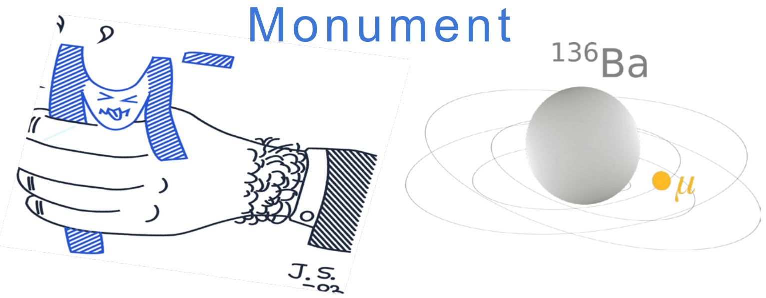
Muon capture measurements with ^{136}Ba target.

M.V. Fomina for the MONUMENT collaboration

The XXVII International Scientific Conference
of Young Scientists and Specialists (AYSS-2023)
30 October - 3 November 2023, Dubna



Overview

- Ordinary muon capture (OMC)
  - Motivation (OMC&DBD)
  - Fundamental concept
- MONUMENT experiment
- Experimental setup
- Measurement principle
- Observables. Total capture rate and partial rate
- Conclusions.

Ordinary muon capture (OMC). Motivation. 0νββ.

$0\nu\beta\beta$

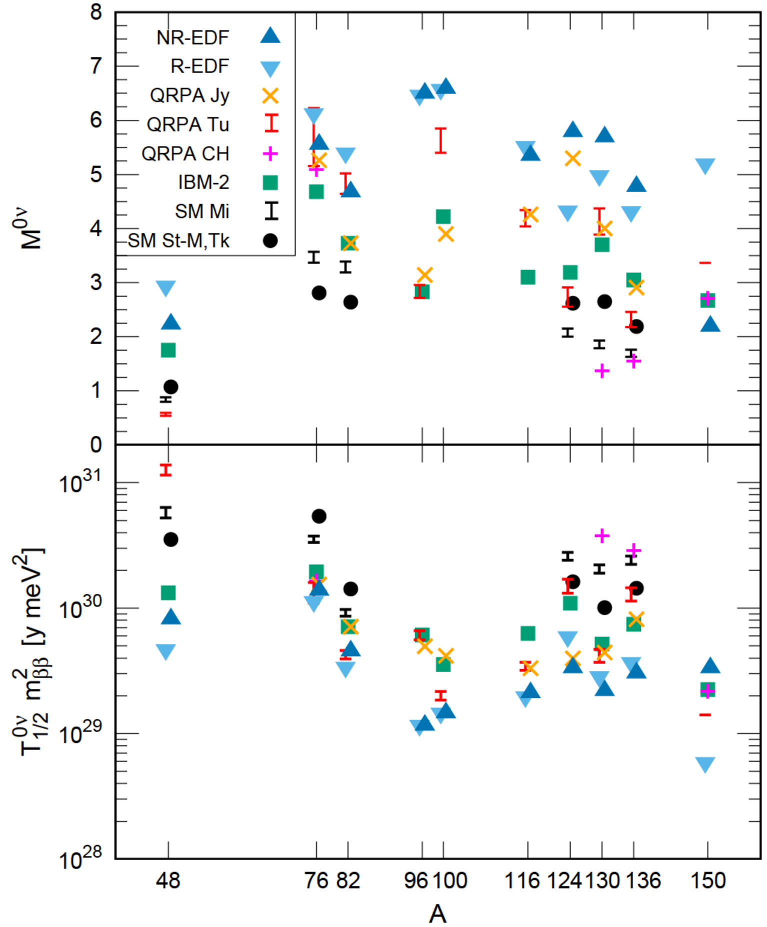
$${}^{A}_{Z}X \rightarrow {}_{Z\pm2}^{\ \ \ A}X + 2e^{\mp}$$

Involves momentum transfer $q \approx 100$ MeV

No restriction on angular momentum and parity change

OMC

$${}^{A}_{Z}X + \mu^{-} \rightarrow {}_{Z-1}^{\ \ \ A}X + \nu_{\mu}$$



J. Engel & J. Menendez Rep. Phys. Prog. 80 (2017) 046301

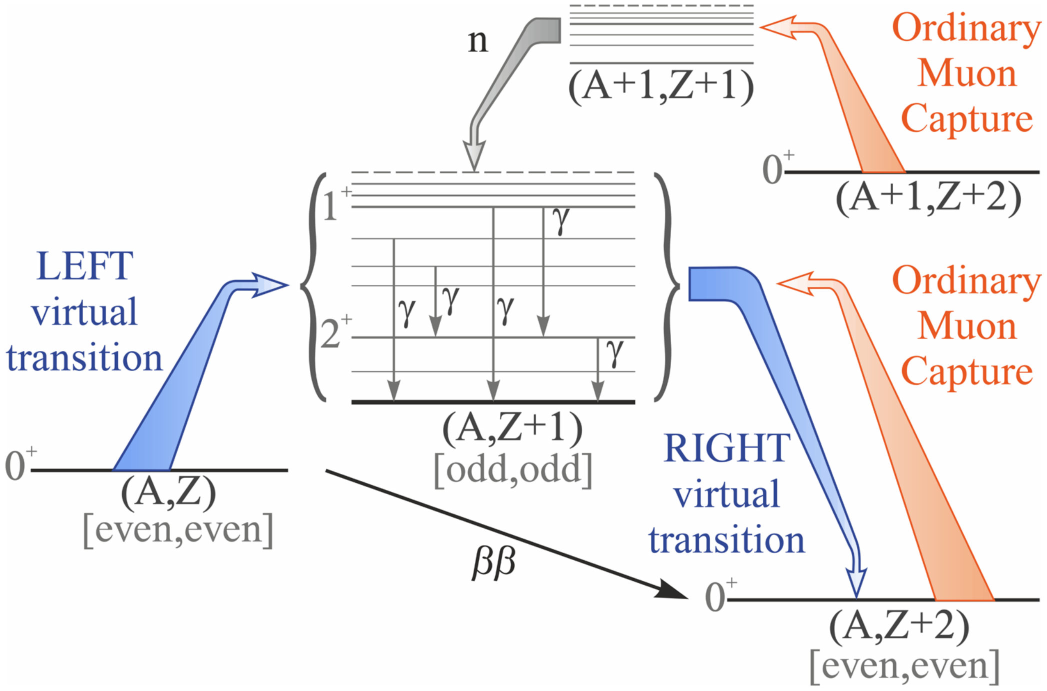
The half-life of the $0\nu\beta\beta$-decay is

$$\frac{1}{T_{1/2}} = G^{0\nu}(E_0, Z)|M^{0\nu}|^2|\langle m_{\beta\beta}\rangle|^2$$

$$\langle m_{\beta\beta}\rangle = \sum_i |U_{ei}|^2 e^{i\alpha_i} m_i$$

$$M^{0\nu} = -\frac{M_F}{g_A^2} + M_{GT} + M_T$$

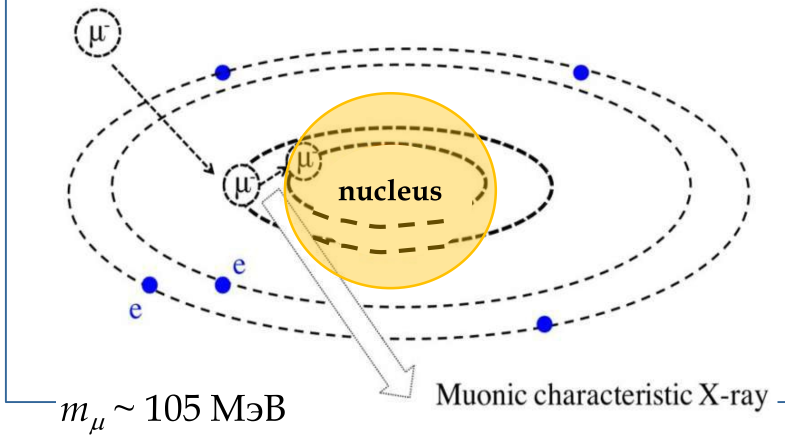
F. Simkovic et al. Phys. Rev. C 77 (2008) 045503



Ordinary muon capture (OMC). Motivation. 0νββ.

$0\nu\beta\beta$-decay candidate	Experiments	OMC target	Status
^{76}Ge	Gerda I/II, Majorana Demonstrator, LEGEND	^{76}Se	2004, 2021
^{48}Ca	TGV, NEMO3, Candles III	^{48}Ti	2002, 2023
^{106}Cd	TGV	^{106}Cd	2004
^{82}Se	NEMO3, SuperNEMO, Lucifer (R&D)	^{82}Kr	2019
^{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
^{136}Xe	nEXO, KamLAND2-Zen, NEXT, DARWIN, PandaX-III	^{136}Ba	2021
^{130}Te	Cuore 0/Cuore, SNO+	^{130}Xe	2019

Ordinary muon capture (OMC) with ^{136}Ba target. Fundamental concepts.



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

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

$\rightarrow (A, Z\text{-}1) + \gamma$ ^{136}Cs

$\rightarrow (A\text{-}1, Z\text{-}1) + \gamma + n$ ^{135}Cs

$\rightarrow (A\text{-}2, Z\text{-}1) + \gamma + 2n$ ^{134}Cs

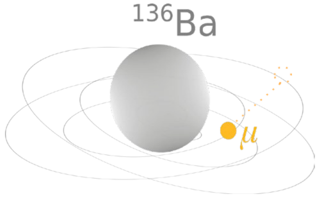
$\rightarrow (A\text{-}2, Z\text{-}2) + \gamma + n + p$ ^{135}Xe…

- Total OMC rate (λ_{cap})

$$\lambda_{\text{tot}} = 1/\tau = \boxed{\lambda_{\text{cap}}} + H \cdot \lambda_{\text{free}}$$

- Partial rate of excitations to level J (λ_j) following OMC $\lambda_j = Y_j \cdot \lambda_{\text{tot}}$

$$Y_j = \sum (I_i^\gamma)_{In} - \sum (I_i^\gamma)_{out} \text{ , where } I_i^\gamma = \frac{\boxed{S_i^\gamma}}{\eta_i\, \varepsilon \boxed{\sum_n I(K_n)}}$$



Observables:

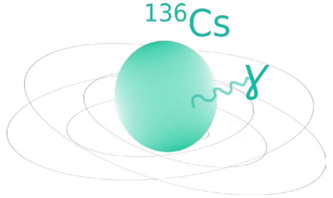
Intensity
μX-rays

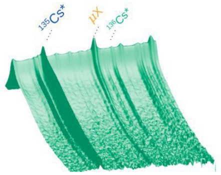
In: observables out: parameters extracted from data

Time evolution
^{135}Cs* γs

+ ^{135}Cs* + ….

Intensity
^{136}Cs* γs





Focus here: γ-line identification, intensity (S_i, I_i) and time evolution (τ, λ_{cap})

MONUMENT

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Experimental setup

PAUL SCHERRER INSTITUT

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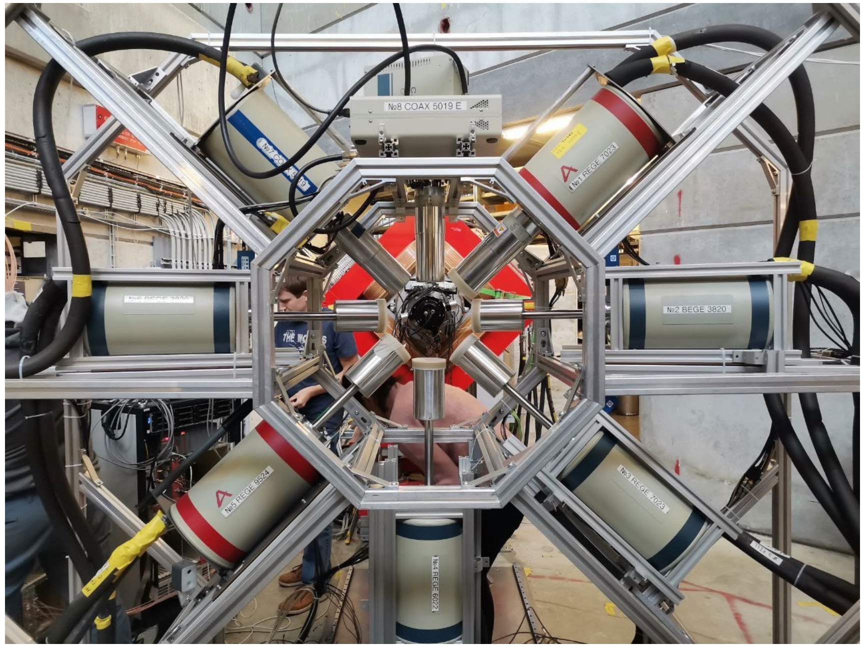
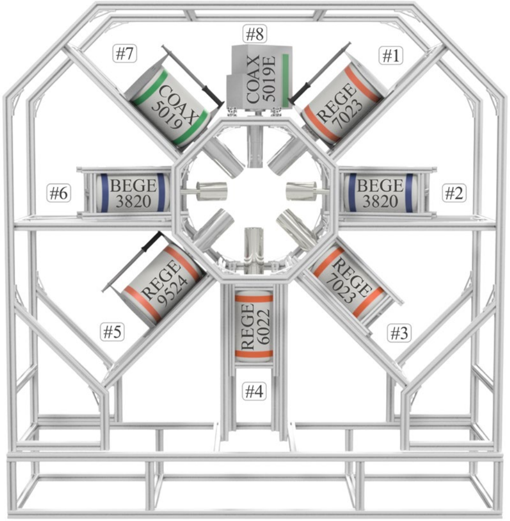
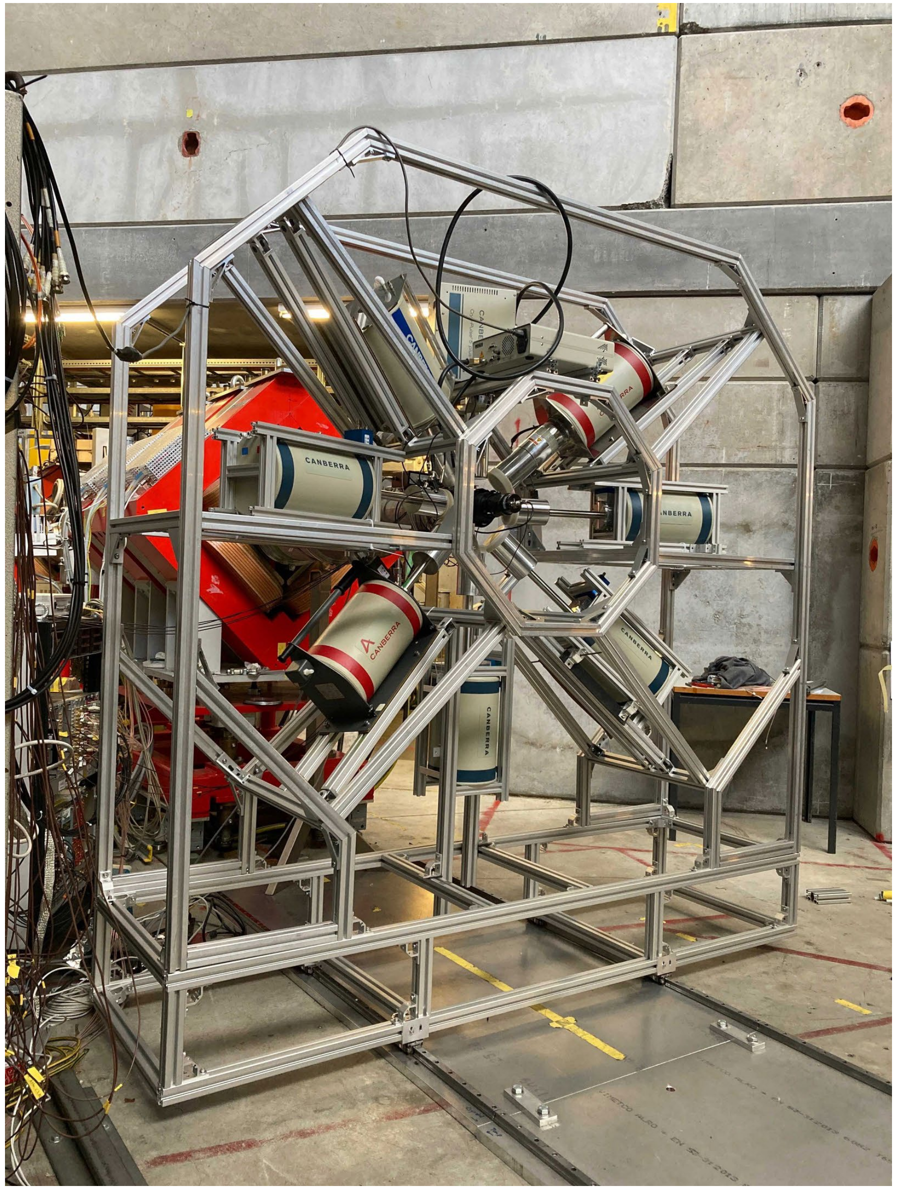


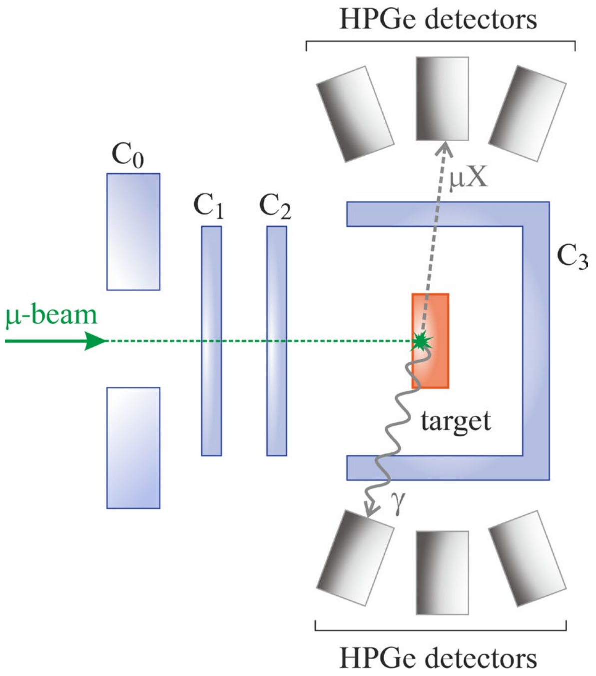


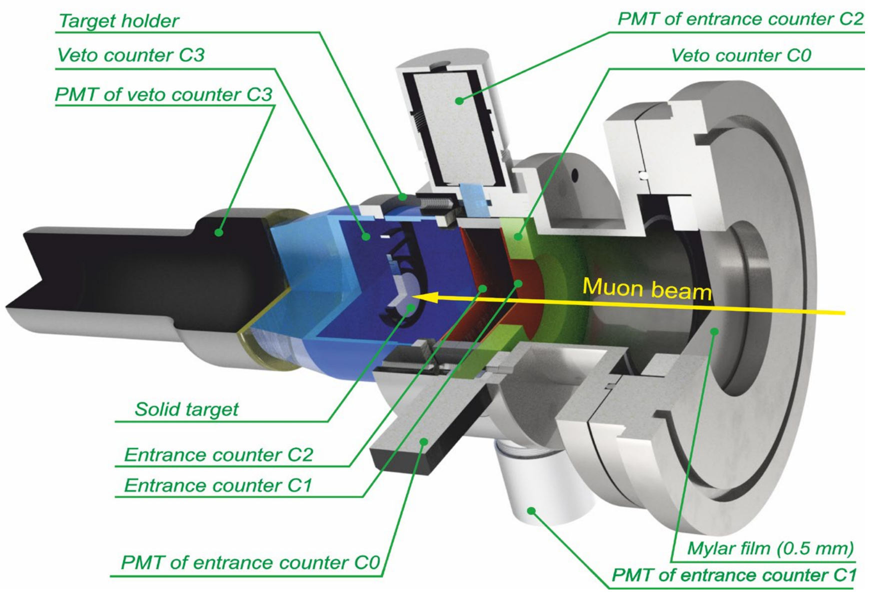


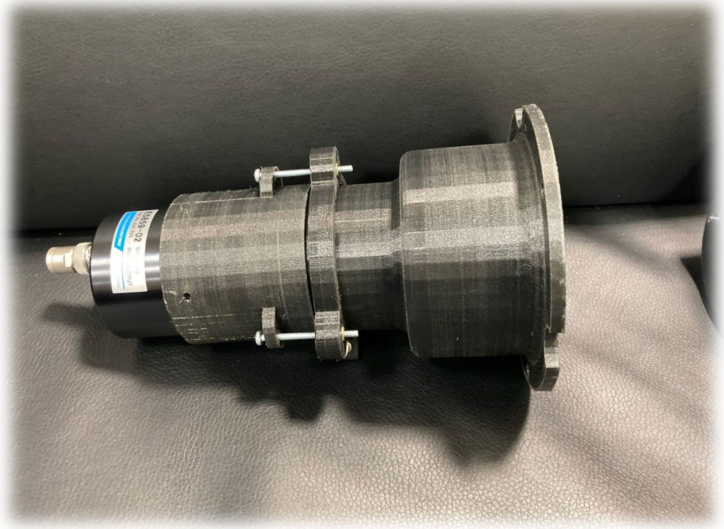
- ❑ **Aluminum frame** with the HPGe detectors mounted at a distance of about 12 cm from the target system
- ❑ **8 HPGe detectors**:
  - Four large-volume n-type Reverse Electrode coaxial Ge detectors (REGe detectors) with thin beryllium entrance windows (3 — PSI, 1 — TUM)
  - One large-volume p-type coaxial detector (COAX detector) with an electro-cooling unit (JINR)
  - Three relatively large-volume p-type Broad Energy BEGe detectors (2 — PSI, 1 — TUM)


C3 Counter
2500
OK
HV control voltage (250 - 4000 mV)
2500
DEC: 32768
C2 Counter
800
OK
HV control voltage (250 - 900 mV)
800
DEC: 10486
C1 Counter
759
OK
HV control voltage (250 - 900 mV)
C0 Counter
700
OK
HV control voltage (250 - 900 mV)
700
DEC: 9175

Experimental setup. Muon trigger system







The muon trigger system combined with the target unit consists of:

- an active muon veto counter **C0** (1 cm thickness), placed at the entrance of the target enclosure;
- two thin (0.5 mm) pass-through counters **C1** and **C2**;
- the actual target volume surrounded by a cup-like counter **C3**.

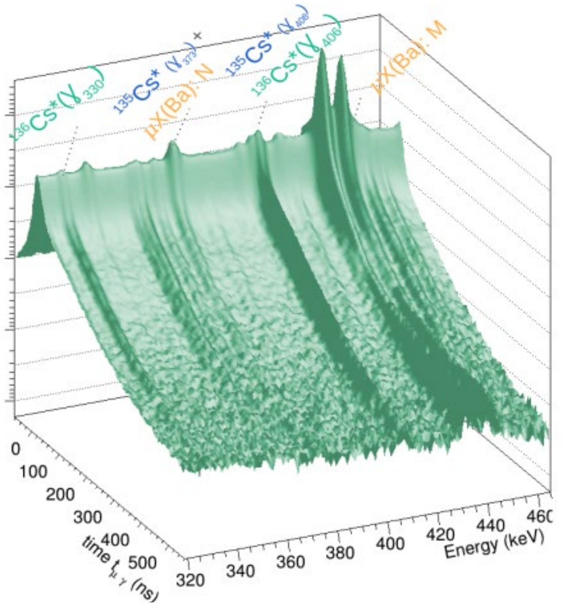
The four muon counters are defining μ-stop trigger

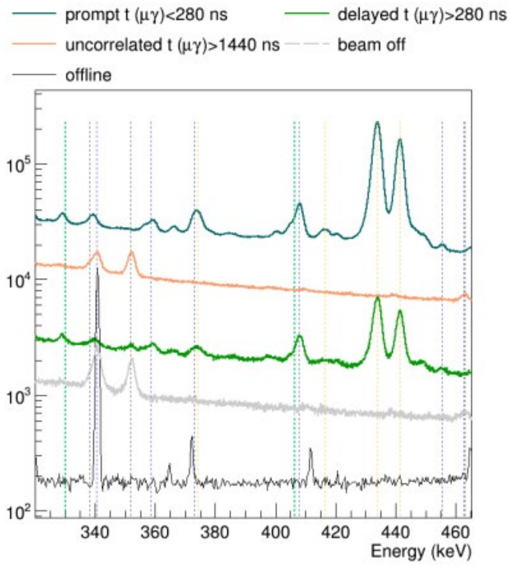
$$\mu_{\mathbf{stop}} = \overline{\mathbf{C0}} \wedge \mathbf{C1} \wedge \mathbf{C2} \wedge \overline{\mathbf{C3}}$$

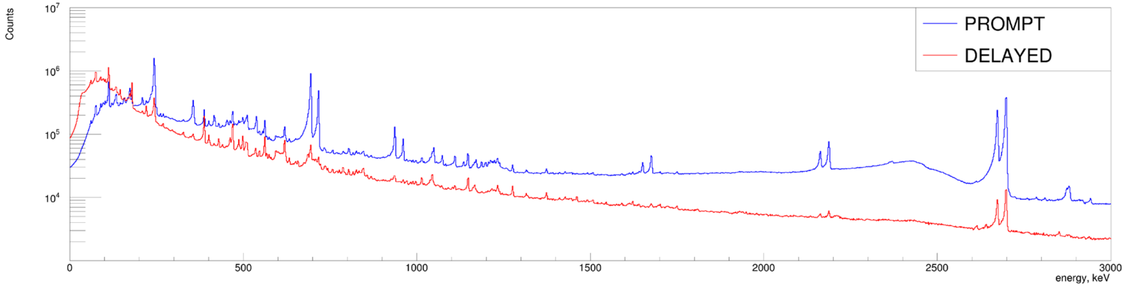
Using this trigger condition, the beam momentum ($\approx \mathbf{35\ MeV/c}$) and its focus point are tuned to maximize intensities of muonic X-rays from a target and minimize background from surrounding materials. Under optimal conditions more than 95% of data sample corresponded to muons stopped in the target. Typical μ_{stop} rate during the measurement campaign was around $\mathbf{3 \times 10^4\ s^{-1}}$.

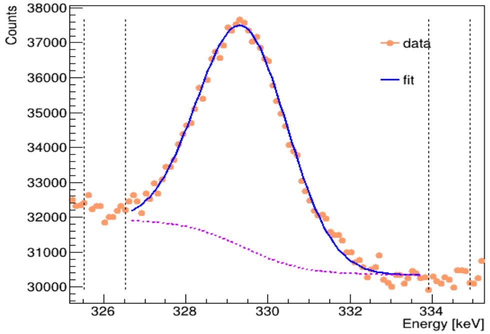
Also, we developed software that allows to set the PMTs' high voltage, hardware thresholds and logic schemes, all remotely, without interrupting the beam or data acquisition runs.

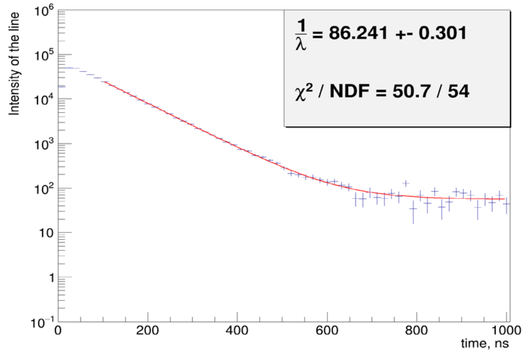
Measurement principle. Total muon capture.











I. Identification of γ-lines

HPGe detector events are classified by their dependence on the software trigger:

Correlated spectra: HPGe events occurring within selected time window following the software trigger ($t_{\mu_{stop}} \in (0\ \text{ns}, 1000\ \text{ns})$)

Prompt spectrum: characteristic μX rays ($t_{\mu_{stop}} < 100$ ns)

Delayed spectrum: the nuclear γ radiation following muon capture (μ^-, xn) reactions ($t_{\mu_{stop}} > 100$ ns)

Uncorrelated spectra: HPGe events occurring outside of the selected time window caused by any of the C counters ($t_{\mu_{stop}} > 1000$ ns)

Note: As far as each μ stopped in a target is followed by characteristic μX rays, the intensity of each spectral line reflects the number of μ stopped in the corresponding isotope. Therefore, μX spectra could be applied to normalize any measurements to amount of muons.

II. Analyzing of the time evolution of the individual γ-lines

The main method for determining of muon lifetime is to define the exponential time evolution of delayed γ-lines of OMC products:

- The measured γ-ray line intensities are histogrammed in two dimensions: energy and delay time $t_{\mu_{stop}}$
- Selection of an energy region with the identified γ-lines
- Fitting of the identified γ-lines
- Total muon capture rate $\boldsymbol{\Lambda_{cap}}$ is evaluated for each detector and each γ-line.
- Weighted average is then performed

Observables. Total capture rate of ^{136}Ba

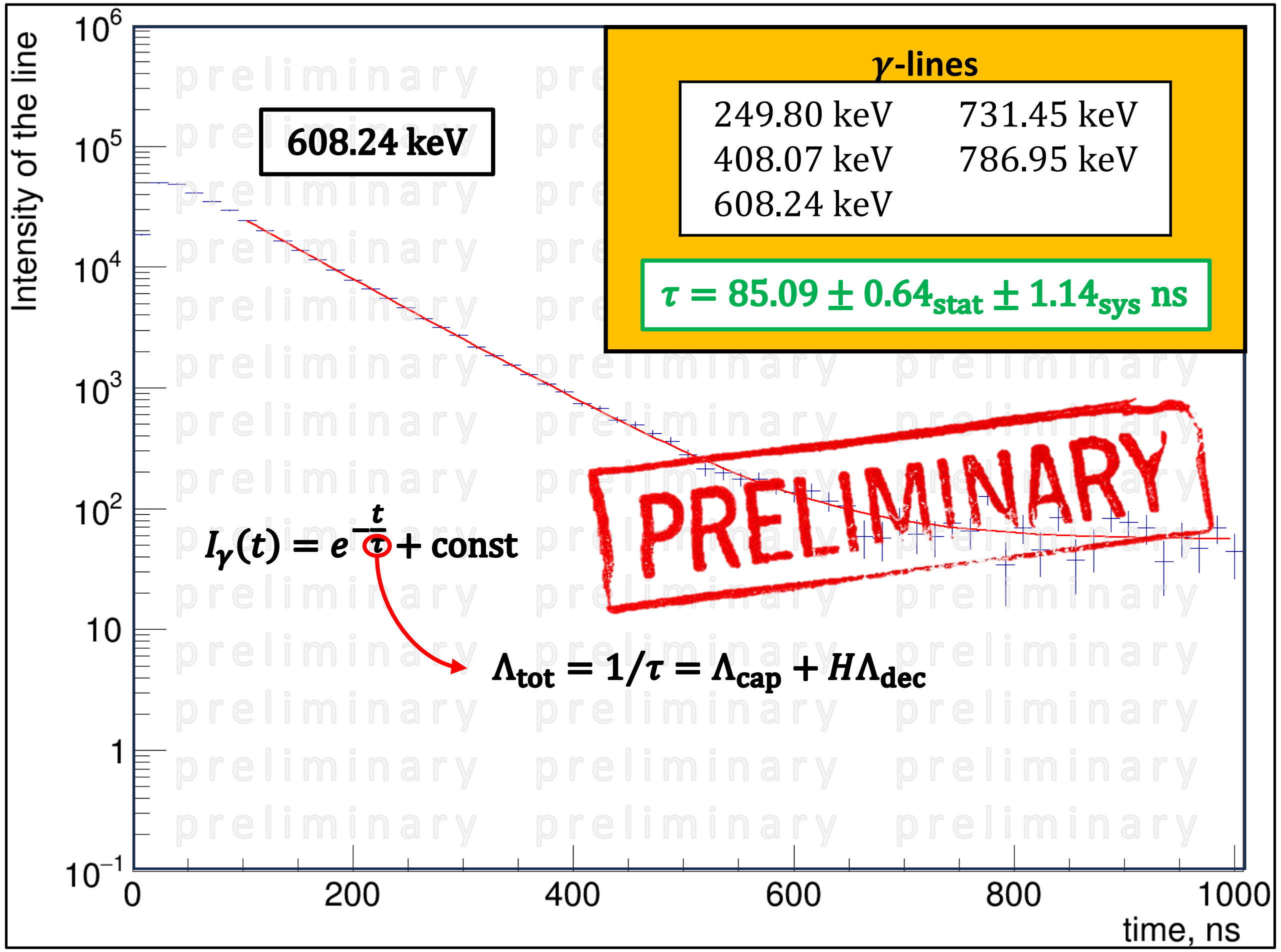
The total muon disappearance rate is

$$\Lambda_{tot} = \frac{1}{\tau} = \Lambda_{cap} + H\Lambda_{decay} \leftarrow$$

Λ_{cap} is total μ-capture rate,

Λ_{decay} is a free muon decay rate ($\mathbf{0.4552 \times 10^{-6}\ s^{-1}}$),

H is Huff factor, which is introduced to take into account, that phase space accessible for a muon on atomic **K**-shell is smaller than that for a muon on a free muon



608.24 keV

γ-lines

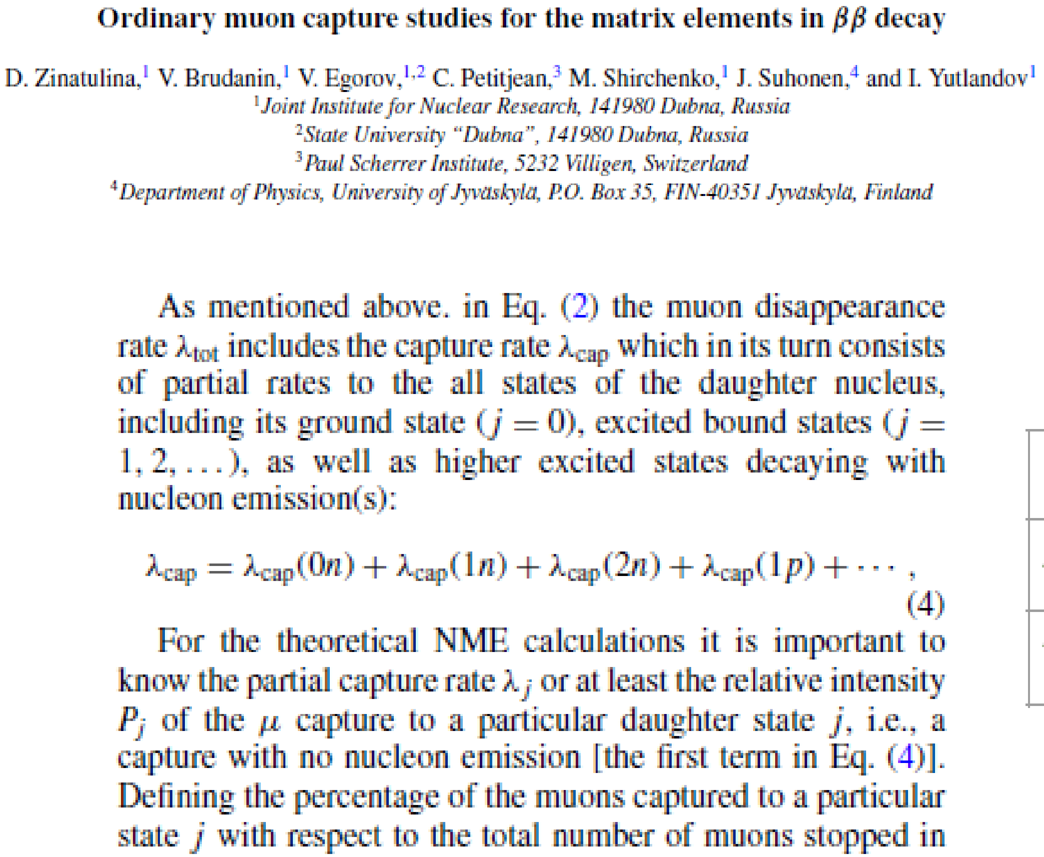
249.80 keV
408.07 keV
608.24 keV
731.45 keV
786.95 keV

$$\boldsymbol{\tau = 85.09 \pm 0.64_{stat} \pm 1.14_{sys}\ ns}$$

$$I_{\gamma}(t) = e^{-\frac{t}{\tau}} + \text{const}$$

$$\Lambda_{tot} = 1/\tau = \Lambda_{cap} + H\Lambda_{dec}$$

Partial rates.



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

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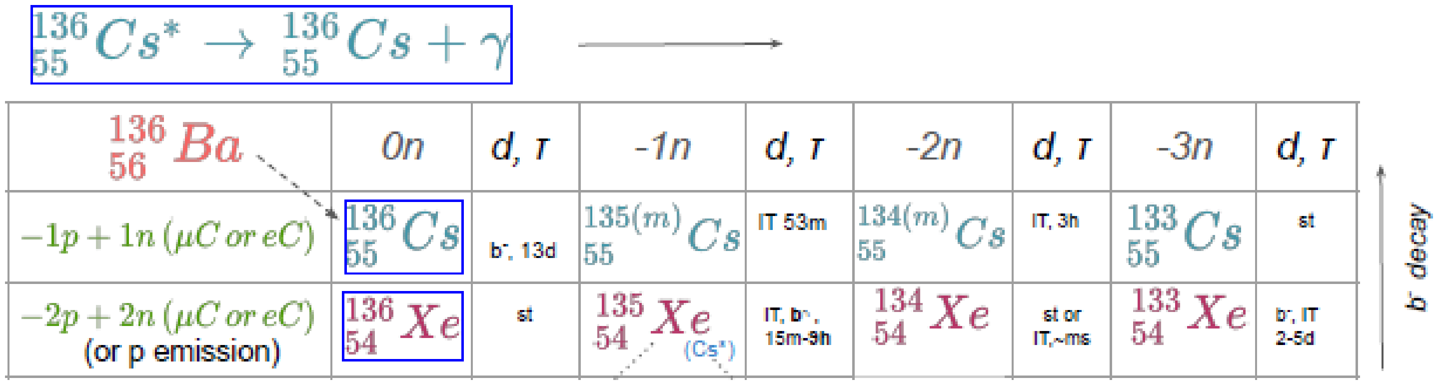
As mentioned above. in Eq. (2) the muon disappearance rate λ_{tot} includes the capture rate λ_{cap} which in its turn consists of partial rates to the all states of the daughter nucleus, including its ground state ($j = 0$), excited bound states ($j = 1, 2, \ldots$), as well as higher excited states decaying with nucleon emission(s):

$$\lambda_{\mathrm{cap}} = \lambda_{\mathrm{cap}}(0n) + \lambda_{\mathrm{cap}}(1n) + \lambda_{\mathrm{cap}}(2n) + \lambda_{\mathrm{cap}}(1p) + \cdots, \tag{4}$$

For the theoretical NME calculations it is important to know the partial capture rate λ_j or at least the relative intensity P_j of the μ capture to a particular daughter state j, i.e., a capture with no nucleon emission [the first term in Eq. (4)]. Defining the percentage of the muons captured to a particular state j with respect to the total number of muons stopped in



$$\boxed{{}^{136}_{55}Cs^* \rightarrow {}^{136}_{55}Cs + \gamma}$$

${}^{136}_{56}Ba$	0n	d, τ	-1n	d, τ	-2n	d, τ	-3n	d, τ
$-1p + 1n\,(\mu C\; or\; eC)$	$\boxed{{}^{136}_{55}Cs}$	b⁻, 13d	${}^{135(m)}_{55}Cs$	IT 53m	${}^{134(m)}_{55}Cs$	IT, 3h	${}^{133}_{55}Cs$	st
$-2p + 2n\,(\mu C\; or\; eC)$ (or p emission)	$\boxed{{}^{136}_{54}Xe}$	st	${}^{135}_{54}Xe$ (Cs*)	IT, b⁻, 15m-9h	${}^{134}_{54}Xe$	st or IT,~ms	${}^{133}_{54}Xe$	b⁻, IT 2-5d

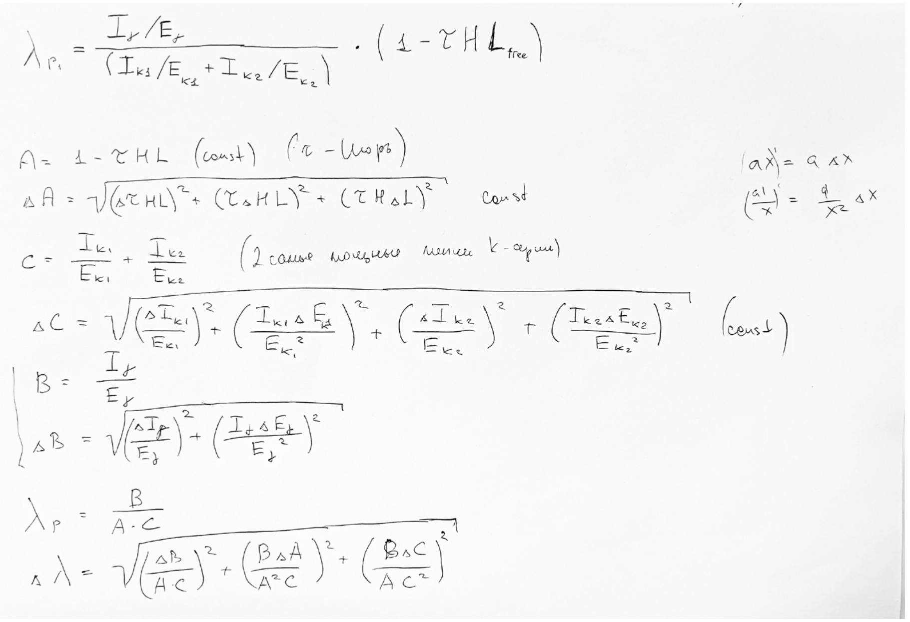
D. Zinatulina, V. Brudanin, V. Egorov, C. Petitjean, M. Shirchenko, J. Suhonen, and I. Yutlandov, Ordinary muon capture studies for the matrix elements in ββ decay, Phys. Rev. C 99, 024327 - 2019

Partial rates (^{135}Cs)

E(level) (keV)	Jπ(level)	$T_{1/2}$(level)	E(γ) (keV)	I(γ)	Final level	
0.0	7/2+	$2.3\times10^{+6}$ y *3* % β^- = 100				
249.767 *4*	5/2+	0.28 ns *8*	249.770 *4*	100	0.0	7/2+
408.026 *5*			158.260 *4* 408.009 *8*	81 *3* 100 *3*	249.767 0.0	5/2+ 7/2+
608.153 *8*	5/2+		200.19 *10* 358.384 *9* 608.151 *12*	0.40 *16* 7.6 *3* 100 *3*	408.026 249.767 0.0	 5/2+ 7/2+
786.838 *13*	11/2+		786.836 *13*	100	0.0	7/2+
981.396 *19*			373.13 *10* 573.36 *4* 731.634 *21*	28 *5* 8.7 *13* 100 *5*	608.153 408.026 249.767	5/2+ 5/2+
1062.385 *13*			454.2 *2* 654.296 *23* 812.635 *22* 1062.41 *2*	5.1 *10* 64 *3* 100 *3* 5.8 *12*	608.153 408.026 249.767 0.0	5/2+ 5/2+ 7/2+
1133?			1133?	100	0.0	7/2+
1192?			1192.2?	100	0.0	7/2+
1358?			1358?	100	0.0	7/2+
1632.9	19/2-	53 m *2* % IT = 100	846.1	100	786.838	11/2+

Analyzing of the correlated spectra for calculation of partial rates

- Searching for possible excited levels of daughter nuclei
- Fitting the spectra lines (for populated levels) considering detectors efficiencies and deexcitation process branching
- Normalization to number of muons stops
- Calculation of partial rates λ_j



$$\lambda_{p_1} = \frac{I_\gamma / E_\gamma}{(I_{k1}/E_{k1} + I_{k2}/E_{k2})} \cdot (1 - \tau H L_{free})$$

$A = 1 - \tau H L$ (const) (τ – [illegible])

$\Delta A = \sqrt{(\Delta\tau H L)^2 + (\tau \Delta H L)^2 + (\tau H \Delta L)^2}$ const

$(ax)' = a \Delta x$

$\left(\frac{a}{x}\right)' = \frac{a}{x^2} \Delta x$

$C = \frac{I_{k_1}}{E_{k_1}} + \frac{I_{k2}}{E_{k2}}$ (2 самые мощные линии k-серии)

$\Delta C = \sqrt{\left(\frac{\Delta I_{k1}}{E_{k1}}\right)^2 + \left(\frac{I_{k1}\Delta E_{k1}}{E_{k_1}^2}\right)^2 + \left(\frac{\Delta I_{k2}}{E_{k2}}\right)^2 + \left(\frac{I_{k2}\Delta E_{k2}}{E_{k2}^2}\right)^2}$ (const)

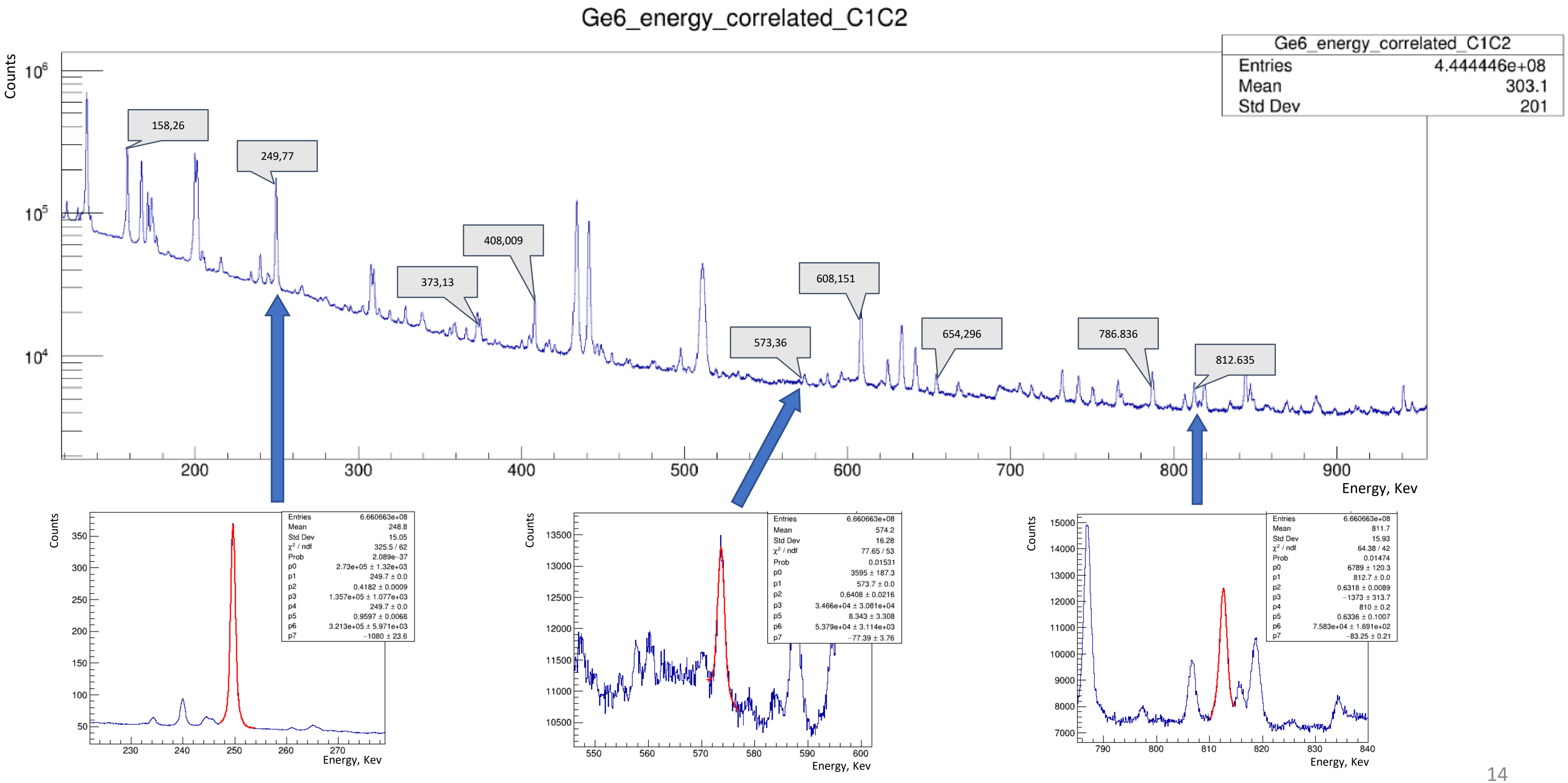
$B = \frac{I_\gamma}{E_\gamma}$

$\Delta B = \sqrt{\left(\frac{\Delta I_\gamma}{E_\gamma}\right)^2 + \left(\frac{I_\gamma \Delta E_\gamma}{E_\gamma^2}\right)^2}$

$\lambda_p = \frac{B}{A \cdot C}$

$\Delta\lambda = \sqrt{\left(\frac{\Delta B}{A \cdot C}\right)^2 + \left(\frac{B \Delta A}{A^2 C}\right)^2 + \left(\frac{B \Delta C}{A C^2}\right)^2}$

Partial rates. The work is ongoing…



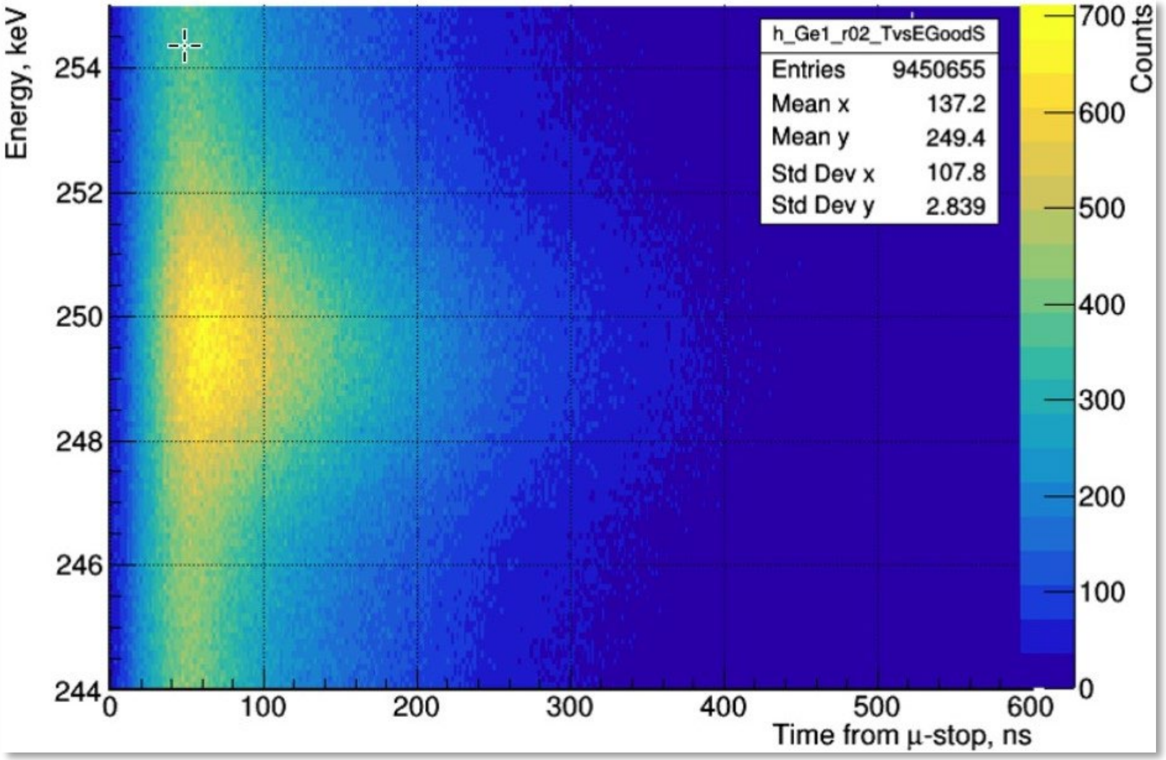
Conclusions

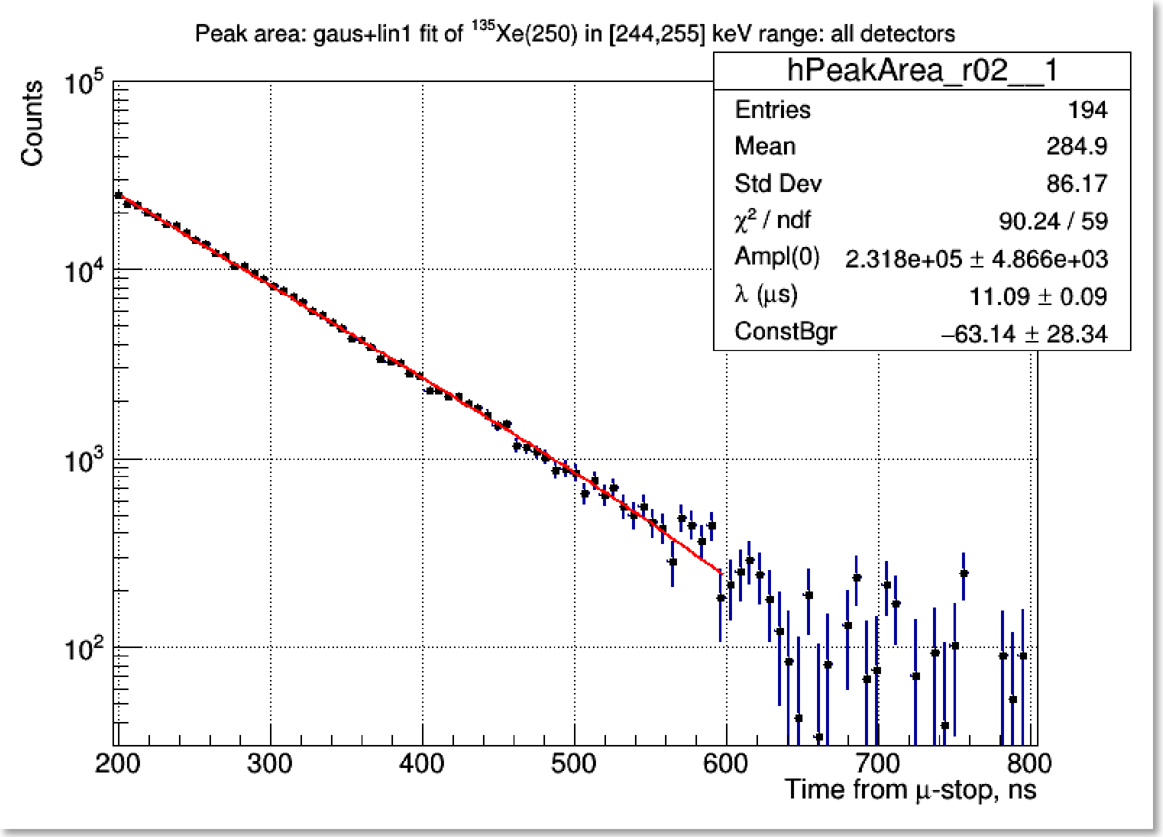
- OMC is a powerful tool for testing the nuclear models and NME calculations. It is based on experimental technique that has been successfully developed since many years
- Data analysis is ongoing. We expect the final results on the total and partial muon capture rates in ^{136}Ba to be available soon
- An intensive multi-year PSI beam research program **is ongoing**

Thank you for attention!

(E, t)-distribution of the correlated events following μ-capture in ^{136}Ba

Preliminary





Time evolution of the 249.7 keV γ-line following OMC in ^{136}Ba.
The corresponding total muon disappearance time is $\Lambda_{tot} = 11.1\ \mu s^{-1}$, and the mean life-time $\tau_\mu = 90$ ns.

Target	**^{136}Ba**
Sample form	^{136}BaCO$_3$ powder (95.27%)
Mass	2 g
Diameter	20 mm
Thickness	~ 4 mm
Muon momentum	38 MeV/c
Irradiation time	~ 138 hours
Time between beam stop and offline measurement	22 hours
Offline measurement time	168.5 hours

Isotopic composition of ^{nat}Ba:

- ^{132}Ba (0,10 %)
- ^{134}Ba (2,42 %)
- ^{135}Ba (6,59 %)
- ^{136}Ba (7,85 %)
- ^{137}Ba (11,23 %)
- ^{138}Ba (71,70 %)