St Petersburg University

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Employing Monte-Carlo codes for Muon Capture Experiments

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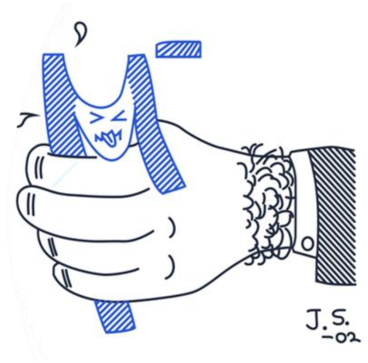
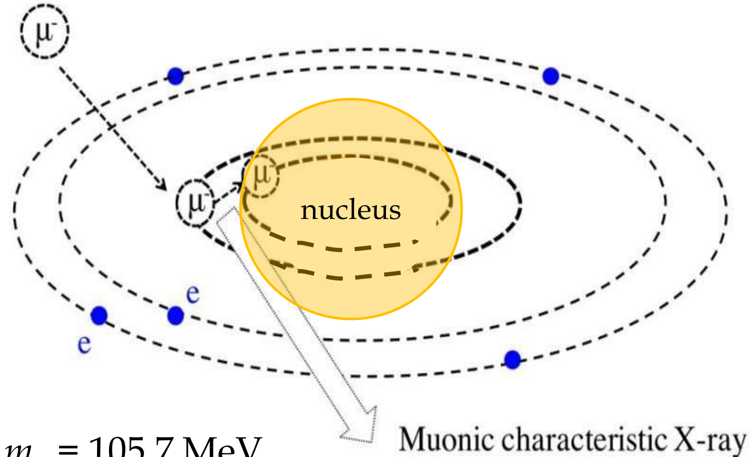
Motivation

- Verification of the accuracy of theoretical calculations of nuclear matrix elements (including for 0νββ-decay)
- Verification of the suppression of the parameter g_A

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



- Obtaining total and partial rates of ordinary muon capture (OMC)
- Filling the atlas of meso-X-ray spectra
- Using OMC to study the astrophysical properties of neutrinos (100Mo)



m_μ = 105,7 MeV

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

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

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

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

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

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

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- Short Theoretical introduction.
- **Advantages of using Monte-Carlo codes like MCNP6.**
- Steps for Monte-Carlo Simulations.
- MONUMENT experiment and Muon-Beam Profile.
- Muon Absorption and Induced Secondary Particles.
- Simulations of the Calibration Sources.
- Separating Spectrum into its Components.
- More for Near Future.

Advantages of using Monte-Carlo codes like MCNP6

- In general, Monte Carlo Transport Codes like *MCNP6* plays a pivotal role in simulating and optimizing experiments. Its ability to model particle interactions, complex geometries, and detector systems makes it an indispensable tool for researchers in this field.

- MCNP6 facilitates the simulation of muon transport, capture, and decay within target materials.

- Additionally, *MCNP6* enables the design and optimization of experimental setups by simulating detector responses, energy deposition, background radiation which can be suppressed (including natural background, Compton, Bremsstrahlung and other background-induced radiations when the beam is on), ensuring accurate measurements and reducing systematic uncertainties.

- The code is also valuable for studying rare phenomena, such as nuclear recoil effects and isotopic shifts, and for separating contributions from different nuclear isotopes in complex samples. Its versatility and accuracy make *MCNP6* an essential tool for advancing muonic X-ray experiments.

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Steps for Monte-Carlo Simulations

1. The geometry and materials of all components of the MONUMENT experiment have been written and constructed employing many codes and softwares: **MCNP6** + **Phig3D-PHITS** + **TopMC**. As a beginning, simulations were applied to the experiment carried out in 2021 at PSI using **BaCO3** target with ~95% enrichment of Ba-136.

2. The full input-files for Monte-Carlo code MCNP6 have been written for different calculations: muon-beam profile simulations; simulations to get all generated-particles during the muon-irradiation; simulations of the background (terrestrial background); the cosmic-rays background; simulations of the generated isotopes in the Target and the Detector and their gamma-intensities; and other related simulations.

3. Getting results (mentioned in the previous paragraph) after processing the data resulting from simulations. The simulated results were compared with the experimental ones.

4. Conducting the simulations using MCNP6 code on the JINR Cluster and Cloud with more Cores and RAMs resources to accelerate simulations (not all types of simulations!).

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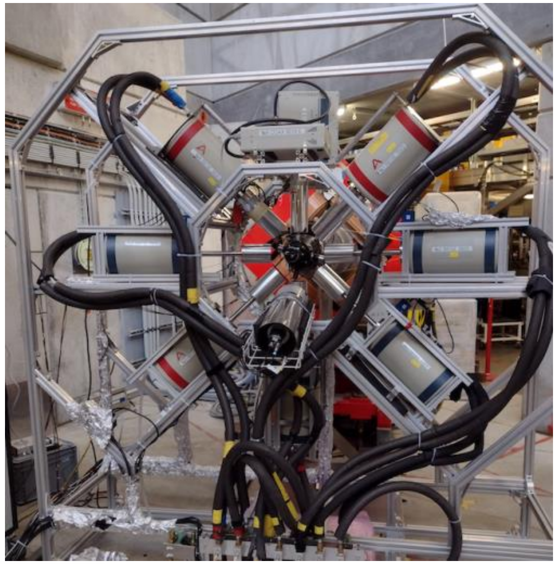
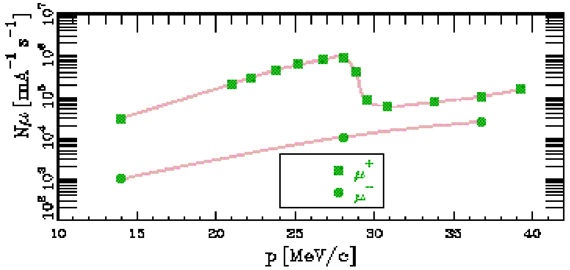
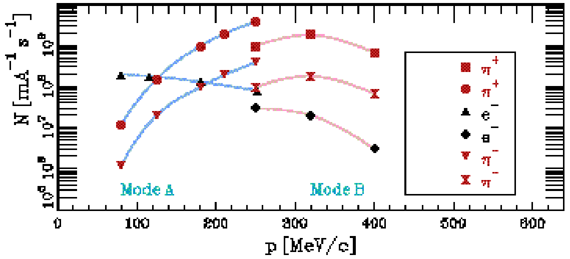
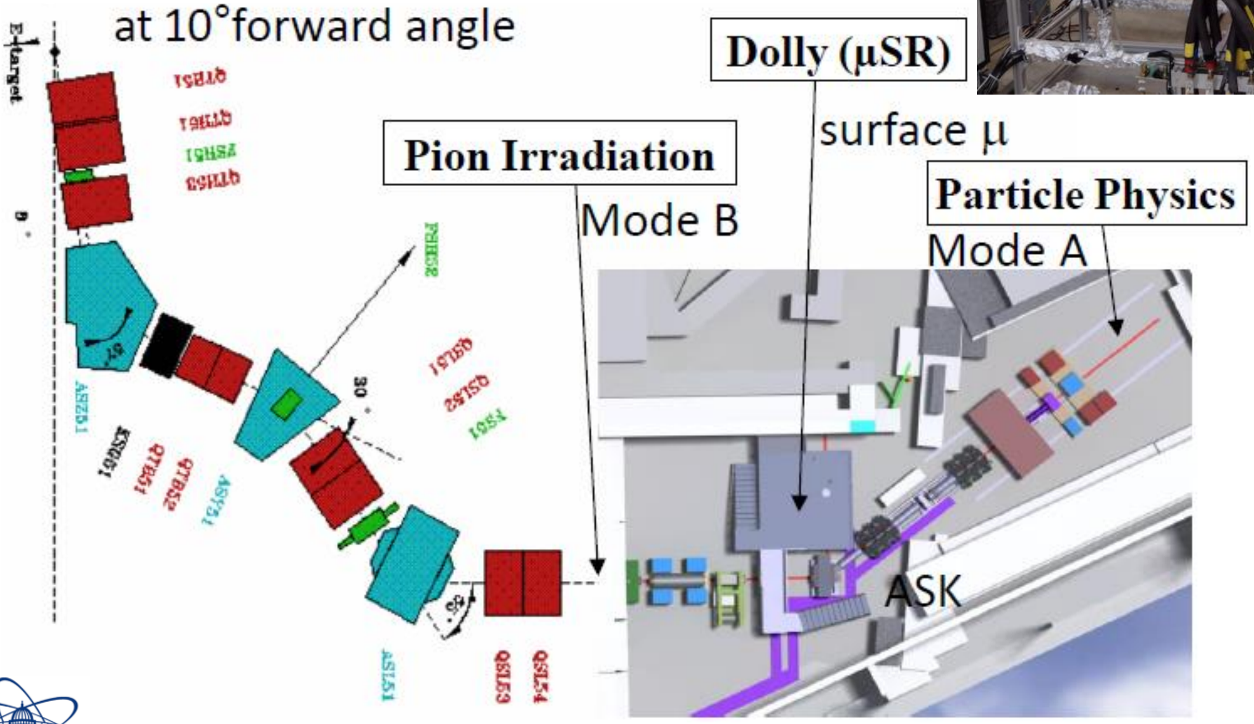
MONUMENT experiment @ πE1 beamline (PSI, Switzerland)





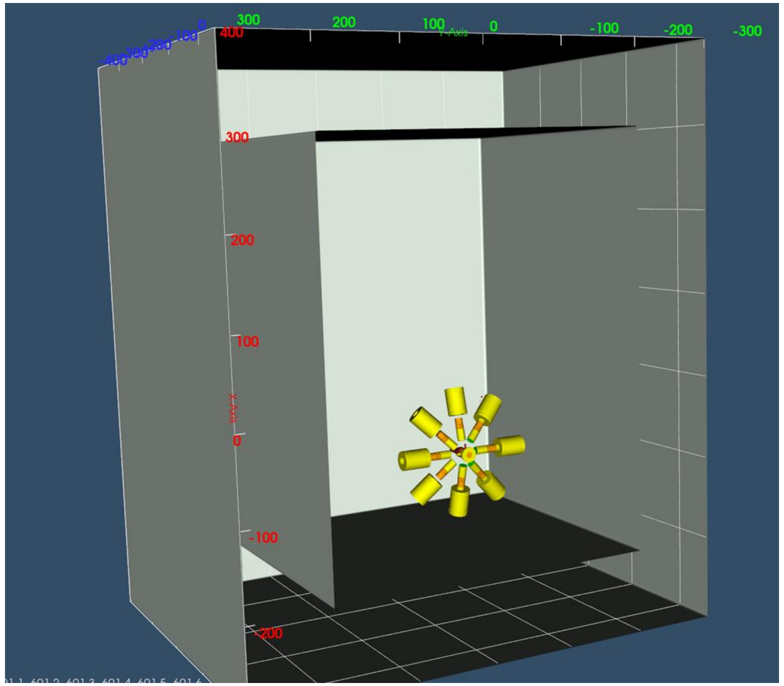
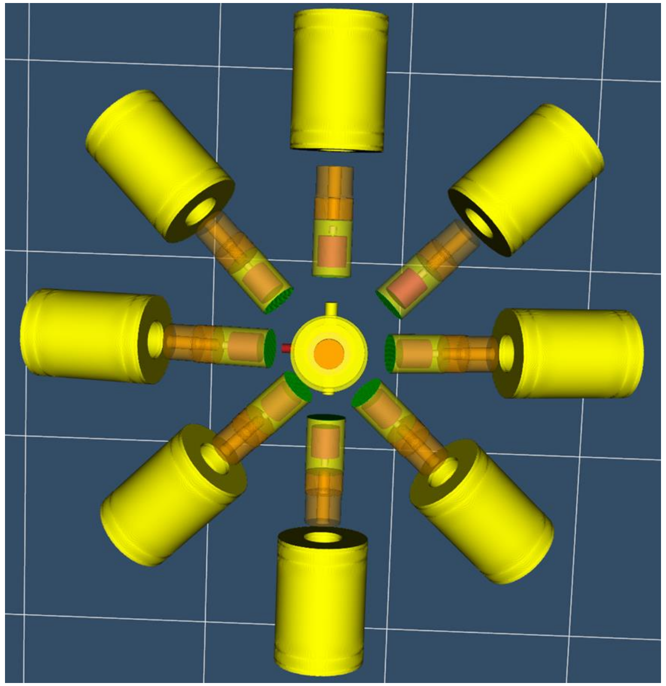
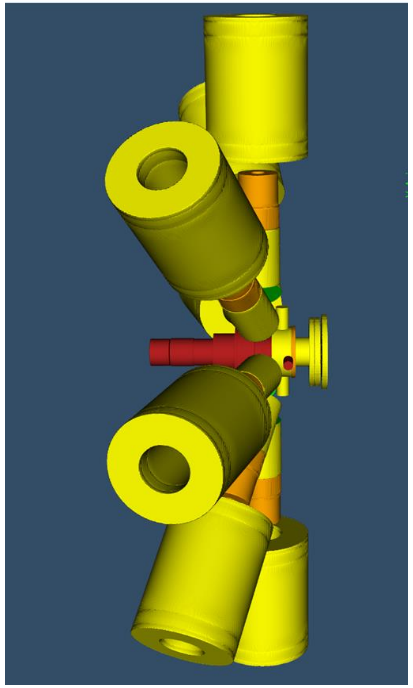
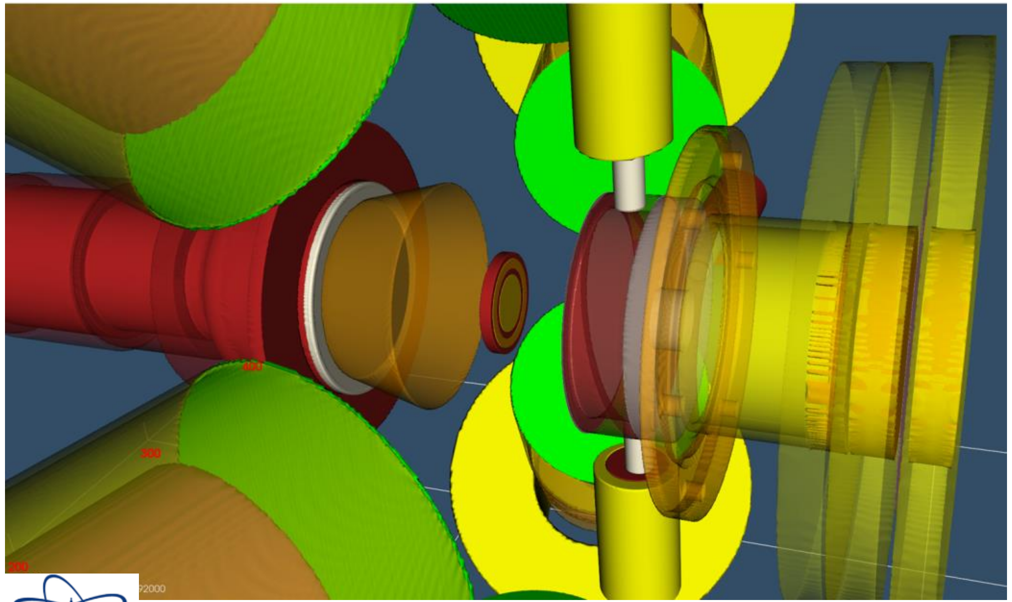
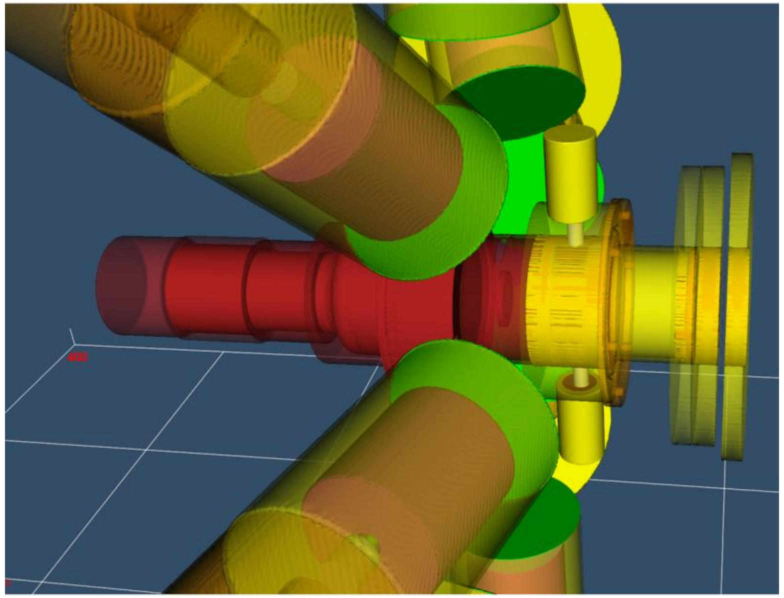


Muon-Beam momentum: 33-40 MeV/c



Purpose	OMC targets (enrichment)	Year/Status
experimental input for DBD NME calculations	^{76}Se (99.97%)	**2021** / analysis and publication
experimental input for DBD NME calculations	^{136}Ba (95.27%)	**2021** / analysis and publication
experimental input for astrophysics investigations with SN	^{100}Mo (97.3%)	**2022** / started data analysis
Nuclear spectroscopy, total cap. rates, yields	^{nat}Mo	**2022** / started data analysis
testing nuclear shell model (SM) calculations	^{48}Ti (99.9%)	**2023** / started data analysis
experimental input for DBD NME calculations, ab-initio calculations	^{96}Mo, ^{12}C, ^{13}C, ^{56}Fe	**2026-2028** / in preparation

Geometry of MONUMENT-Experiment described in the MCNP-input file and generated using Phig3D-PHITS program.

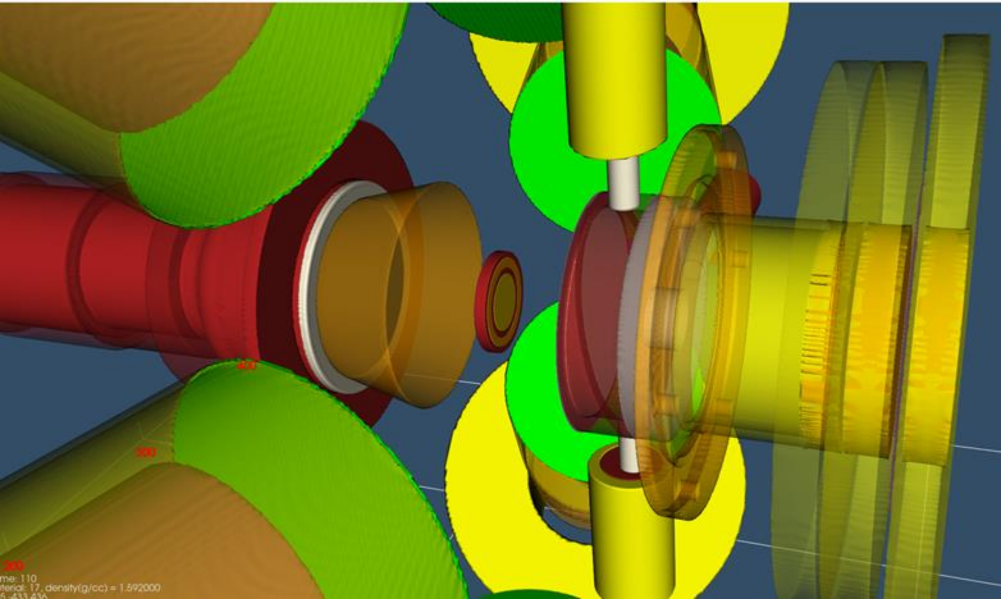






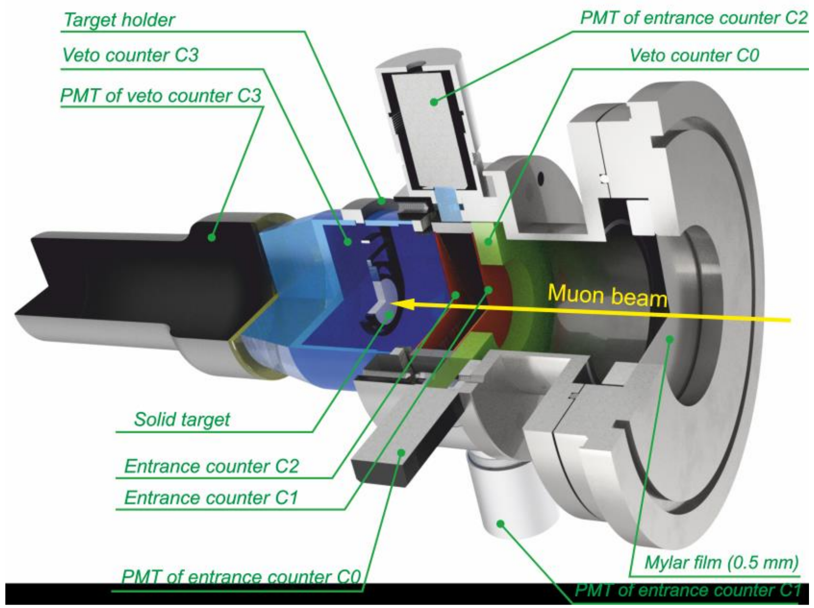
The following codes and programs were used to obtain the geometry:

- **MCNP6** (Monte Carlo N-Particle Transport is a general-purpose, continuous-energy, generalized-geometry, time-dependent, Monte Carlo radiation transport code designed to track many particle types over broad ranges of energies and is developed by Los Alamos National Laboratory.)

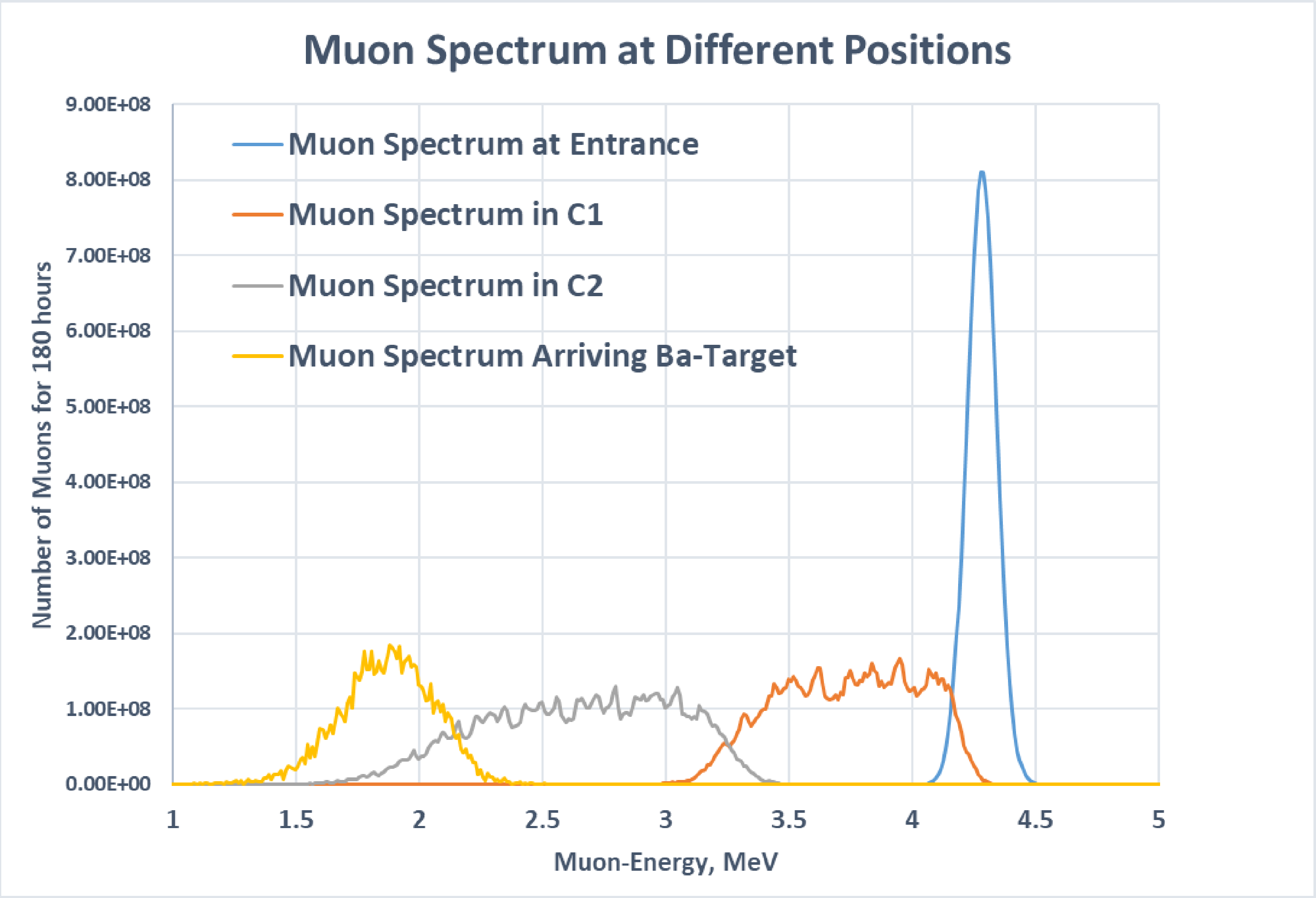
- **Phig3D-PHITS** (Particle and Heavy Ion Transport code System) is a general purpose Monte Carlo particle transport simulation code developed under collaboration between JAEA, RIST, KEK and several other institutes)

- **TopMC** (Multi-Functional Program for Neutronics Calculation, Nuclear Design and Safety Evaluation, which has been developing by FDS

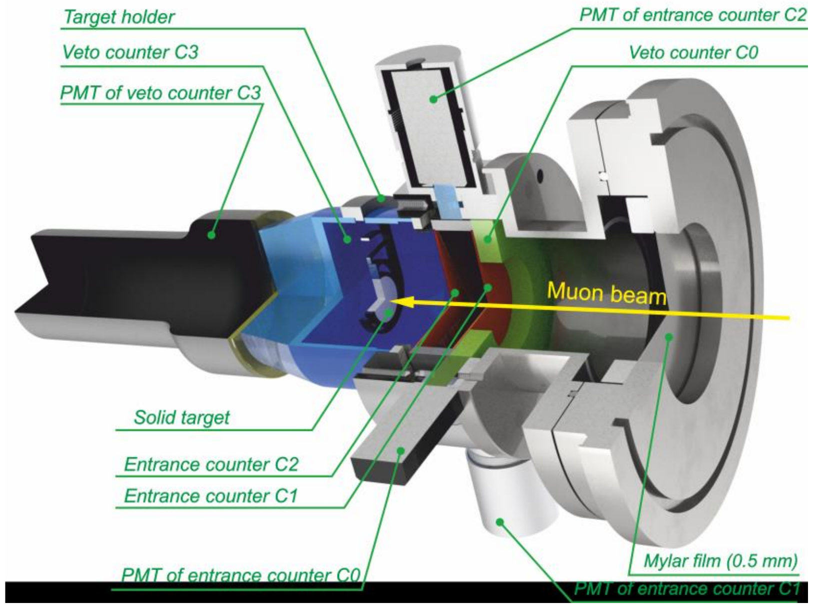


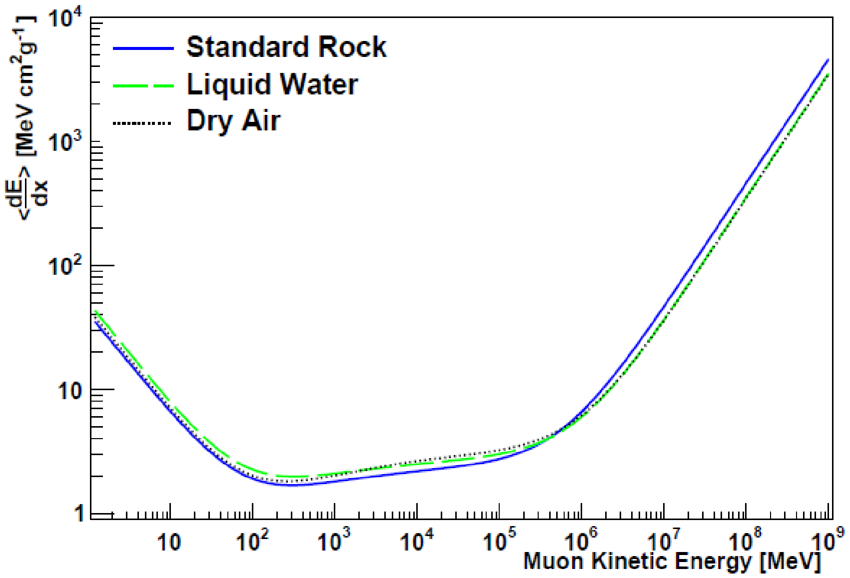


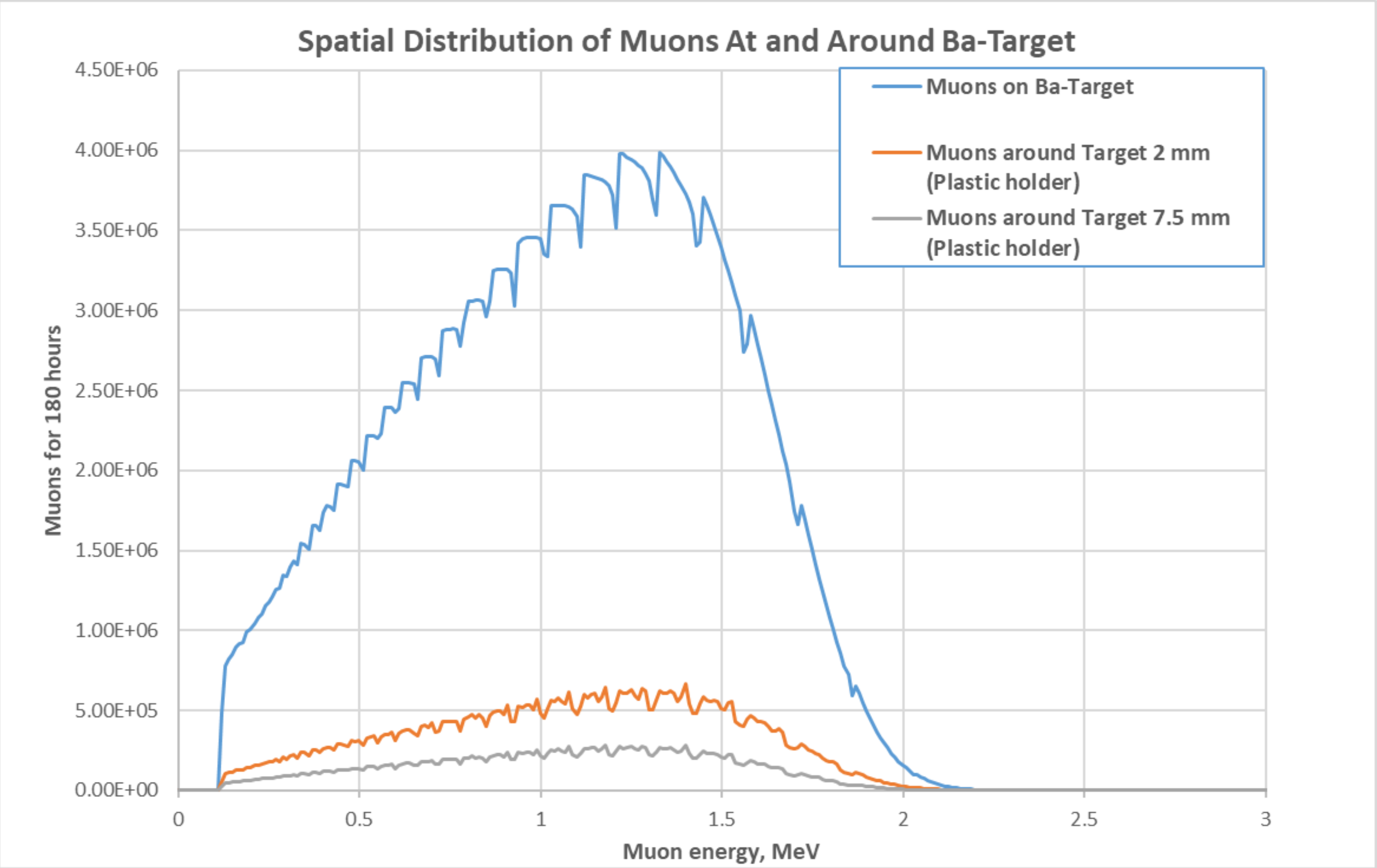
Picture of the solid target unit with the scintillation counters **C0**, **C1**, **C2** and **C3**



The muons decreases in numbers after **C2** by about 34% and the muon-energy was shifted by elastic-scattering.







http://dx.doi.org/10.1103/PhysRevD.98.030001

The stopping power for muons in C1, C2 for 1 mm thickness = 1.5 MeV

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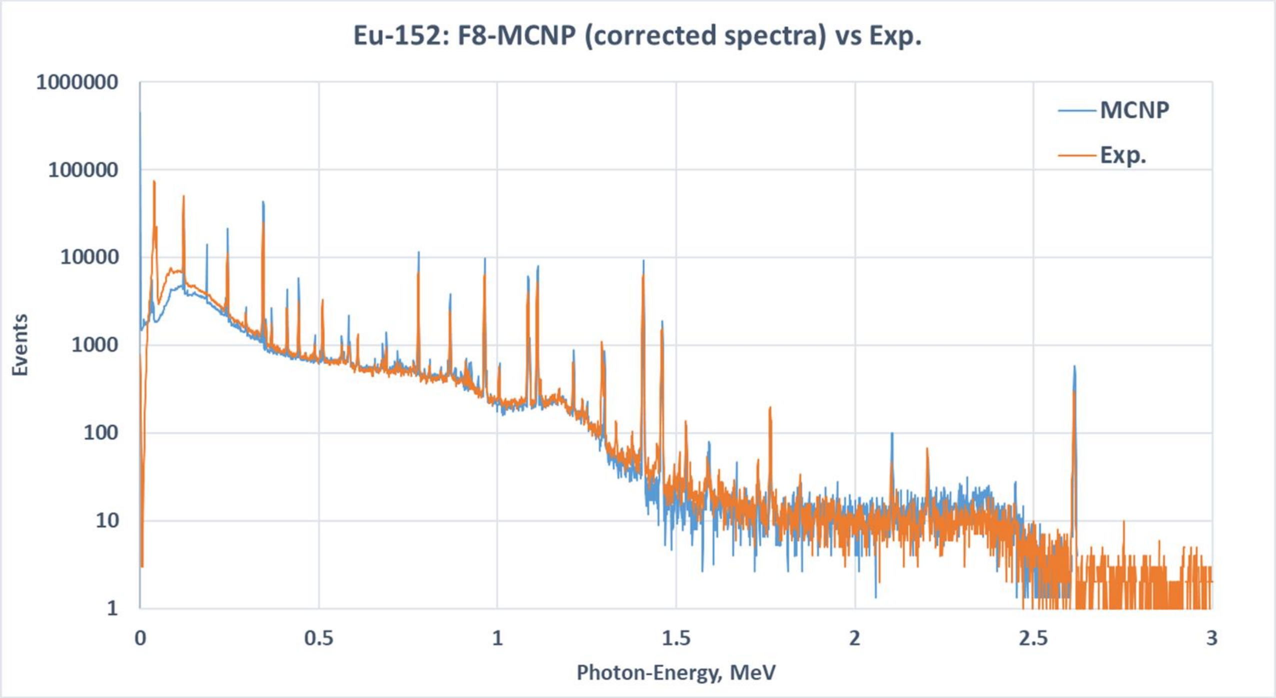
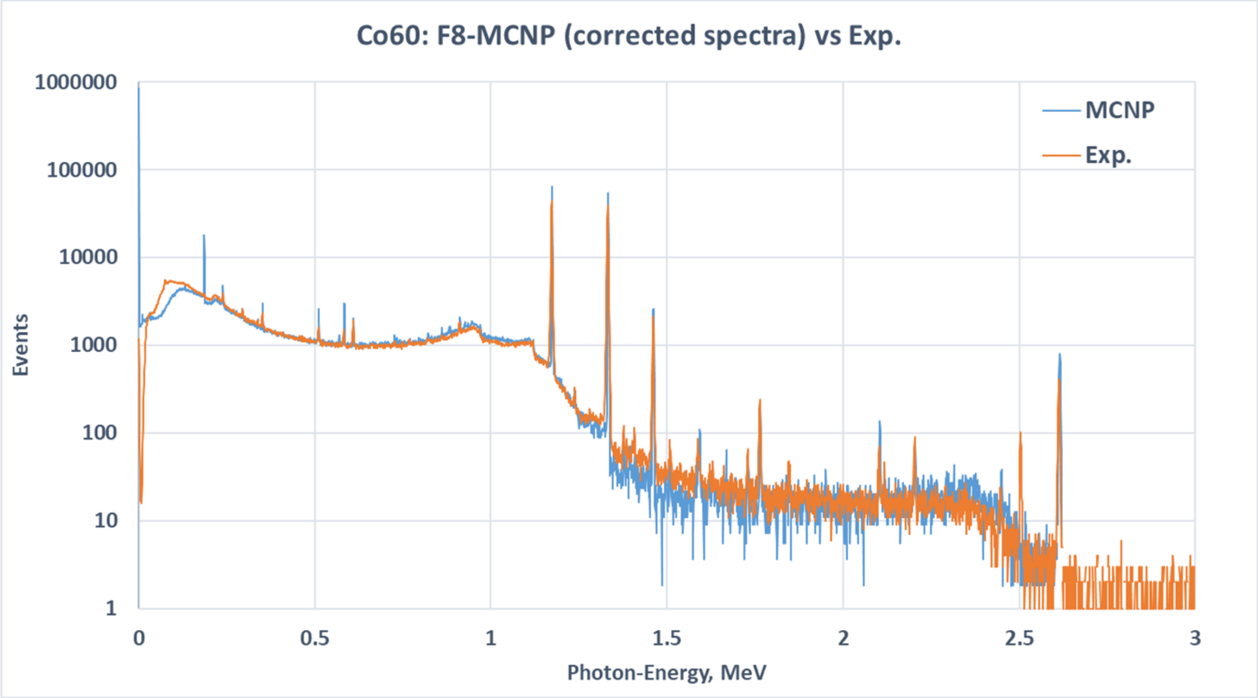
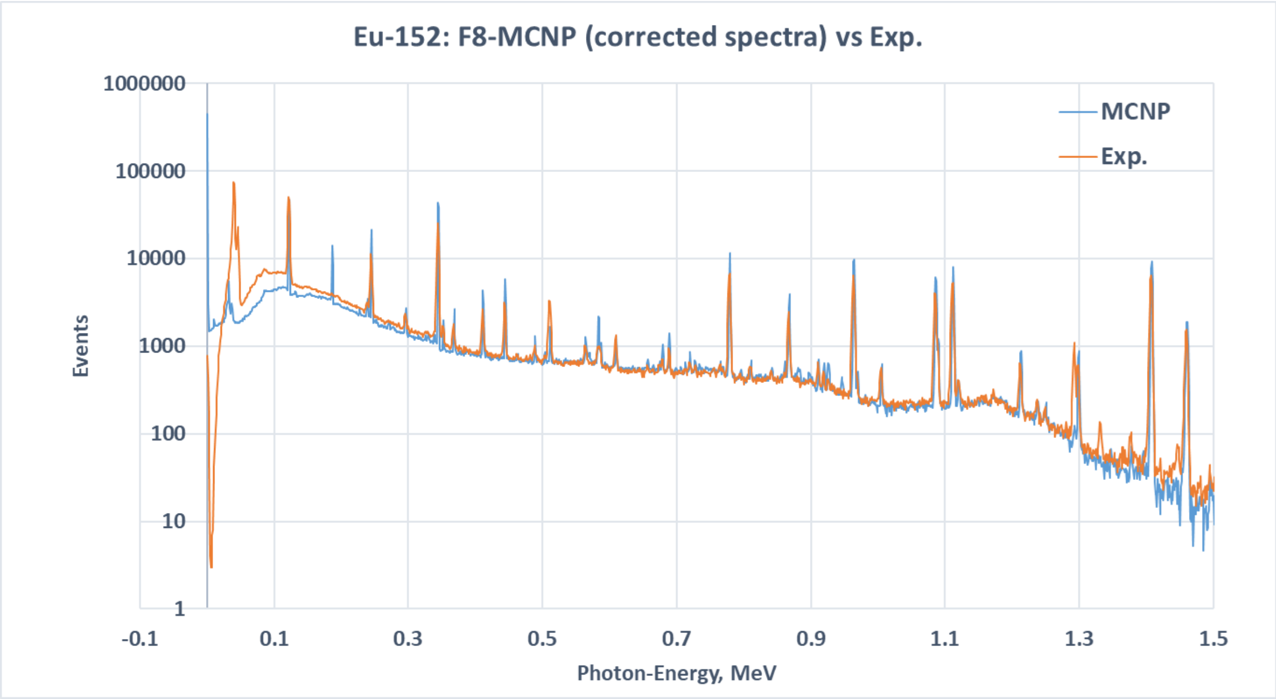
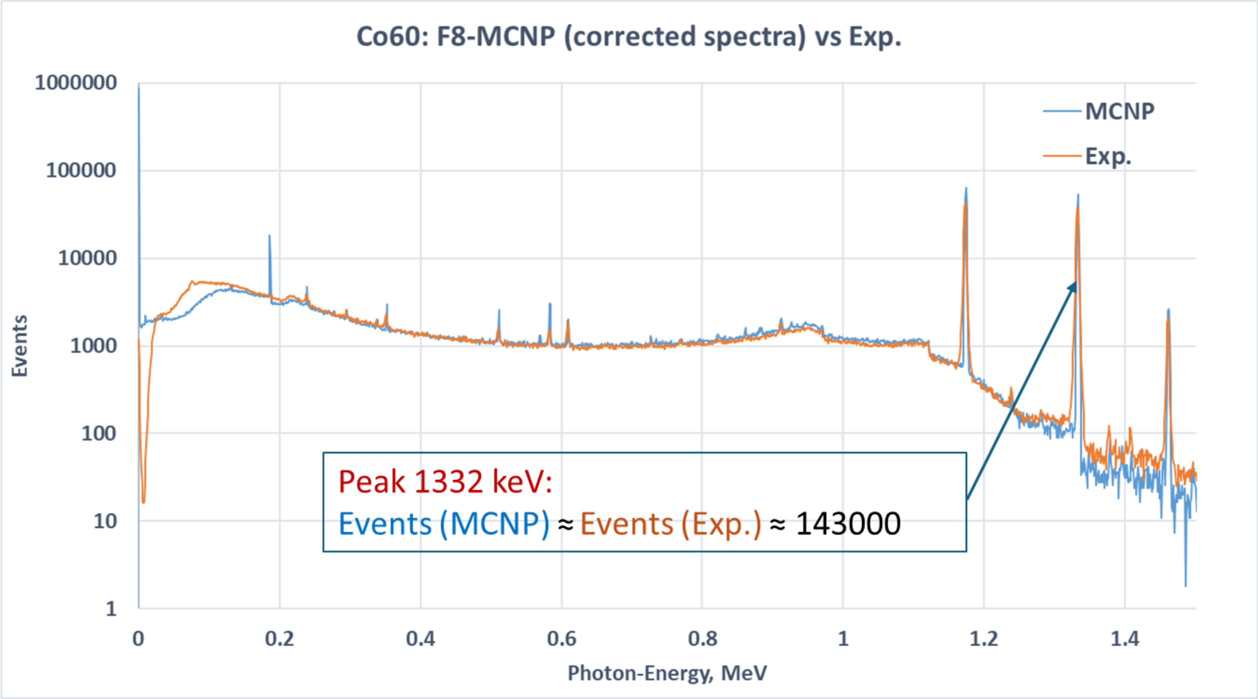

Eu-152: F8-MCNP (corrected spectra) vs Exp.
MCNP
Exp.
Events
Photon-Energy, MeV


Co60: F8-MCNP (corrected spectra) vs Exp.
MCNP
Exp.
Events
Photon-Energy, MeV


Eu-152: F8-MCNP (corrected spectra) vs Exp.
MCNP
Exp.
Events
Photon-Energy, MeV


Co60: F8-MCNP (corrected spectra) vs Exp.
MCNP
Exp.
Peak 1332 keV:
Events (MCNP) ≈ Events (Exp.) ≈ 143000
Events
Photon-Energy, MeV

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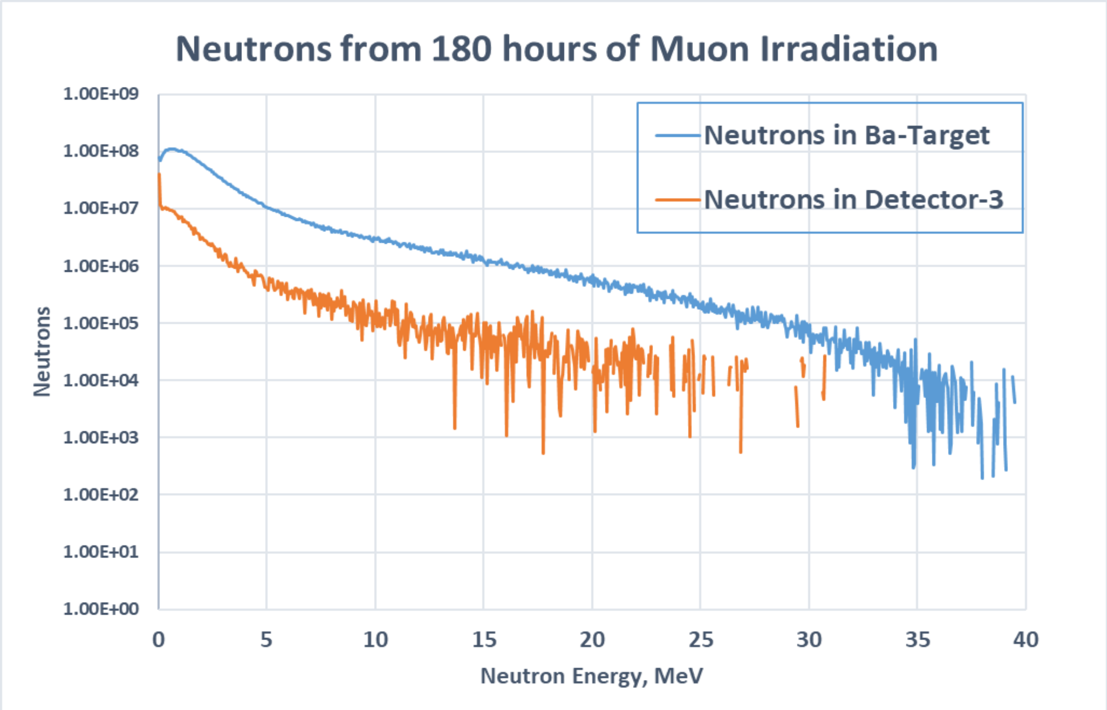

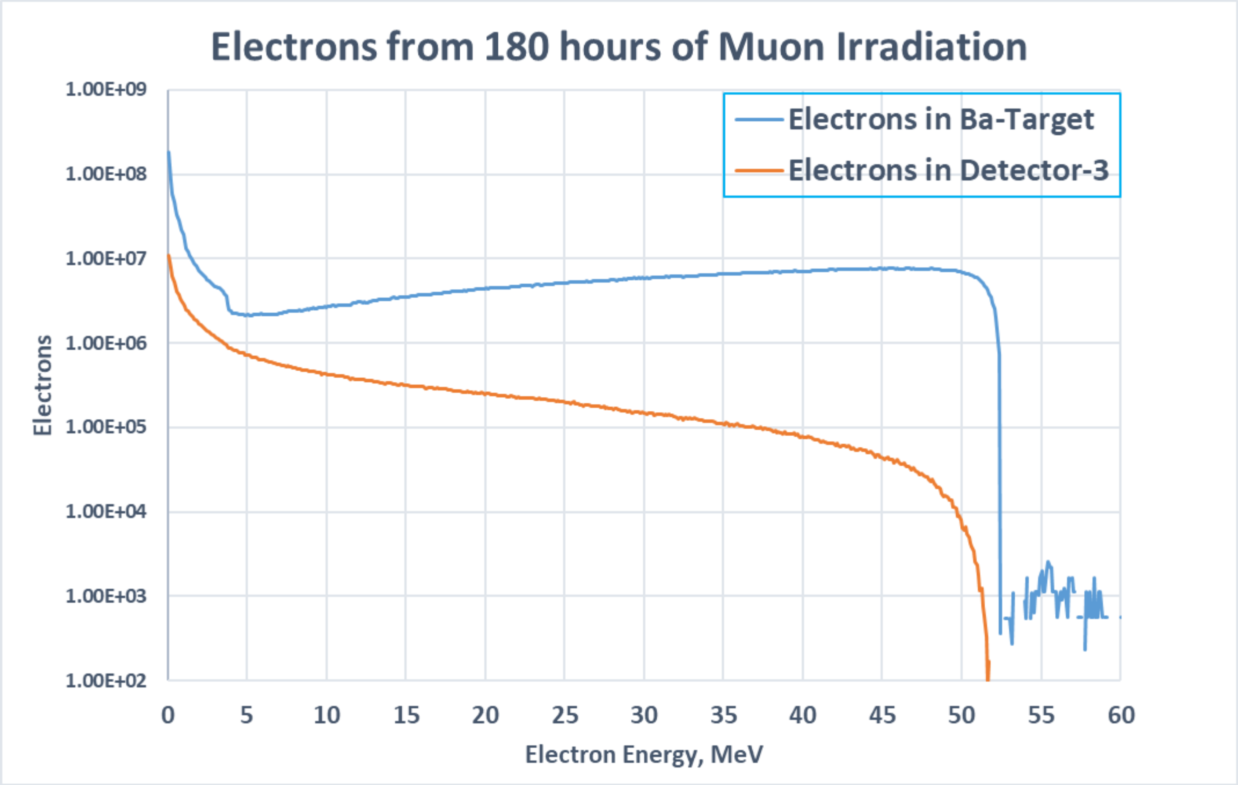

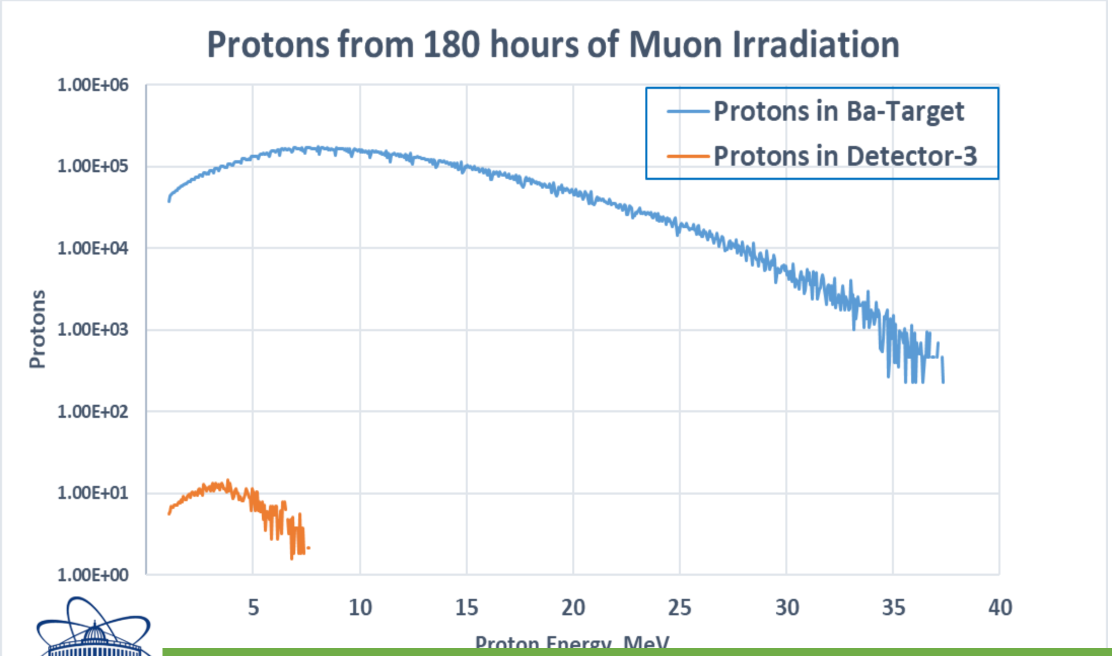

Secondary induced-particles can interact with all parts of the experiment and induce isotopes mainly important at Target and Detector, and can have considerable contributions of background.

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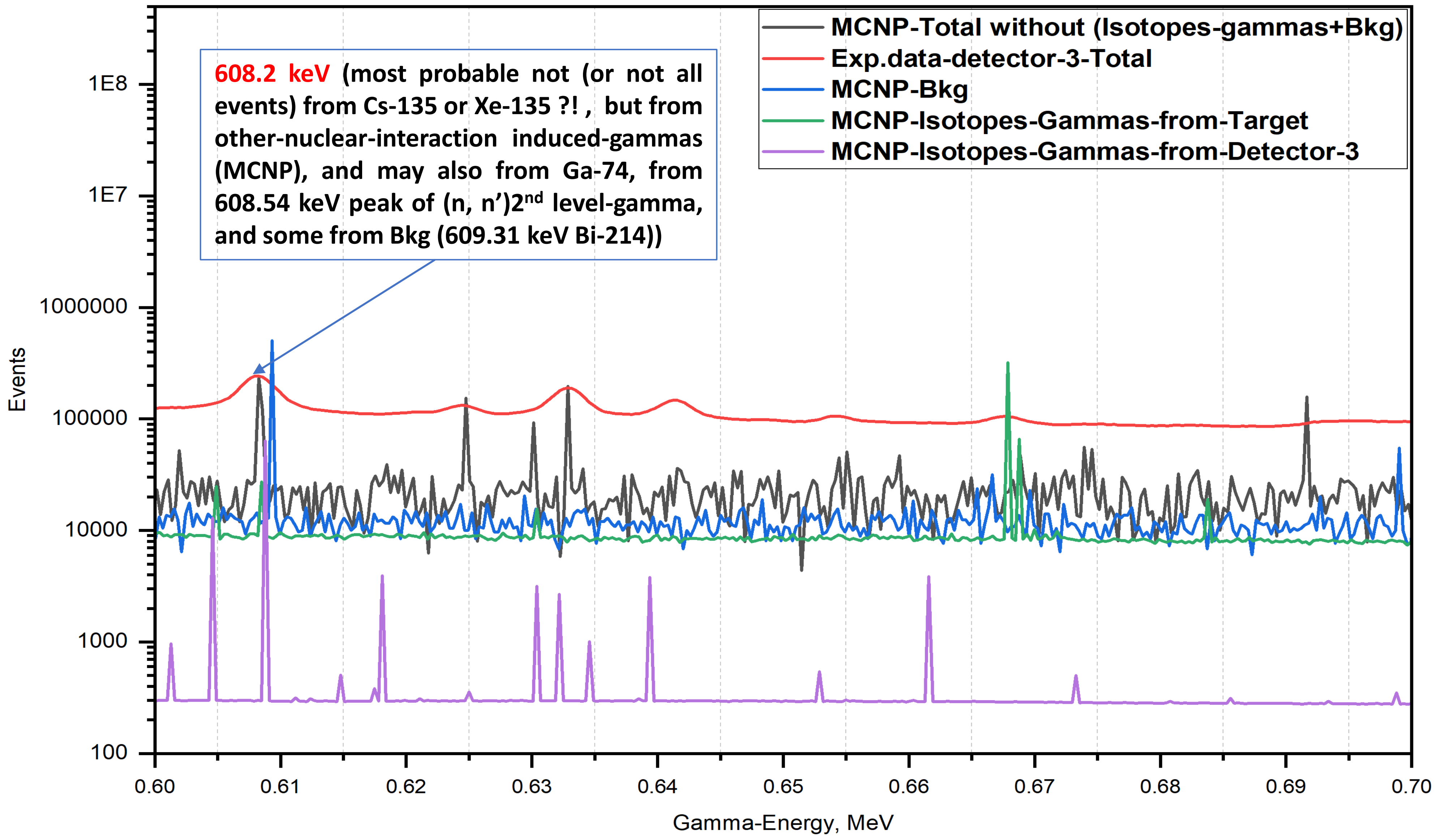
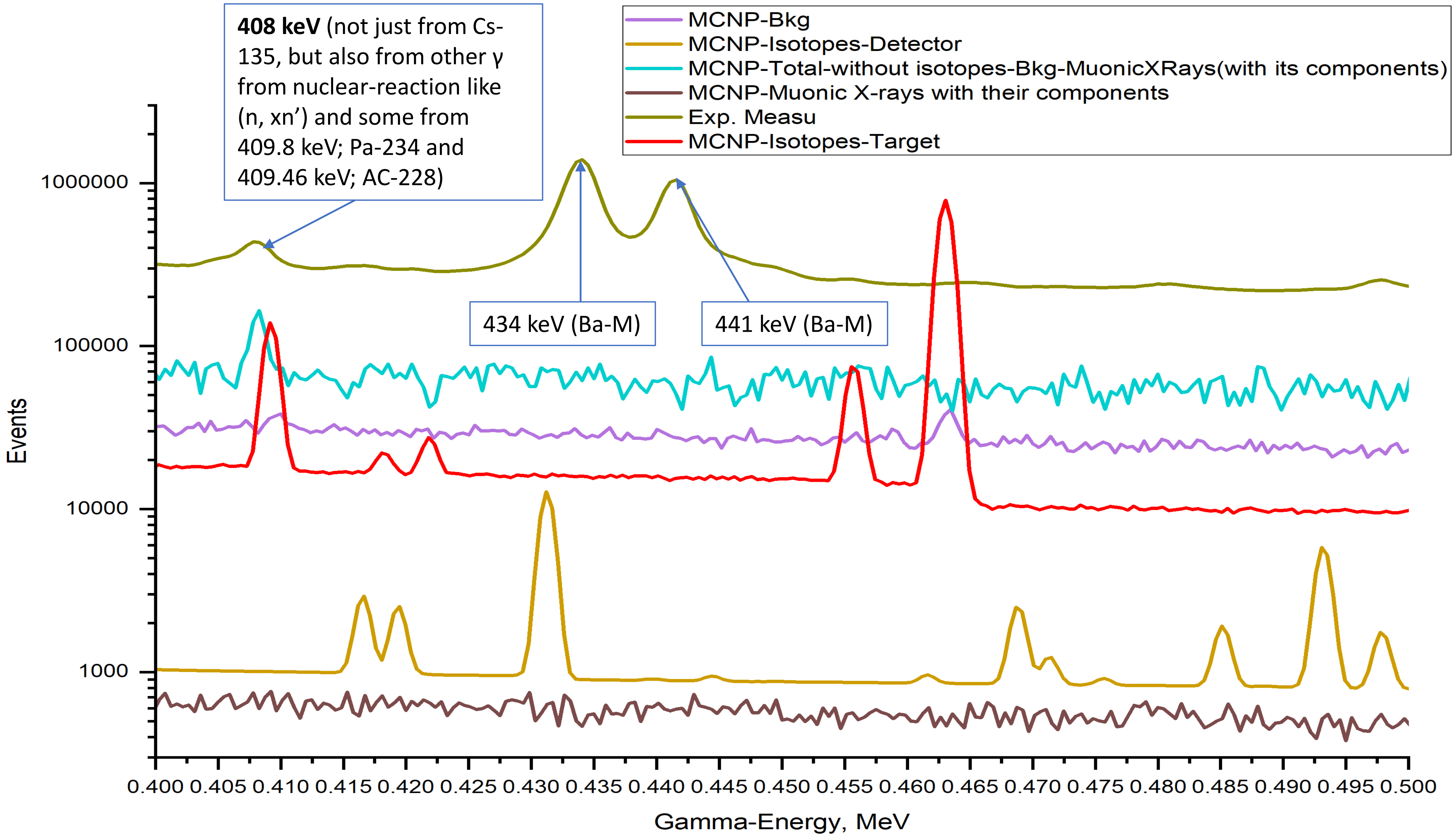

608.2 keV (most probable not (or not all events) from Cs-135 or Xe-135 ?! , but from other-nuclear-interaction induced-gammas (MCNP), and may also from Ga-74, from 608.54 keV peak of (n, n')2nd level-gamma, and some from Bkg (609.31 keV Bi-214))
MCNP-Total without (Isotopes-gammas+Bkg)
Exp.data-detector-3-Total
MCNP-Bkg
MCNP-Isotopes-Gammas-from-Target
MCNP-Isotopes-Gammas-from-Detector-3
Events
1E8
1E7
1000000
100000
10000
1000
100
0.60
0.61
0.62
0.63
0.64
0.65
0.66
0.67
0.68
0.69
0.70
Gamma-Energy, MeV


408 keV (not just from Cs-135, but also from other γ from nuclear-reaction like (n, xn') and some from 409.8 keV; Pa-234 and 409.46 keV; AC-228)
MCNP-Bkg
MCNP-Isotopes-Detector
MCNP-Total-without isotopes-Bkg-MuonicXRays(with its components)
MCNP-Muonic X-rays with their components
Exp. Measu
MCNP-Isotopes-Target
434 keV (Ba-M)
441 keV (Ba-M)
1000000
100000
10000
1000
Events
0.400 0.405 0.410 0.415 0.420 0.425 0.430 0.435 0.440 0.445 0.450 0.455 0.460 0.465 0.470 0.475 0.480 0.485 0.490 0.495 0.500
Gamma-Energy, MeV

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More for Near-Future:

- **Allow more physics and MCNP6 tallies to be incorporated into pulses:**
  - All previous and on-going simulations are Time-independent, and it is very important to do the simulations with **Time-Dependent**, which is available in MCNP6 code: Time binning; Time Triggering.
  - Coincidence/Anti-Coincidence between many detectors.
  - Coincidence-Summing Peaks.
  - Delayed particles production.
  - Detailed exploring muonic X-ray production – **MUON/RURP codes** included with MCNP6 code.
  - Nuclear resonance fluorescence.
  - Micro/macro beam pulse option – nesting of time distributions provides accurate beam modeling.
  - ROC curve tally option – generates **ROC** (Receiver Operator Characteristic) curves from signal & noise tallies using batches of samples.
  - The possibility of optimizing the **Beam-profile** and **Target** to get the same gamma-intensities with less secondary particles which decrease the background, and maybe also with less Target-material used in the experiments and therefor decreasing the costs !.
- Start doing simulations for other Targets: **Mo-100, Se-76, Ti-48** …

THANK YOU FOR YOUR ATTENTION

Q & A