General OMC4DBD collaboration on-line meeting, 19 – 20th April 2021

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KU LEUVEN
NUCLEAR AND RADIATION PHYSICS

Proposal for BVR 51

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

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Open Users Meeting BV51, 29.01.2020

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Contributions:

- **Paul Sherrer Insitute (PSI),** Switzerland: **A.Knecht, S.M. Vogiatzi** – HPGe detectors, mounting, data taking, administrative work at PSI;
- **Joint Institute for Nuclear Research (JINR)**, Russia: **D. Zinatulina, V. Belov, M. Fomina, K. Gusev, , S. Kazartsev, N. Rumyantseva, E. Shevchik, M. Shirchenko, Yu. Shitov, I. Zhitnikov**– management, logistics, setup (targets, HPGe detectors, detectors frame, counters), mounting, data-taking and analysis, publications;
- **Technische Universität München (TUM),** Germany: **T. Comellato, M. Schwarz, S.Schönert, C. Wiesinger, E. Mondragon** – HPGe detectors, logistics, data taking and analysis, software for DAQ;
- **University of Alabama (ALABAMA),** USA: **I.Ostrovskiy** – ^{136}Ba, data taking, publication preparation;
- **University of Jyväskylä,** Finland: **I.Suhonen, L. Jokiniemi** – NME calculations, interpretation experimental data with NME models, publications;
- Physik-Institut, **University of Zurich (ETH),**Switzerland: **L.Baudis, G. Araujo, J.Huang** – administrative work, HPGe detector, data-taking and analysis;
- **KU Leuven,** Belgium: **T. Cocolios, M. Heines** – HPGe detector?, shifts during data taking, mounting, data analysis;
- **Research Center on Nuclear Physics (RCNP),** Osaka University, Japan: **H. Ejiri** – interpretation experimental data for the proton-neutron model, publication preparation;
- **Universiti Teknologi Malaysia (UTM),** Malaysia.: **I.H. Hashim, F. Othman, Zh.W. Ng** – data taking, offline analysis, calculations with proton-neutron model.

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Funding:

- **<u>Joint Institute for Nuclear Research (JINR)</u>**, Russia:

  The project MONUMENT (OMC4DBD) officially supported by JINR

- **<u>Swiss “Research Preparation Grnats” in collaboration with Paul Sherrer Insitute (PSI) and JINR</u>**:

  coordinator - **A.Knecht** (materials, equipment, transport expenses and part of accommodation during beam-time)

- **<u>DFG-RFBR grant: “Joint German-Russian Project” (Technische Universität München (TUM) & JINR)</u>**:

  coordinators **S.Schönert (from TUM)** and **D. Zinatulina (from JINR)** (materials, logistics, transportation, supporting PhD student, equipment expenses, part of accommodation during beam-time)

- **<u>Research funding from Ministry of Higher Education Malasia (UTM)</u>** Malaysia.: coordinator - **I.H. Hashim**

Joint Institute for Nuclear Research
Dzhelepov Laboratory of Nuclear Problems

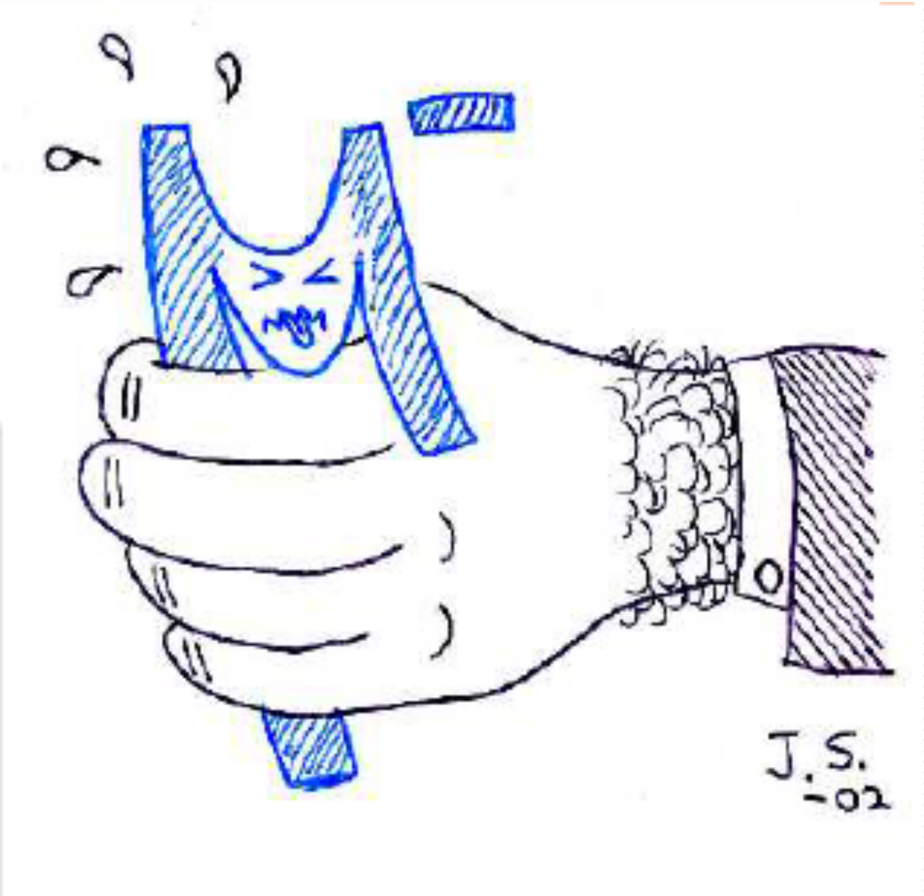
General collaboration meeting, 19 - 20th April 2021

Ordinary Muon Capture (OMC4DBD) measurements in 2021 year at PSI

Daniya Zinatulina

19.04.2021, *ZOOM*

The Motivation

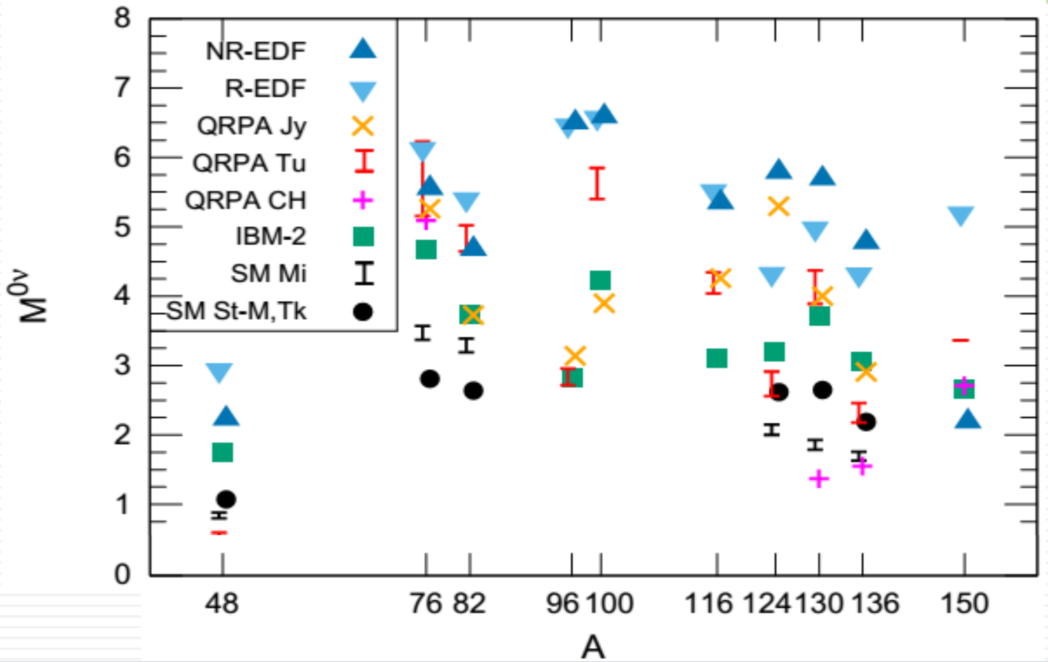


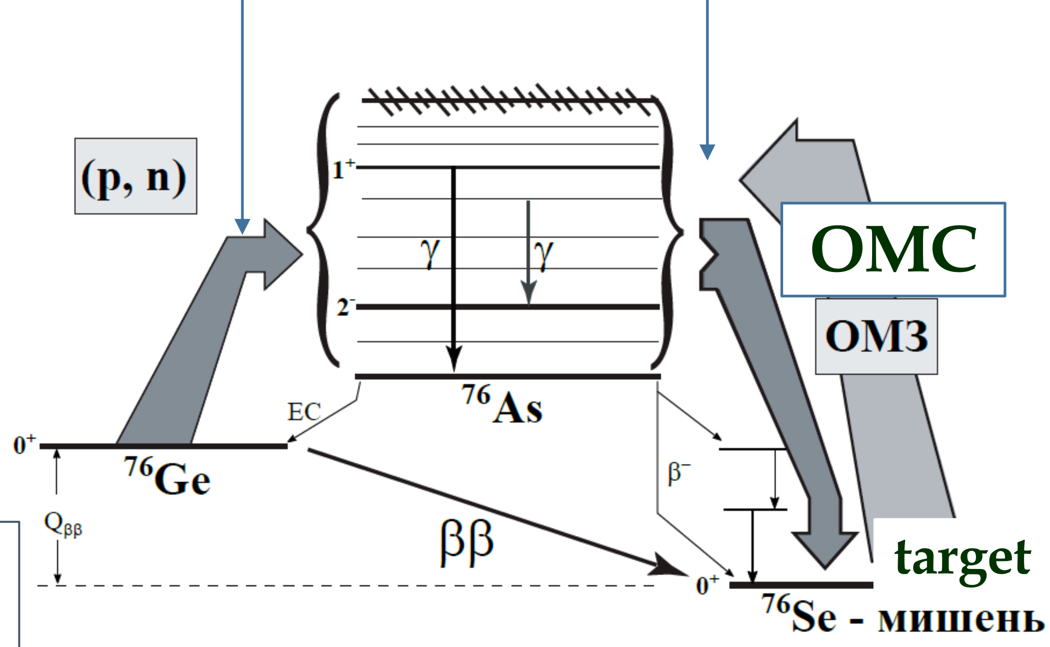
Experimental input for DBD NME calculations

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

$\langle m_{\beta\beta}\rangle$ $\qquad M^{0\nu}$

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





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.*

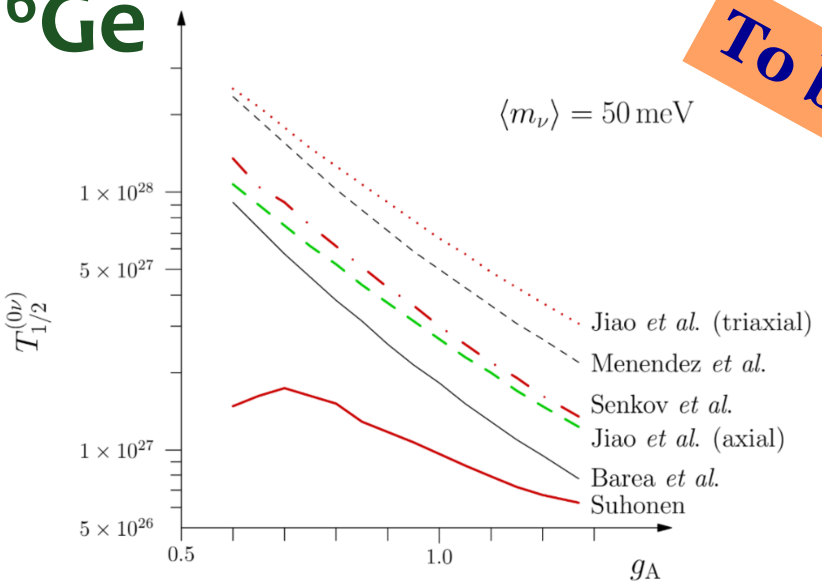
g_A – suppression probing -- via capture rates calculations

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

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

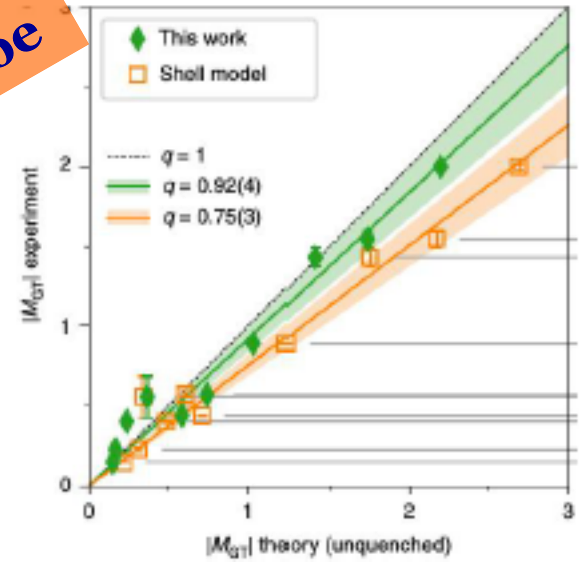
^{76}Ge

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

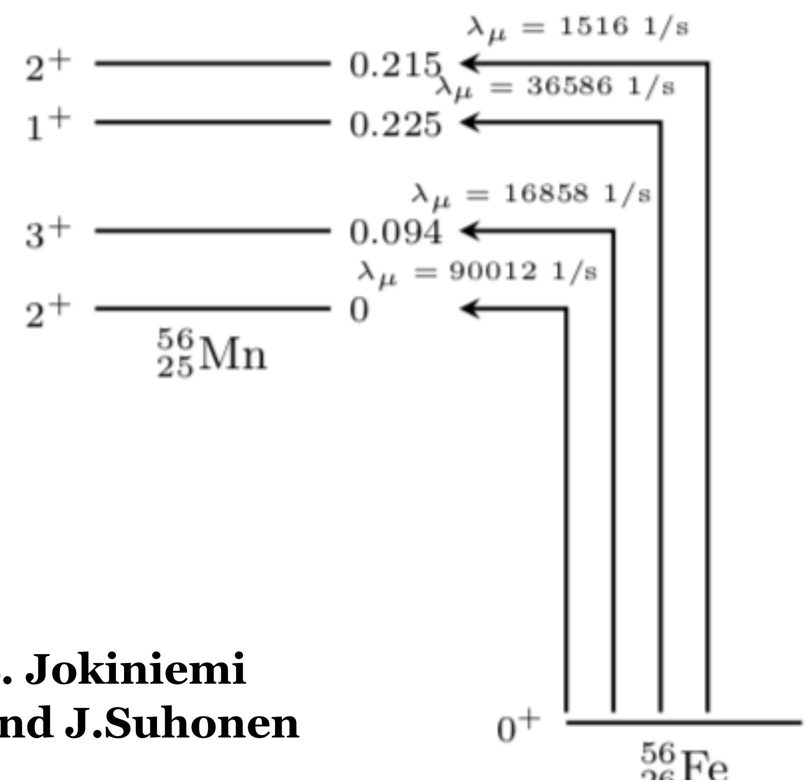


Gysbers et al. Nature Phys. 15 428 (2019)

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

Testing shell model calculations for ^{56}Fe, ^{24}Mg, ^{32}S (L. Jokiniemi talk in detail)

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

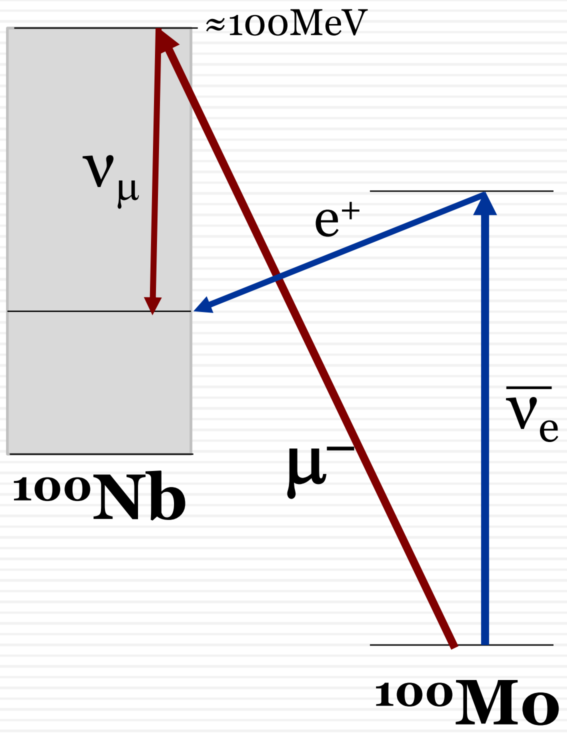


L. Jokiniemi and J.Suhonen

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

Astrophysics with ^{100}Mo (H. Ejiri talk in detail)

- 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



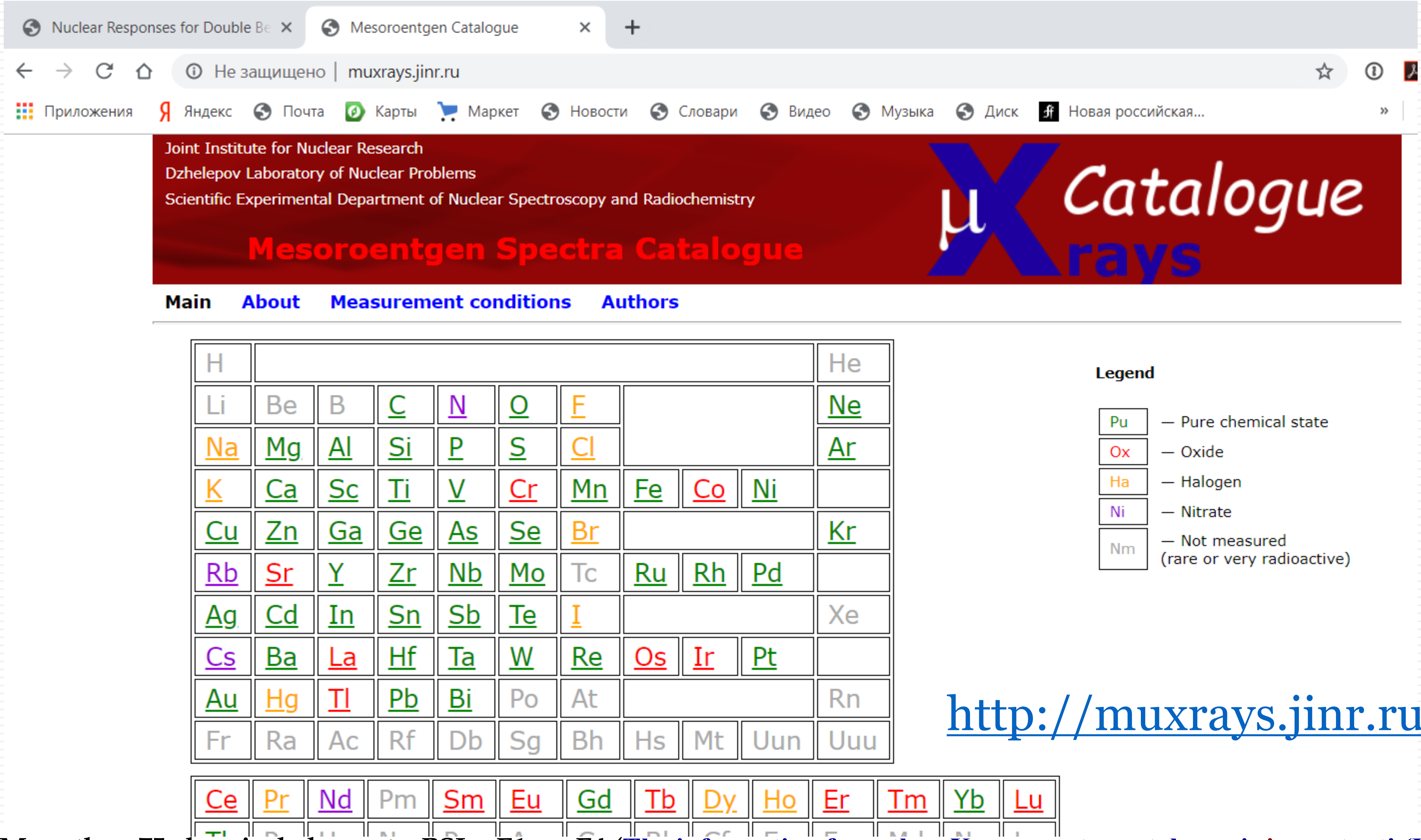
^{100}Mo($\overline{\nu}_e$, e$^+$)^{100}Nb (SN)

^{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

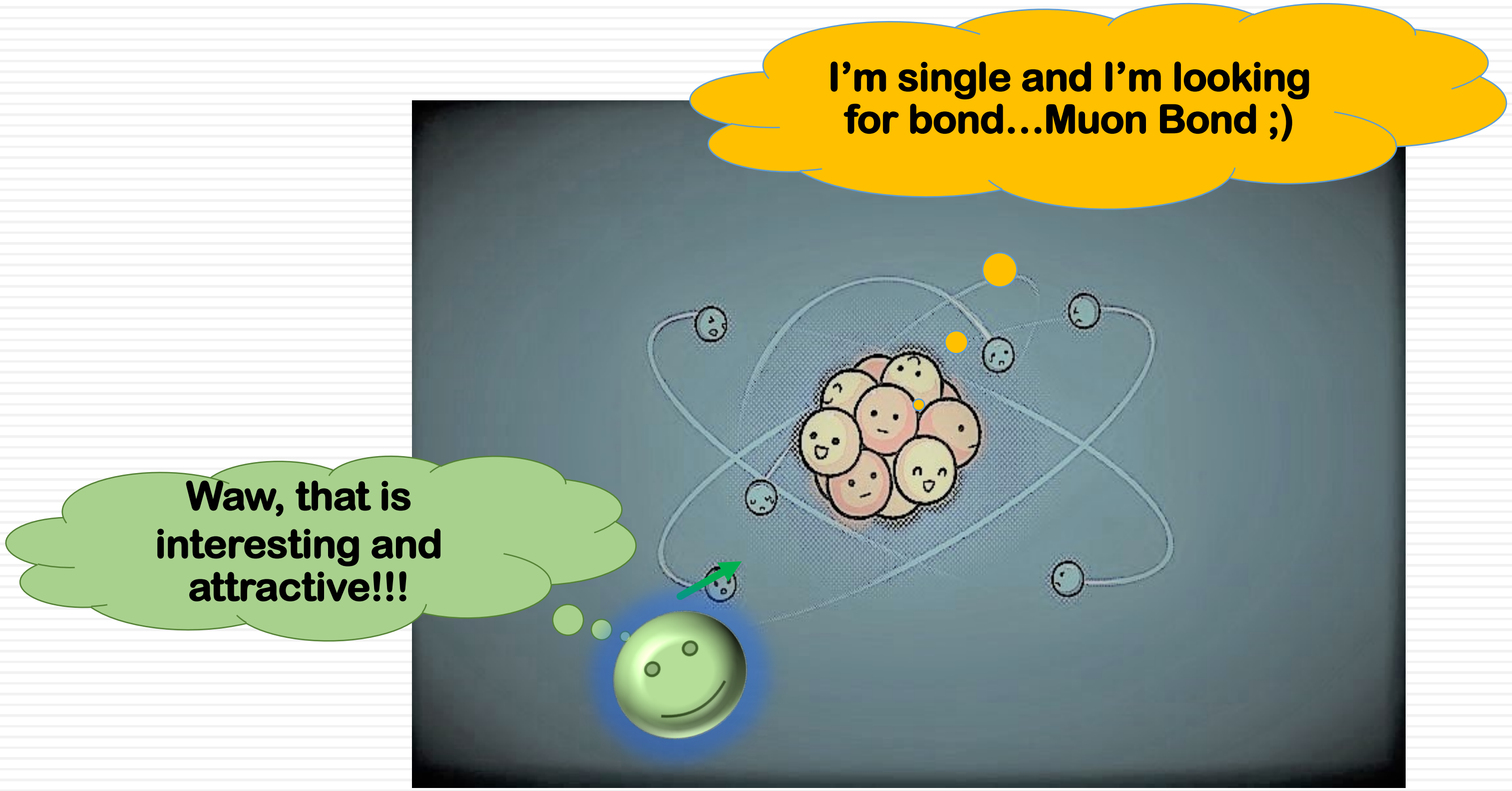
Muonic X-rays Catalogue



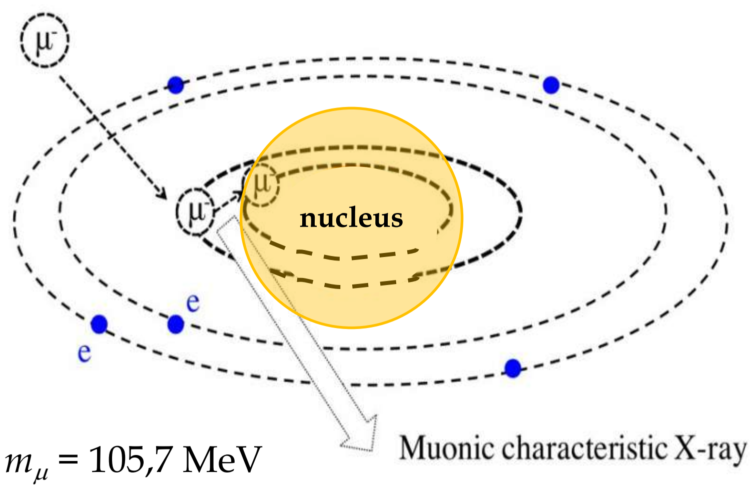
http://muxrays.jinr.ru/

More than 75 chemical elements, PSI, μE1 и μE4 (The information from the μX-ray spectra catalogue is important! (It helps us to identify γ-lines, background, and gives correct selection of the targets and construction materials for different experiments with muons)

The Ordinary Muon Capture itself



What do we get from the Ordinary Muon Capture (OMC)?



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

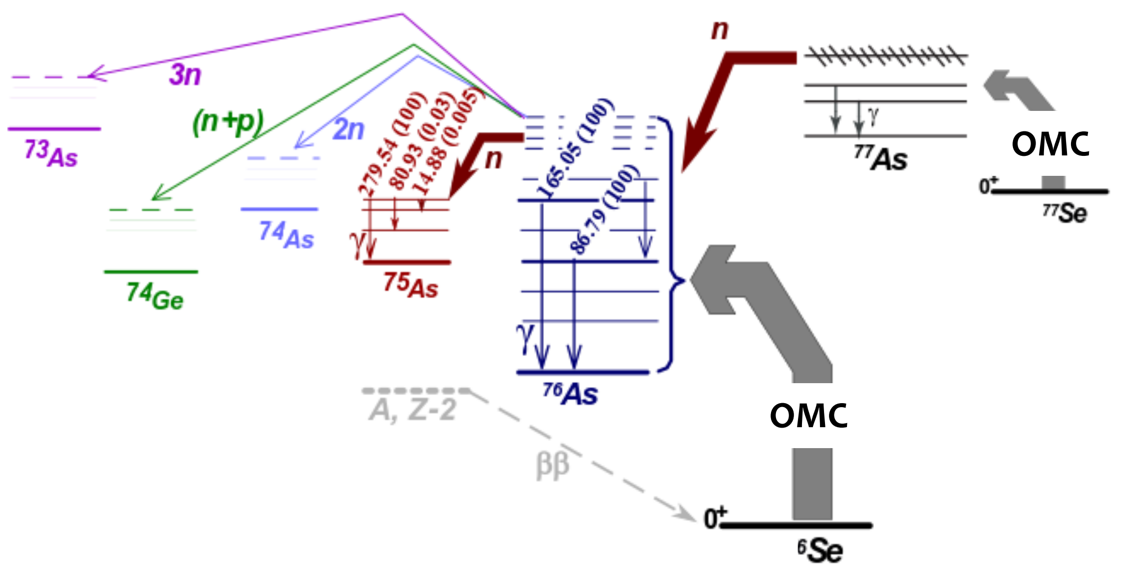
$(A, Z) + \mu^- \rightarrow (A, Z\text{-}1)^* + \nu_\mu$

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

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

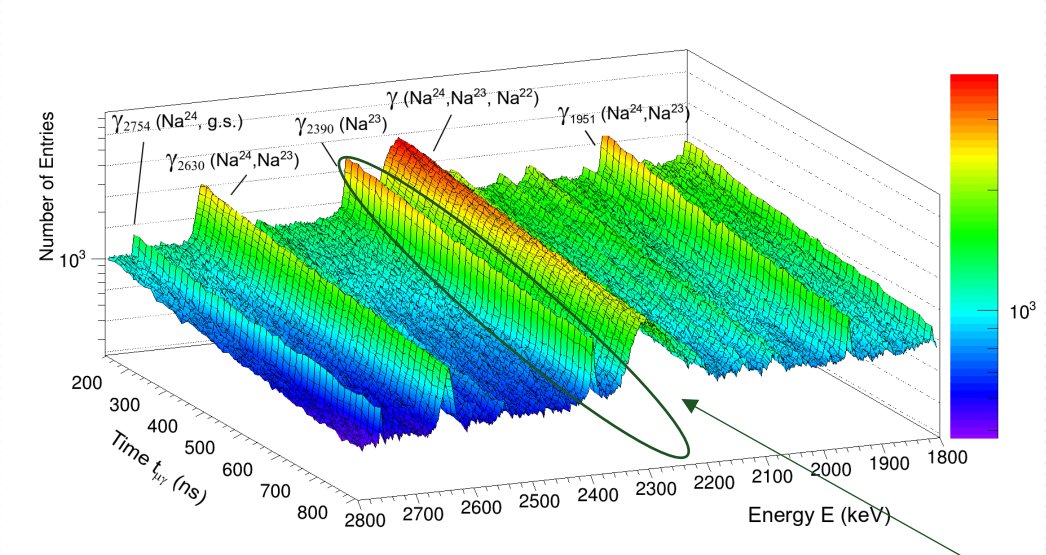
$\rightarrow (A\text{-}2, Z\text{-}1) + \gamma + 2n$

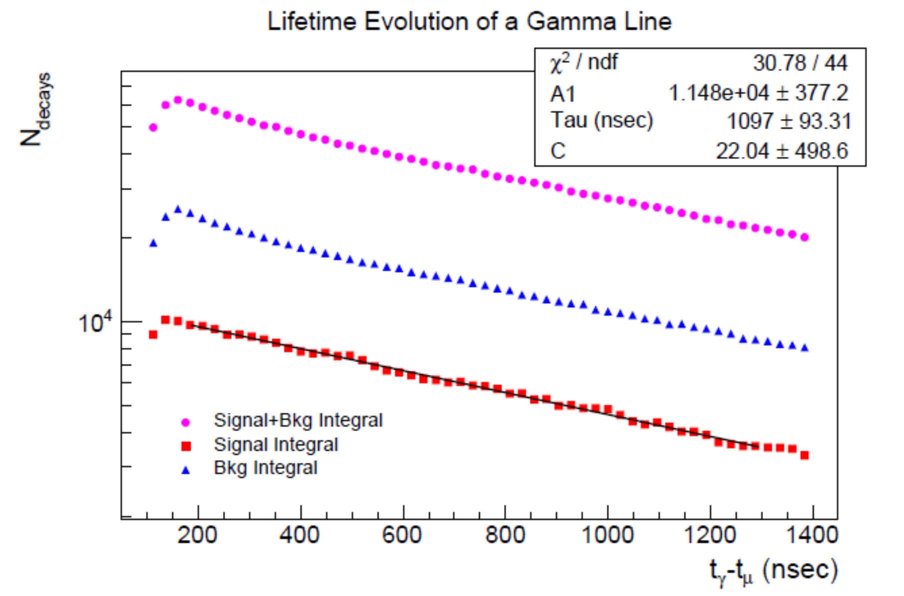
$\rightarrow (A\text{-}1, Z\text{-}2) + \gamma + n + p$

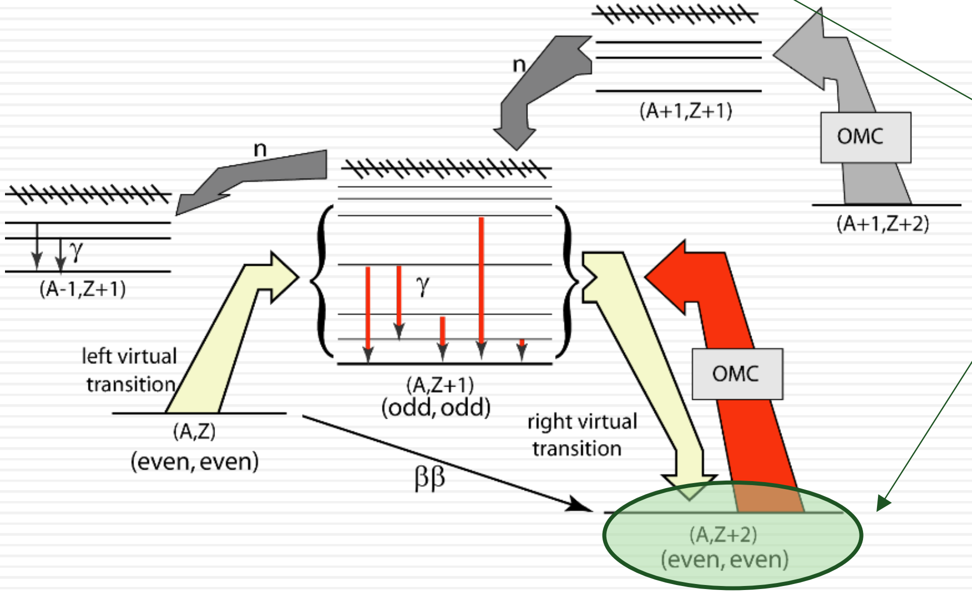


- ✓ **Muonic cascades** (our by-product)
- ➢ High momentum transfer (up to 100 MeV) – High-lying states population
- ✓ **Partial capture rates**
- ✓ **The radioactive production rates (yelds of isotopes/ isomers)**

(E, t) distribution of the correlated events following μ-capture in ^{24}Mg target (I.Zhitnikov talk in detail)



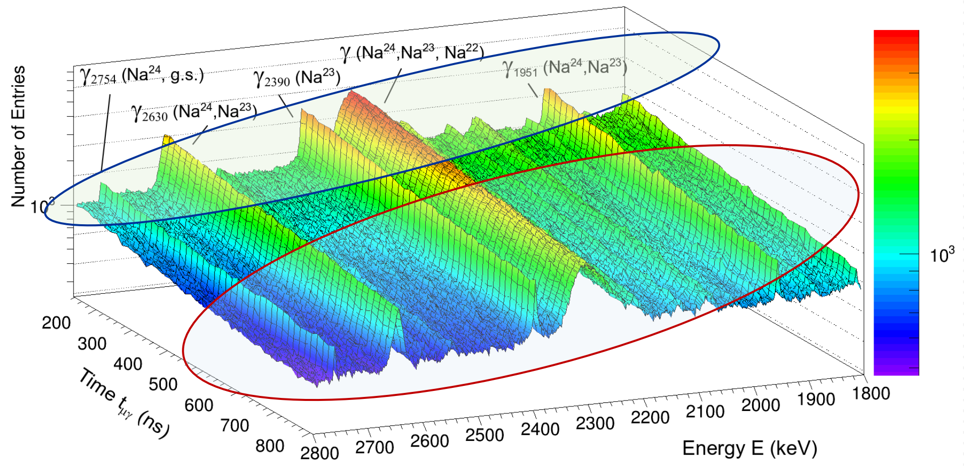




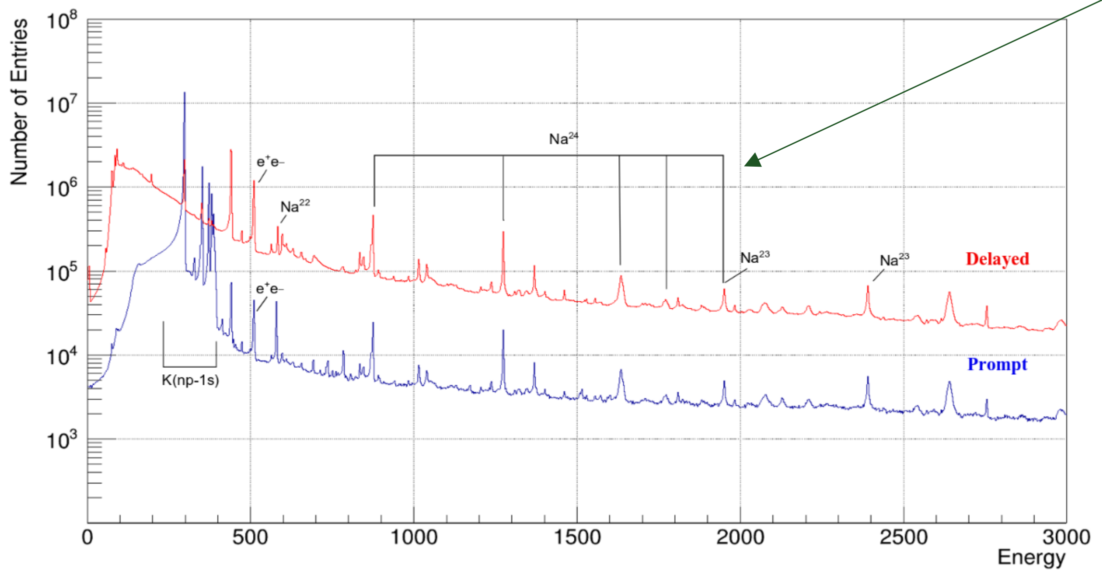
Time evolution of the 2390.6 k…
^{23}Na γ-line gives us the T…
muon capture rate i…

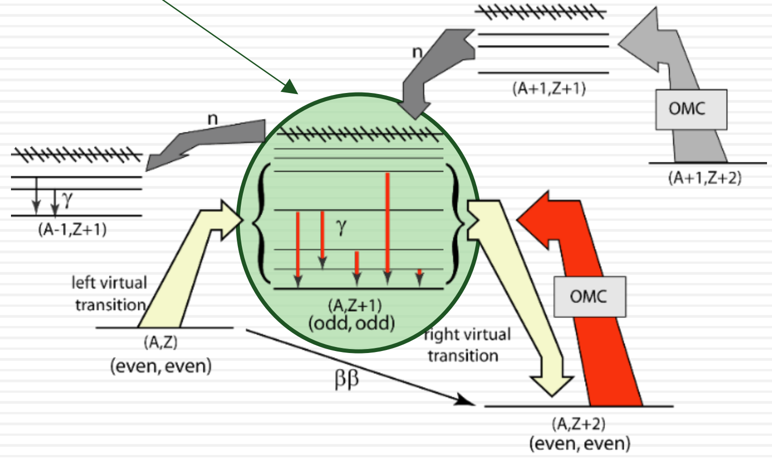
M. Shirchenko talk

(E, t) distribution of the correlated events following μ-capture in ^{24}Mg target (I.Zhitnikov talk in detail)

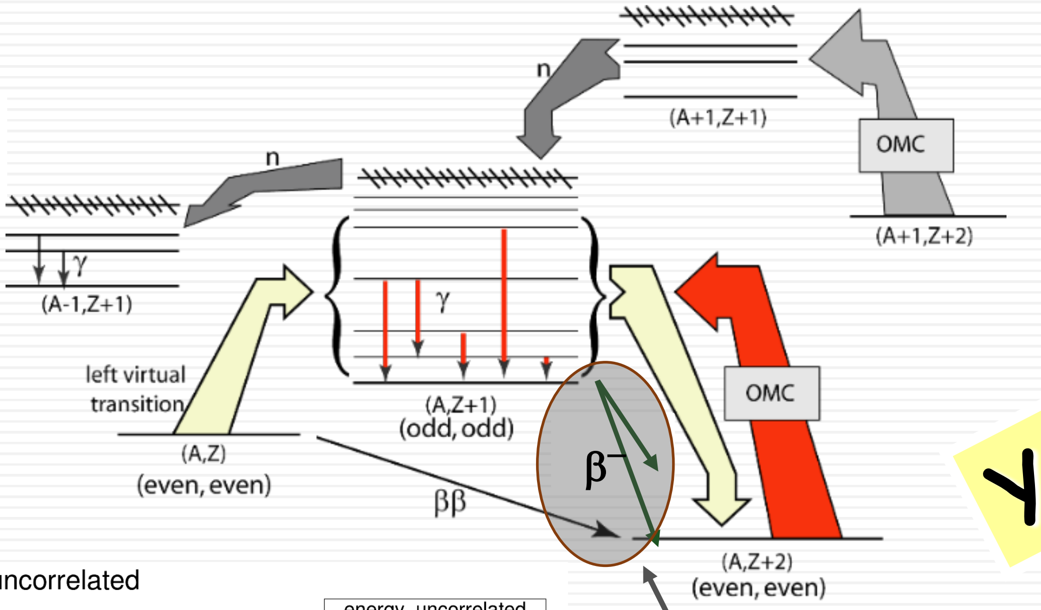


- $t_{\mu\gamma}$ = 0-200 ns: μX-cascades (**Prompt** spectra) – normalization, identification, composition of the surrounded materials and target itself;
- $t_{\mu\gamma}$ = 200-2000 ns: γ-radiation following OMC (**Delayed** spectra) – partial μ-capture rates – strength function of the right side

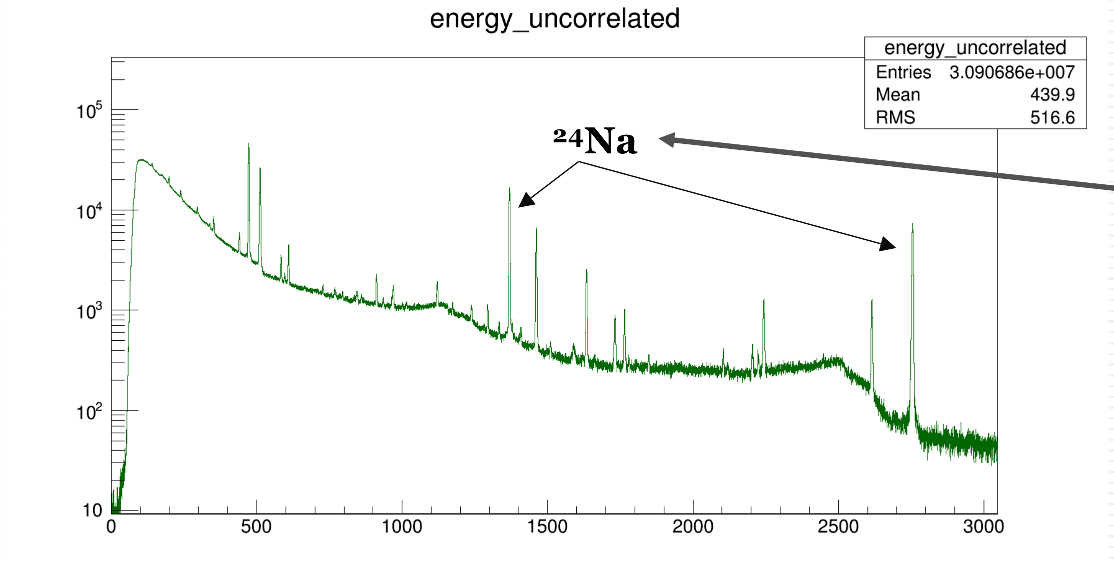




Uncorrelated events of short-lived RI isotopes produced by μ-capture in ^{24}Mg target



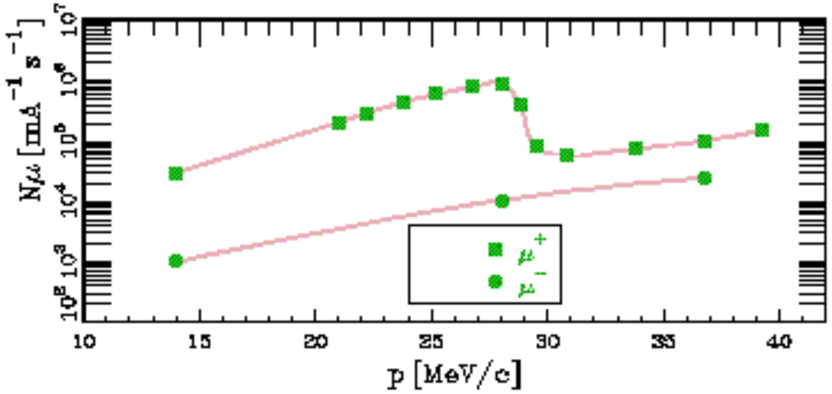
Yu. Shitov talk

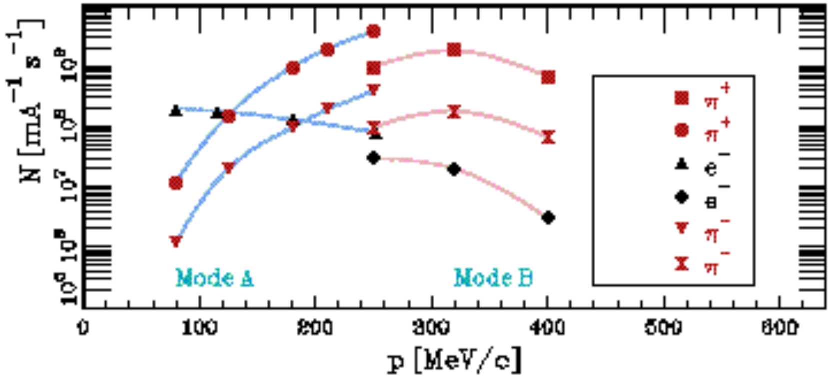


- T >> $t_{\mu\gamma}$: background radiation (**Uncorrelated** spectra) – calibration of the detectors, identification, yields of short-lived RI during exposure

Upcoming 2021 beam-time at PSI

πE1-2 beam-line (PSI)

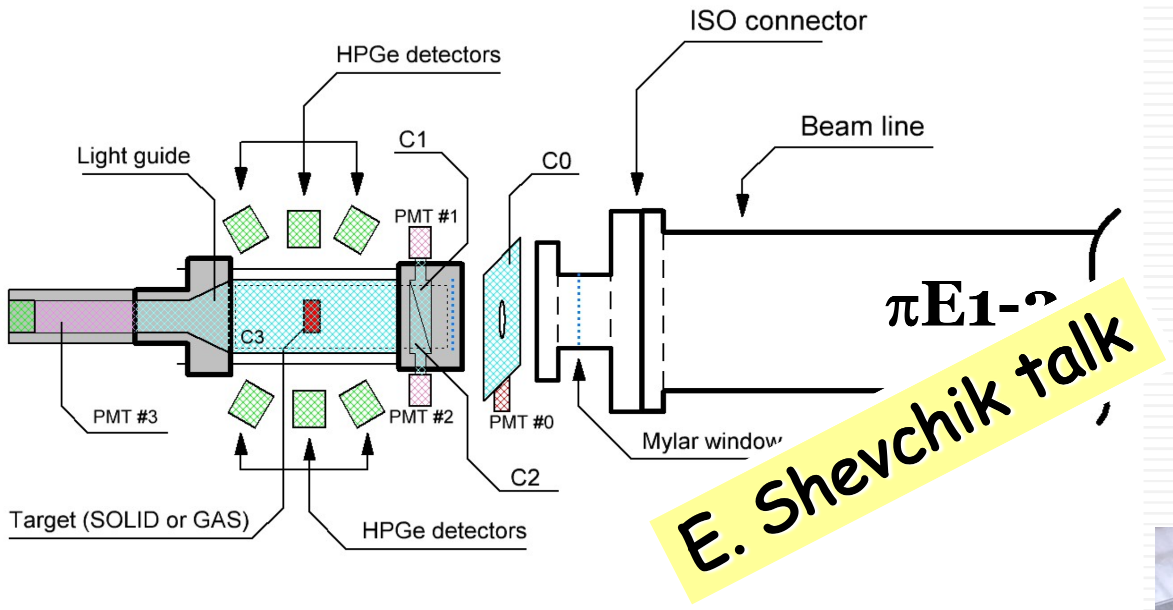


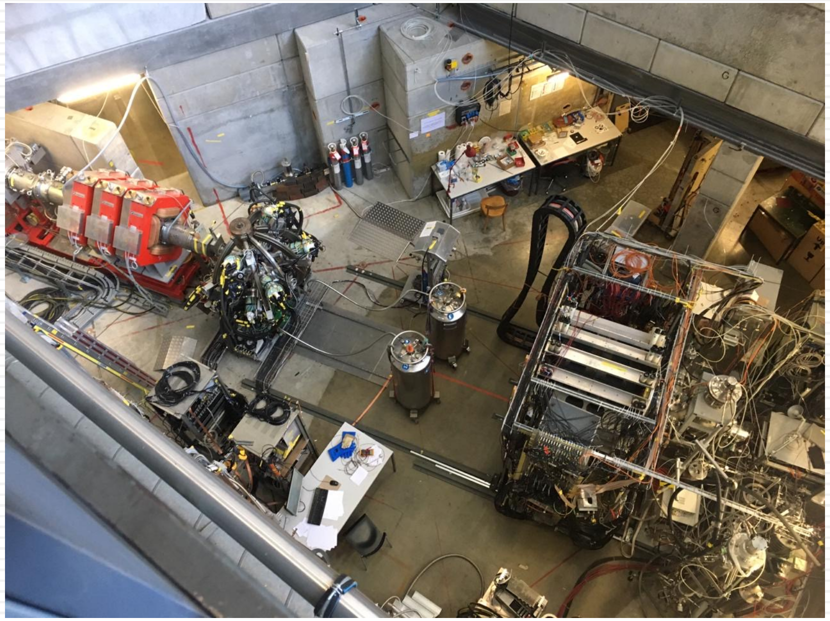


Beam momentum **-> 15 – 40 MeV/C**

Muon flux **-> 2** x **10^3 – 6** x **10^4 s^{-1}**

Proposed measurements in the first year of the project





0ν2β-decay	0ν2β-Experiments	OMC targets
^{136}Xe	nEXO, KamLAND2-Zen, NEXT, DARWIN, PandaX-III	^{136}Ba (95.27%)/ ^{nat}Ba
^{76}Ge	LEGEND	^{76}Se (99.7%)

Detection system and DAQ

- **Set of 7 HPGe detectors + 1 spare HPGe detector :**

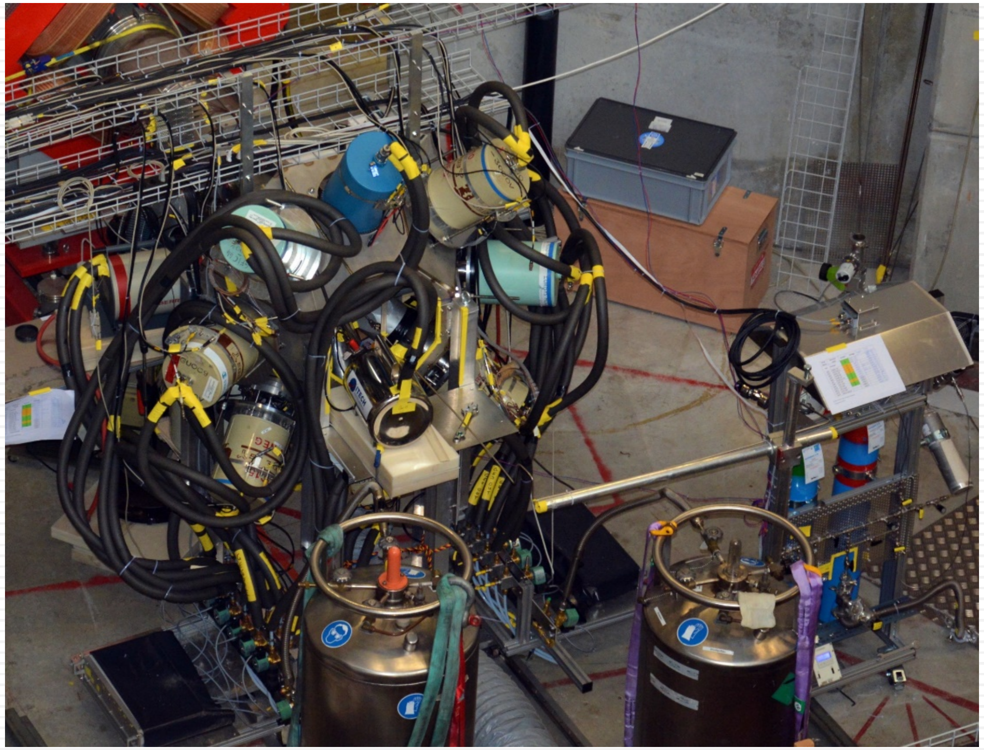
  K. Gusev & E. Mondragon talks

- **Beam control: C0**

  C1-C2

  C3

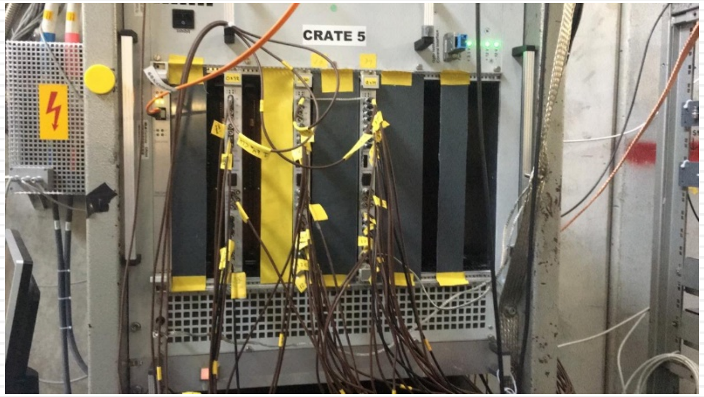
  E. Shevchik talk



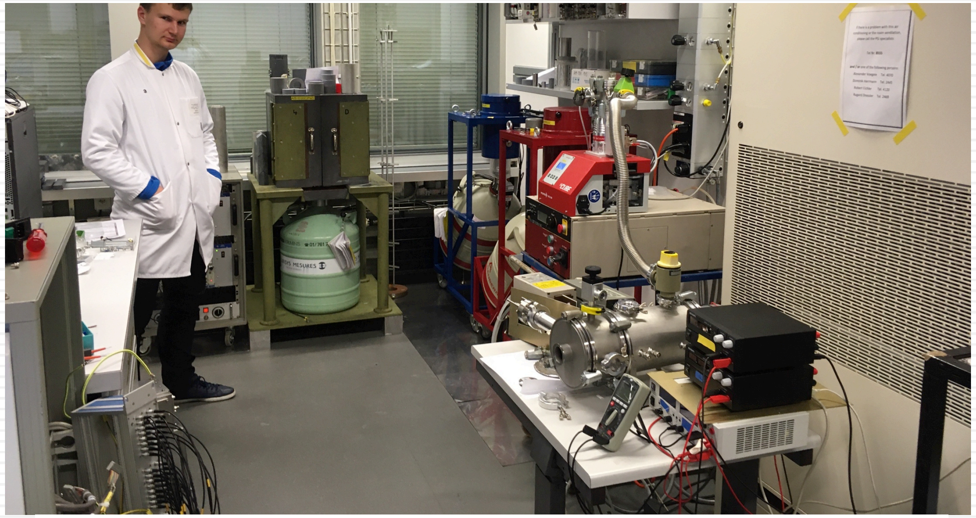
- **DAQ-1:** 2 SIS 3310 digitizers@250 MHz MIDAS DAQ

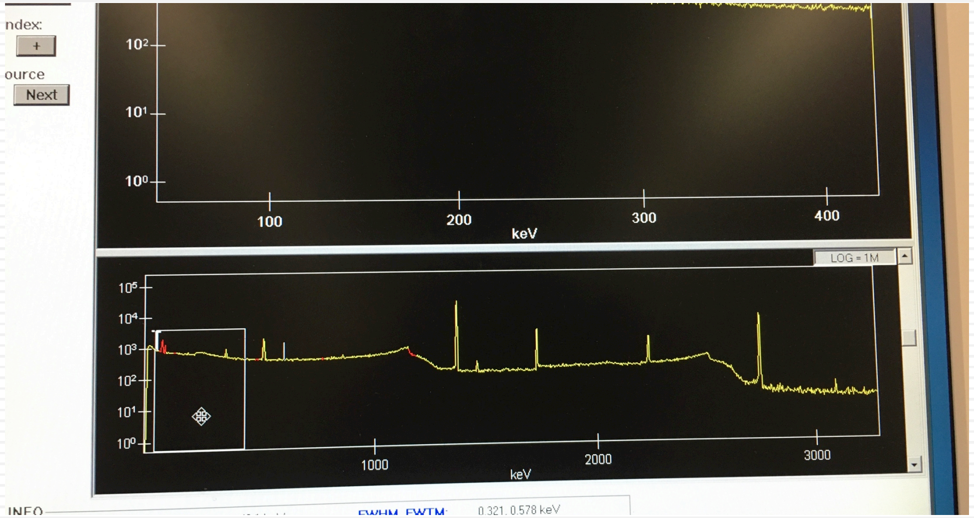
- **DAQ-2:** 2 SIS 3316 digitizers@250 MHz LAMA DAQ

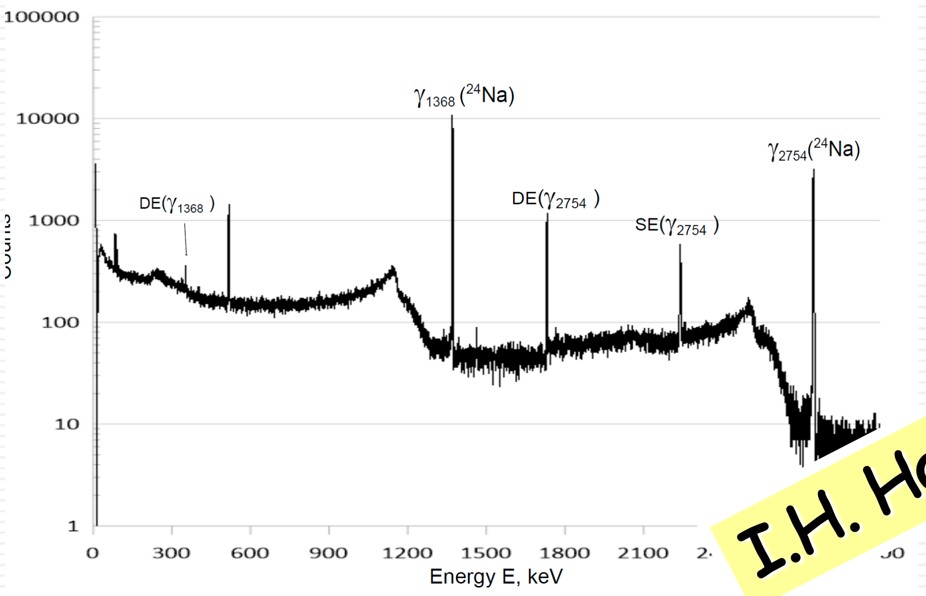
M. Schwarz talk



Off-line measurements @ LRC PSI



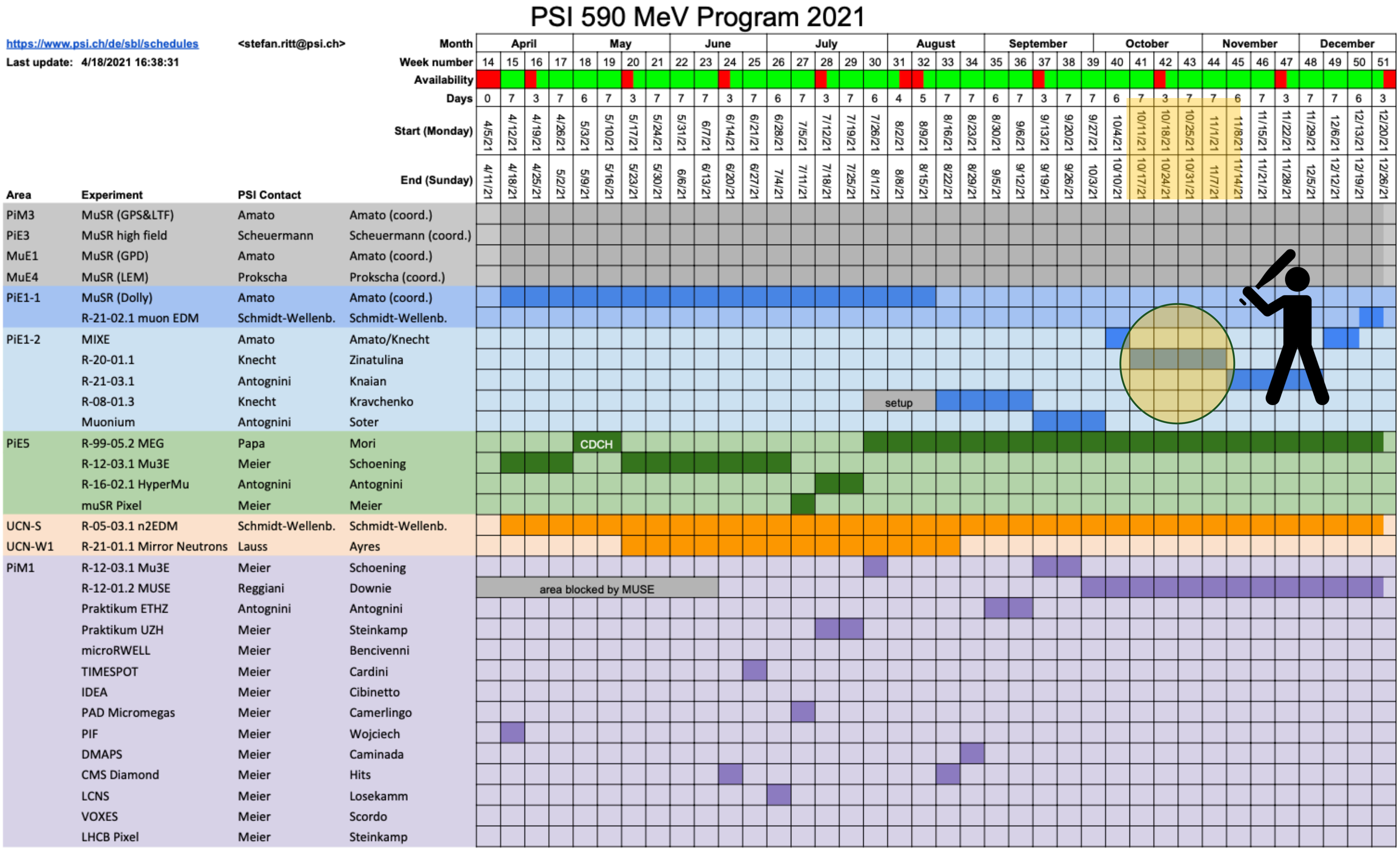




Off-line energy spectra with ^{24}Mg target

I.H. Hashim talk

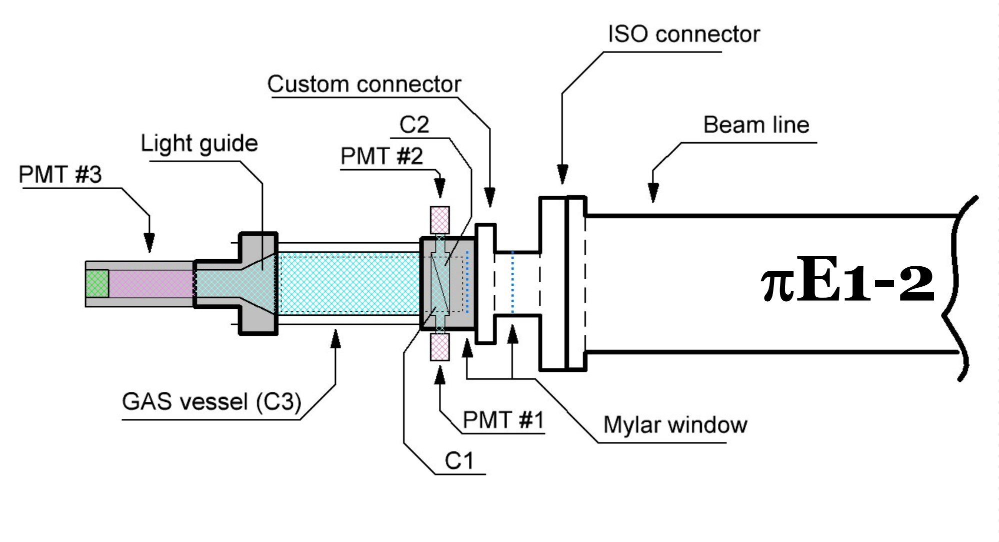
Beam Schedule 2021 (OMC: 10 October – 7 November)



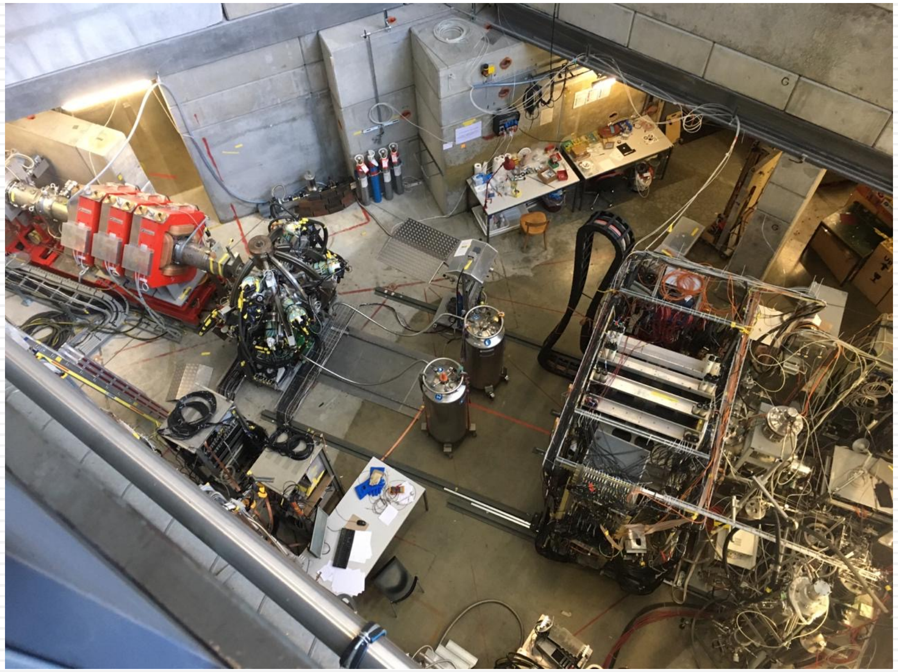
Backup Slides

Preliminary measurements in 2019 in frame of the muX collaboration

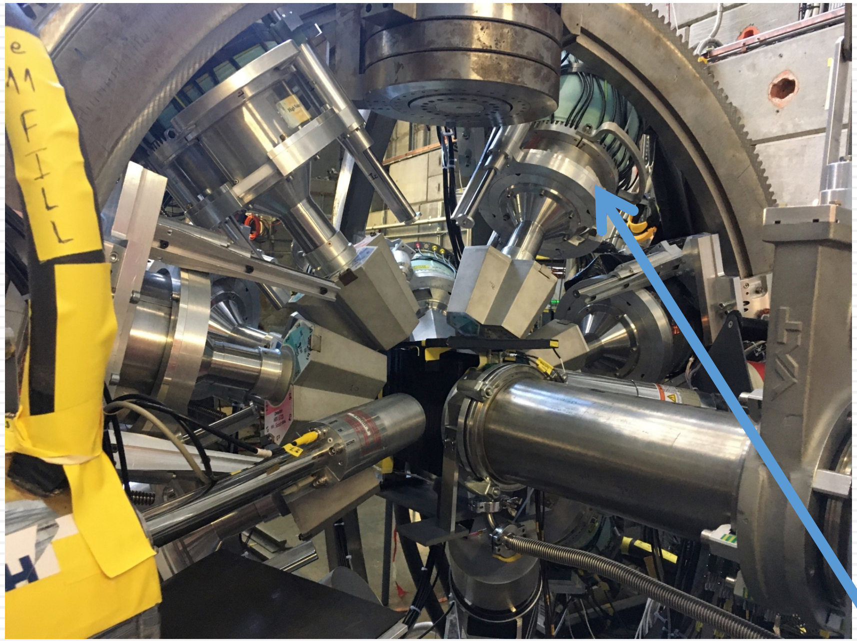
Addendum to proposal R-16-01.1 ("Muon capture on double beta decay nuclei of ^{130}Xe, ^{82}Kr and ^{24}Mg to study neutrino nuclear responses")

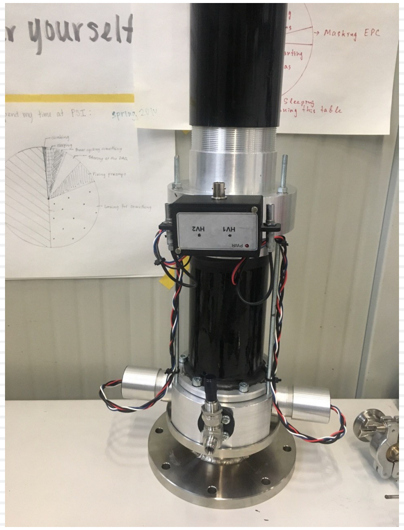


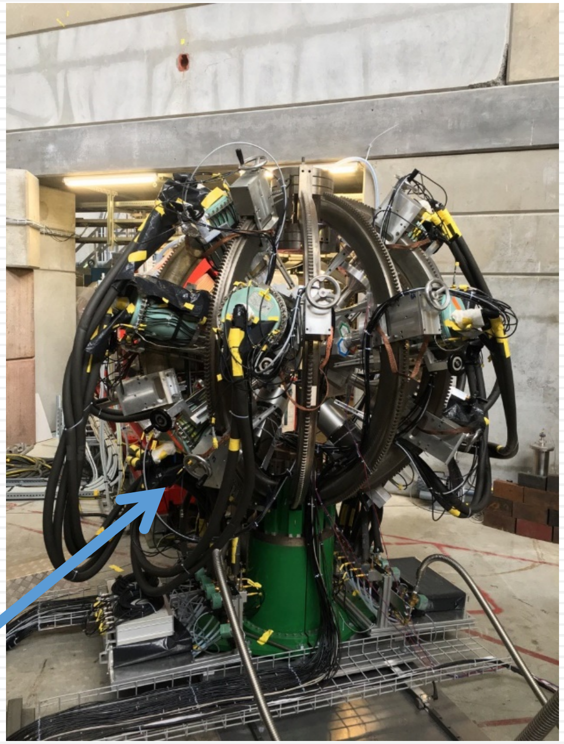
0ν2β-decay	0ν2β-Experiments	OMC targets
^{82}Se	NEMO3, SuperNEMO, CUPID-0 (R&D)	^{82}Kr (99.9%)
^{130}Te	Cuore, SNO+	^{130}Xe (99.9%)
---	Testing shell model for NME	^{24}Mg (99.85%)



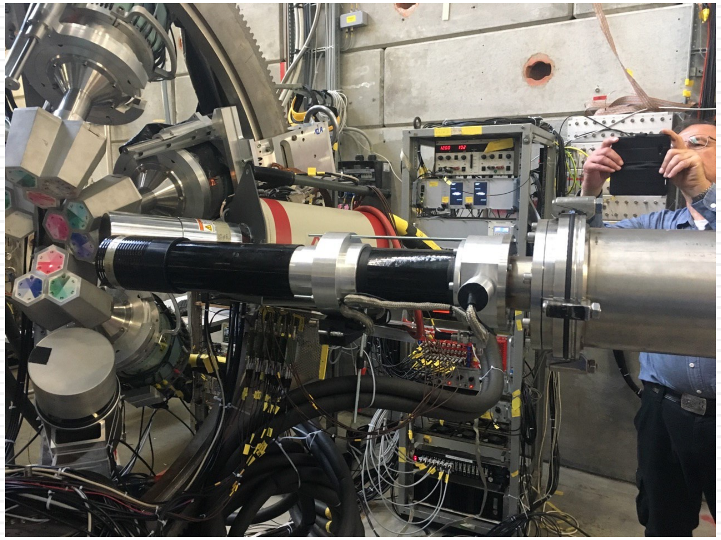
Preliminary measurements in 2019 at PSI

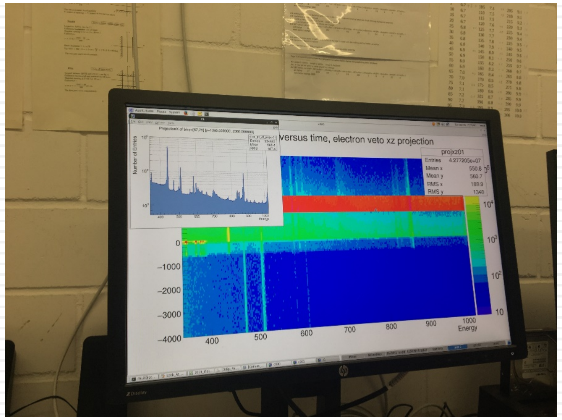






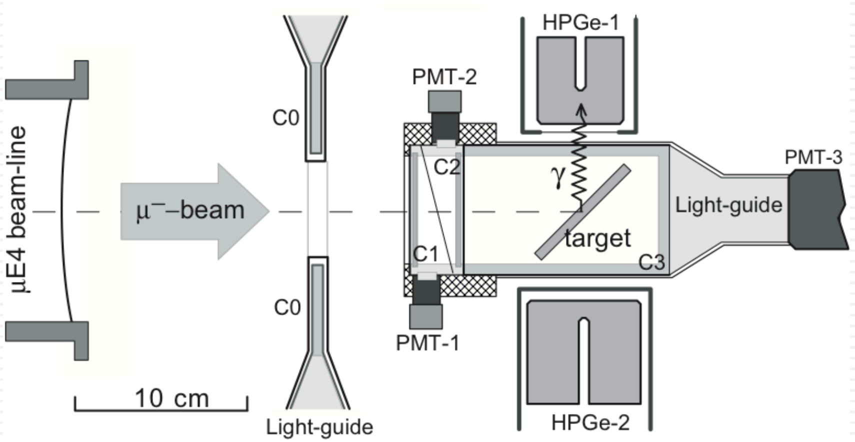
«Miniball» HPGe detectors array

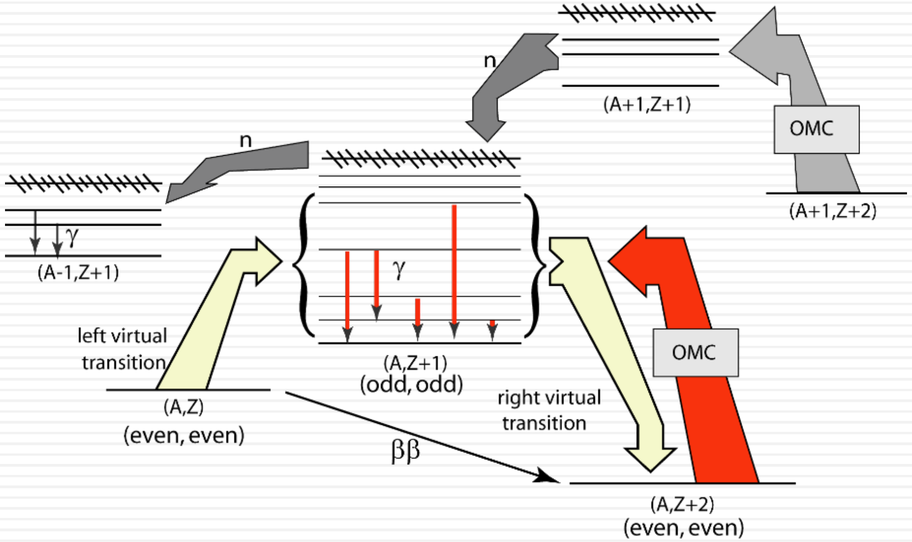




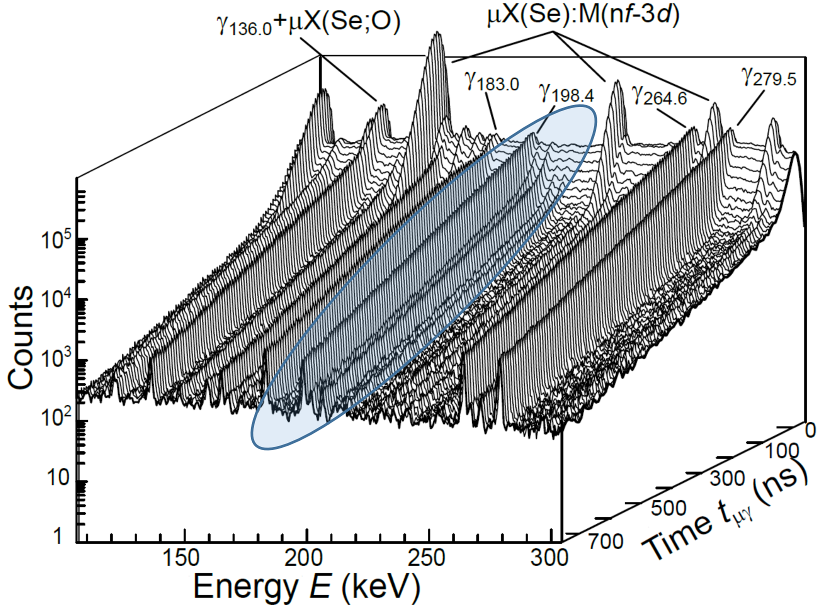
DAQ: 3 digitizers@250 MHz
MIDAS DAQ
MIDAS slow control
Online analysis
Data backup

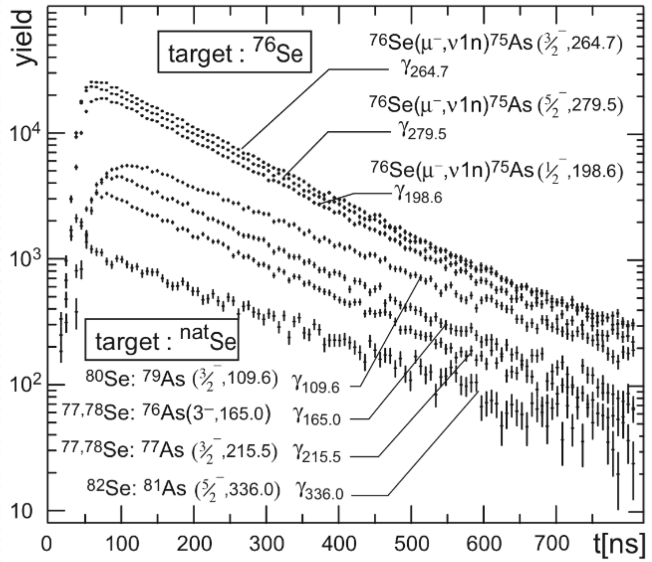
Experimental method of OMC





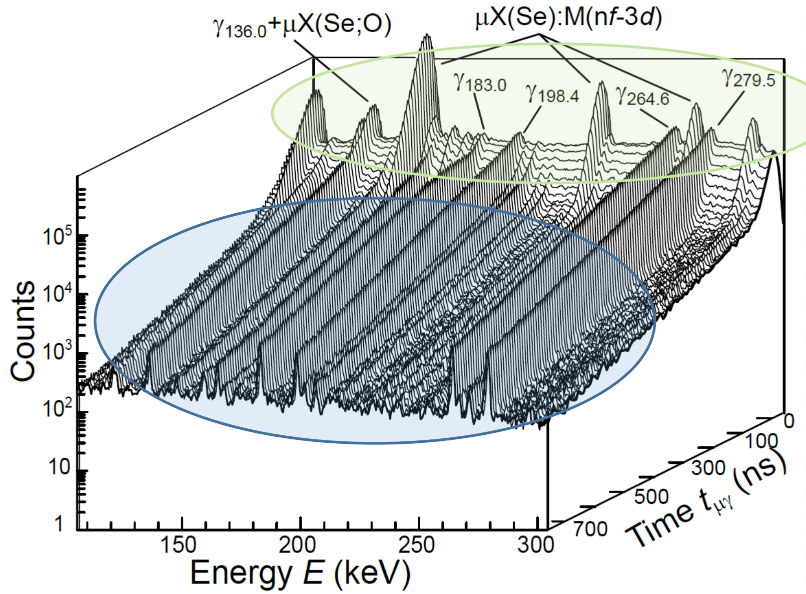
PSI: μE4 beam-line
Number of μ-stop = (8 – 25) x 10³ with 20 – 30 MeV/c

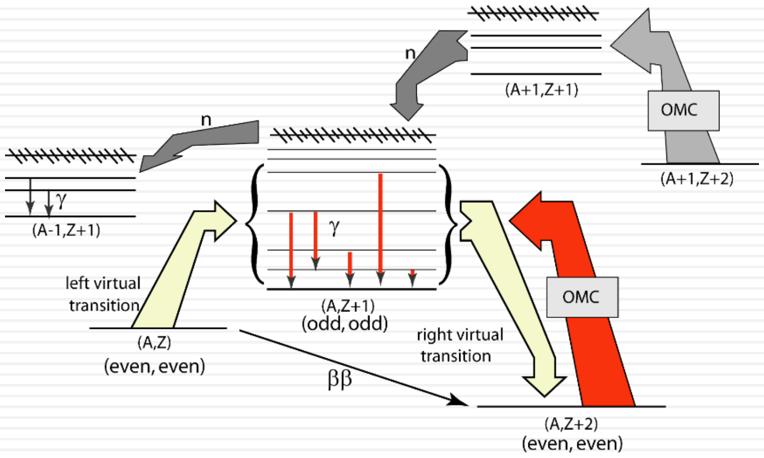


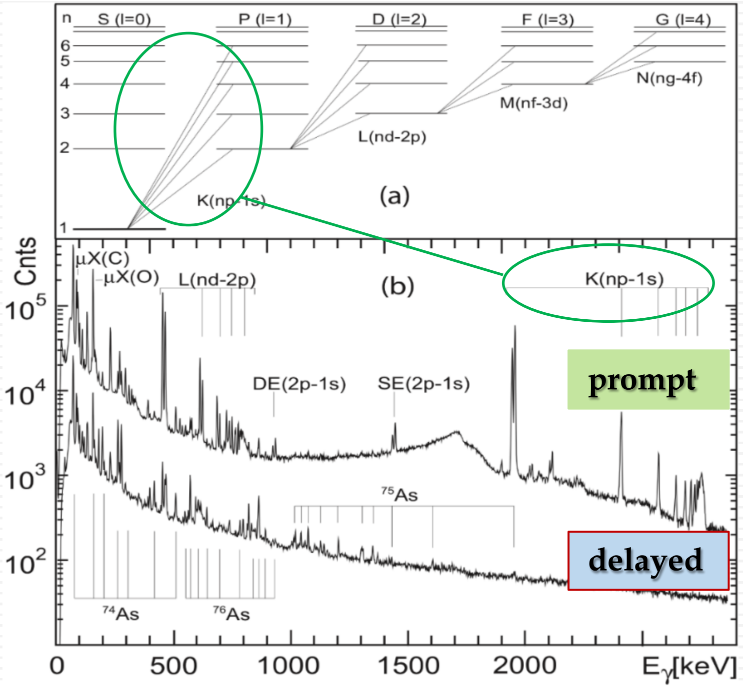


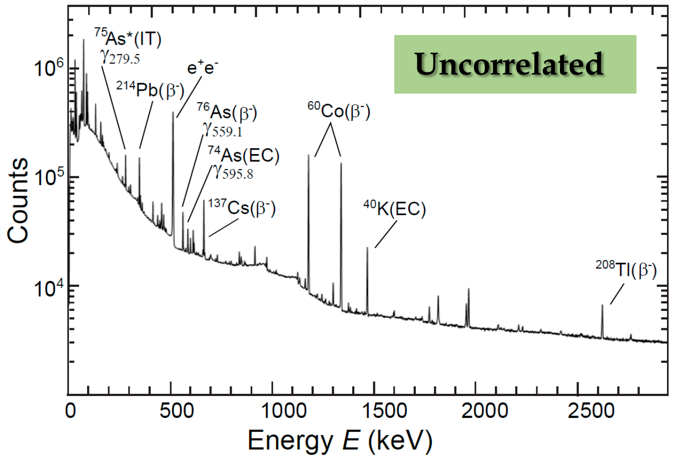
D. Zinatulina, V. Egorov et al. // Phys. Rev. C 99(2019)024327

Experimental method of OMC







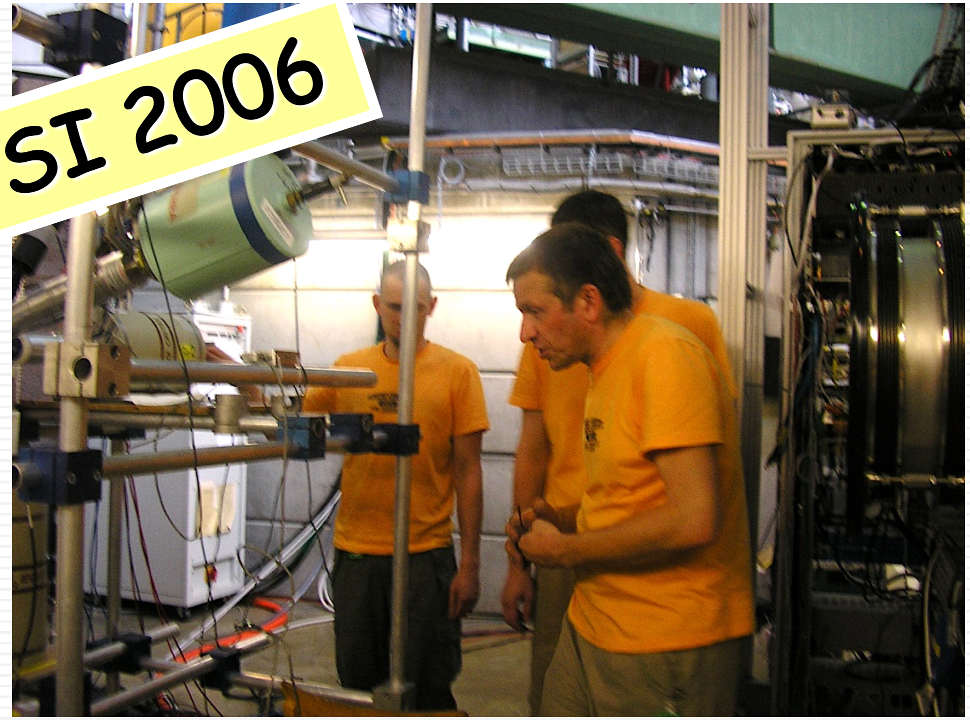


All results have been published in 9 different journals.
The main article with methods is - >
D. Zinatulina, V. Egorov et al. // Phys. Rev. C 99(2019)024327

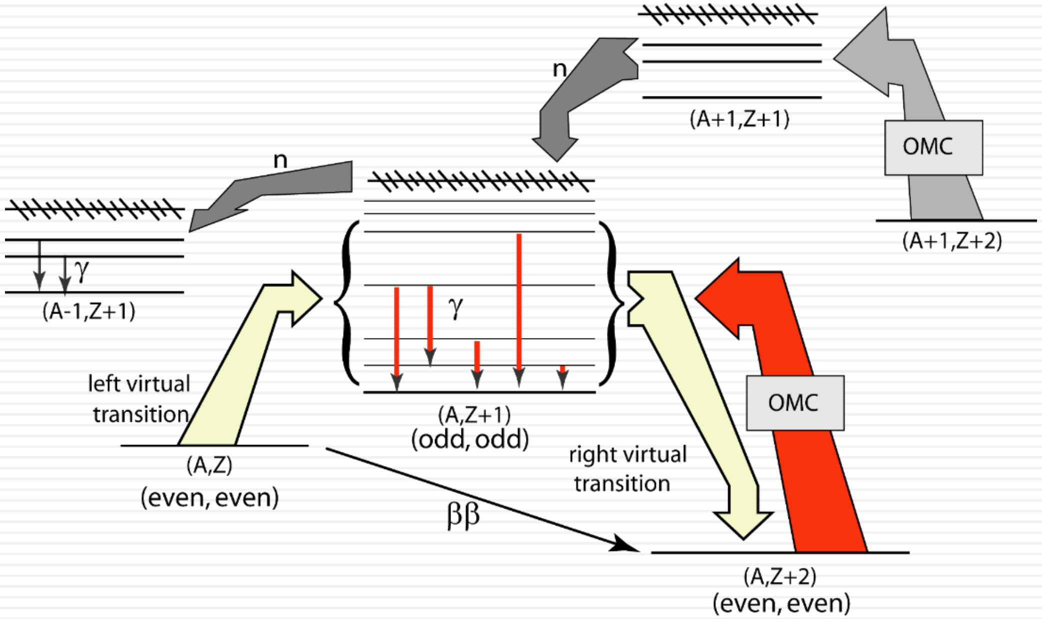

PSI 1998
AC/MC

PSI 2006

OMC



Comparison of experimental OMC results with theoretical calculations



OMC in ^{76}Se

J^{π}	OMC rate (1/s) Exp.[A]	OMC rate (1/s) 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**

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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.
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9. Electronic catalogue of muonic X-rays / *D. Zinatulina* // Physics of Atomic Nuclei - 2019. - Vol. 82, no. 3. - Pp. 228-234.
10. **Construction of the Gaseous and Solid-State Targets for the Muon Capture Measuring System in ^{130}Xe, ^{82}Kr, and ^{24}Mg / *V. V. Belov, V. B. Brudanin, K. N. Gusev, V. G. Egorov et al.* // Physics of Particles and Nuclei Letters, 17(6), 848-855**