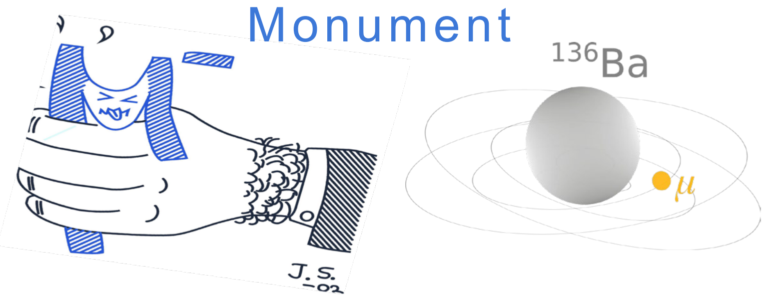
Muon capture measurements with ^{136}Ba target.

M.V. Fomina for the MONUMENT collaboration



The LXXIV International Conference
Nucleus-2024: Fundamental problems and applications
1-5 Jule 2024, Dubna, Russia

Overview

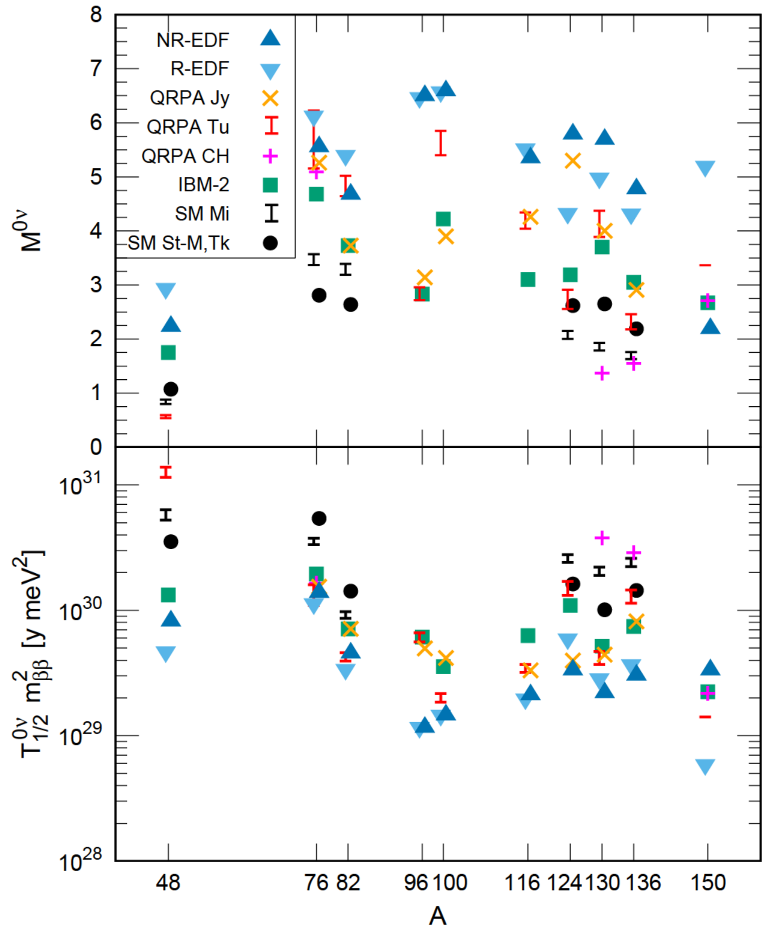
- ➢Ordinary muon capture (OMC)
  - Motivation (OMC&DBD)
  - Fundamental concept
- ➢MONUMENT experiment
- ➢Experimental setup
- ➢Measurement principle
- ➢Observables. Total capture rate and partial rate
- ➢Conclusions.

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

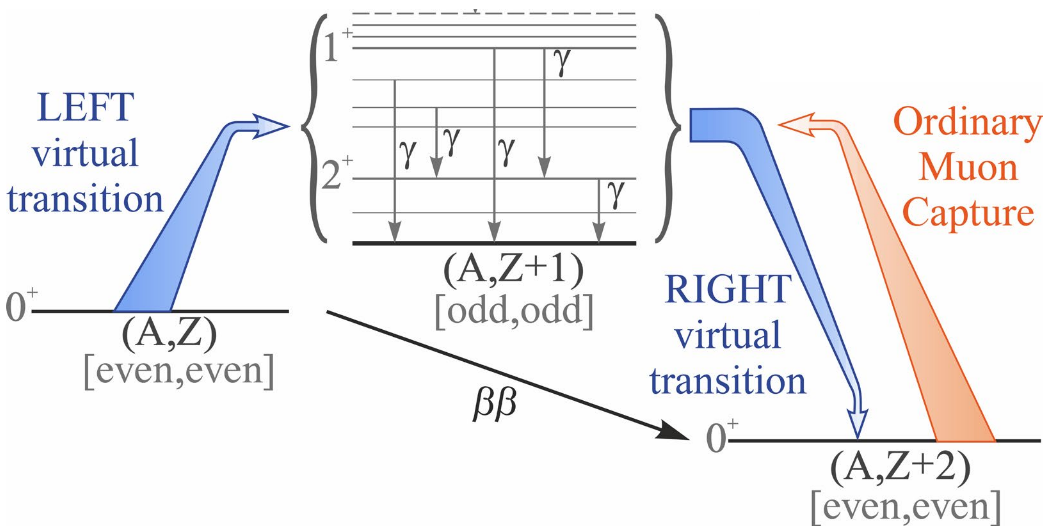
The half-life of the $0\nu\beta\beta$-decay is

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

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

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

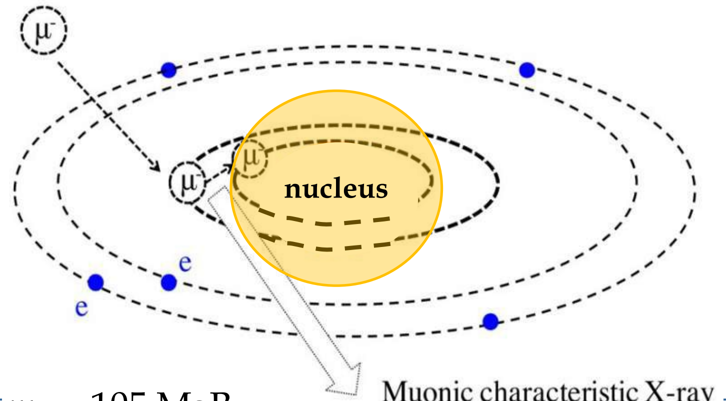
F. Simkovic et al. Phys. Rev. C 77 (2008) 045503



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.



$m_\mu \sim 105$ MэВ

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

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

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

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

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

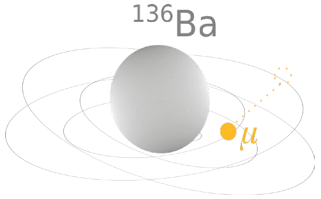
$\rightarrow (A\text{-}2, Z\text{-}2) + \gamma + n + p$ ^{135}Xe…

- Total OMC rate (λ_{cap})

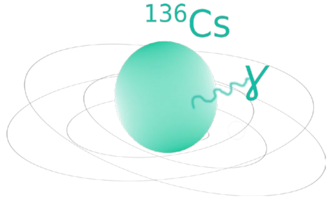
$$\lambda_{\text{tot}} = 1/\tau = \lambda_{\text{cap}} + H \cdot \lambda_{\text{free}}$$

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

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



In: observables
out: parameters extracted from data



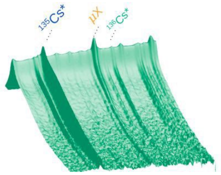
Observables:

Intensity
μX-rays

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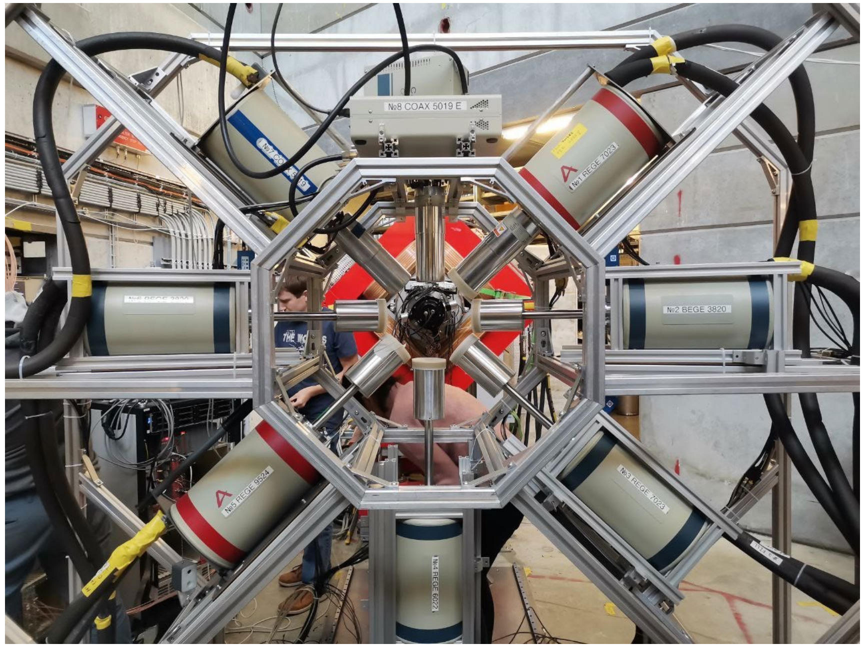
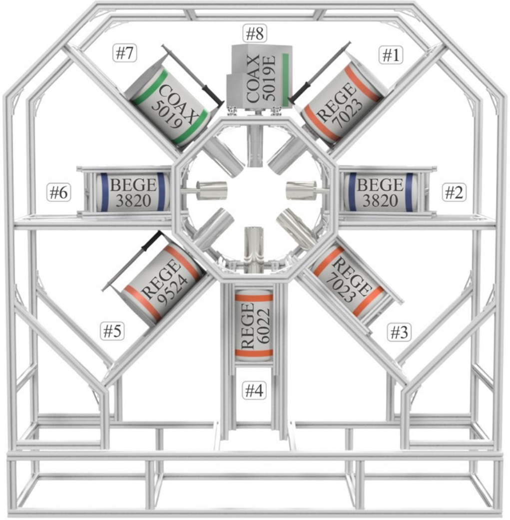
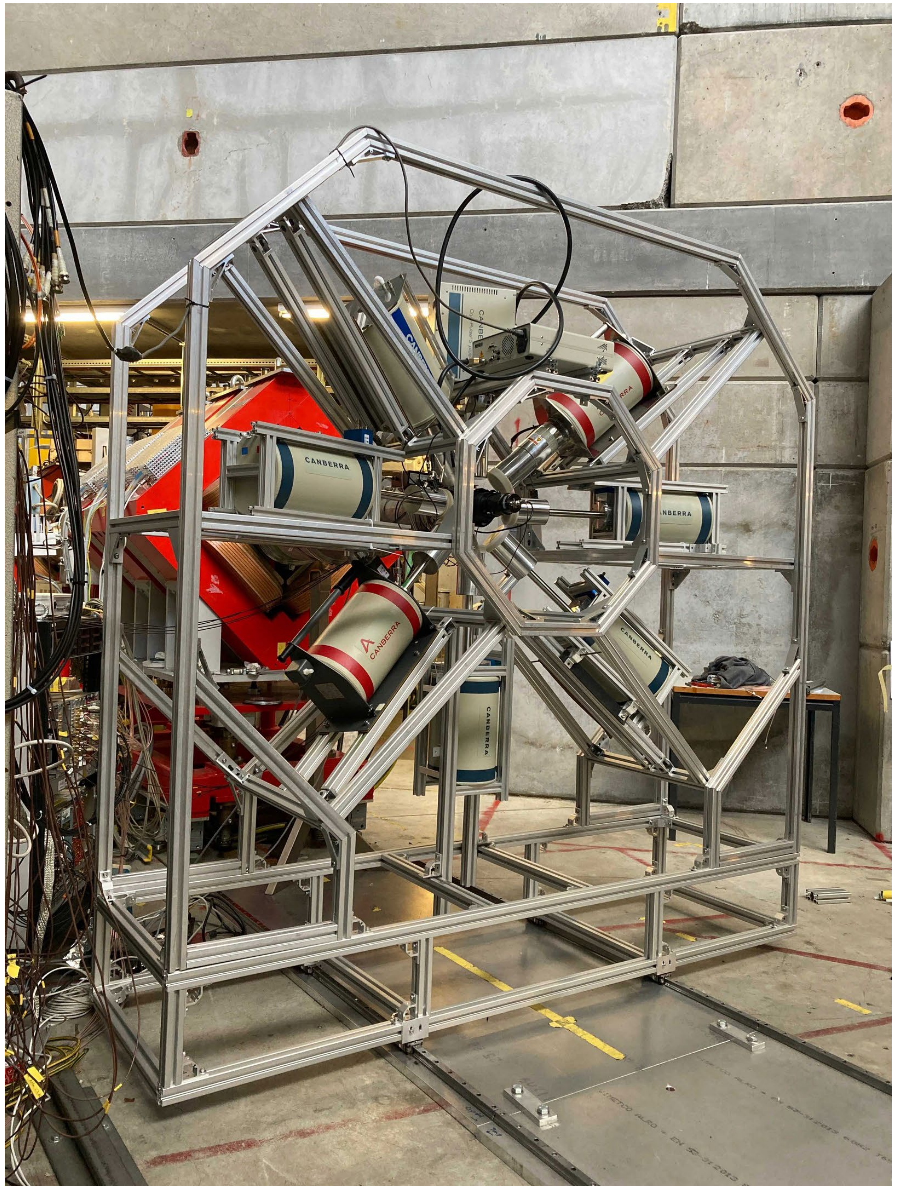
C3 Counter
2500
HV control voltage (250 - 4000 mV)
2500
DEC: 32768
C2 Counter
800
HV control voltage (250 - 900 mV)
800
DEC: 10486
C1 Counter
759
HV control voltage (250 - 900 mV)
C0 Counter
700
HV control voltage (250 - 900 mV)
700
DEC: 9175

Experimental setup

PAUL SCHERRER INSTITUT

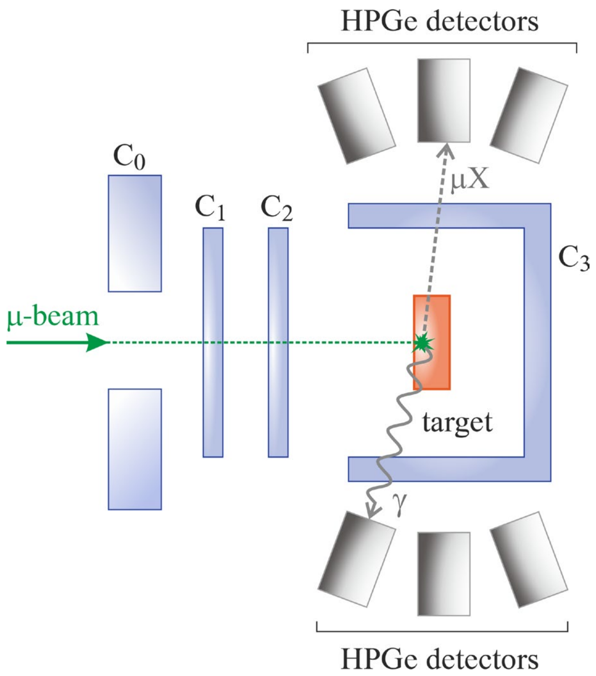


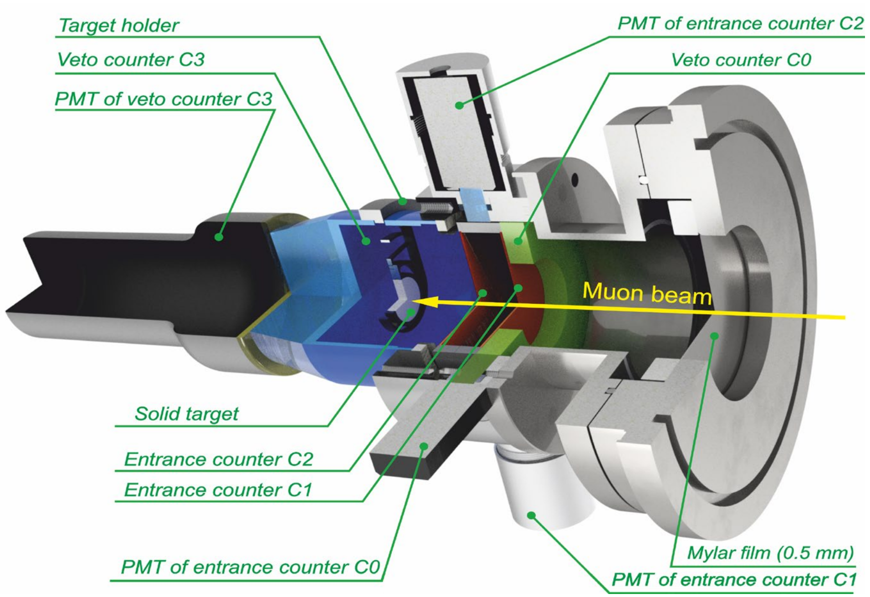


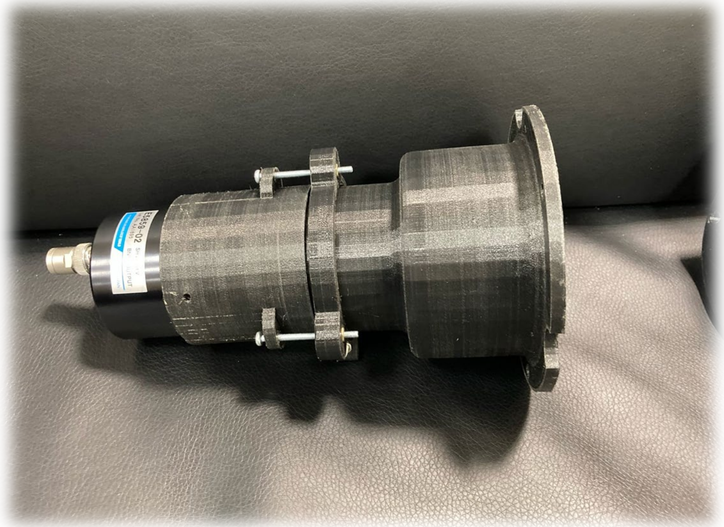


- **Aluminum frame** with the HPGe detectors mounted at a distance of about 12 cm from the target system
- **8 HPGe detectors**:
    - Four large-volume n-type Reverse Electrode coaxial Ge detectors (REGe detectors) with thin beryllium entrance windows (3 — PSI, 1 — TUM)
    - One large-volume p-type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

Experimental setup. Muon trigger system







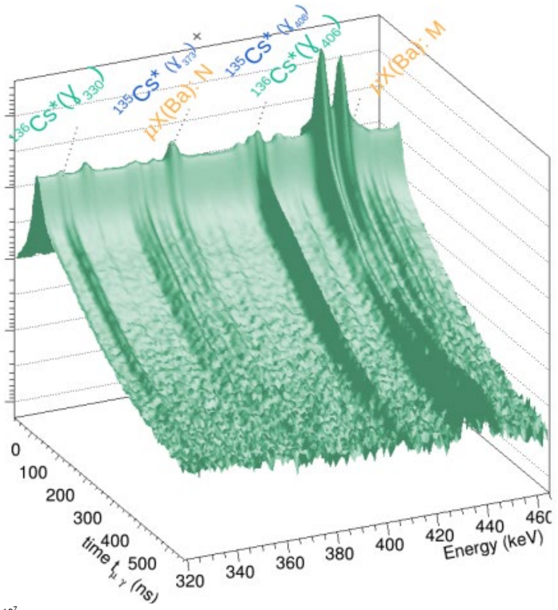
The muon trigger system combined with the target unit consists of:

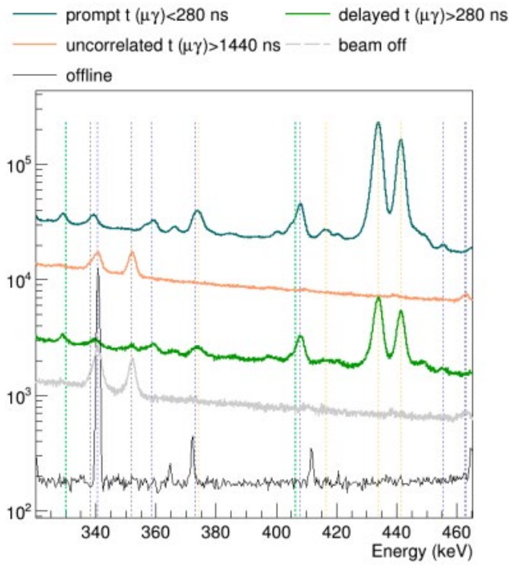
- an active muon veto counter **C0** (10 mm thickness), placed at the entrance of the target enclosure;
- two thin (0.5 mm) pass-through counters **C1** and **C2**;
- the actual target volume surrounded by a cup-like counter **C3**.

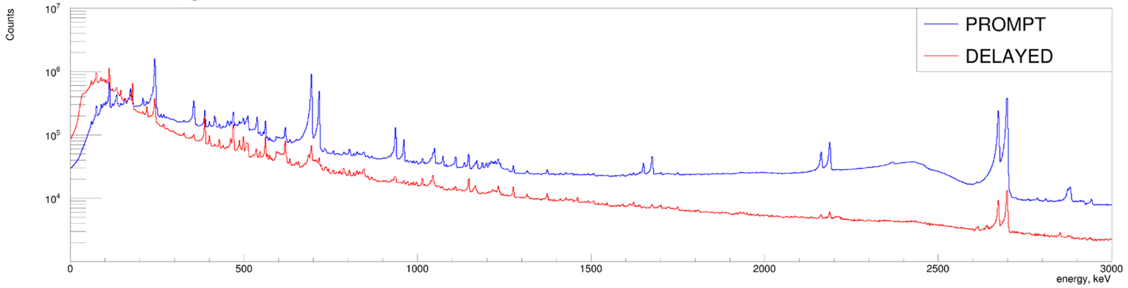
The four muon counters are defining μ-stop trigger

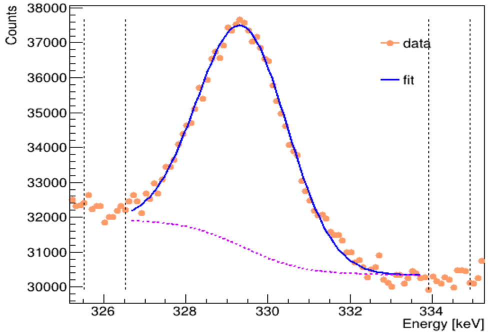
$$\mu_{\text{stop}} = \overline{\text{C0}} \wedge \text{C1} \wedge \text{C2} \wedge \overline{\text{C3}}$$

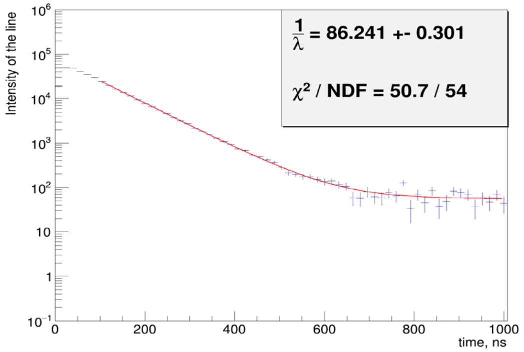
Measurement principle. Total muon capture.











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 ($t_{\mu_{stop}} \in (0\text{ ns}, 1440\text{ ns})$)

Prompt spectrum: characteristic μX rays ($t_{\mu_{stop}} < 280$ ns)

Delayed spectrum: the nuclear γ radiation following muon capture (μ^-, xn) reactions ($t_{\mu_{stop}} > 280$ ns)

Uncorrelated spectra: HPGe events occurring outside of the selected time window caused by any of the C counters ($t_{\mu_{stop}} > 1440$ 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

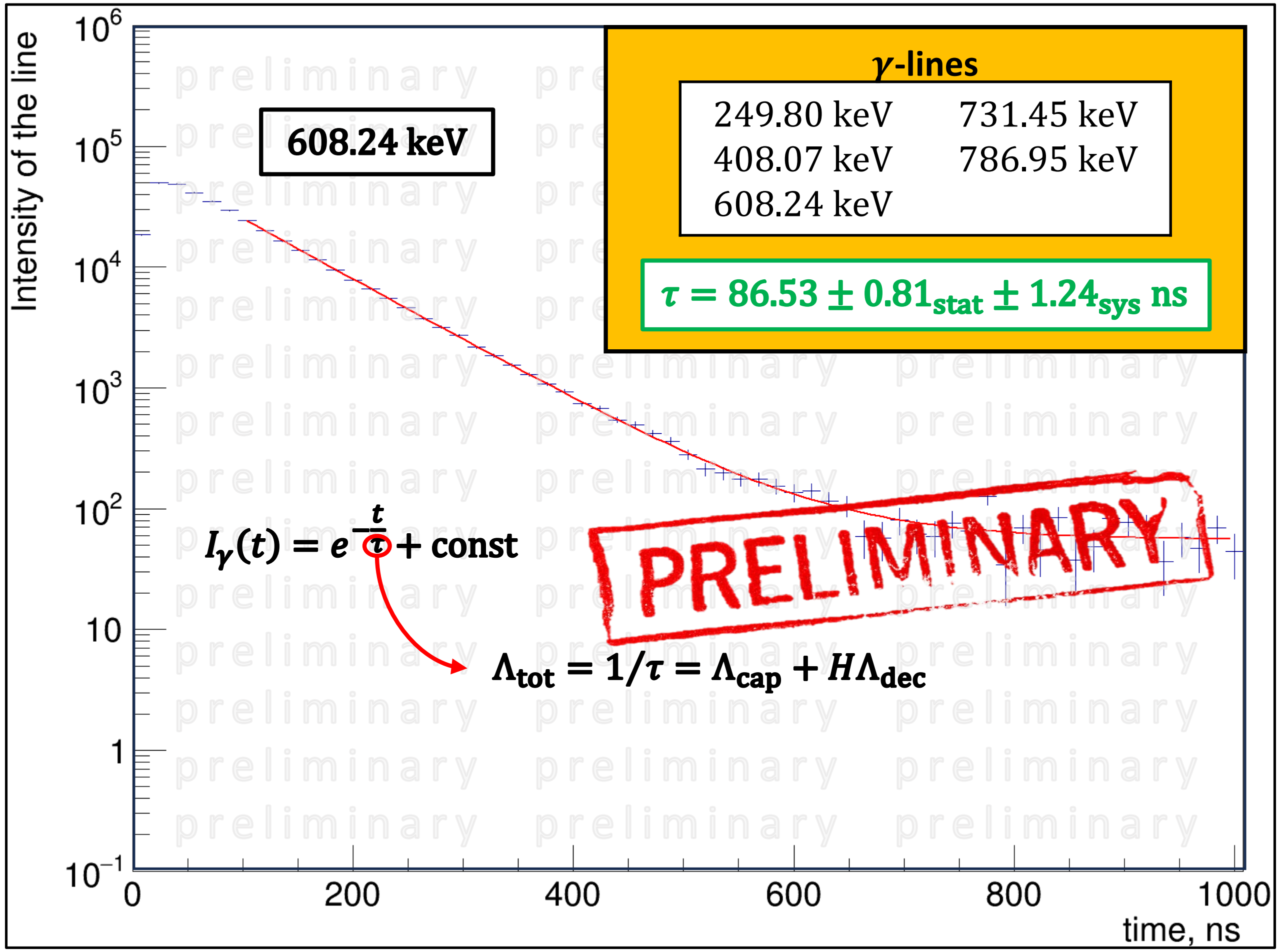
The total muon disappearance rate is

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

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 free muon



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 ($j = 1, 2, \dots$), as well as higher excited states decaying with nucleon emission(s):

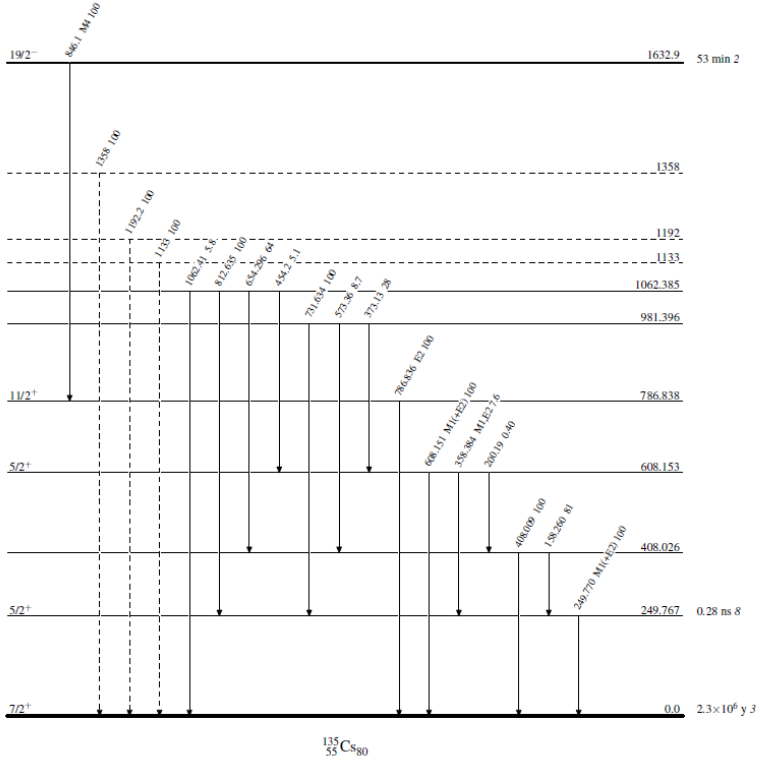
$$\lambda_{cap} = \lambda_{cap}(0n) + \lambda_{cap}(1n) + \lambda_{cap}(2n) + \lambda_{cap}(1p) + \cdots , \quad (4)$$

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

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

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

b⁻ decay



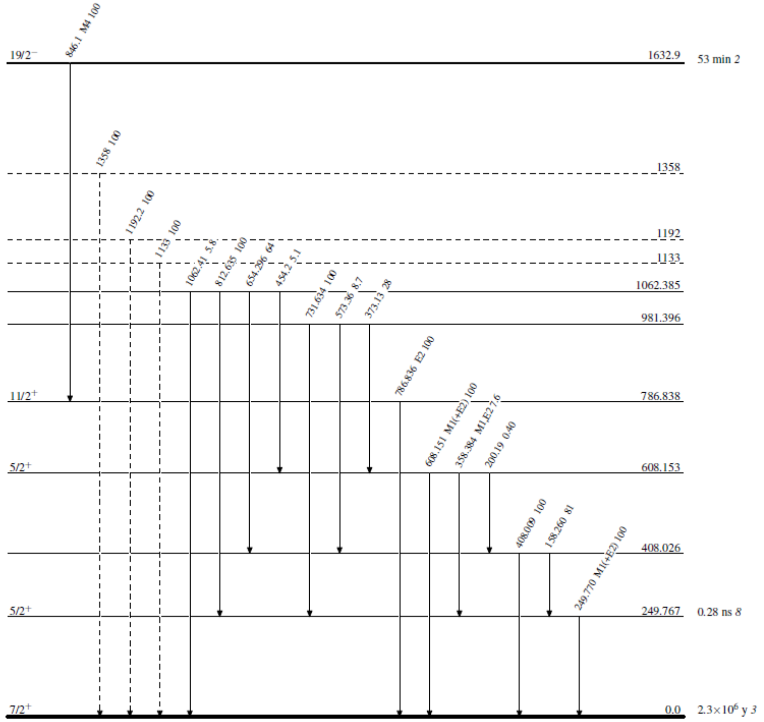
D. Zinatulina, V. Brudanin, V. Egorov, C. Petitjean, M. Shirchenko, J. Suhonen, and I. Yutlandov, Ordinary muon capture studies for the matrix elements in ββ decay, Phys. Rev. C 99, 024327 - 2019

Partial rates (^{135}Cs)

E(level) (keV)	Jπ(level)	T1/2(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+

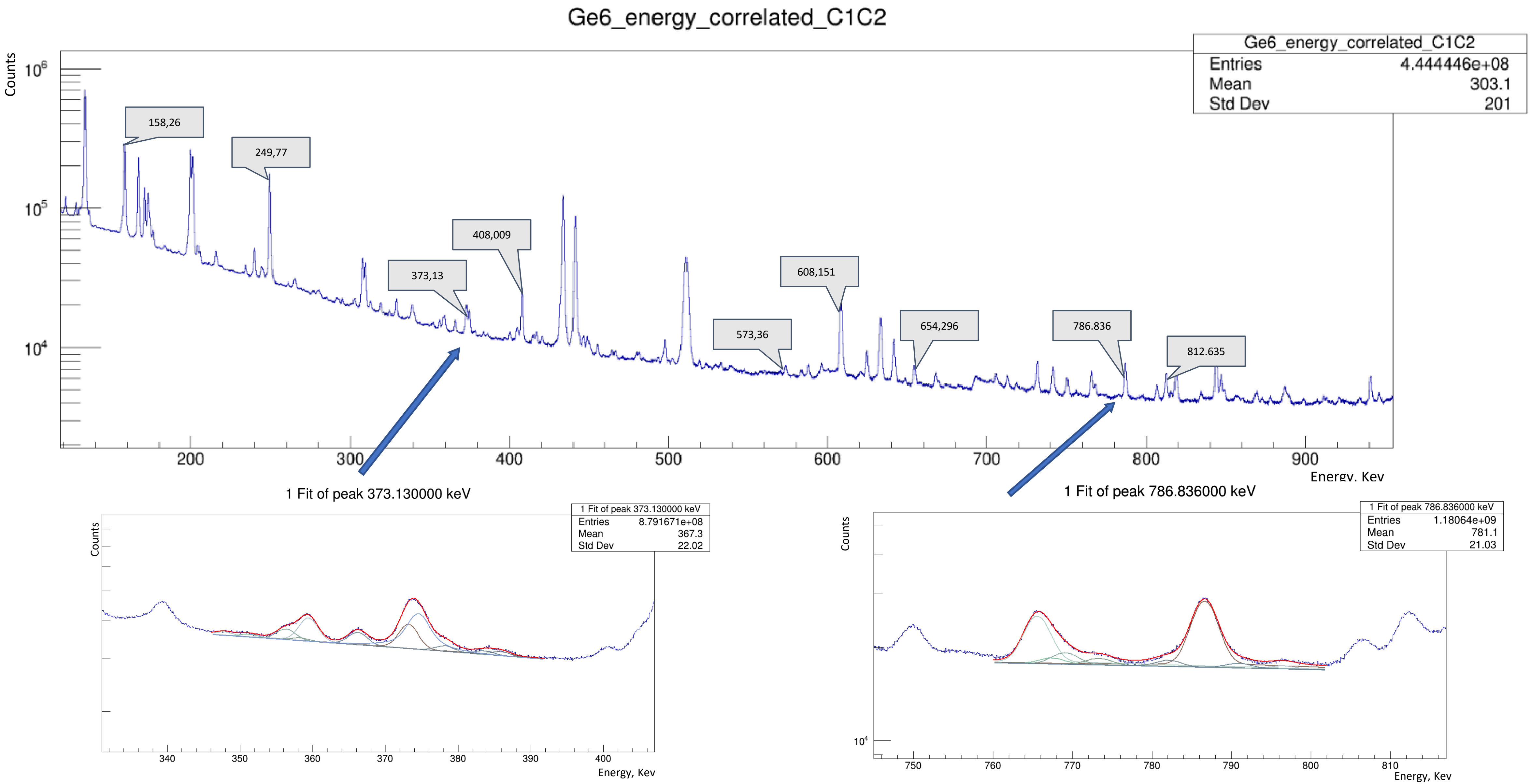
Analyzing of the correlated spectra for calculation of partial rates

- 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



$^{135}_{55}Cs_{80}$

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

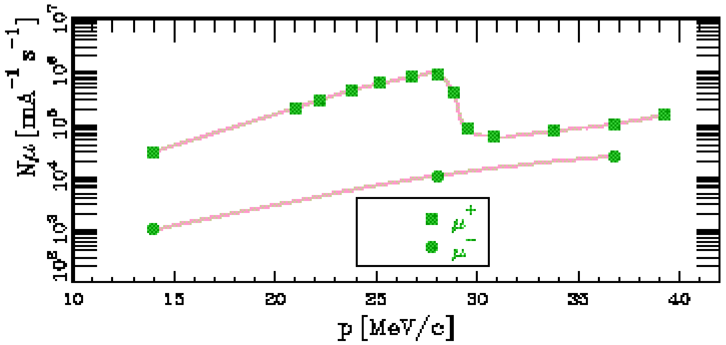
- Data analysis is ongoing. We expect the final results on the total and partial muon capture rates in ^{136}Ba to be available soon.

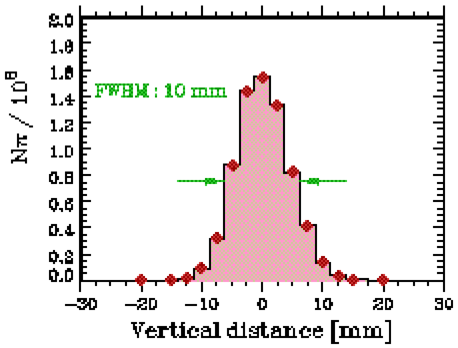
Thank you for attention!

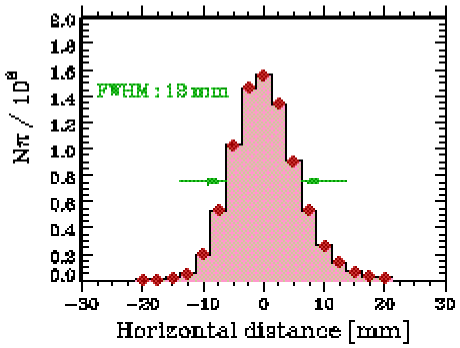
Target	^{136}Ba
Sample form	$^{136}BaCO_3$ powder (95.27%)
Mass	2 g
Diameter	20 mm
Thickness	~ 4 mm
Muon momentum	38 MeV/c
Irradiation time	~ 138 hours
Time between beam stop and offline measurement	22 hours
Offline measurement time	168.5 hours

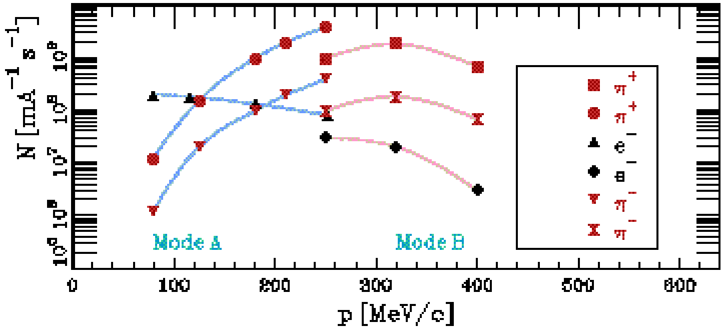
Isotopic composition of ^{nat}Ba:

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









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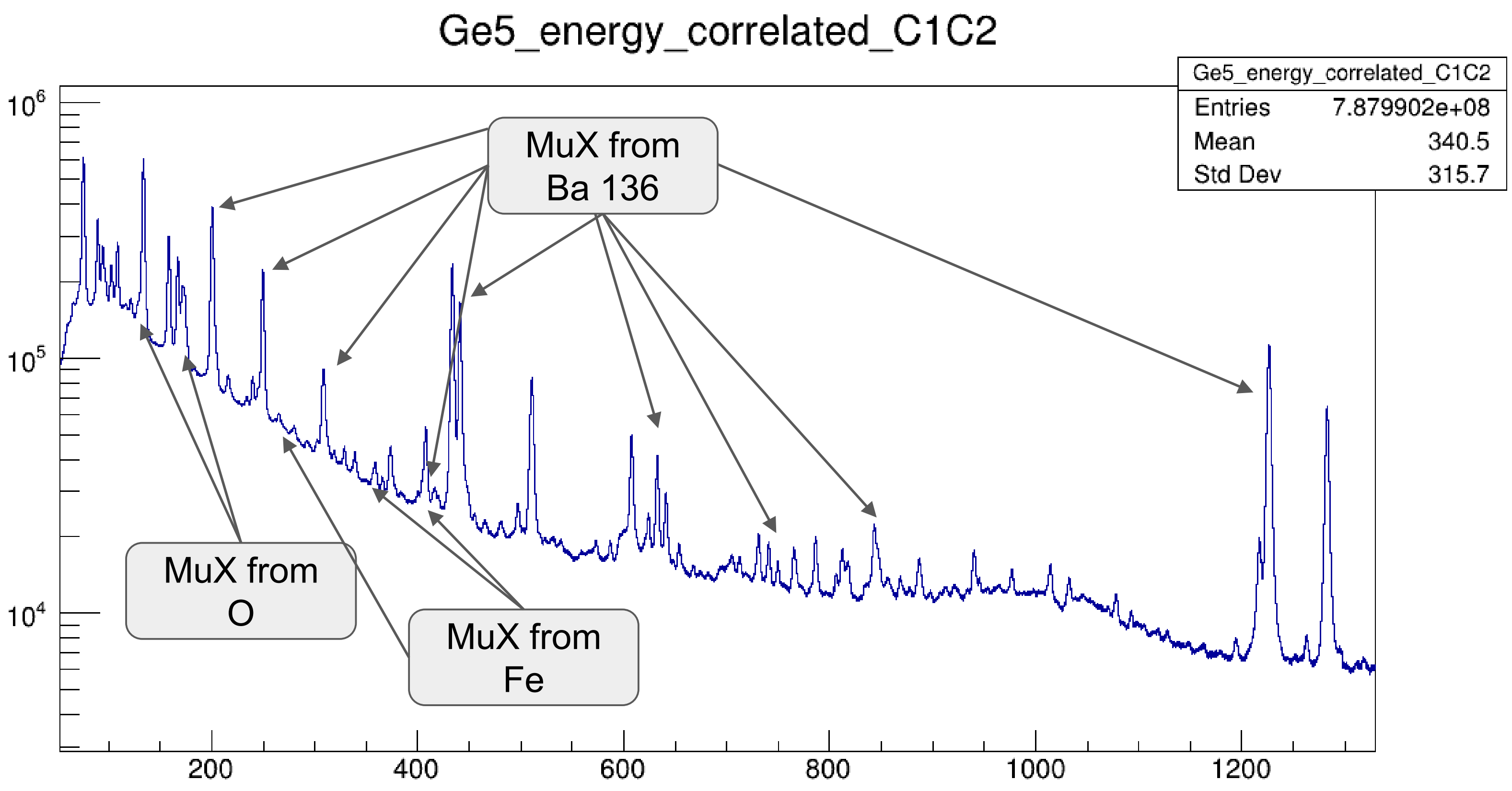

Ge5_energy_correlated_C1C2
Ge5_energy_correlated_C1C2
Entries 7.879902e+08
Mean 340.5
Std Dev 315.7
MuX from Ba 136
MuX from O
MuX from Fe
10^6
10^5
10^4
200
400
600
800
1000
1200