UTM UNIVERSITI TEKNOLOGI MALAYSIA

Exploring Delayed Gamma-Ray following Ordinary Muon Capture: Insights into Double Beta Decays and Antineutrino Nuclear Responses

IZYAN HAZWANI HASHIM

NME2025
RCNP WORKSHOP FOR THEORETICAL AND EXPERIMENTAL APPROACHES FOR NUCLEAR MATRIX ELEMENTSOF DOUBLE BETA DECAYS

Innovating Solutions

UTM UNIVERSITI TEKNOLOGI MALAYSIA

OUTLINE

www.utm.my

Innovating Solutions

Introduction

- Overview of Ordinary Muon Capture (OMC)
- Relationship between OMC and Double Beta Decays (DBDs)

Overview of Ordinary Muon Capture (OMC)

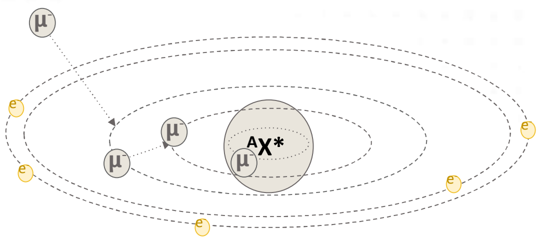
- OMC is a weak nuclear process that involves the exchange of charged bosons to transform a proton (p) into a neutron (n).

$$\mu^- + {}^1_1p \rightarrow {}^1_0n + \nu_\mu$$

- As a result, OMC on ${}^A_ZX$ produces a new isotope of (${}_{Z-1}^{A}X$).
  - shown its utility in nuclear transformation for medical applications and elemental analysis, archaeological and astronomical purposes[1, 2, 8].
- The OMC process is initiated by the muon (μ) stopping in the target atom and is eventually captured into the nucleus by emitting a muon neutrino (ν_μ).
- Once the μ is captured, the nucleus is excited up to around 5-50 MeV, and then decays by emitting many particles, mostly neutrons.

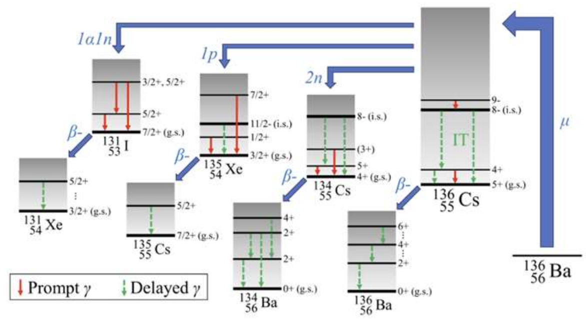
[1] I. Hashim, et al Phy. Rev. C, 97(1): 014617 (2018)
[2] I. Hashim et al, Inst. and Methods in Physics Research Section A: 163749 (2020)

Overview of Ordinary Muon Capture (OMC)



- Alpha, proton, deuteron and neutron were emitted after muon captured into nucleus.
- These particle emissions are accompanied by gamma ray by transition to its' ground state.

Measday, D. F. (2001). Phys. Rep. 354, 243409.



Ng. Z. W. , Hashim, I.H., Ejiri. H., J. Phys. G: Nucl. Part. Phys. In preparation.

Innovating Solutions

www.utm.my

Relationship between OMC and Double Beta Decays (DBDs)

- OMC and DBD are fundamentally linked through their dependence on Nuclear matrix elements (NMEs) and nuclear structure properties.
- While the processes differ in their mechanisms, both provide valuable insights into weak interactions and the fundamental properties of neutrinos.
- NMEs play a critical role in governing the rates of DBD, particularly in determining the probability of neutrinoless double beta decay, a process crucial for probing the Majorana nature of neutrinos.
- The study delayed gamma rays from OMC provides detailed information about nuclear transitions of DBD intermediate nucleus.

H. Ejiri, J. Suhonen and K. Zuber Phys. Rep. 797, 1, 2019.

Innovating Solutions

www.utm.my

Relationship between OMC and Double Beta Decays (DBDs)

- Both OMC and DBD capable to describe the distribution of transition probabilities between nuclear states.
- OMC serves as an experimental proxy to test and refine nuclear models used in DBD studies.
- By analyzing OMC rates, and N-Z dependence, researchers gain indirect but significant insights into the nuclear structure factors that influence DBD.

www.utm.my

Innovating Solutions

OMC response M^{μ} versus $M^{0\nu}$

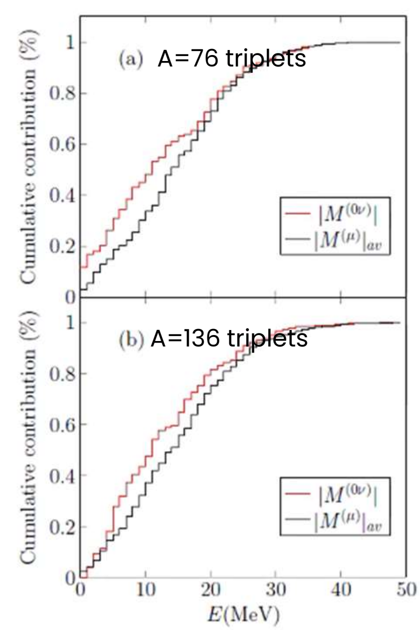
- Involvement of both g_A and g_P coupling:

$$W^{OMC} \propto |g_A M_A + g_V M_V + g_P M_P|^2$$

$$M^{0\nu} = M^{0\nu}_{GT}(g_A, g_P, g_M) - \left(\frac{g_V}{g_A}\right)^2 M^{0\nu}_F(g_V) + M^{0\nu}_T(g_A, g_P, g_M)$$

- Transitions through the multipoles states 1⩽J⩽3 dominate both OMC and $0\nu\beta\beta$

$$[t^{0\nu}_{1/2}]^{-1} = g_A^4 G_{0\upsilon} |M^{0\upsilon}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$



[1] L. Jokiniemi and J.Suhonen, PRC 102 024303 (2020)

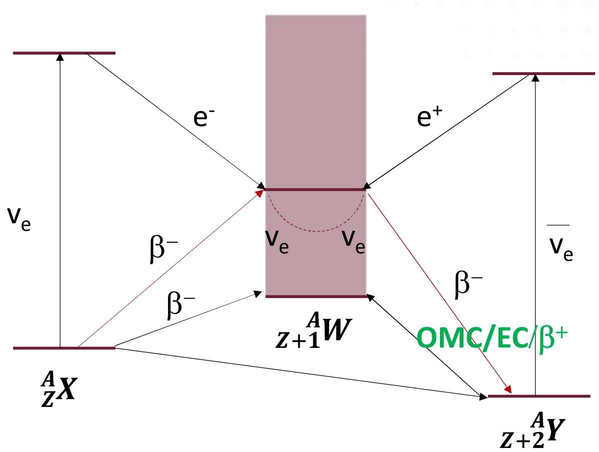
Unique features of antineutrino nuclear responses by OMC

- Unique features of antineutrino nuclear responses (ANR)
- Role of OMC in ANRs

www.utm.my

Innovating Solutions

Unique features of antineutrino nuclear responses (ANR)



- Antineutrino nuclear responses play a pivotal role in understanding fundamental processes and interactions involving weak forces.
- These responses reflect how nuclei interact with antineutrinos, revealing valuable information about nuclear structure, transitions, and fundamental symmetries.

H. Ejiri, J. Suhonen and K. Zuber Phys. Rep. 797, 1, 2019.

www.utm.my

Innovating Solutions

Unique features of antineutrino nuclear responses (ANR)

- ANRs are governed by weak interaction operators, including Gamow-Teller (GT), Fermi, and forbidden transitions. These operators probe different aspects of nuclear structure, such as spin-isospin excitations and higher-order corrections, offering a comprehensive view of nuclear dynamics.
- ANRs exhibit a pronounced dependence on the neutron-proton (N-Z) ratio, which influences the strength of nuclear transitions.
- By analyzing ANRs, researchers can validate theoretical models used to predict key properties of neutrino and solar neutrino interactions, bridging gaps between experiment and theory.

H. Ejiri, J. Suhonen and K. Zuber Phys. Rep. 797, 1, 2019.

Innovating Solutions

www.utm.my

Measurement of Delayed Gamma Rays in OMC

- Techniques for detecting delayed gamma rays.
- Significance of delayed gamma-ray spectroscopy for DBD studies.

Innovating Solutions

www.utm.my

Early Work on OMC

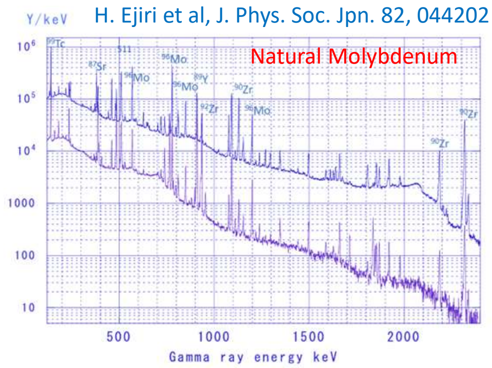
MUSIC, Osaka Univ.

Journal of the Physical Society of Japan **82** (2013) 044202 FULL PAPERS
http://dx.doi.org/10.7566/JPSJ.82.044202

Nuclear γ Rays from Stopped Muon Capture Reactions for Nuclear Isotope Detection

Hiroyasu EJIRI[1,2*], Izyan H. HASHIM[3], Yuko HINO[3], Yoshitaka KUNO[3], Yuki MATSUMOTO[3], Kazuhiko NINOMIYA[3], Hideyuki SAKAMOTO[3], Akira SATO[3], Tatsushi SHIMA[1], Atsushi SHINOHARA[3], Keiji TAKAHISA[1], and Nam H. TRAN[3]

H. Ejiri et al, J. Phys. Soc. Jpn. 82, 044202 (2013)



D2 beamline, J-PARC

PHYSICAL REVIEW C **97**, 014617 (2018)

I. H. Hashim et al, Phys. Rev. C **97**, 014617

Muon capture reaction on ^{100}Mo to study the nuclear response for double-β decay and neutrinos of astrophysics origin

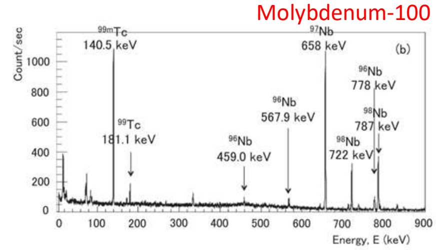
I. H. Hashim*
Physics Department, Faculty of Science, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia; Department of Physics, Osaka University, 560-0043 Toyonaka-shi, Osaka, Japan; and Research Center for Nuclear Physics, Osaka University, 567-0047 Ibaraki-shi, Osaka, Japan

H. Ejiri,† T. Shima, and K. Takahisa
Research Center for Nuclear Physics, Osaka University, 567-0047 Ibaraki-shi, Osaka, Japan

A. Sato and Y. Kuno
Department of Physics, Osaka University, 560-0043 Toyonaka-shi, Osaka, Japan

K. Ninomiya
Department of Chemistry, Osaka University, 560-0043 Toyonaka-shi, Osaka, Japan

N. Kawamura and Y. Miyake
Muon Science Laboratory, Institute of Materials Structure Science, High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan and Muon Science Section, Materials and Life Science Division, Japan Proton Accelerator Research Complex (J-PARC), Tokai, Ibaraki 319-1195, Japan



www.utm.my

Techniques for detecting delayed gamma rays

Isotope	Facility/ Momentum	Muon intensity	Method	References
^{100}Mo	JPARC (30 MeV/c)	1.8 ×10^6/s	Measure delayed gamma rays to deduce Br(X')	[1]
^{Nat}Mo, ^{100}Mo	MuSIC (45-55 MeV/c)	2.5 ×10^6/s		[2]
^{127}I, ^{197}Au, ^{209}Bi	TRIUMF (90 MeV/c)	2.0 ×10^5/s	Measure gamma ray from bound states (short lived) and muonic X-rays to deduce Br(X')	[3]
^{27}Al, ^{28}Si, ^{Nat}Ca, ^{56}Fe, ^{61}Ni, ^{127}I, ^{197}Au, ^{209}Bi	TRIUMF (90 MeV/c)	-		[4]
^{48}Ti, ^{76}Se, ^{82}Kr, ^{116}Cd and ^{150}Sm	PSI (28 MeV/c)	3.0 ×10^3/s and 2.5 ×10^4/s		[5,6]

[1]Hashim, I. H. Osaka University. 2014
[2]Hashim, I., Ejiri, H., Othman, F., Ibrahim, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2020:163749
[3]Measday, D. F., Stocki, T. J. and Tam, H. Physical Review C, 2007. 75(4): 045501.
[4]Measday, D. F. and Stocki, T. J. AIP Conference Proceedings. American Institute of Physics. 2007, vol. 884. 169–175
[5]Zinatulina, D., Brudanin, V., Briançon et al. AIP Conference Proceedings. American Institute of Physics. 2013, vol. 1572. 122–125.
[6]Zinatulina, D., Brudanin, V., Egorov, V., Physical Review C, 2019. 99(2): 024327.

Techniques for detecting delayed gamma rays

A	14≤A≤28 [1]	40≤A≤58 [1]	76≤A≤100 [2,3]	127≤A≤150 [1,2,4]
(μ,0n)	9 - 26%	27 - 32%	10-15%	8 -12%
(μ,1n)	45 - 49%	42 - 60%	45 - 60%	40 - 50%
(μ,2n)	6 - 27%	3 - 9%	15 - 20%	15 - 20%
(μ,3n)	1 - 4%	~1%	5 - 9%	12 - 15%
(μ,4n)	~0	~0	2 - 4%	5 - 10%
(μ, xn) x>4	~0	~0	<3%	<2%
(μ,p)	~2%	5-10%	<1%	<1%
(μ,pxn) x>0	5 - 9%	5-11%	~0	<1%
(μ,αn)	~0	~0	<1%	~0
(μ,αxn) x>0	~3%	0-3%	~0	~0

- Light nuclei can emit up to 3 neutrons with total probability of 85%.
- Medium-heavy nuclei can emit more than 4 neutrons with total probability of 96%.
- Light nuclei have higher proton and alpha emission (~10-15%) than medium-heavy nuclei (<5%).

[8]Measday, D. F. and Stocki, T. J. AIP Conference Proceedings. American Institute of Physics. 2007, vol. 947. 253–257.
[9]Zinatulina, D., et al, I Physical Review C, 2019. 99(2): 024327
[10] Hashim, I., Ejiri, H., Othman, et al NIMA, 2020:163749.
[11] Measday, D. F., Stocki, T. J. et al Physical Review C, 2007. 75(4): 045501.

15

UTM

Techniques for detecting delayed gamma rays

First evidence of alpha emission from OMC on ^{136}Ba

PSI 2021 Campaign

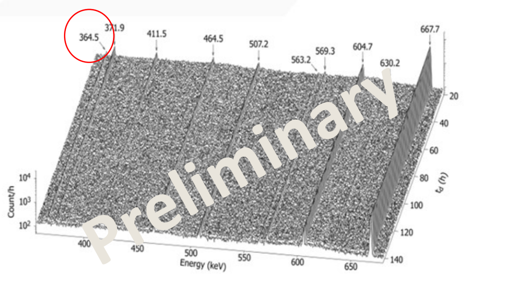
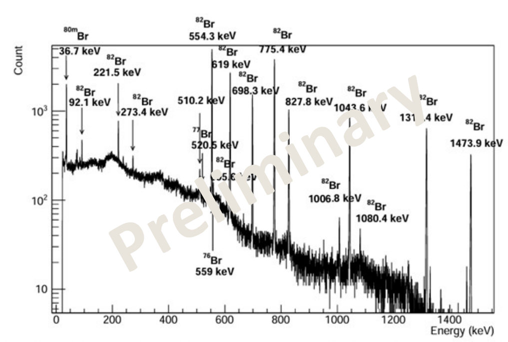


Figure 4. The time evolution of acquired γ spectra from the off-line measurement on ^{136}Ba in the energy range of 50 to 680 keV.

Ng. Z. W. , Hashim, I.H., Ejiri. H., In preparation

Our first trial with gas target from OMC on ^{82}Kr

PSI 2019 Campaign



Ng. Z. W. , Hashim, I.H., Ejiri. H., In preparation

UTM

Significance of delayed gamma-ray spectroscopy for DBD studies.

Table 6

RIs produced by OMC on ^{Nat}Mo. Columns 1 and 2 show the RI produced by μ capture and the residual nucleus, and column 3 gives the emission process involved. Column 4 gives the half-life of the RIs produced by OMC. Column 5 is the number of the RIs, column 6 lists the typical γ ray(s) [7], and column 7 is the calculated N(X′) by the PNEM.

RI	Final N	Process	Half-life (h)	N(X′)×10^8	γ rays (keV)	calc. N(X′)×10^8
^{100}Nb	^{100}Mo	^{100}Mo(μ,0n)	4.4×10^{-3}	0.6 ± 0.1	535.6[a]	0.35 ± 0.26
^{99}Mo	^{99m}Tc	^{100}Mo(μ,nβ^-)	66	3.8 ± 0.4	140.5, 181.0, 739.5	2.91 ± 1.02
^{98}Nb	^{98}Mo	^{100}Mo(μ,2n)	7.1×10^{-3}, 0.855	3.0 ± 0.8	734.7[a], 787.4	2.08 ± 1.01
^{97}Nb	^{97}Mo	^{98}Mo(μ,1n)	1.2	8.8 ± 1.5	658.1	8.51 ± 0.83
^{97}Zr	^{97}Nb	^{98}Mo(μ,p)	16.9	0.05 ± 0.02	743.5	–
^{96}Nb	^{96}Mo	^{97}Mo (μ,1n)	23.4	4.5 ± 1.0	568.8, 778.2, 1091.3	7.02 ± 1.37
^{95}Nb	^{95}Mo	^{96}Mo(μ,1n)	1205	6.7 ± 1.0	765.8	7.52 ± 2.16
^{94}Nb	^{94}Mo	^{98}Mo(μ,1n)	1.75×10^8	8.62 ± 1.0[b]	–	8.29 ± 1.13
^{93}Nb	^{93}Nb	^{94}Mo(μ,1n)	1.41×10^5	5.26 ± 1.0[b]	–	5.06 ± 1.35
^{92}Nb	^{92}Zr	^{94}Mo (μ,2n)	244.8	3.0 ± 0.15	934.5	2.78 ± 1.17
^{91}Nb	^{91}Zr	^{92}Mo (μ,1n)	6×10^6	5.19 ± 1.0[b]	–	5.00 ± 1.17
^{90}Nb	^{90}Zr	^{92}Mo (μ,2n)	14.6	1.9 ± 0.3	1129.2, 2186, 2319.0	–

[a] The γ rays measured in the ^{100}Mo experiment.
[b] N(X′) obtained by calculation using PNEM.

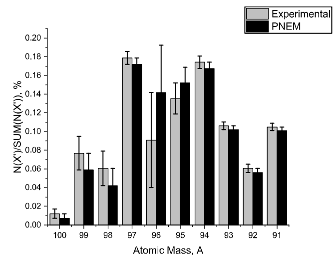
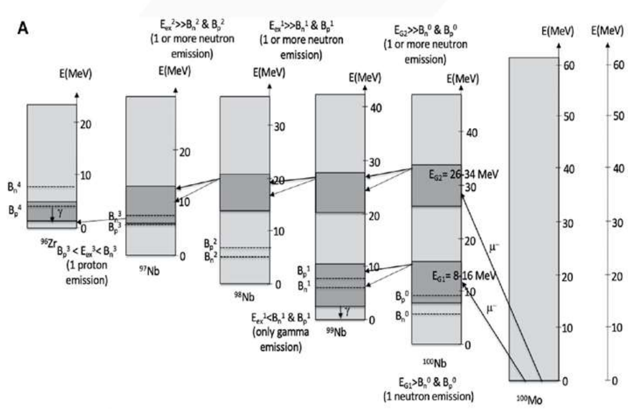


Fig. 6. Isotope mass distributions of RIs produced by MuCIP on ^{Nat}Mo.

[1] H. Ejiri, I. H. Hashim, et al. J. Phys. Soc. Japan, 82 (2013) 044202.
[2] I. H. Hashim et al, Nucl. Instr. Method. A, Mar 2020

- In different cases, neutron are measured on time of flight (TOF) measurement[3].
- The main problem is how to relate delayed γ-ray to the neutrino nuclear responses
  - Using proton neutron emission model (PNEM) to obtain the β^+ virtual transition distribution

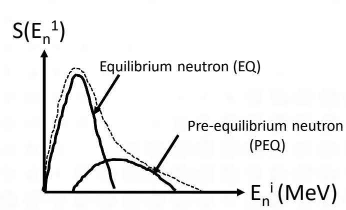
Significance of delayed gamma-ray spectroscopy for DBD studies.



I.H. Hashim and H.Ejiri. Front. Astron. Space Sci. 8:666383. 2021

- Neutron emission model (NEM) and proton neutron emission model (PNEM) have been developed to calculate the **β⁺** virtual transition [1,2].
- Overall **β⁺** virtual transition gives equivalent information of excitation energy involve after muon capture process (muon capture strength).

$$S(E_n^1) = k\left[E_n^1 exp\left(-\frac{E_n^1}{T_{EQ}(E)}\right) + pE_n^1 exp\left(-\frac{E_n^1}{T_{PEQ}(E)}\right)\right]$$



18

Significance of delayed gamma-ray spectroscopy for DBD studies.

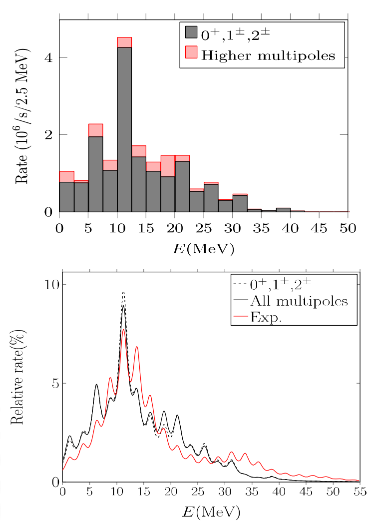
Isotope	Method	E_{G1} (MeV)	E_{G2} (MeV)	Reference
^{100}Mo	Exp + NEM	12	30	[1]
^{23}Na, ^{24}Mg, ^{27}Al, ^{28}Si, ^{40}Ca, and ^{56}Ni	Exp + NEM	12-18	30-46	[2]
^{76}Se, ^{106}Cd, ^{127}I, ^{150}Sm, ^{197}Au and ^{209}Bi	Exp + NEM	9.9-12.2	25.7-31.5	[3]
^{100}Mo	Exp + NEM + pn-QRPA	10.5	29.5	[4]
^{100}Mo, ^{107}Pd, ^{108}Pd, ^{127}I and ^{209}Bi.	Exp + PNEM	10-18	25-45	[5]

[1] Hashim, I.et al,. Physical Review C, 2018
[2] Muslim, N.F.H. BSc Thesis, UTM. 2018
[3] Ibrahim. F. BSc Thesis, UTM. 2018
[4] Jokiniemi, L. et al. Phys Lett B, 2019
[5] Hashim, I.,et al. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2020

F. Othman, UTM PhD Thesis 2023

Significance of delayed gamma-ray spectroscopy for DBD studies.

- Total OMC rate for nuclei
- Involvement of overall individual spin states for intermediate nuclei
- Theoretical pn-QRPA simulate the same distribution by g_A and g_p combination => **Absolute capture strength.**
- The first comparison of experimental data of ^{100}Mo with pn-QRPA:
  - More than 90% of the contribution is from $0^{\pm}$, $1^{\pm}$ and $2^{\pm}$.
  - Remaining coming from higher multipole states.
- The present calculation was using Neutron Emission Model (NEM) with lower energy resolution.
  - The new PNEM is expected to provide much accurate capture strength with inclusion of proton and Coulomb barrier effect with higher energy resolution.



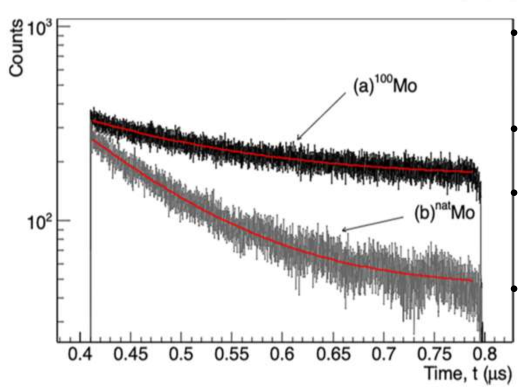
[1] L. Jokiniemi J. Suhonen. H. Ejiri and I. Hashim PL B 794 143 (2019)

N-Z dependence of OMC Rates

- Observations on neutron-proton ratio (N-Z) dependence.
- Implications for nuclear structure and decay mechanisms.

Observations on neutron-proton ratio (N-Z) dependence.

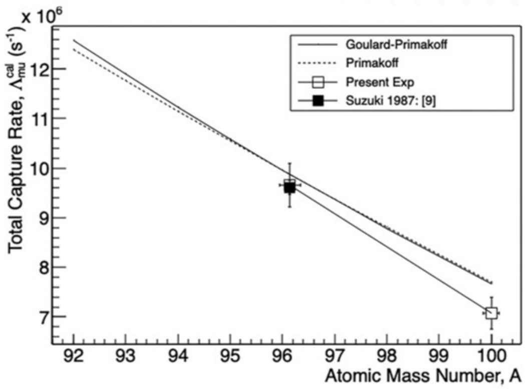
Measurement of muon disappearance rate on ^{100}Mo and ^{Nat}Mo shows that



I. H. Hashim et al. Physical Review C 108, 014618 (2023)

- The experimental OMC rates for ^{100}Mo and ^{nat}Mo are determined by examining the time spectra of the electron decaying from the trapped muon.
- The increment of A resulting in significantly lower OMC rates.
- The OMC rate for ^{100}Mo is 27% lower than the rate for ^{nat}Mo, with the effective A around 96 due to the blocking effect of the surplus neutrons in ^{100}Mo[3].
- The present experiment show, for the first time, a significant reduction in the OMC rate for the DBD nucleus of ^{100}Mo with N − Z = 16 compared to the rate for ^{nat}Mo with A ≈ 96 and N − Z = 12.

Implications for nuclear structure and decay mechanisms.



- This N − Z dependence is consistent with the general N − Z dependence observed in other nuclei [9,26] and supports the phenomenological OMC rate as a function of N − Z proposed by Primakoff [34].
- This demonstrates that some g_A quenching was detected in nuclear structural effects on the OMC process.

I. H. Hashim et al. Physical Review C 108, 014618 (2023)

Innovating Solutions

www.utm.my

Perspectives on OMC experiments

- Current challenges and advancements in experimental techniques.
- Future directions for OMC in studying antineutrino nuclear responses.

Innovating Solutions

www.utm.my

Current challenges and advancements in experimental techniques

- The original Monument proposal envisaged three series of measurements at PSI on isotopes of interest for 0νββ decay and astrophysical applications.
- Our efforts started in ^{76}Se and ^{136}Ba (2021), ^{100}Mo for astrophysical applications in 2022, followed by ^{48}Ti in 2023 for setting a benchmark of ab initio calculations for 0νββ decay.

G.R.Araujo, et al. (MONUMENT experiment). Eur. Phys. J. C (2024) 84:1188

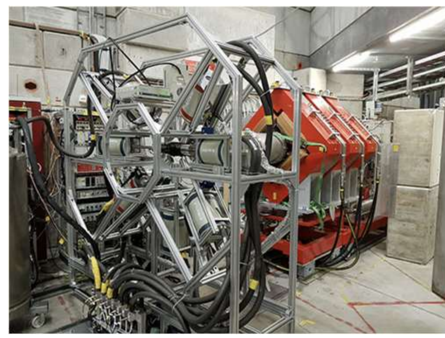

Eur. Phys. J. C (2024) 84:1188
https://doi.org/10.1140/epjc/s10052-024-13470-6
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article
Experimental Physics

The MONUMENT experiment: ordinary muon capture studies for $0\nu\beta\beta$ decay

G. R. Araujo[1], D. Bajpai[2], L. Baudis[1], V. Belov[4,5], E. Bossio[5,6,a], T. E. Cocolios[7], H. Ejiri[8], M. Fomina[4], K. Gusev[4,5], I. H. Hashim[9], M. Heines[7], S. Kazartsev[4], A. Knecht[10], E. Mondragón[5,b], Z. W. Ng[9], I. Ostrovskiy[2,3], F. Othman[9], N. Rumyantseva[4,5], S. Schönert[5], M. Schwarz[5], E. Shevchik[4], M. Shirchenko[4], Yu Shitov[11], E. O. Sushenok[4], J. Suhonen[12,13], S. M. Vogiatzi[10], C. Wiesinger[5], I. Zhitnikov[4], D. Zinatulina[4]

[1] Physik-Institut, University of Zurich, Zurich, Switzerland
[2] Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL, USA
[3] Present address: Institute of High Energy Physics, Beijing, China
[4] Joint Institute for Nuclear Research, Dubna, Russia
[5] Technische Universität München, Garching, Germany
[6] Present address: IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
[7] KU Leuven, Institute for Nuclear and Radiation Physics, Leuven, Belgium
[8] Research Center on Nuclear Physics, Osaka University, Ibaraki, Osaka, Japan
[9] Department of Physics, Faculty of Science, Universiti Teknologi Malaysia, Johor Bahru, Malaysia
[10] Paul Scherrer Institut, Villigen, Switzerland
[11] Institute of Experimental and Applied Physics, Czech Technical University in Prague, Prague, Czech Republic
[12] Department of Physics, University of Jyväskylä, Jyvaskyla, Finland
[13] International Centre for Advanced Training and Research in Physics (CIFRA), Bucharest-Magurele, Romania

Received: 13 April 2024 / Accepted: 7 October 2024



Future directions for OMC in studying ANRs

- Looking ahead, measurement on light nuclei motivated by further exchanges with nuclear physics theorists, would be aimed at comparison with ab initio calculations.
- Despite the lack of a direct link to the 0νββ decay isotopes, these isotopes can help to study theoretical aspects such as the role of meson exchange currents infinite momentum transfer, in light systems where the calculations are more under control than in the heavier ones.
- However, this desired measure would require a revision of the experimental approach, as a challenging plethora of γ-rays and μX-rays are expected.

G.R.Araujo, et al. (MONUMENT experiment). Eur. Phys. J. C (2024) 84:1188

Concluding Remarks

Concluding Remarks

- OMC can efficiently transmute the target isotope into isotope of mass number *Z*-1 along with emission of neutral and charged particle.
- measurement of delayed gamma rays gives majority branching ratio observation from (μ,*1n*) channel.
- OMC and DBD are linked through their dependence on NMEs and nuclear structure properties. These processes differ in their mechanisms, both provide valuable insights into weak interactions and the fundamental properties of neutrinos.
- ANRs obtained by the observation of delayed gamma rays following OMC reflect how nuclei interact with antineutrinos, revealing valuable information about nuclear structure, transitions, and fundamental symmetries.

Concluding Remarks

- The extensive experimental programs on OMC for other nuclei of DBD and supernova anti-neutrino interests are under progress at Research Center Nuclear Physics (RCNP), Osaka and Paul Scherrer Institute (PSI), Zurich, by the join group of OMC4DBD/MONUMENT collaboration.
- Current focused revolved on $0\nu\beta\beta$ decay of astrophysical applications and benchmarking of ab initio calculations.

www.utm.my

Innovating Solutions

THANK YOU

univteknologimalaysia utm.my utmofficial