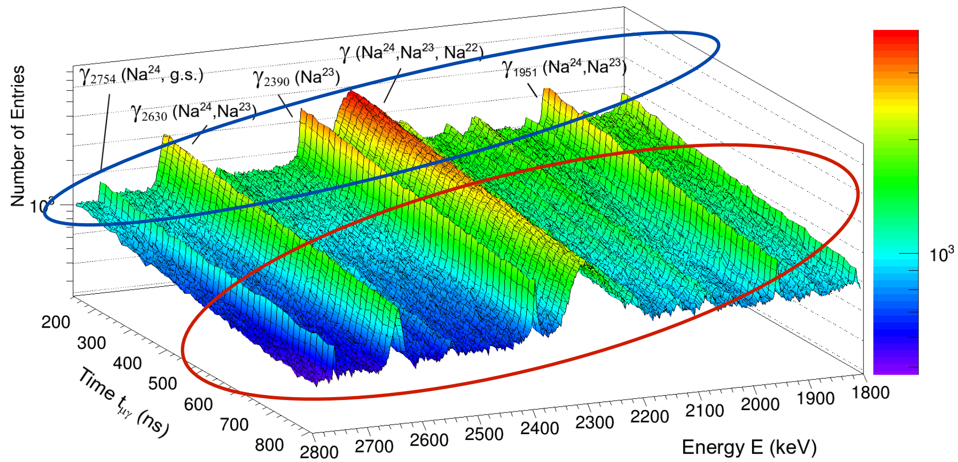
Preliminary 2019 results: *(E, t)* distribution of the correlated events following μ-capture in ^{24}Mg target

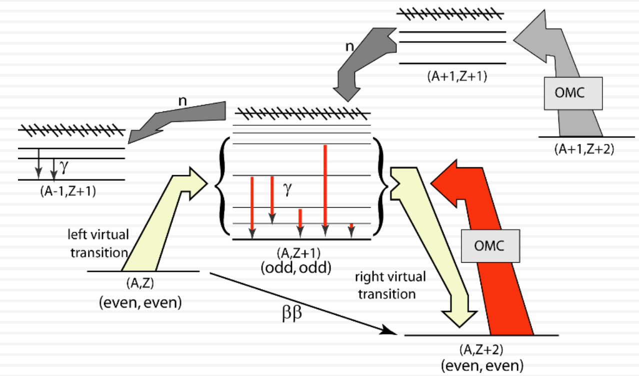


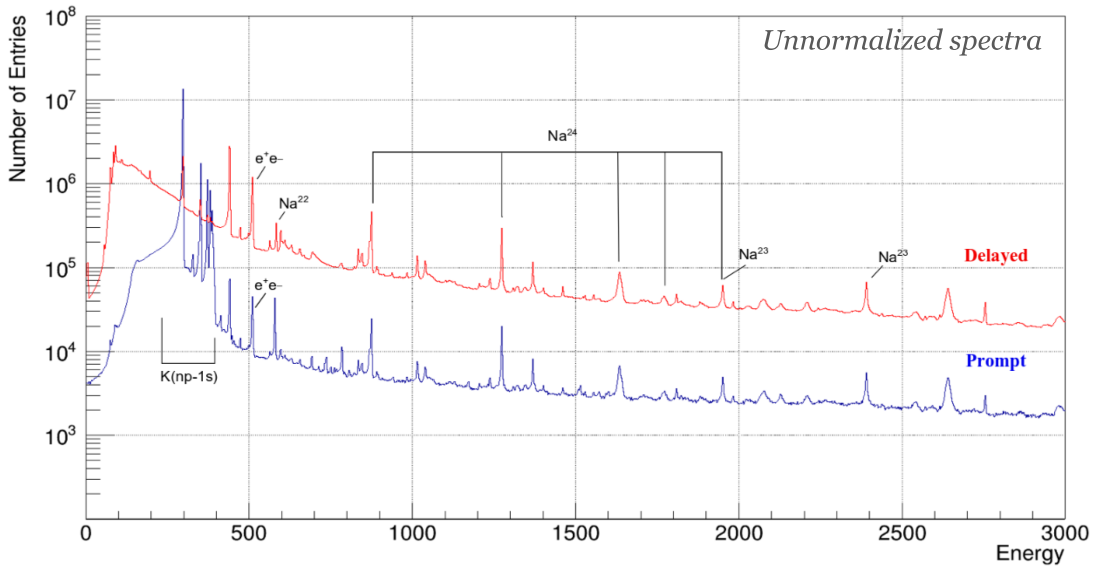


Time evolution of the 2390.6 keV γ-line, following OMC in ^{24}Mg.

Preliminary 2019 results: *(E, t)* distribution of the correlated events following μ-capture in ^{24}Mg target

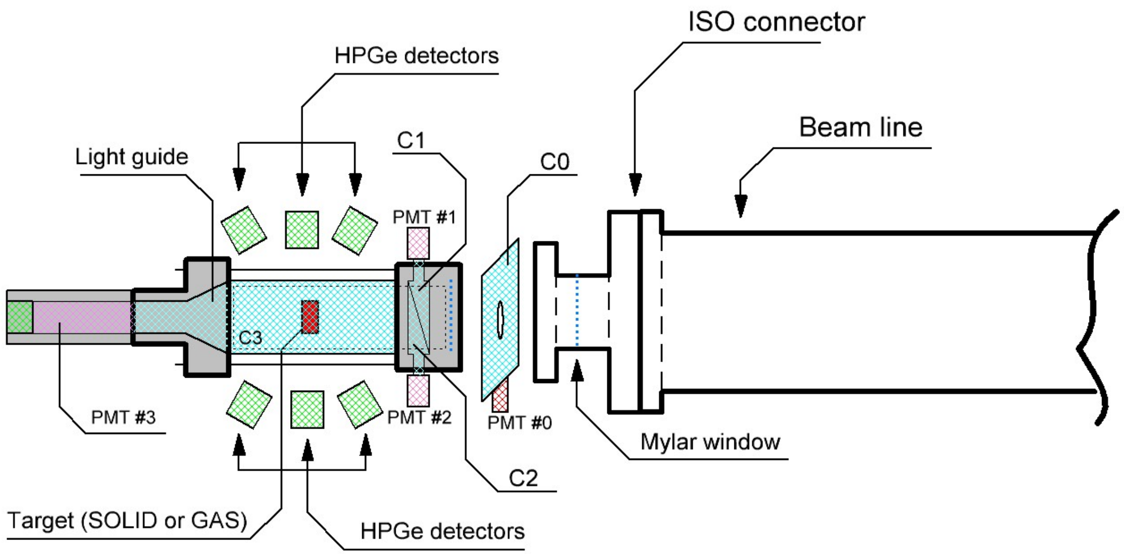


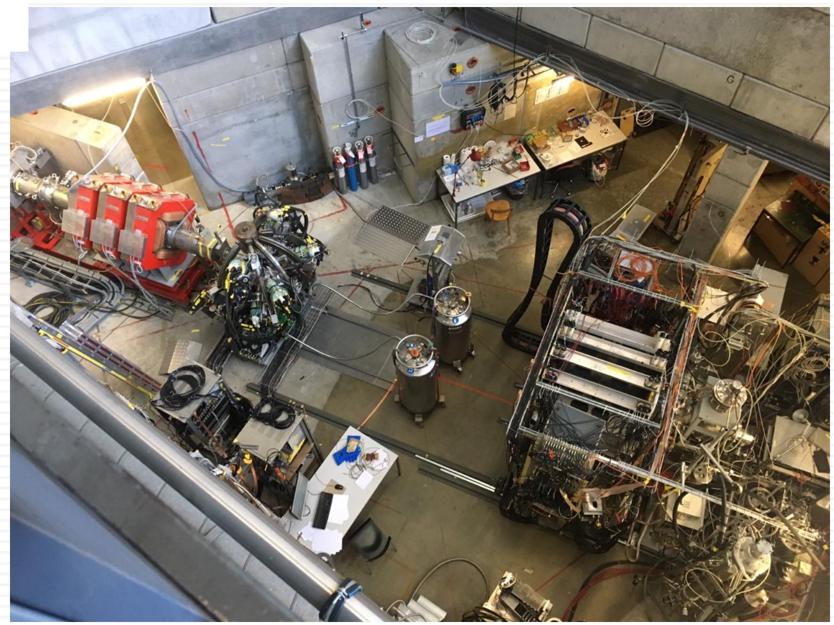




- $t_{\mu\gamma}$ = 0-50 ns: μX-cascades (**Prompt** spectra) – normalization, identification, composition of the surrounded materials and target itself;
- $t_{\mu\gamma}$ = 50-700 ns: γ-radiation following OMC (**Delayed** spectra) – partial m-capture rates – strength function of the right side;
- T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

Proposed measurements in 2020





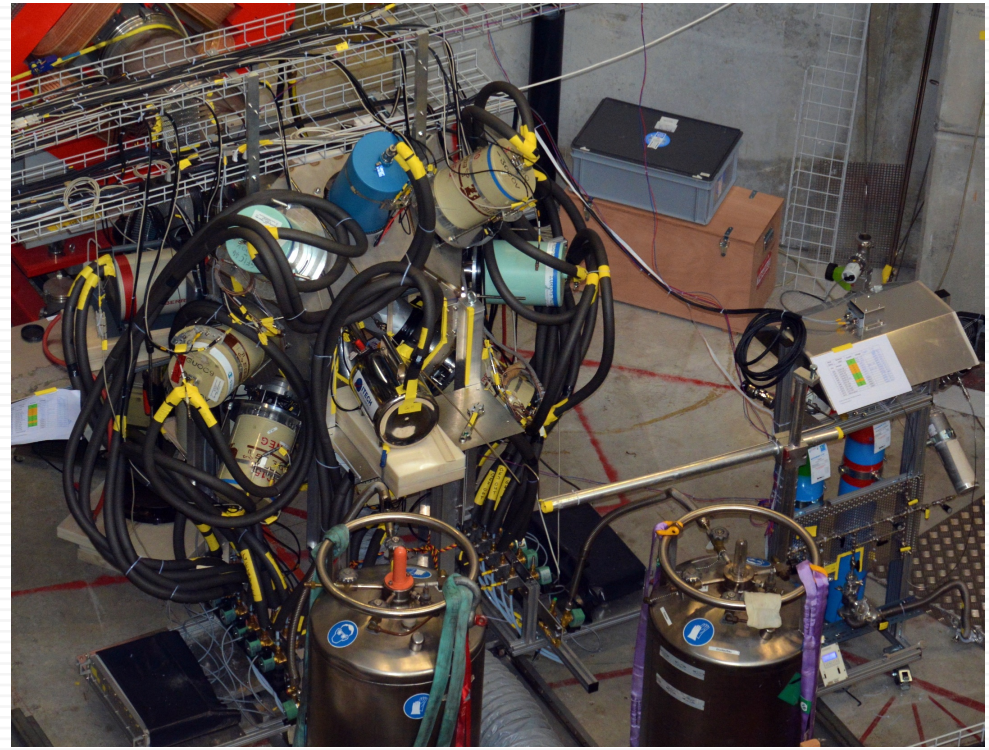
0ν2β-decay	0ν2β-Exper-ts	OMC targets	Quant-ty
^{136}Xe	nEXO, KamLAND2-Zen, NEXT, DARWIN, PandaX-III	^{136}Ba (95.27%)	2 g
---	---	^{nat}Ba	2 g

Detection system and DAQ

PAUL SCHERRER INSTITUT

- **<u>Set of 8 HPGe detectors :</u>**
  3 n-type (250 cm^3
  and low-region (PSI) + 1 from JINR)
  2 p-type BEGe det's (TUM)
  2 p-type inverted-coaxial
  (TUM+JINR)
  1 low-region det. (UZH)

- **C0** (aperture defining veto counter)
- **C1-C2** (pass-through counters)
- **C3** (cup-like counter)



- **<u>DAQ: </u>** 2 digitizers@250 MHz
  MIDAS DAQ
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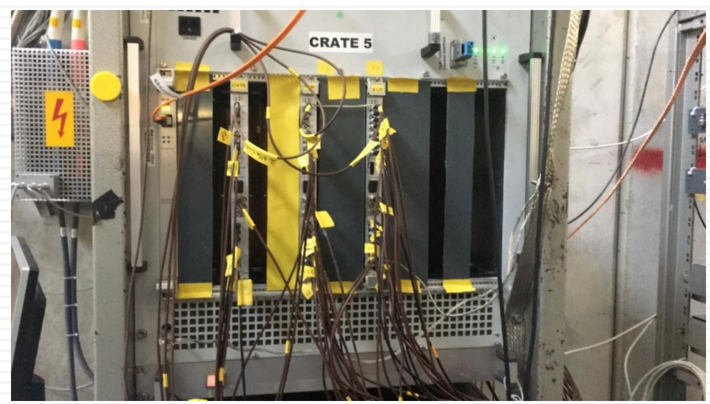
  Online analysis
  Data backup



Rate estimates:

Parameter	Value	Comment
Muon rate	30-40 kHz	Rate at entrance det. for ^{24}Mg target (2 g)
Beam momentum	31-33 MeV/c	Used to ^{24}Mg solid target
Solid angle	1.5 - 2 % / detector	60% germanium detector at 10 cm distance
Detection efficiency	50%	For ~ 1 MeV
Timing resolution	10 ns	
Detection rate	1,5-2 kHz	Per detector unit in case of ^{24}Mg

Beam request:

- **2020**: 3 weeks beam time in πE1

  1 week: setup and beam tuning,

  2 weeks: data taking (first for ^{136}Ba and second for ^{nat}Ba, the rest time for ^{76}Se)

- Off-line measurements: 2 weeks

Conclusions:

- OMC is the sensitive tool to probe properties of DBD process. It is based on mature experimental technique successfully developed during many years, which demonstrates satisfactory agreement between experimental and theoretical data;

- The unique information obtained at OMC will provide a significant experimental contribution to the theory of ββ decay and astropartical physics researches. In particular, it will help improve NME calculations for DBD. Leading ββ decay theorists have shown serious interest in obtaining this new experimental information;

- An intensive multi-year PSI beam research program was proposed;

- As a by-product -- the muonic X-rays spectra will be added to Mesoroentgen electronic catalogue (muxrays.jinr.ru)

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UTM UNIVERSITI TEKNOLOGI MALAYSIA

THE UNIVERSITY OF ALABAMA

KU LEUVEN NUCLEAR AND RADIATION PHYSICS

ETH zürich

RCNP

Back Slides

Conclusions & Outlook:

- The proposed experiment unravels the gross features of weak responses with $J^{\pi} = 0^{\pm}, 1^{\pm}, 2^{\pm}, \ldots$ for ^{136}Ba isotope which is the daughter nucleus of the DBD nuclei of ^{136}Xe;
- The present project is also extended to other DBD nuclei in the atomic mass number region between 70 to 140;
- It should be mentioned that recent results with calculations for the ^{76}Se nicely agrees with experimental one, additional statistic for the ^{76}Se would be helpful;
- The measurements proposed here will allow to determine for the first time huge stuff of the information (total μ-cap rates, partial muon capture probabilities, the yields of the isotopes and isomers)
- As a by-product -- the muonic X-rays spectra will be added to Mesoroentgen electronic catalogue (muxrays.jinr.ru)

Conclusions & Outlook:

- It should be mentioned that recent results with calculations for the ^{76}Se nicely agrees with experimental one, additional statistic for the ^{76}Se would be helpful;

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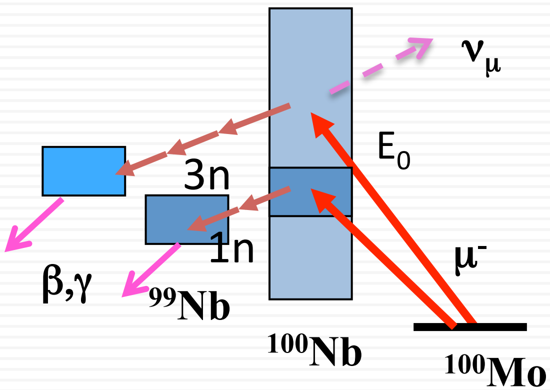
Related to this, important information about the weak coupling constants and nuclear-theory aspects will be obtained from the muon-capture strength function and the associated giant resonance when compared with the presently available and future calculations of the strength functions;

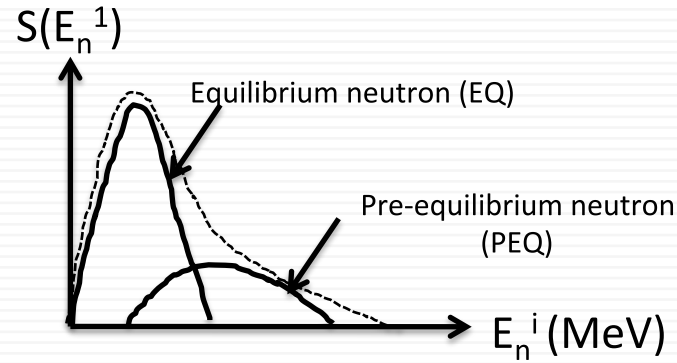
- As a by-product -- the muonic X-rays spectra will be added to Mesoroentgen electronic catalogue (muxrays.jinr.ru)

Publications:

1. Ordinary muon capture studies for the matrix elements in $\beta\beta$ decay / *D. Zinatulina, V. Brudanin, V. Egorov et al.* // Phys. Rev. C . --- 2019 . --- Feb . --- Vol. 99 . --- P. 024327.
2. μCR42β: Muon capture rates for double-beta decay / *V. G. Egorov, V. B. Brudanin, K. Ya. Gromov et al.* // Czechoslovak Journal of Physics . --- 2006 . --- May . --- Vol. 56, no. 5 . --- Pp. 453–457.
3. Ordinary muon capture (OMC) studies by means of γ-spectroscopy / *D. Zinatulina, V. Brudanin, V. Egorov et al.* // AIP Conf. Proc . --- 2017 . --- Vol. 1894, no. 1 . --- P. 020028.
4. Muon capture in Ti, Se, Kr, Cd and Sm / *D. Zinatulina, K. Gromov, V. Brudanin et al.* // AIP Conf. Proc . --- 2007 . --- Vol. 942 . --- Pp. 91–95.
5. OMC studies for the matrix elements in $\beta\beta$ decay / *D. Zinatulina, V. Brudanin, Ch. Briançon et al.* // AIP Conf. Proc . --- 2013 . --- Vol. 1572 . --- Pp. 122–125.
6. Muon capture rates in Se and Cd isotopes / *D. R. Zinatulina, K. Ya. Gromov, V. B. Brudanin et al.* // Bulletin of the Russian Academy of Sciences: Physics . --- 2008 . --- Jun . --- Vol. 72, no. 6 . --- Pp. 737–743.
7. Negative-muon capture in ^{150}Sm / *D. R. Zinatulina, Ch. Briançon, V. B. Brudanin et al.* // Bulletin of the Russian Academy of Sciences: Physics . --- 2010 . --- Jun . --- Vol. 74, no. 6 . --- Pp. 825–828.
8. Electronic catalogue of muonic X-rays / *D. Zinatulina, Ch. Briançon, V. Brudanin et al.* // EPJ Web Conf . --- 2018 . --- Vol. 177 . --- P. 03006.
9. Электронный каталог мезорентгеновских спектров излучения / *Д. Зинатулина* // Ядерная Физика . --- 2019. -- Vol. 82, no. 3. - Pp. 228-234.

PRC 97(2018) 014617 (J-PARC 2014)





$$S(E_n^1) = k\left[E_n^1 exp\left(-\frac{E_n^1}{T_{\mathrm{EQ}}(E)}\right) + pE_n^1 exp\left(-\frac{E_n^1}{T_{\mathrm{PEQ}}(E)}\right)\right]$$

{EQ} {PEQ}

μ response(strength) distribution

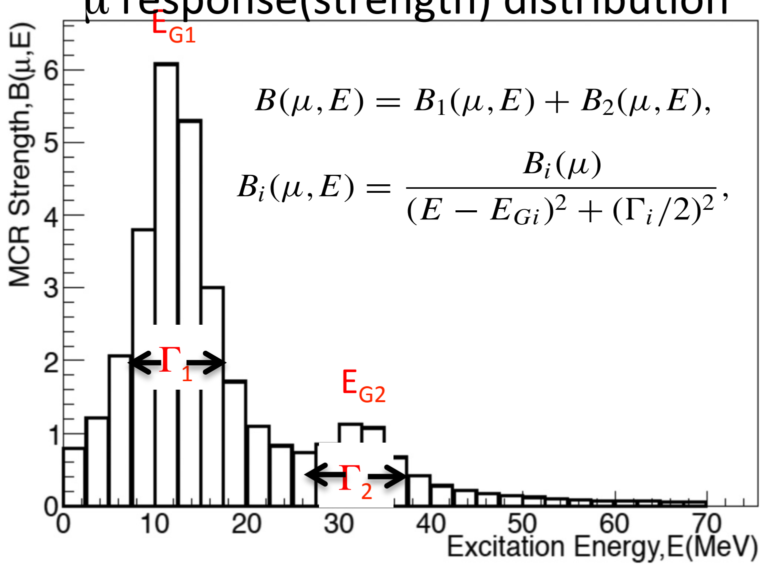
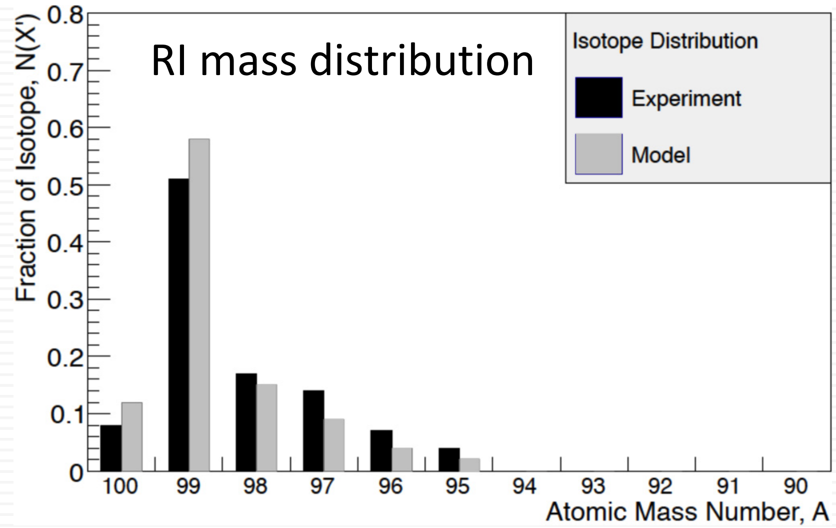
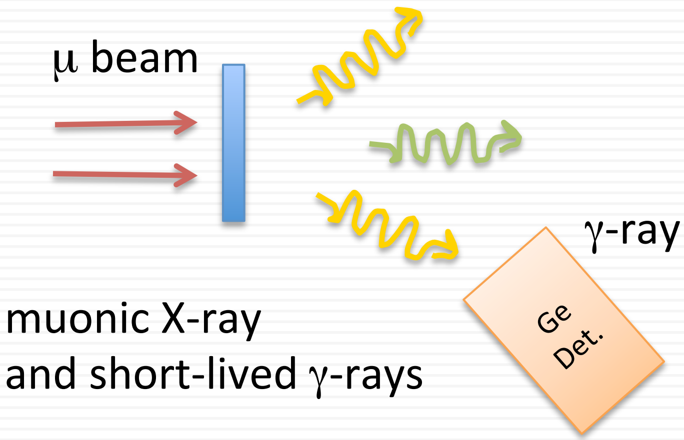


FIG. 6. The OMC strength distribution suggested from the experimental RI distribution. E_{G1} and E_{G2} are the OMC GRs at around 12 MeV and 30 MeV.



Overview of the method

Irradiation of target



Measurement of delayed γ-rays

$^{100}Mo + \mu^- \rightarrow Nb^* + \nu_\mu + xn$

$\rightarrow Nb^* + \beta^- + \overline{\nu}_e + \gamma$

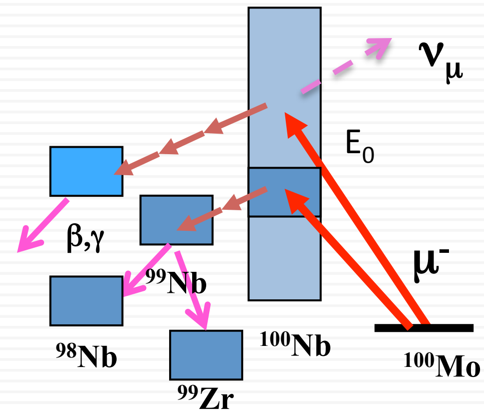
Exp. data give the dist. of isotope mass population of the final nuclei after neutron emission.

Muon capture reaction

Weak/ neutrino nuclear response

Calculation by proton and neutron emission model

Provides initial capture strength ^{100}Nb after muon capture



Distribution of initial strength can provide the final nuclei isotope population

compare

Relative capture strength

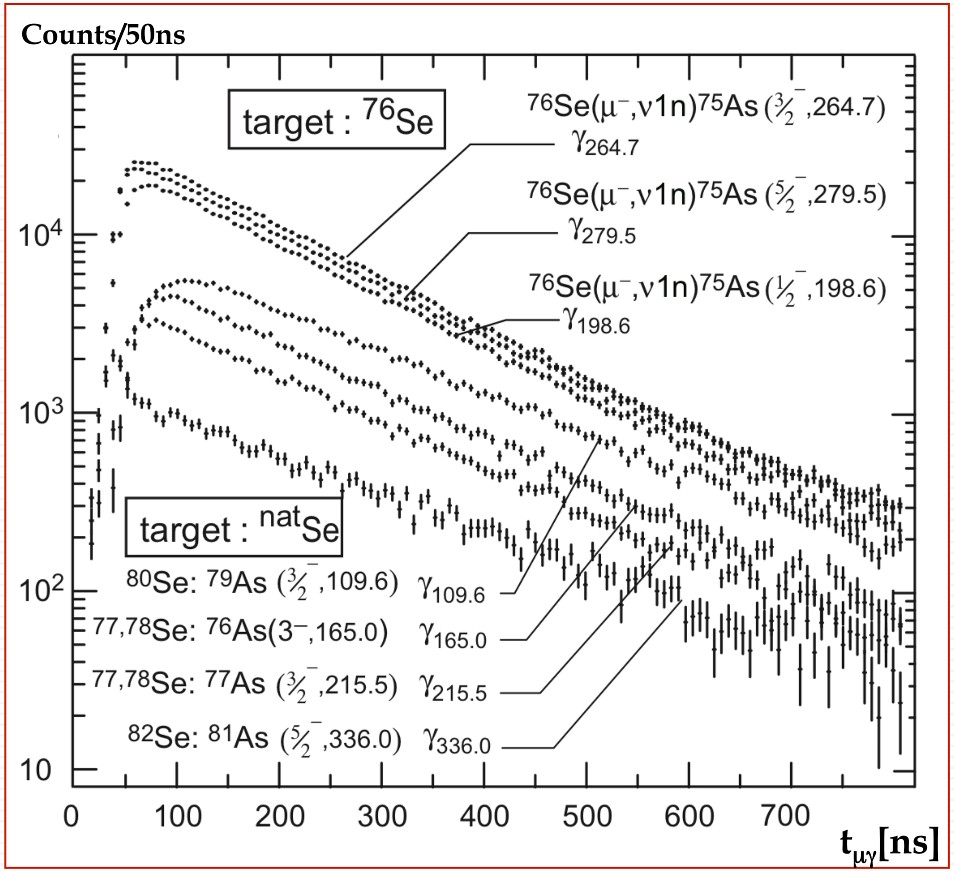
Absolute capture strength

Nuclear matrix element, NME for DBD

- Provide μ capture rate
- If pnQRPA with g_A can reproduce the μ capture rate or they need to adjust g_A.

- Used adjusted g_A to calculate DBD NME

Total μ-capture rates in different isotopes of Se



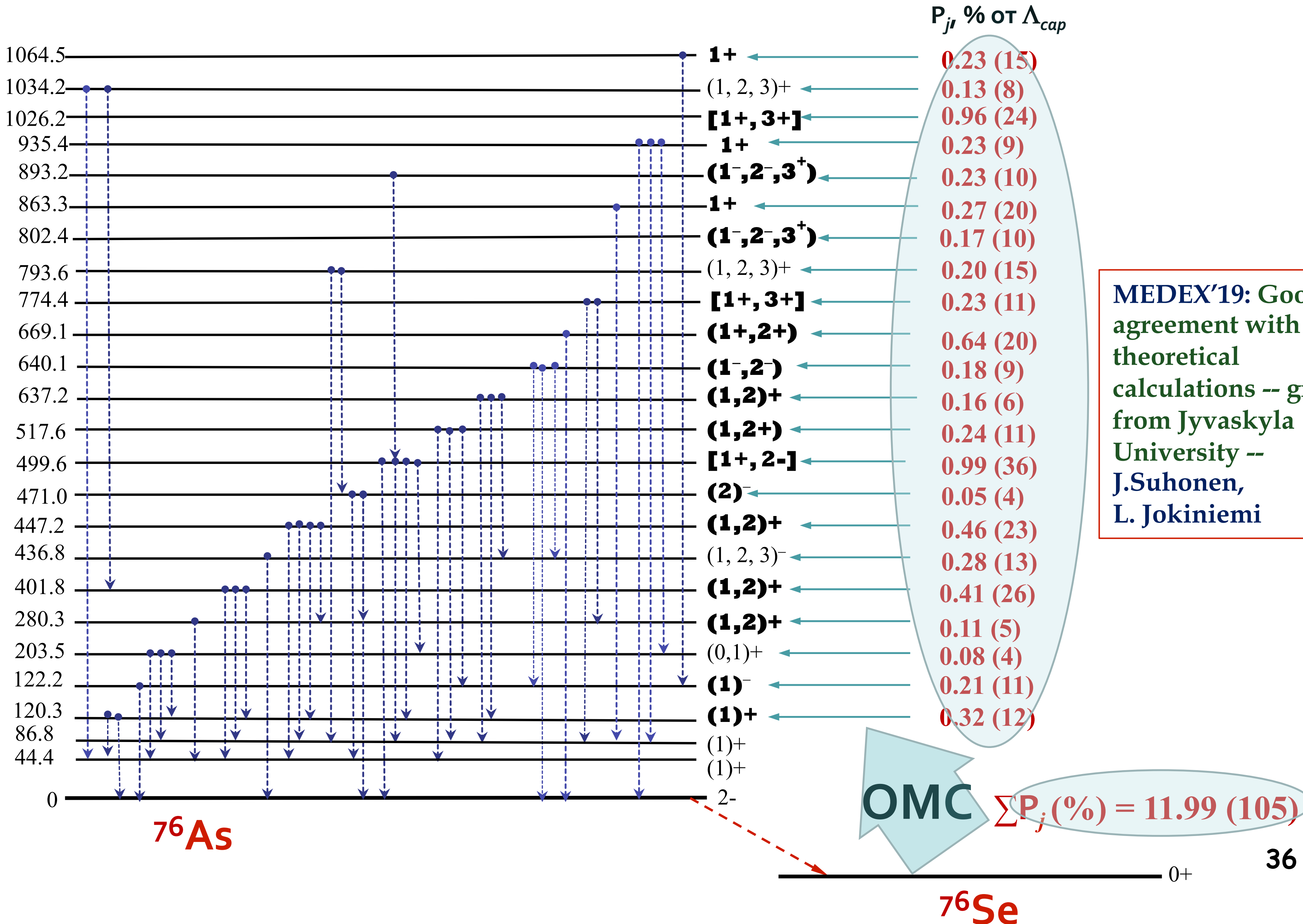
Time evolution of the γ-lines, following OMC in ^{76}Se (top) и ^{nat}Se (bottom) (A.

Target	Daugh. Nuclei	E_i^{γ} [keV]	τ [n c]	$<\lambda_{cap}>$ [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**

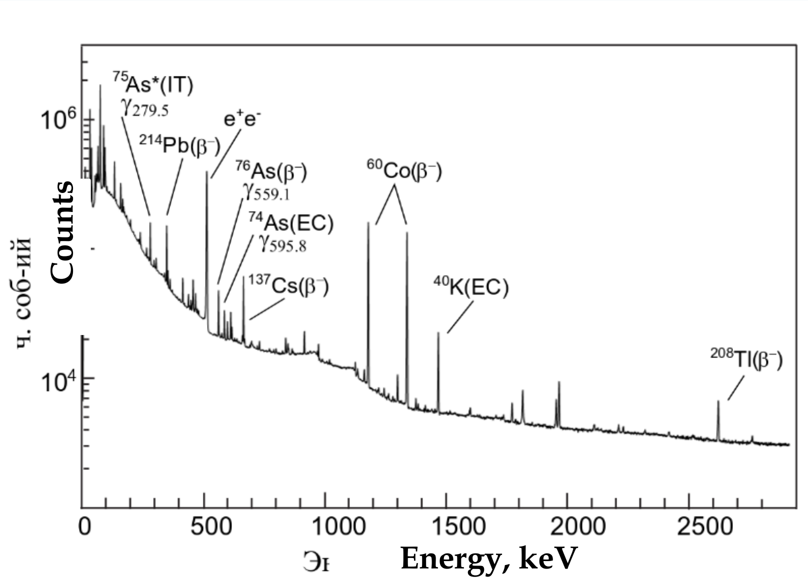
B) **T. Suzuki, D.F. Measday // Phys. Rev. C 35(1987)2212**

Partial μ-capture probabilities to ^{76}As



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

Results measured with U-spectra in ^{76}Se and ^{150}Sm

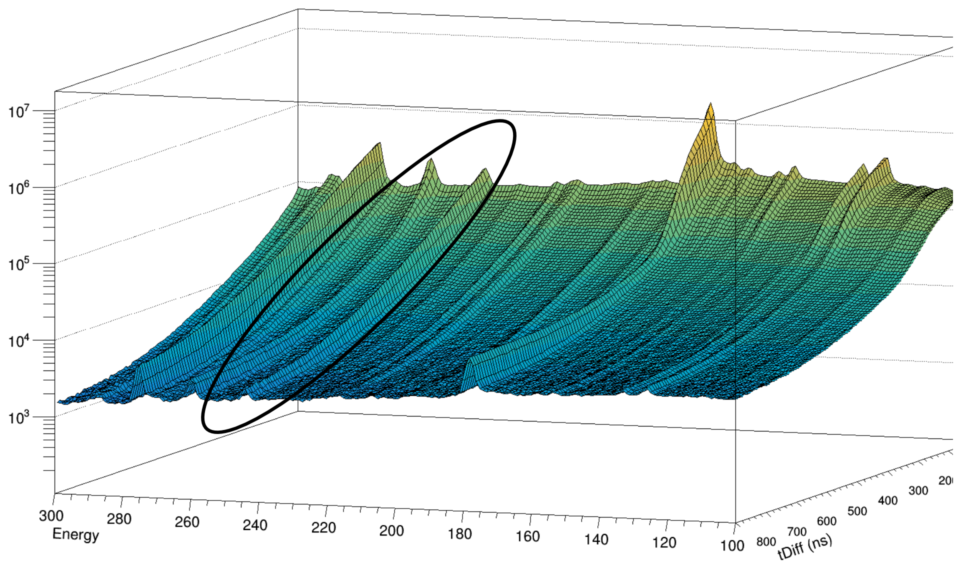


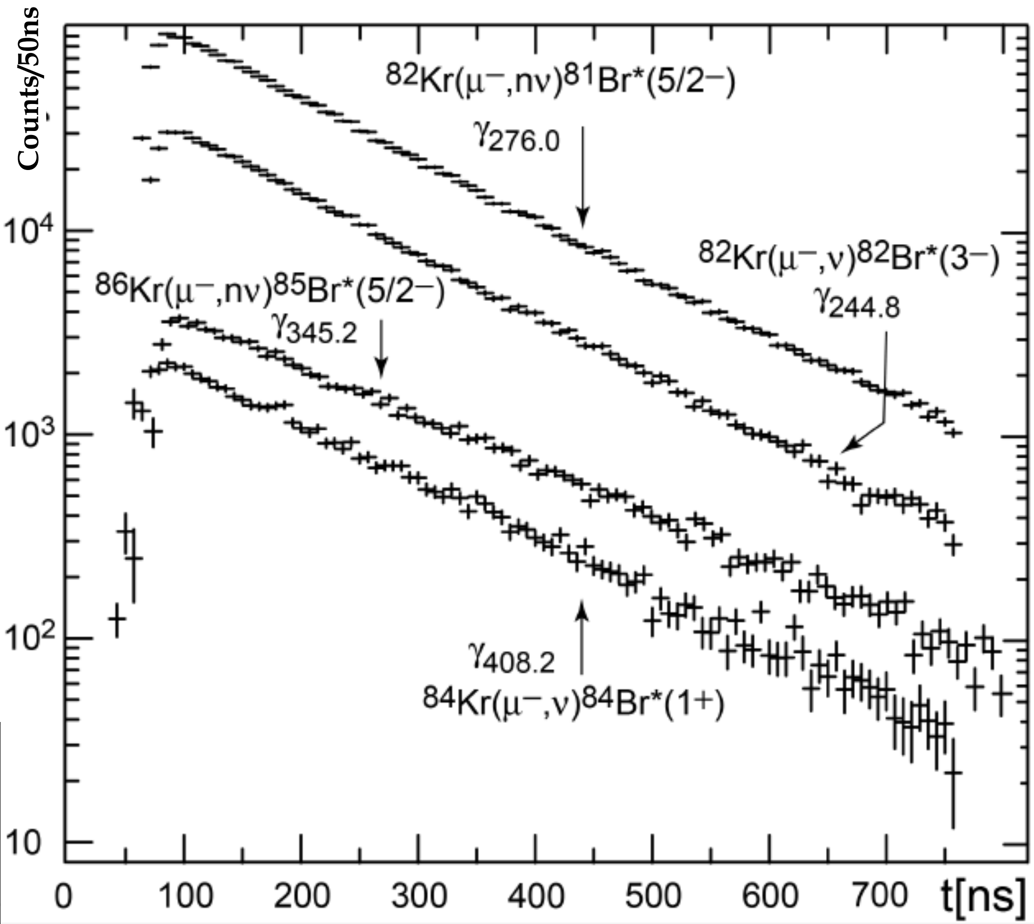
Isotope	Decay type	$T_{1/2}$	$\lambda_{cap}(xn)$ (10^6 s^{-1})	P_{cap}
^{76}As	β^-	26.3 h	0.86(3)	13.65(255)
^{75m}As	IT	17.6 ms	0.41(7)	6.5(11)
^{75}As	stable		unmeasured	
^{74}As	β^-, EC	17.8 d	1.1(2)	17.5(32)
^{73}As	EC	80.3 d	unmeasured	
^{72}As	β^+	26 h	0.15(3)	2.4(5)
^{71}As	β^+	65.3 h	0.061(18)	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 ms	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)
^{150}Pm	β^-	2.68 h	1.45(11)	12.3(9)
^{149m}Pm	IT	35 μs	1.80(31)	15.3(26)
^{149}Pm	β^-	53.1 h	2.93(60)	24.9(51)
^{148}Pm	β^-	5.37 d	0.77(26)	6.6(22)
^{148m}Pm	IT	41.3 d	0.10(2)	0.85(17)
^{148m}Pm	β^-	41.3 d	0.21(6)	1.79(51)
^{149}Nd	β^-	1.73 h	0.78(35)	6.6(29)
^{148}Nd	stable		unmeasured	
				$\sum$=68.3(69)

Background radiation (**Uncorrelated** spectra) –

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

(E, t) distribution of the correlated events following μ-capture in ^{82}Kr target

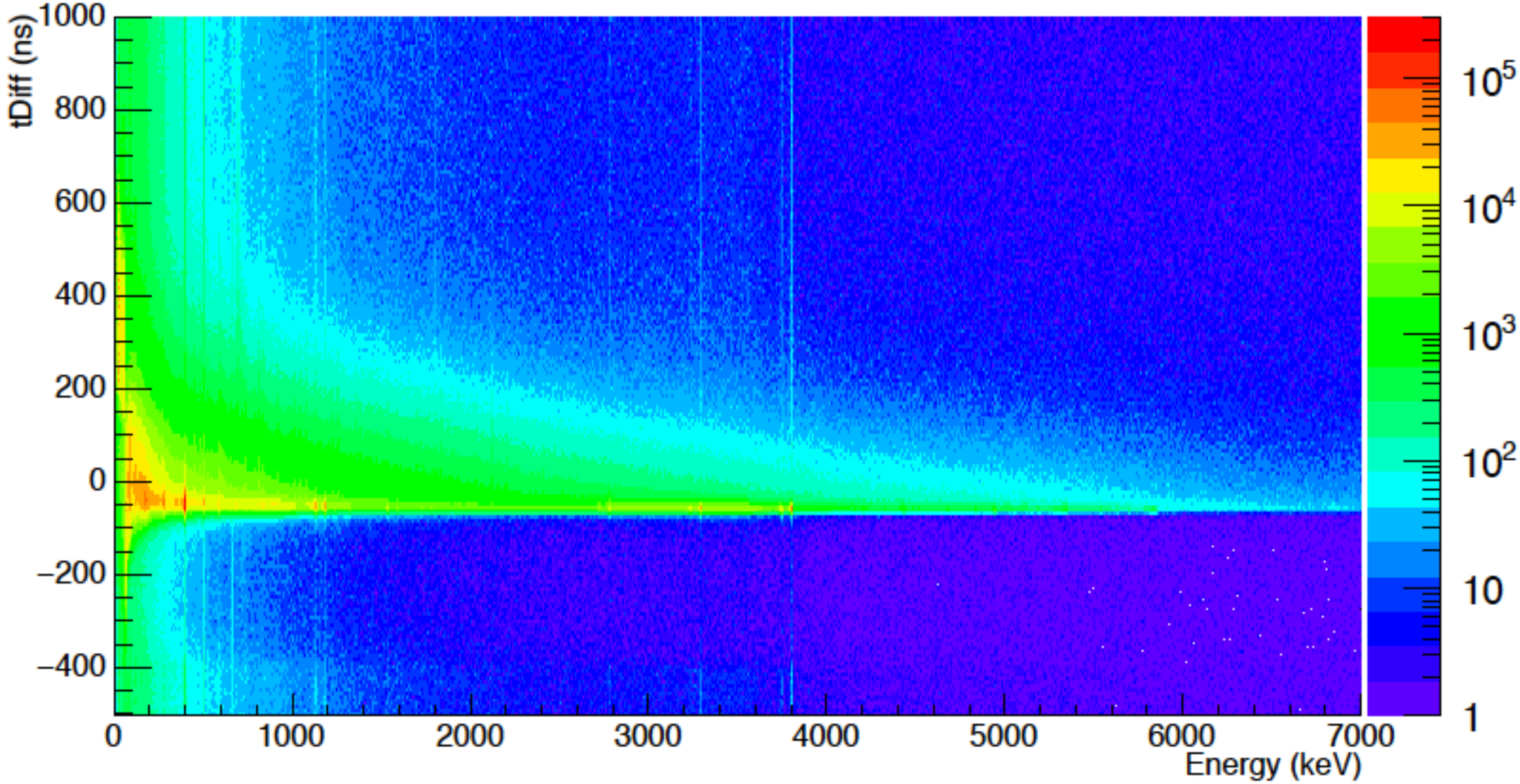




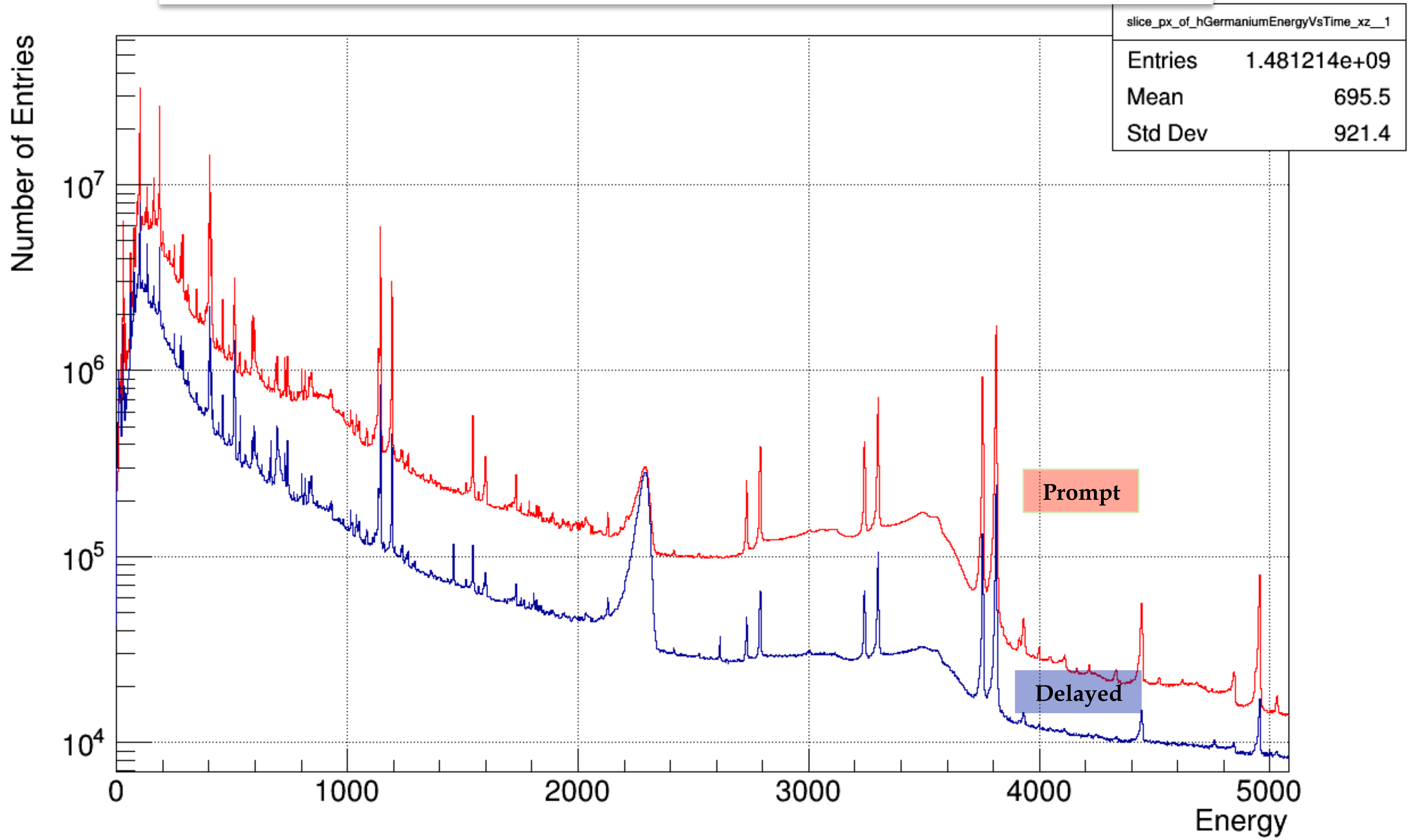
Мишень	Доч. ядро	E_i^{γ} [кэВ]	τ [нс]	$\langle\Lambda_{cap}\rangle$ [10^6 c^{-1}]
^{82}Kr	^{82}Br	244.8	142.9(6)	
	^{81}Br	276.0	142.6(3)	
			<142.68(37)>	6.576(17)

Временная эволюция γ-линий, сопровождающих ОМЗ в ^{82}Kr (верх) и ^{nat}Kr (низ).

24.10 to 28.10 – measurements with ^{130}Xe

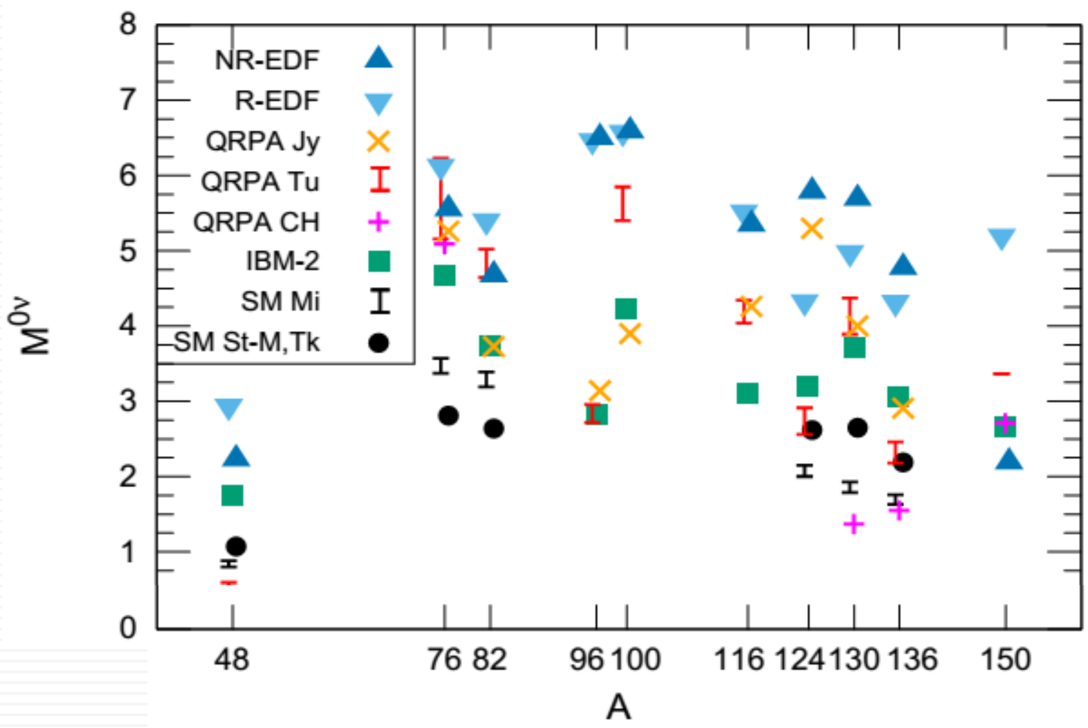


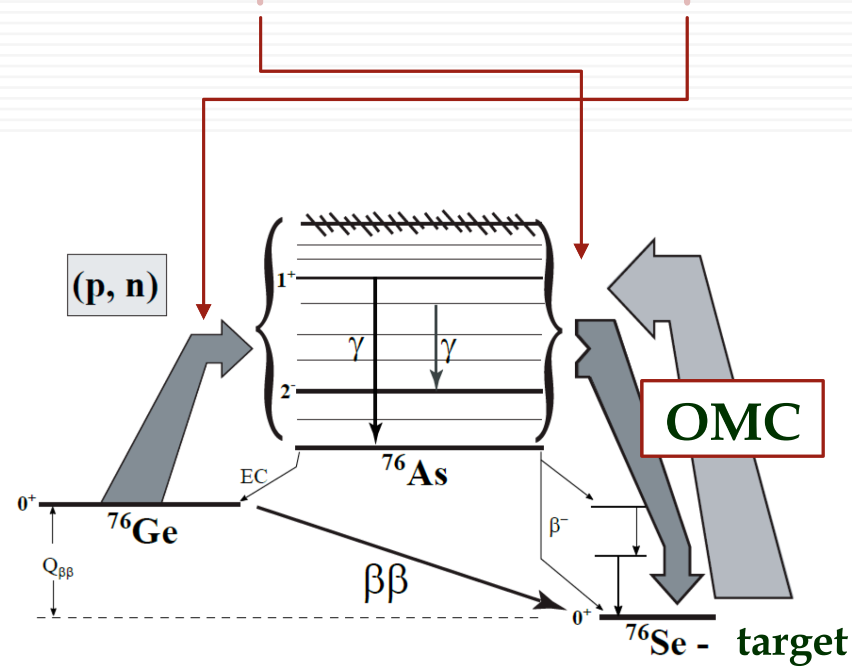
Energy spectra with ^{130}Xe



Experimental input for NME calculations

$$\langle A, Z+2 | S | A, Z \rangle \propto \sum_n \langle Z+2 | \hat{H} | Z+1, n \rangle \langle Z+1, n | \hat{H} | Z \rangle$$





APPECC-2019, Recommendation 6: *The computation of nuclear matrix elements is challenging and currently is affected by an uncertainty which is typically quantified in a factor of 2-3... An enhanced effort is required and a stronger interactions between the particle physics and nuclear community would be highly beneficial. Dedicated experiments may be required.*