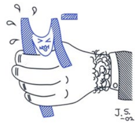
BVR 57: Progress Report R-20-01.1



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

G.R. Araujo[1], D. Bajpai[2], L. Baudis[1], V. Belov[3], E. Bossio[4], A. Bystryakov[3], T.E. Cocolios[6], H. Ejiri[7], M. Fomina[3], I.H. Hashim[8], M. Heines[6], K. Gusev[3,4], L. Jokiniemi[9], S. Kazartsev[3,10], A. Knecht[11], E. Mondragon[4,12], Z.W. Ng[8], F. Othman[8], I. Ostrovskiy[13], **N. Rumyantseva**[3,4], M. Schwarz[4], S. Schönert[4], A. Shehada[3], E. Sushenok[3], M. Shirchenko[3], E. Shevchik[3], Yu. Shitov[14], J. Suhonen[15], S.M. Vogiatzi[6], C. Vogl[4], C. Wiesinger[4,12], I. Zhitnikov[3] and D. Zinatulina[3,10]

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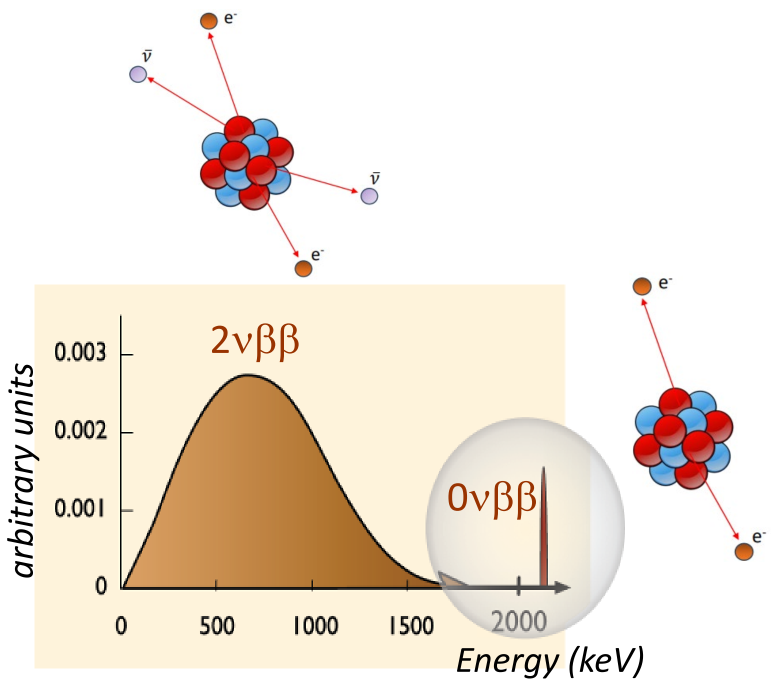
Rumyantseva N. | OMC4DBD | Open Users Meeting BVR57, 4.02.2026

Motivation



2νββ decay observed in several isotopes

^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128,130}Te, ^{136}Xe, ^{150}Nd, ^{238}U

Detection **0νββ** would:

- Prove neutrinos are Majorana in nature
- Lepton-Number-Violating (LNV) process → matter-antimatter asymmetry of the universe
- Probe the absolute neutrino mass scale and neutrino mass ordering

Experimental observable | *Nuclear physics (isotope properties)* | *Neutrino properties*

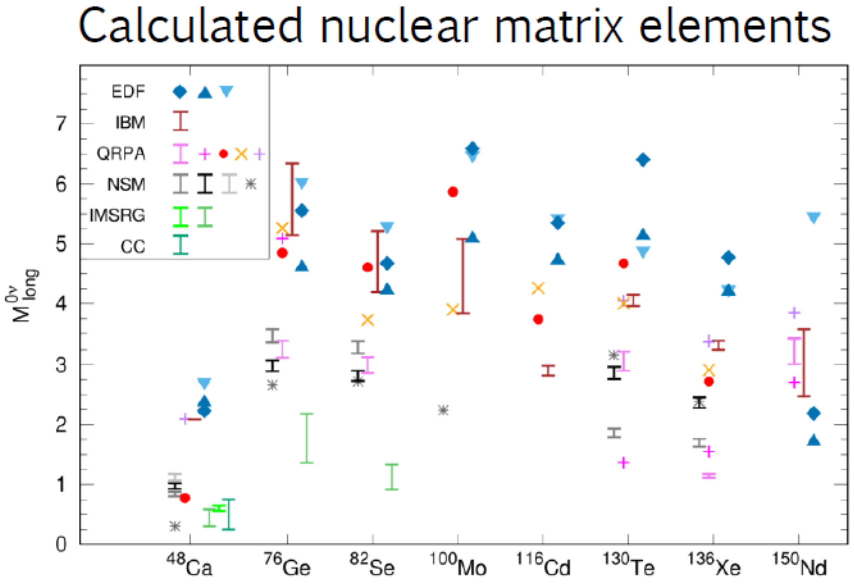
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\,|M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Half-life | Phase space (~Q⁵) | Nuclear matrix element (NME)

Majorana neutrino mass

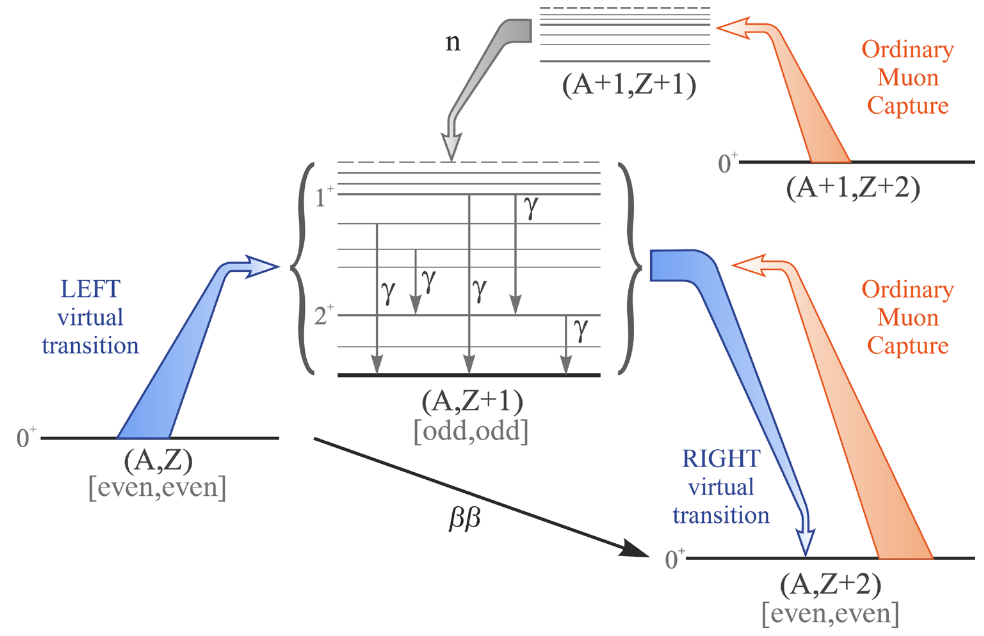
$$m_{\beta\beta} = \sum_{i=1}^{3} U^2_{ei} m_i$$

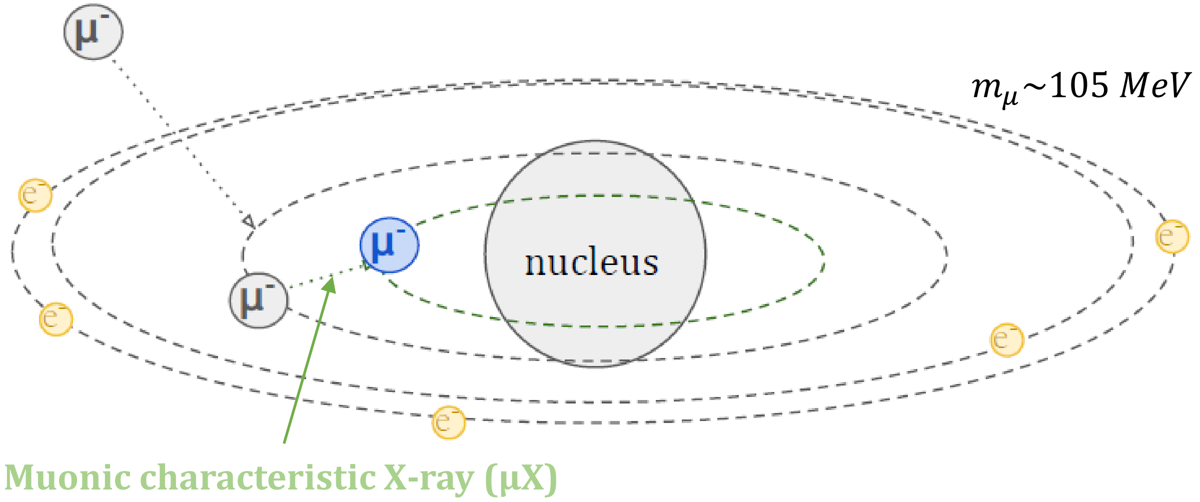
Nuclear matrix element (NME): Large theoretical uncertainties, much recent progress



Rev. Mod. Phys. 95, 025002 (2023)

Ordinary Muon Capture (OMC)





$$\mu^- \rightarrow e^- + \nu_e + \nu_\mu$$

$(\tau_{dec} \approx 2.2\ \mu s)$

(A, Z) + μ^- → (A, Z-1)* + ν_μ

→(A, Z-1)+ γ

→(A-1, Z-1) + γ +n

→(A-2, Z- 1)+γ+2n

→ (A-2, Z-2) + γ + n + p

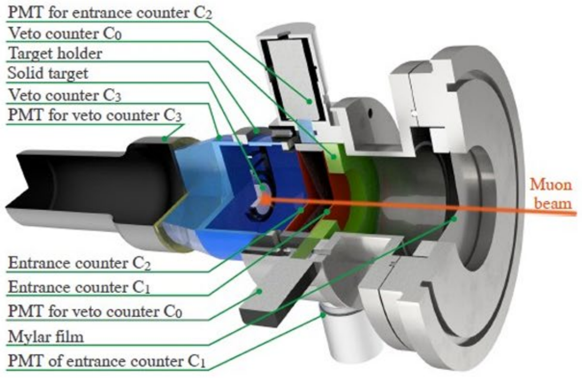
→ ...

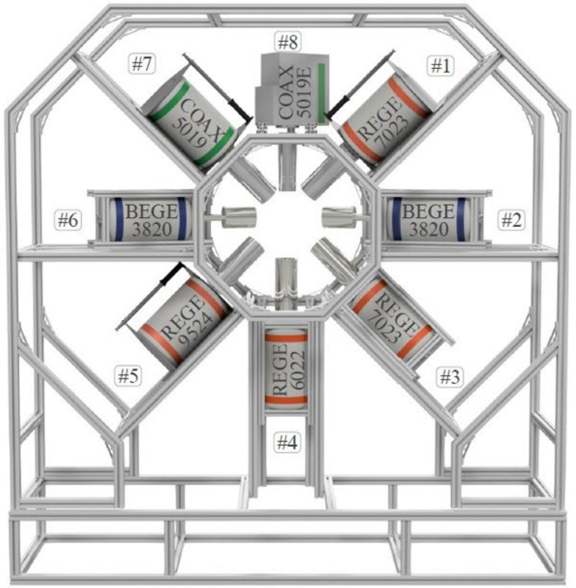
- Muonic cascades (muxrays.jinr.ru)
- High momentum transfer (up to 100 MeV) – High-lying states population
- γ-radiation following OMC in targets
- Yields of short-lived RI during exposure

Campaigns 2021-2023

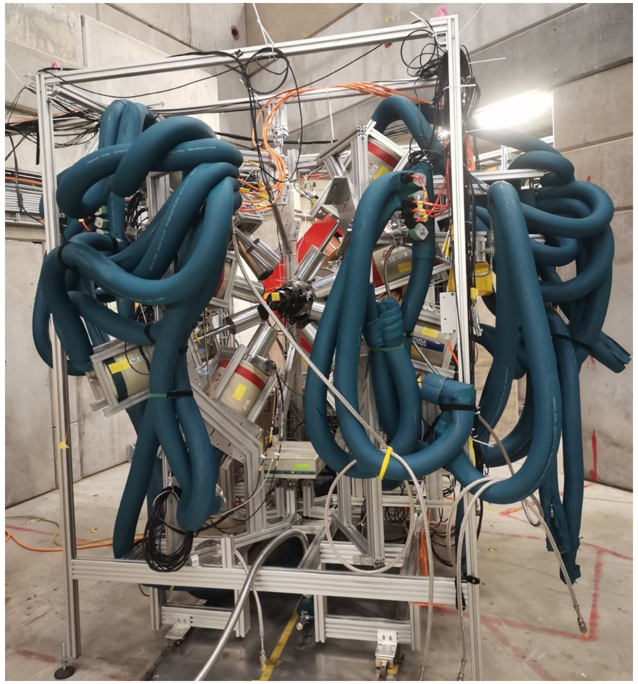
2021-2022

- The experiment[1] is situated at the πE1 beamline of PSI, and meets the necessary muon energy and beam intensity required for the OMC
- The setup consists of a target chamber and an array of high-purity germanium (HPGe) detectors
- The target chamber is placed in the path of a μ^- beam
- 4 muon counters comprising the target chamber are made of scintillating material and connected to the photomultiplier tubes





2023



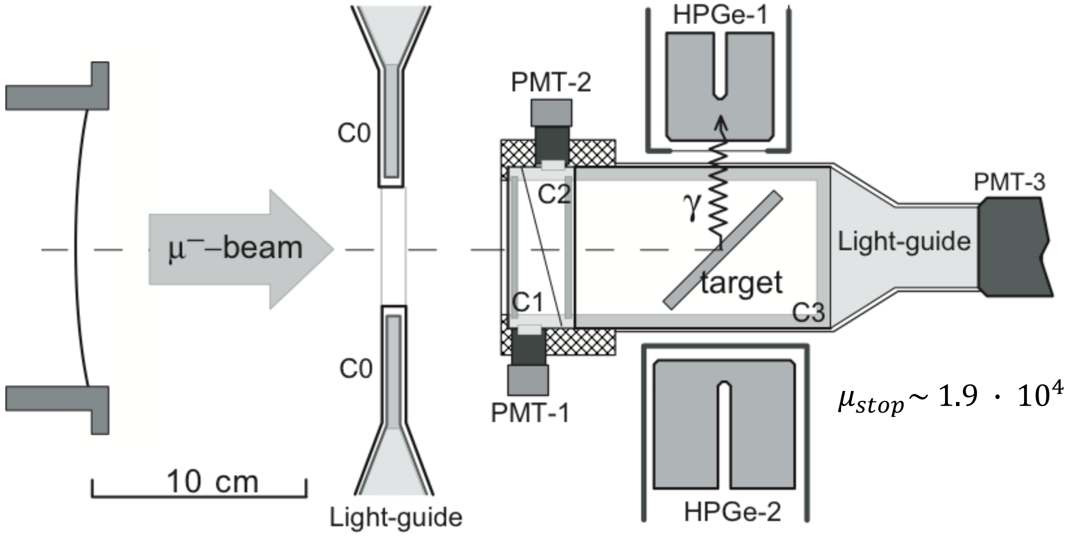
GIANT setup developed by the *muX / MIXE* [2],[3] group was utilized during the 2023 measurement campaign

- 12 HPGe detectors
- autofilling system for all detectors
- 4 muon counters in target chamber with independent online system of monitoring counter's status

[1] Araujo, G.R., Bajpai, D., Baudis, L. et al. The Monument experiment: ordinary muon capture studies for decay. Eur. Phys. J. C 84, 1188 (2024). https://doi.org/10.1140/epjc/s10052-024-13470-6

[2]A. Adamczak et al., "Measurement of the charge radius of radium," (2018), muX721Progress Report.
[3] L. Gerchow, S. Biswas, G. Janka, C. Vigo, A. Knecht, S. M. Vogiatzi, N. Ritjoho, T. Prokscha, H. Luetkens, and A. Amato, "Germanium array for non-destructive testing (GIANT) setup for muon-induced x-ray emission (MIXE) at the Paul Scherrer Institute," Review of Scientific Instruments 94, 045106 (2023)

Campaigns 2021-2023



$\mu_{stop} \sim 1.9 \cdot 10^4\ s^{-1}$

target	enrichment	main purpose	year
^{136}Ba	95.27%	partial cap.rates for NME for DBD	2021
^{nat}Ba	–	tuning/identification for enriched Ba	2021
^{100}Mo	99.8%	astroneutrinos	2022
^{nat}Mo	–	tuning/identification for enriched Mo	2022
^{76}Se	99.7%	partial cap.rates for NME for DBD	2021
^{48}Ti	99.95%	testing SM and pnQRPA	2023
^{nat}Ti	–	tuning/identification for enriched Ti	2023

The materials used in the measurements — such as isotopically enriched compounds or elemental isotopes — are changed depending on the experimental goals and are collectively referred to as the "target."

The trigger system consists of:

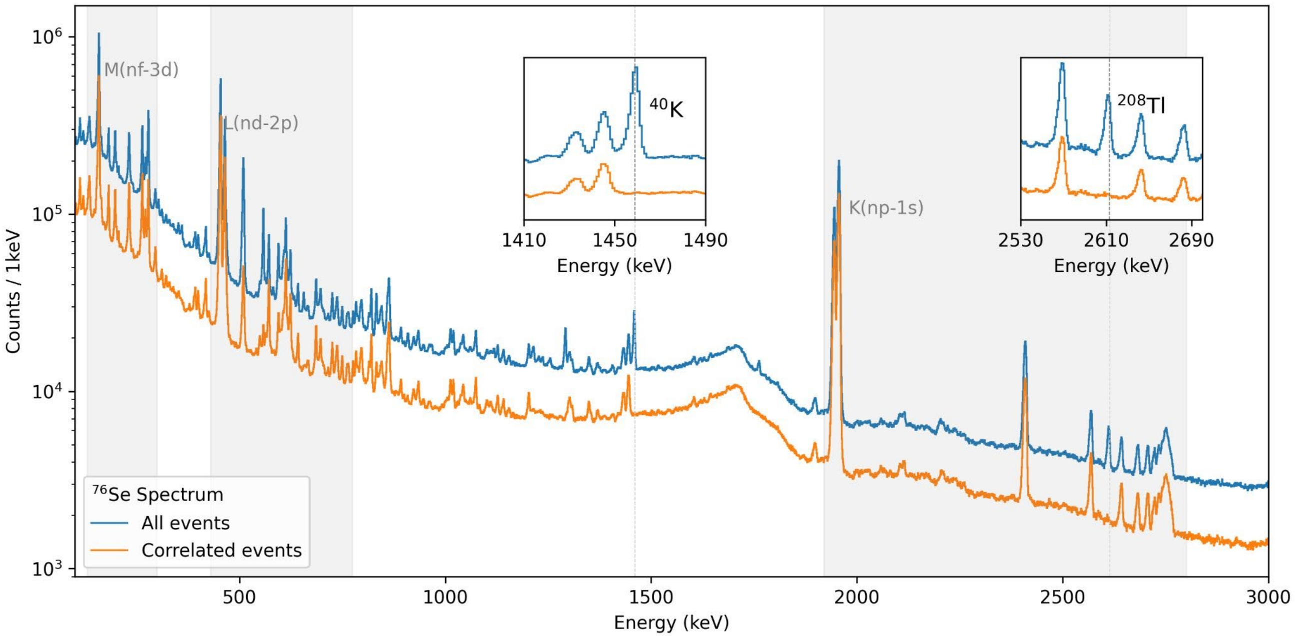
- ✓ an active muon counter C0 of 1cm thickness at the entrance of the target unit;
- ✓ two thin (0.5 mm) pass-through counters C1 and C2;
- ✓ actual target volume surrounded by a plastic cylinder with C3 disk counter.

The four muon counters define a trigger for a muon stopped in the target as:

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

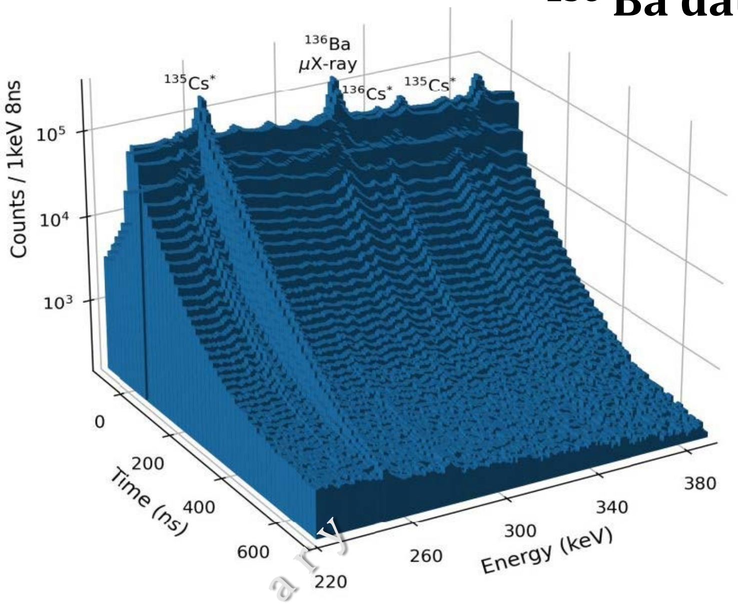
Results of the Measurements

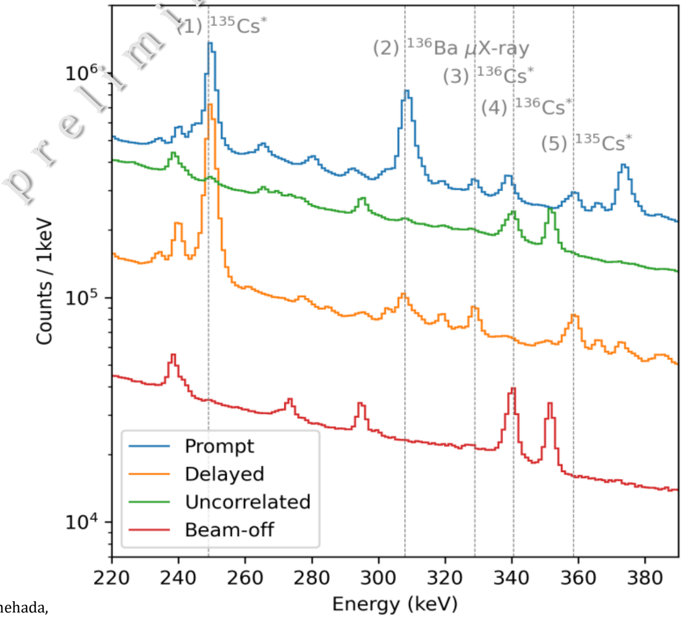
^{76}Se[4] data



Target	Daughter isotopes	τ (ns)	$\Delta\tau$ (ns)
^{76}Se	^{75,74}As	135.1	± 0.5
^{136}Ba	^{135,133}Cs	86.7	± 0.3
^{100}Mo	^{99}Nb	122.9	± 1.7
^{48}Ti	^{47,48}Sc	330.5	± 0.5

^{136} Ba data





[4] G. R. Araujo, D. Bajpai, L. Baudis, V. Belov, E. Bossio, T. E. Cocolios, H. Ejiri, M. Fomina, K. Gusev, I. H. Hashim, M. Heines, S. Kazartsev, A. Knecht, E. Mondragon, Z. W. Ng, I. Ostrovskiy, N. Rumyantseva, S. Schoenert, M. Schwarz, A. Shehada, E. Shevchik, M. Shirchenko, Y. Shitov, J. Suhonen, S. M. Vogiatzi, C. Vogl, C. Wiesinger, I. Zhitnikov, and D. Zinatulina, "Determination of the muon life time in ^{76}Se with the monument experiment," (2025), arXiv:2510.23401 [nucl-ex]

Publications Status

- ✓ Conceptual paper summarizes MONUMENT experiment has been published in *Eur.Phys.J.C.* *

It includes a short introduction with motivation behind MONUMENT experiment, description of the measurement, of the setup and the experimental performance in 2021.

- ✓ The total muon capture rates in isotopically enriched ^{76}Se has been submitted to the *Phys. Rev. C* and *arXiv*.
- ✓ The experimental and calculated total muon capture rate in isotopically enriched ^{136}Ba will be submitted to the *Phys. Lett. B* soon.
- ✓ The radioactive production rates following OMC in ^{136}Ba have been compared with the proton and neutron emission models to evaluate the μ capture strength function and the associated giant resonance (GR) peak. A publication has been prepared for submission to *Physical Review C* and is going to be submitted early in 2026.
- ✓ Partial muon capture rates to the bound states in ^{136}Cs and ^{76}As following OMC in ^{136}Ba and ^{76}Se respectively, are expected to be extracted during 2026. They will be used to compare experimental and theoretical values of the nuclear matrix elements.

* Eur. Phys. J. C (2024) **84**: 1188
https://doi.org/10.1140/epjc/s10052-024-13470-6

BVR57: R-20.01.2

OMC4BDB Addendum: MONUMENT

(Muon Ordinary capture for NUclear Matrix elemENTs)

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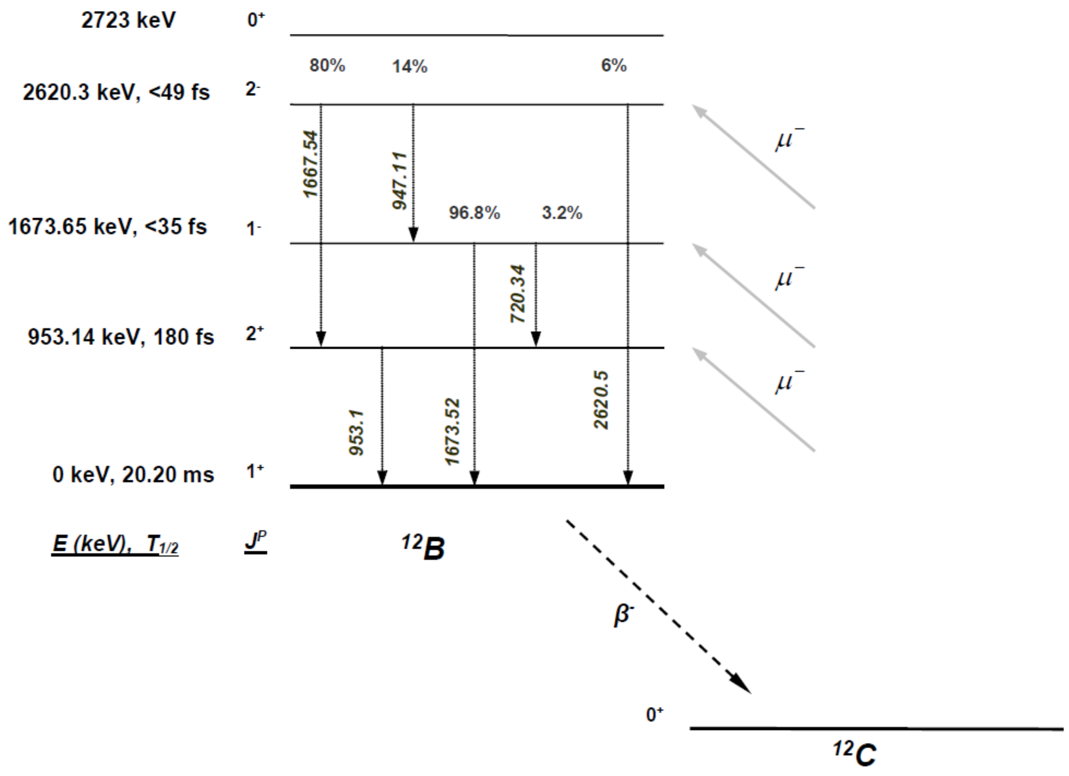
Study of the OMC on Light Nuclei and Implications for Double Beta Decay Nuclei

- Level schemes of light nuclei are known very well

- Muon capture measurements with ^{12}C could serve as a bridge for shell model calculations between light nuclei, where this model is well established, and medium to heavy isotopes that are potential candidates for double beta decay investigations

- Testing g_A quenching



Muon Capture on ^{12}C and ^{13}C

2026

^{12}C: clean benchmark nucleus

$J^p = 0^+$, closed p-shell

- Dominated by Gamow–Teller operator
- Forbidden multipoles suppressed
- Weak sensitivity to nuclear correlations

⇒Multipole structure is trivial

Role:

✓ reference nucleus

2027

^{13}C: probe of nuclear structure & axial current

$J^p = 1/2^-$, unpaired neutron

- Allowed and forbidden transitions
- Higher multipoles contribute
- Strong sensitivity to:
  - configuration mixing
  - effective axial coupling g_a

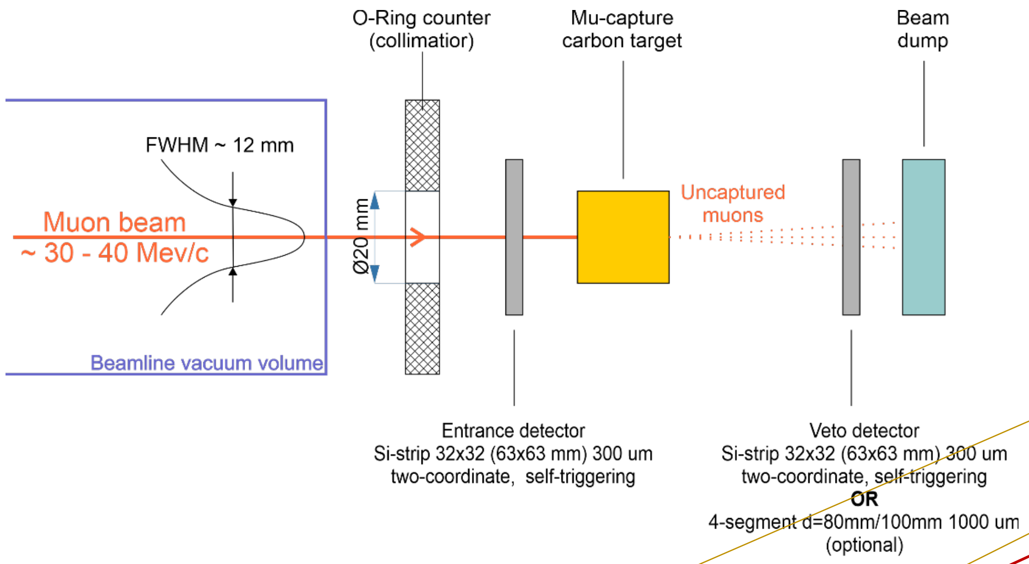
⇒non-trivial and model-dependent

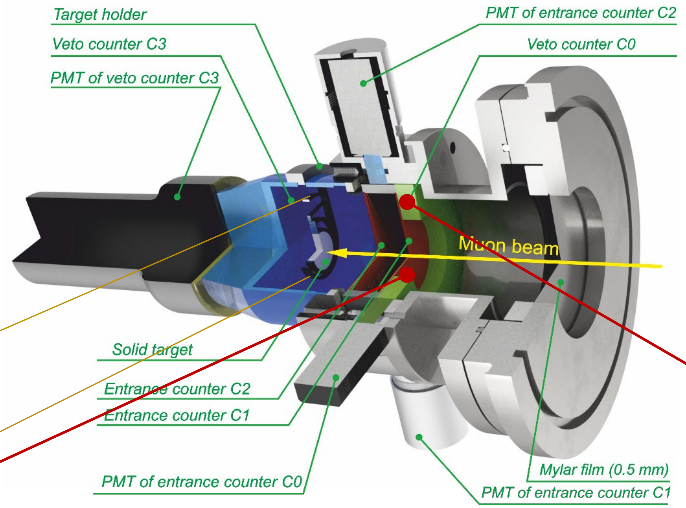
Role:

✓ tests nuclear structure and axial currents

^{12}C reference nucleus→ ^{13}C reveals nuclear structure effects

Modification of the Setup in 2026

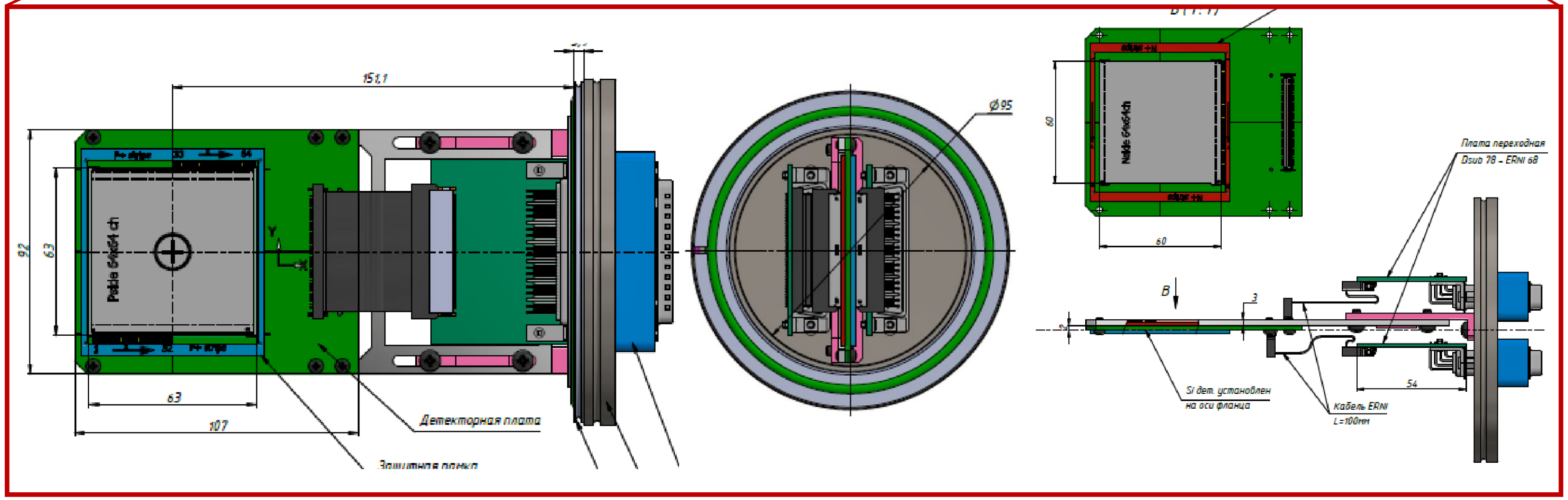




It is supposed to be enriched ^{12}C in the solid (powder) form, 1-2 g

Target holder will be modernized as well →

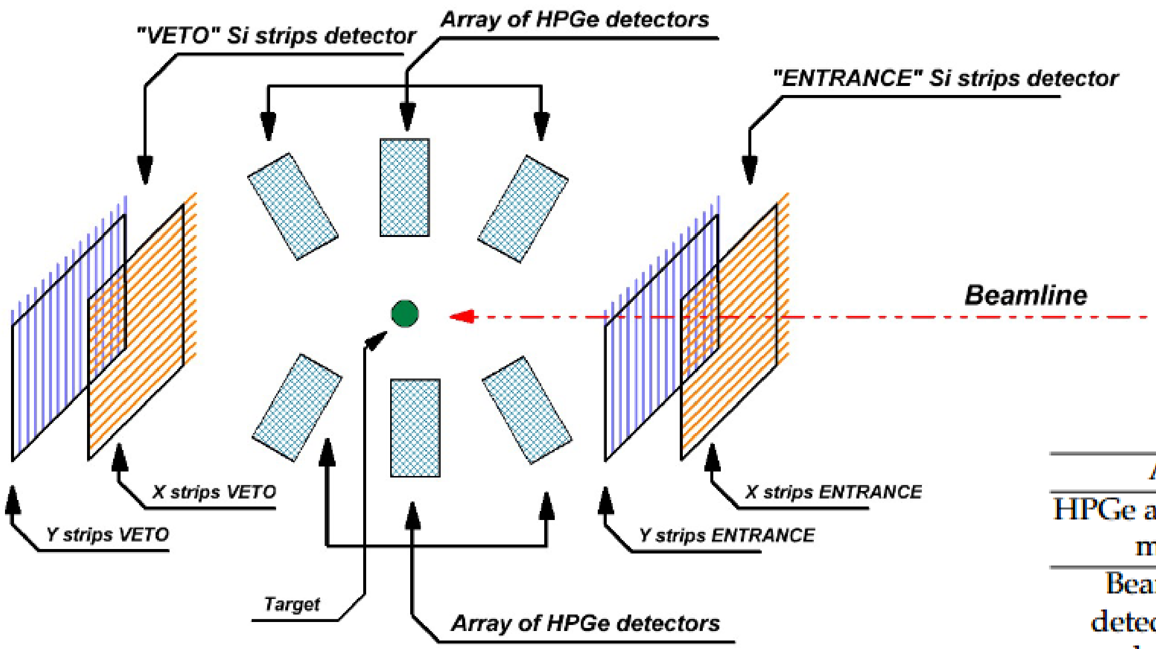
- we will make it from the materials which are not consist of C admixture (should be investigated);
- instead of the kapton tape or nanomembranes – the Me foils made from the different elements, and during the tuning of the beam, tune it by the intensity of muonic X-rays

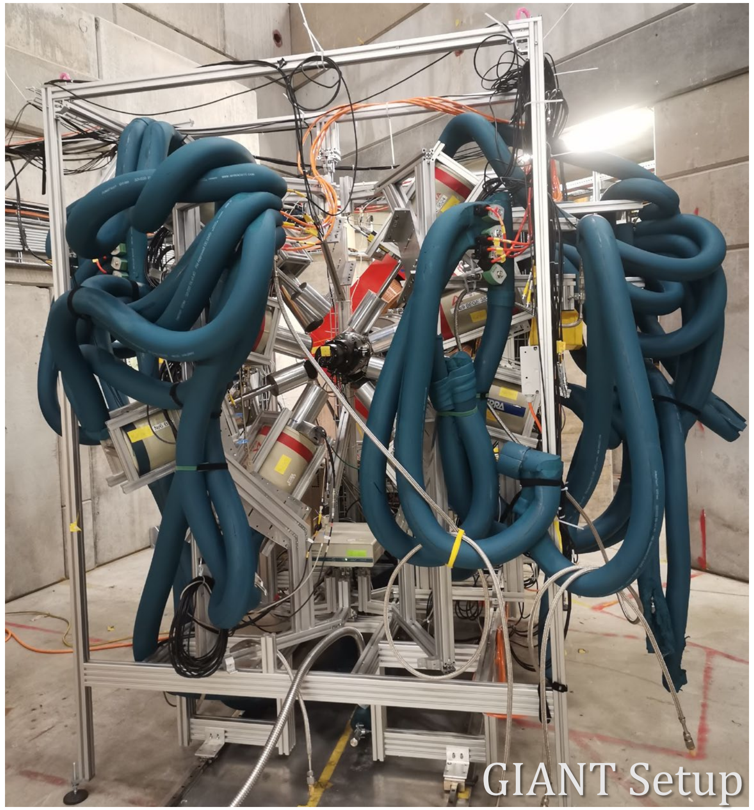


Proposed Measurements in 2026

The muon counters define a trigger for a muon stopped in the target as:

$$\mu_{\text{stop}} = (X_{entrance} \wedge Y_{entrance}) \wedge \overline{(X_{veto} \wedge Y_{veto})}$$





Activity	Estimated time
HPGe and Target unit mounting	12-14 hours
Beam tunings, detector settings and adjustments	36 hours
Beam-on measurements	160 hours
Off-line measurements	336 hours

Proposed Measurements in 2026

Rate estimations:

Parameter	Value	Comment
Muon rate	$3 \cdot 10^4\ s^{-1}$	Rate for the muon trigger system with ^{12}C (1-2 g)
Beam momentum	28-33 MeV/c	Following simulations
Solid angle	1.5 - 2 % / detector	60% germanium detector at 10 cm distance
Detection efficiency	50%	For ~ 1 MeV
Time resolution	10 ns	
Detection rate	$1{,}5\text{-}2 \cdot 10^3\ s^{-1}$	Per detector unit in case of ^{12}C

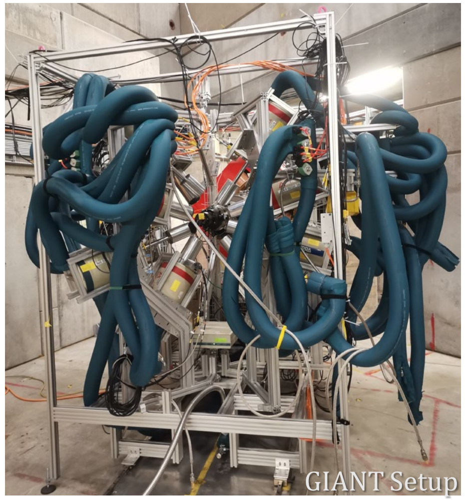
Proposed Measurements in 2026

Beamtime request:

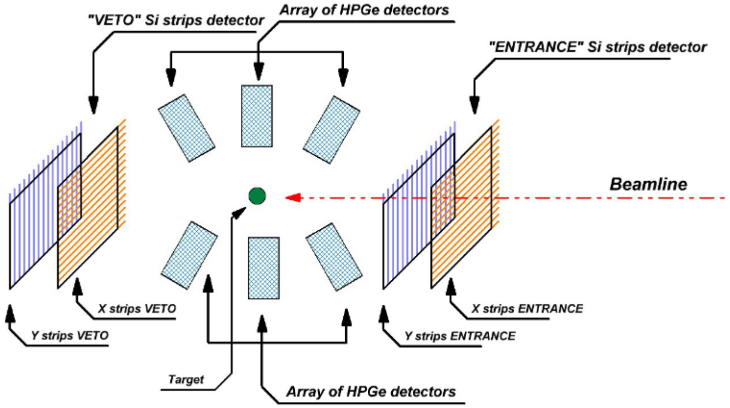
- **<u>2026</u>:** 10 days beam time in πE1 →

  3 days: setup and beam tuning,

  7 days: data taking with ^{12}C target



- ❑ Using GIANT setup after the “MIXE” beamtime campaign
- ❑ Modernization of Target Unit → replace counters with Si strip detectors (R&D in JINR)
- ❑ Modification of Target Holder for ^{12}C



Outlook

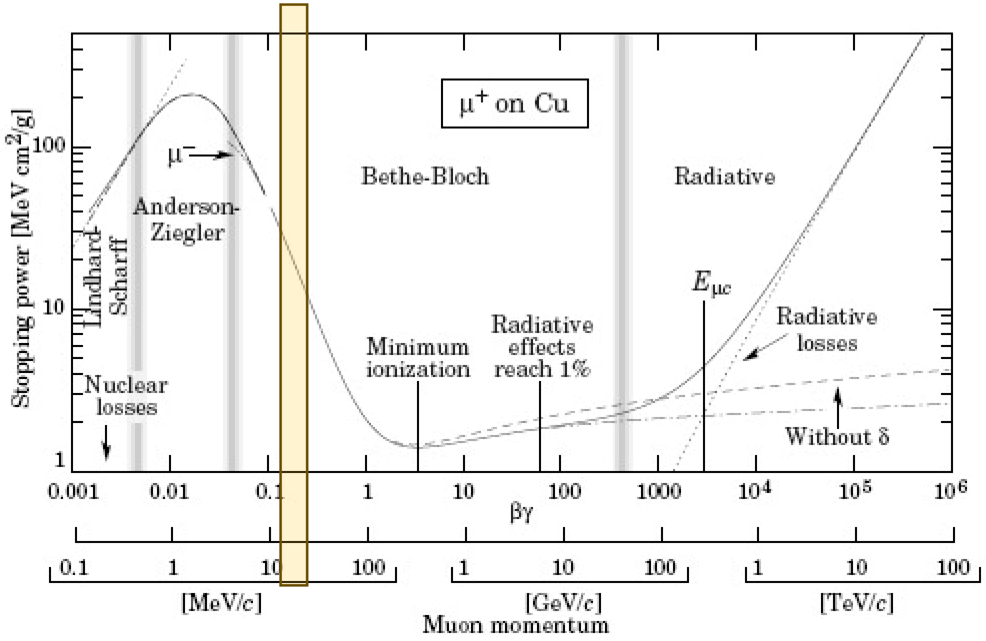
- ✓ The measurement campaigns with ^{76}Se/ ^{nat}Se and ^{136}Ba/ ^{nat}Ba targets in 2021, ^{100}Mo/^{nat}Mo in 2022 and ^{48}Ti/ ^{nat}Ti in 2023 were successfully accomplished
- ✓ Preliminary results for the total muon capture rates were extracted
- ✓ Data analysis continues
- ✓ Conceptual paper of the MONUMENT project was published in EPJC, the total muon capture rates in isotopically enriched ^{76}Se has been submitted to the Phys. Rev. C and arXiv, a paper with ^{136}Ba targets is in progress

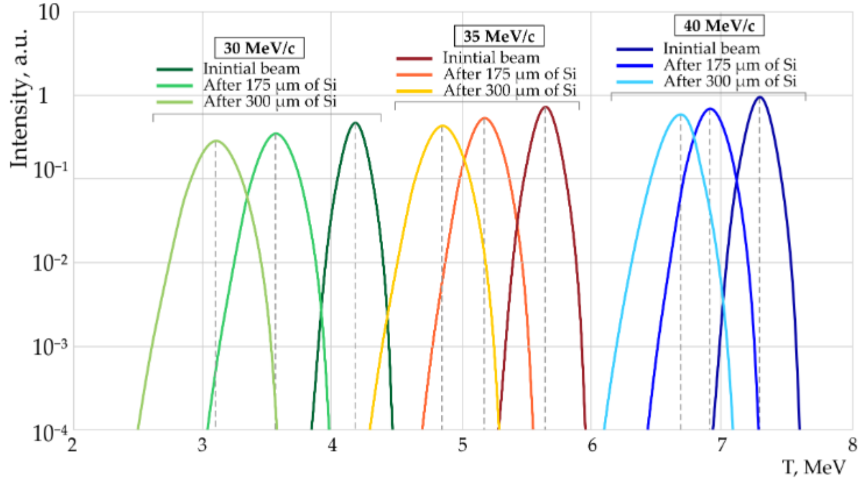
In order to investigate ordinary muon capture on the light nuclei (in particular ^{12}C) we want:

- ❑ to request the beamtime: 10 days (for commissioning of the germanium detector array, tuning of the beam parameters and data taking) using GIANT setup after the “MIXE” beamtime campaign
- ❑ to modernize Target Unit
- ❑ to modify Target Holder for ^{12}C

Backup

Target Unit evolution





Simulation of the muon beam attenuation after 175 μm and 300 μm silicon detectors for 30 MeV/c, 35 MeV/c and 40 MeV/c beam momenta

Simulations of muon passage through Si and energy loss estimates for thicknesses of 175 μm and 300 μm (see the figures) have been performed. The three groups of curves on the lower diagram correspond to momenta of 30, 35, and 40 MeV/c **for the initial beam, after passing through 175 μm, and after passing through 300 μm**, respectively. The results appear quite realistic and are in good qualitative agreement with both the theoretical assumptions and our experimental observations on scintillation counters. The average (or most probable) energy losses for the given momenta are in the range of 300 to 700 keV for 175 μm and from 600 to 1000 keV for 300 μm.

Some other additional simulations need to be done, such as:

- Since the Si muonic X-rays region lies in the ROI, exactly close to the carbon, we need to understand the contribution of this effect in the experiment;

Needs:

- Simulations (mX-rays, momentum)
- Maybe temperature stabilization for the Si detectors
- Modernization of the tube for ISO connector
- Additional SIS3316 (3-4) – since Si strip detectors have 32x32 channels

Target in 2026

In 2023 For each momentum value we compared:
- count rates of the counters as well as germanium detectors;
- rates of μX-rays line 932 keV from Ti-48 (Ge04);
- amplitude ratios of Ti-48 (932 keV) and carbon (74 keV) lines (Ge04).

Momentum	30 MeV/C	31.5 MeV/C	33 MeV/C	34 MeV/C
Run #	67207	67218	67229	67235
A (Ti-48 *932 keV*)	111	325	359	249
A (C *74 keV*)	1296	807	675	453
A (Ti-48 *932 keV*) / A (C *74 keV*)	5.3E-05	1.69E-04	2.26E-04	2.44E-04

It is supposed to be enriched ^{12}C in the solid (powder) form, 1 g

Target holder will be modernized as well →
•we are going to use it from the materials which are not consist of C admixture (should be investigated);
•instead of the kapton tape or nanomembranes we are thinking about the Me foils made from the different elements, and during the tuning of the beam, tune it by the intensity of muonic X-rays presences in the energy spectra