UNIVERSITI TEKNOLOGI MALAYSIA

Ordinary Muon Capture Delayed Gamma Ray Analysis for double beta decays (DBDs) and anti-neutrino nuclear responses

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NEWS Colloquium
20 July 2023

Innovating Solutions

Based on our manuscript for submission:
I.H. Hashim, H. Ejiri, Z.W. Ng, F. Othman PTEP 2023

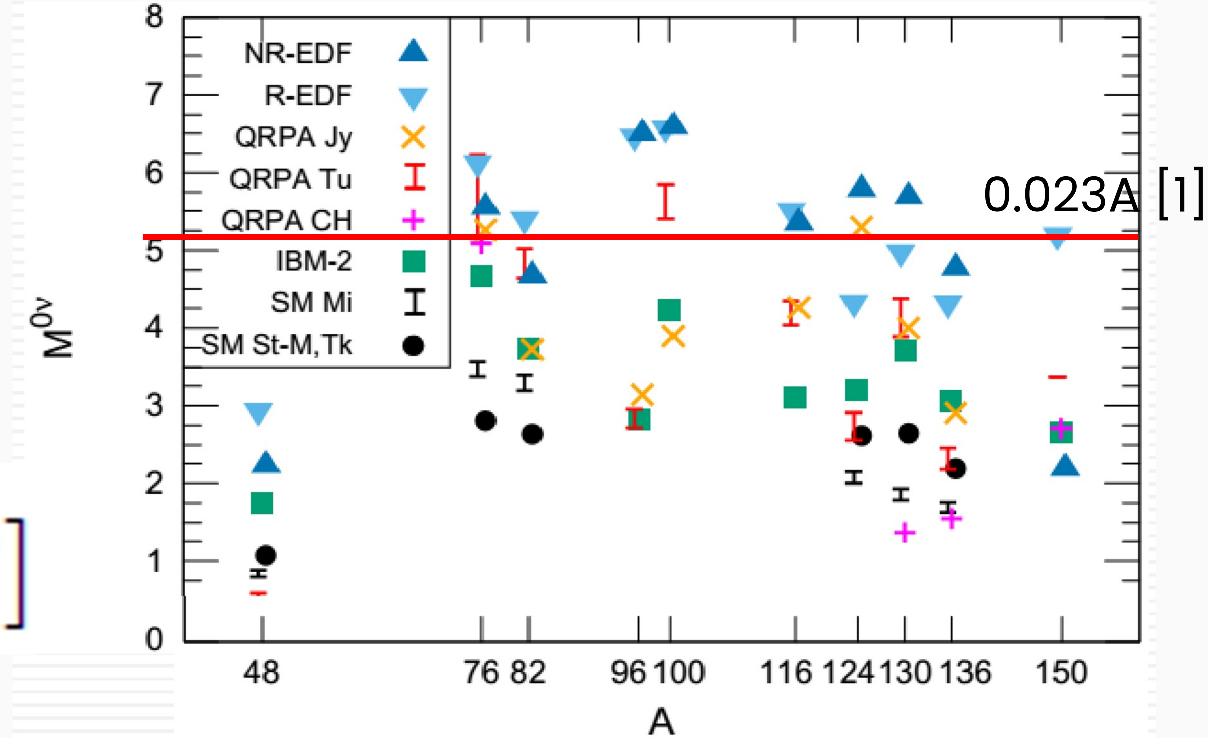
Double Beta Decay(DBD) and Neutrino Nuclear Response(NNR)

Transition rate of DBD

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

Definition of DBD NME from several theoretical papers

$$M^{0\nu} = \left(\frac{g_A^{\mathrm{eff}}}{g_A}\right)^2 \left[M^{0\nu}_{\mathrm{GT}} + \left(g_V/g_A^{\mathrm{eff}}\right)^2 M^{0\nu}_{\mathrm{F}} + M^{0\nu}_{\mathrm{T}}\right]$$



In 2νββ, the NME $M_{2\nu}$ is taken as sum the product of single beta matrix $M(\beta^+)$ and $M(\beta^-)$.

- However, definition for the NME $M_{0\nu}$ is not the same as $M_{2\nu}$.

Understanding both single beta matrix is important to evaluate the factor of 2 or 3 in theoretical NME uncertainties.

[1] H. Ejiri, L. Jokiniemi, and J. Suhonen, Phys. Rev. C 105, L022501

Double Beta Decay(DBD) and Neutrino Nuclear Response(NNR)

EM probe

γ-capture, e scattering

Facility: Spring-8

Nuclear probe

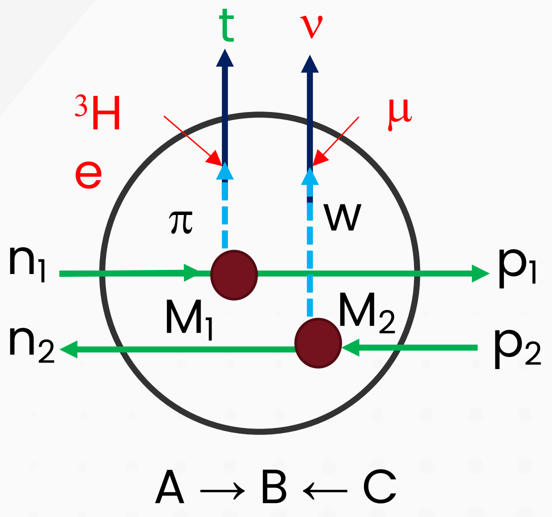
CER (^{3}He,t) (t,^{3}He) (d,^{2}He)

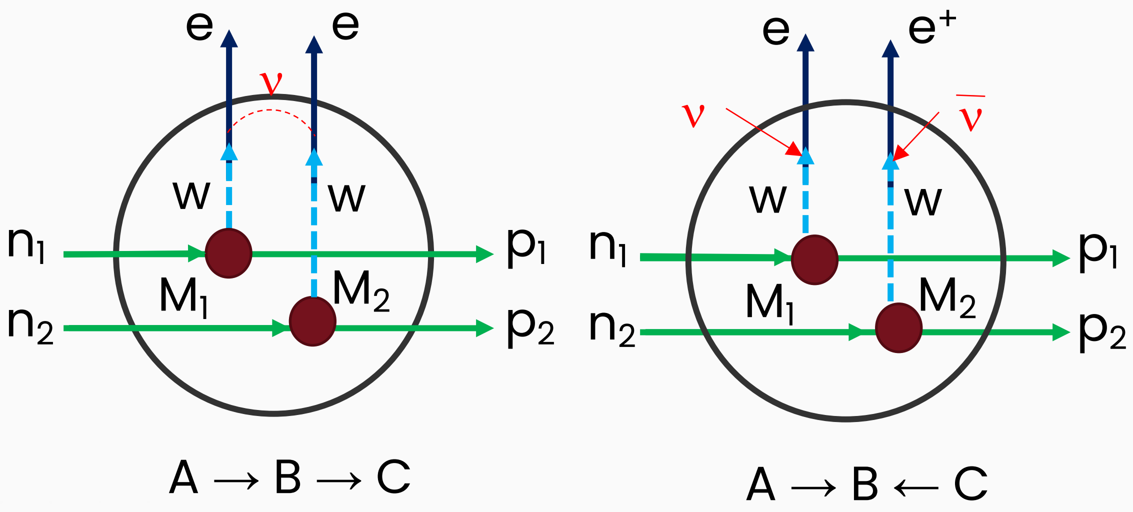
Facilities: RCNP, MSU, KVI

Weak probe

e^- and μ^- capture, ν probe

Facilities: RCNP, J-PARC, SμS





[2] H. Ejiri
Phys. Rev. C **108**, L011302

Double beta decay (DBD) nuclear matrix elements (NME) and neutrino/antineutrino responses indicate by M_1 and M_2 are studied by single beta decay (SBD) and CERs ((^{3}He,t) and OMC).

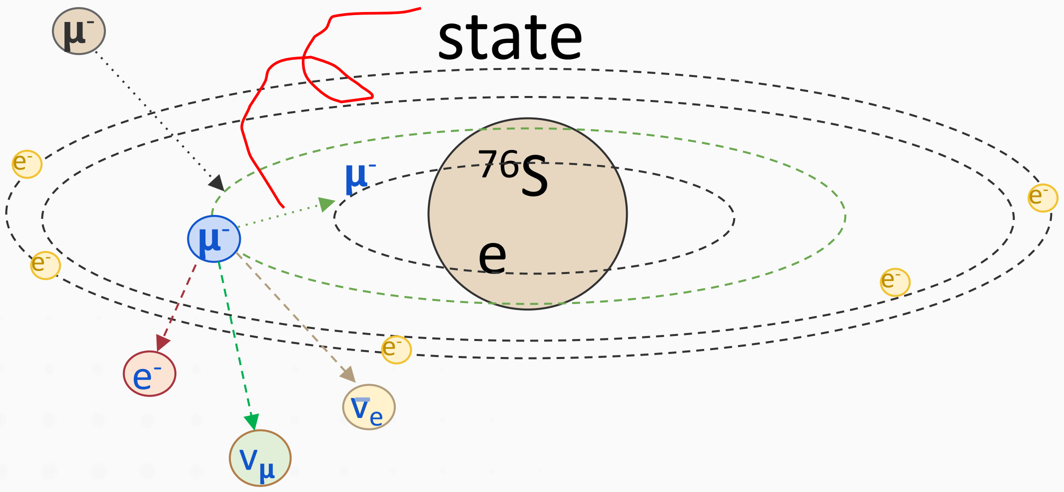
Unique features of OMC for studying DBDs and anti-neutrino nuclear responses.

Upon captured with the electronic orbit, muon can either:

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

$$\mu^- + {}^A_ZX \rightarrow {}^{\;\;A}_{Z-1}X + \nu_\mu$$

ii) cascade down to 1 s atomic state



i) decay into electron and neutrino

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

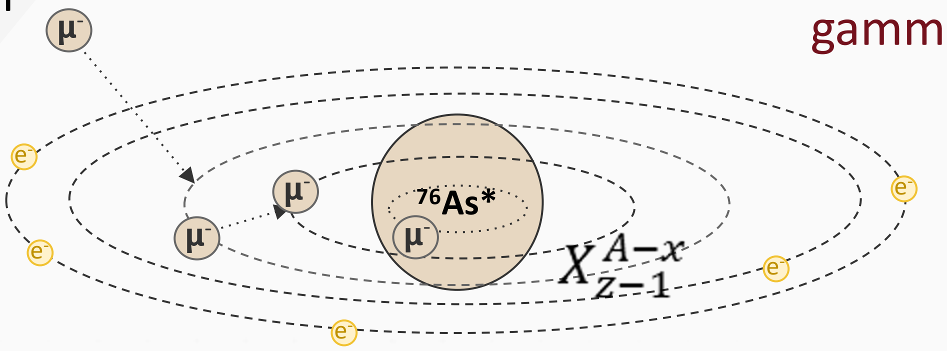
[4]Singer, P. (1973). *Muon Physics Conference.* 6-10 September 1971. Colorado State University Fort Collins, Colorado, 39-87.

Unique features of OMC for studying DBDs and anti-neutrino nuclear responses.

if (ii), then more cascade

- Auger electron emission
- Muonic X-ray emission

Electron unbound process in this can result in short-lived gamma rays



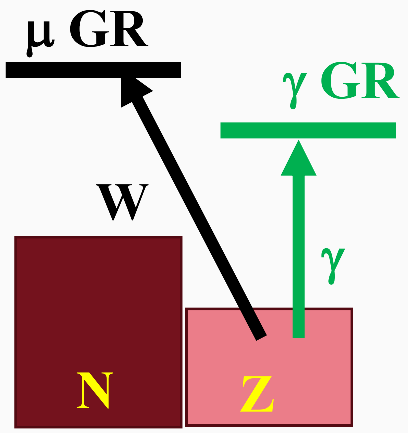
iv)The formed nucleus tend to stay in some excited energy states before emission of radioisotope gamma rays, where x indicates the **number of neutron/proton/charged particle emission (x=0,1,2,...5).**

Particle (neutron/proton/alpha/etc) unbound process in this can result in short-lived and long-lived gamma rays also refer as **delayed gamma rays.**

[3]Measday, D. F. (2001). Phys. Rep. 354, 243409.
[4]Singer, P. (1973). *Muon Physics Conference.* 6-10 September 1971. Colorado State University Fort Collins, Colorado, 39-87.

Unique features of OMC for studying DBDs and anti-neutrino nuclear responses.

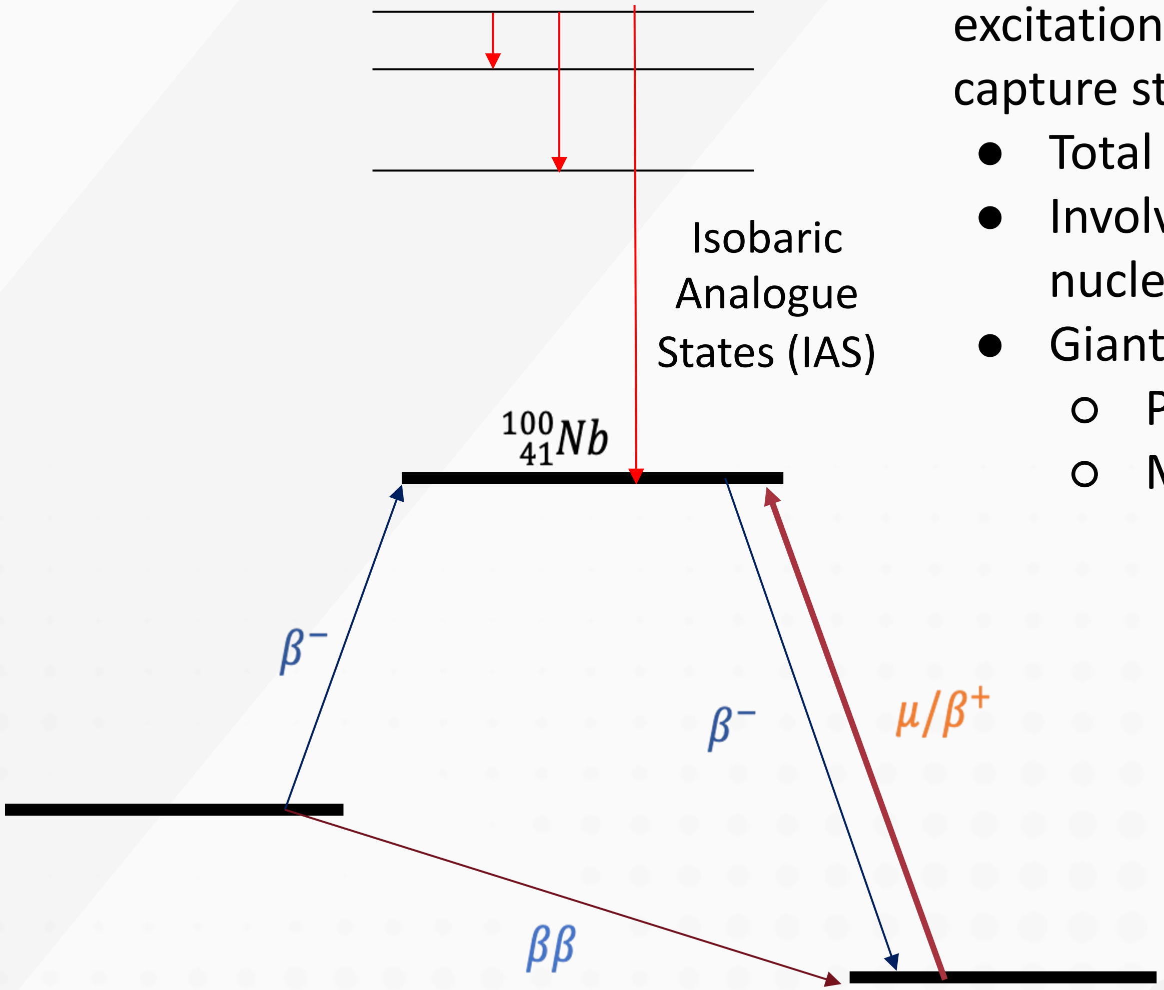
(μ,xnν) is a reliable method in producing radioisotopes (RIs) with X_{Z-1}^{A-x} where x = 0,1,2…5 especially for environmental and biomedical applications.
Other method using (n,γ) and (γ,n) reactions are complimentary methods



[5] H. Ejiri, I. H. Hashim, et al. J. Phys. Soc. Japan, 82 (2013) 044202.

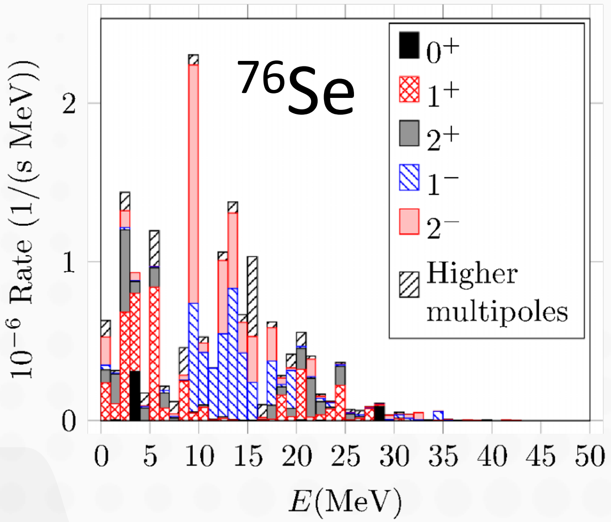
Isotope	μ reaction	RI (half life)	Comments on (γ, n)
^{54}Fe	(μ, 2n)	^{52}Mn (5.59 d)	^{53}Fe: short life
^{56}Fe	(μ, 0n)	^{56}Mn (2.58 h)	^{55}Fe: no γ
^{65}Cu	(μ, 0n)	^{65}Ni (2.5h)	^{64}Cu: 12.7 h
^{90}Zr	(μ, 0n)	^{90}Y (64.1 h)	^{89}Zr: 78.4 h
^{92}Zr	(μ, 0n)	^{92}Y (3.54 h)	^{91}Zr: stable
^{99}Tc	(μ, 0n)	^{99}Mo (65.9 h)	^{98}Tc: long life
^{109}Ag	(μ, 0n)	^{109}Pd (13.7 h)	^{108}Ag: short/ long life
^{128}Te	(μ, 1n)	^{127}Sb (3.85 d)	^{127}Te: 9.4 h, 109 d
^{187}Re	(μ, 0n)	^{187}W (23.7 h)	^{186}Re: 90.6 h
^{197}Au	(μ, 0n)	^{197}Pt (18.3 h)	^{196}Au: 6.18 d
^{233}U	(μ, 0n)	^{233}Pa (27.0 d)	^{232}U: long life
^{235}U	(μ, 1n)	^{234}Pa (6.7 h)	^{234}U: long life
^{239}Pu	(μ, 0n)	^{239}Np (2.36 d)	^{238}Pu: long life
^{240}Pu	(μ, 0n)	^{240}Np (1.03 h)	^{239}Pu: long life

Unique features of OMC for studying DBDs and anti-neutrino nuclear responses.



Overall β^+ virtual transition gives equivalent information of excitation energy involve after muon capture process (muon capture strength).

- Total OMC rate for nuclei
- Involvement of overall individual spin states for intermediate nuclei
- Giant Resonance (GR) region in nuclear excitation after OMC
  - Position of GR
  - Majority spin states contribution



[6] L. Jokiniemi and J. Suhonen Phys. Rev. C 100, 014619

PHYSICAL REVIEW C **00**, 004600 (2023)

Measurements of ordinary muon capture rates on ^{100}Mo and natural Mo for astro-antineutrinos and double-β decays

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Ordinary muon capture (OMC) rates are valuable for studying the neutrino nuclear responses of astrophysical antineutrinos and double-β decays (DBDs). Currently, there is interest in experimental studies of the OMC rates and their mass number (A) dependence for ^{100}Mo and natural Mo. To obtain these rates, a negative muon beam from the MuSIC facility at the Research Center for Nuclear Physics (RCNP), Osaka University was utilized. The half-lives of trapped muons were measured by using a muon stopping signal from a scintillation counter and the time distribution of the OMC nuclear gamma rays and the muon-decay electrons by Ge detectors. The present measurements yielded OMC rates for enriched and natural molybdenum of $\Lambda(^{100}\text{Mo}) = (7.07 \pm 0.32) \times 10^6\ \text{s}^{-1}$ and $\Lambda(^{\text{nat}}\text{Mo}) = (9.66 \pm 0.44) \times 10^6\ \text{s}^{-1}$, respectively. The observed OMC rate for ^{100}Mo is approximately 27% smaller than that for natural Mo due to the blocking effect of the excess neutrons on the proton-to-neutron transformation in OMC. The present experimental observation is consistent with the Goulard-Primakoff (GP)

Total OMC rate for ^{100}Mo and $^{\text{Nat}}$Mo PRC 2023 (accepted July 2023)

The measurement of delayed gamma for study DBDs and anti-neutrinos nuclear responses.

Isotope	Facility/ Momentum	Muon intensity	Method	References
^{100}Mo	JPARC (30 MeV/c)	1.8×10^{6}/s	Off beam measurement	[7]
^{Nat}Mo, ^{100}Mo	MuSIC (45-55 MeV/c)	2.5×10^{6}/s		[8]
^{127}I, ^{197}Au, ^{209}Bi	TRIUMF (90 MeV/c)	2.0×10^{5}/s	On beam measurement	[9]
^{27}Al, ^{28}Si, ^{Nat}Ca, ^{56}Fe, ^{61}Ni, ^{127}I, ^{197}Au, ^{209}Bi	TRIUMF (90 MeV/c)	-		[10]
^{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		[11, 12]

[7]Hashim, I. H. Osaka University. 2014
[8]Othman, F. APPC 2020:163749
[9]Measday, D. F., Stocki, T. J. and Tam, H. Physical Review C, 2007. 75(4): 045501.
[10]Measday, D. F. and Stocki, T. J. AIP Conference Proceedings. American Institute of Physics. 2007, vol. 884. 169–175
[11]Zinatulina, D., Brudanin, V., Briançon et al. AIP Conference Proceedings. American Institute of Physics. 2013, vol. 1572. 122–125.
[12]Zinatulina, D., Brudanin, V., Egorov, V., Physical Review C, 2019. 99(2): 024327.

The measurement of delayed gamma for study DBDs and anti-neutrinos nuclear responses.

Method 1: Off beam Measurement

Ejiri et al, JPSJ2013

after beam off → Gamma yield evaluated by peak fitting → Activity calculation → Number of isotope → Production rate → Branching ratio

*use low background + shielding could help optimize the RIs statistics.
** measured in low background setup [7], measured in irradiation setup and low background setup [8].

Method 2: On beam Measurement

Zinatulina, D., et al, I PR C, 2019. 99(2): 024327

during beam on → separated by time window → fitting of decay curve for lifetime → analysis of muonic X-ray → Branching ratio

***measured in irradiation setup only [9-12].

UTM
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The measurement of delayed gamma for study DBDs and anti-neutrinos nuclear responses.

$t_{\mu\gamma}$ = 0-200 ns

- Muonic X-rays

$t_{\mu\gamma}$ = 200-2000 ns

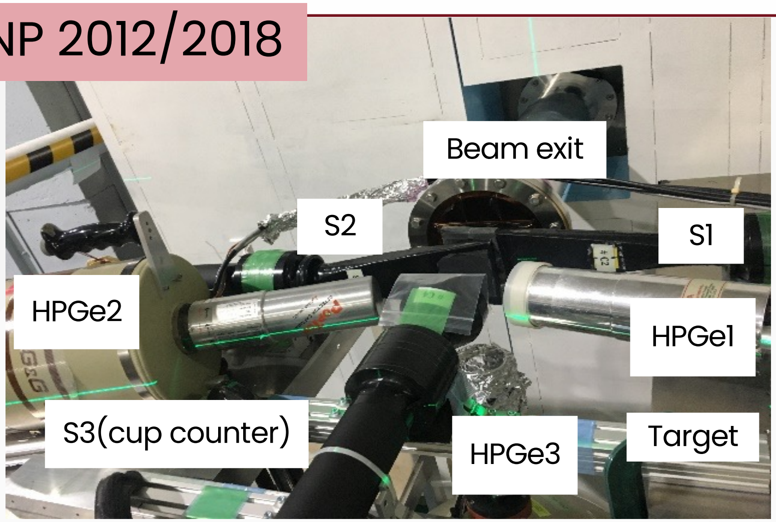
- γ-radiation from bound states

T >> $t_{\mu\gamma}$

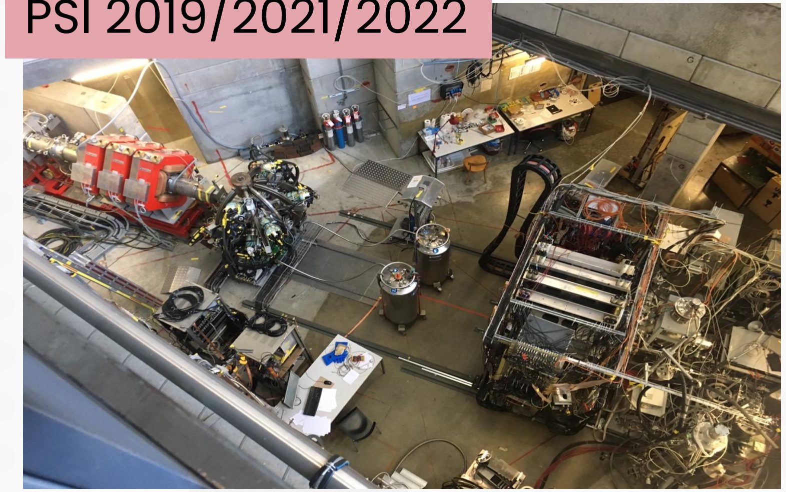
- Radioactive γ-radiation associated with particle emission
- irradiation and off beam setup (depends on RIs half-life)

Year	Target	Facility
2010	^{27}Al	RCNP
2012	^{Nat}Mo	RCNP
2013	^{100}Mo	PSI
2014	^{100}Mo, ^{93}Nb, ^{181}Ta	J-PARC
2018	^{100}Mo, ^{Nat}Mo, ^{76}Se, ^{Nat}Ru	RCNP
2019	^{24}Mg, ^{82}Kr, ^{130}Xe	PSI
2021	^{76}Se, ^{136}Ba, ^{Nat}Ba	PSI
2022	^{96}Mo, ^{100}Mo	PSI

RCNP 2012/2018



PSI 2019/2021/2022



The measurement of delayed gamma for study DBDs and anti-neutrinos nuclear responses.

DBD nuclei

A	^{40}Ca [13]	^{100}Mo [14]
(μ,0n)	27%	8%
(μ,1n)	43%	51%
(μ,2n)	3%	16%
(μ,3n)	~0	13%
(μ,4n)	~0	3%
(μ, xn) x>4	~0	~0
(μ,p)	10%	~0
(μ,pxn) x>0	14%	~0
(μ,αn)	~0	~0
(μ,αxn) x>0	~3%	~0

non-DBD nuclei

A	14≤A≤58 [13,15,16]	76≤A≤136 [13,15]	208≤A≤209 [13]
(μ,0n)	9 - 31%	6-27%	5 -8%
(μ,1n)	46 - 61%	NA	44 - 47%
(μ,2n)	6 - 27%	12 - 49%	29 - 37%
(μ,3n)	1 - 6%	5 - 14%	9 - 11%
(μ,4n)	~0	2 - 5%	0 - 5%
(μ, xn) x>4	~0	~1%	<2%
(μ,p)	0 - 3%	~1%	<1%
(μ,pxn) x>0	1 - 9%	<1%	<1%
(μ,αn)	~0	<1%	<1%
(μ,αxn) x>0	~3%	~1%	~1%

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

The measurement of delayed gamma for study DBDs and anti-neutrinos nuclear responses.

- 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%).

Why non-DBD?

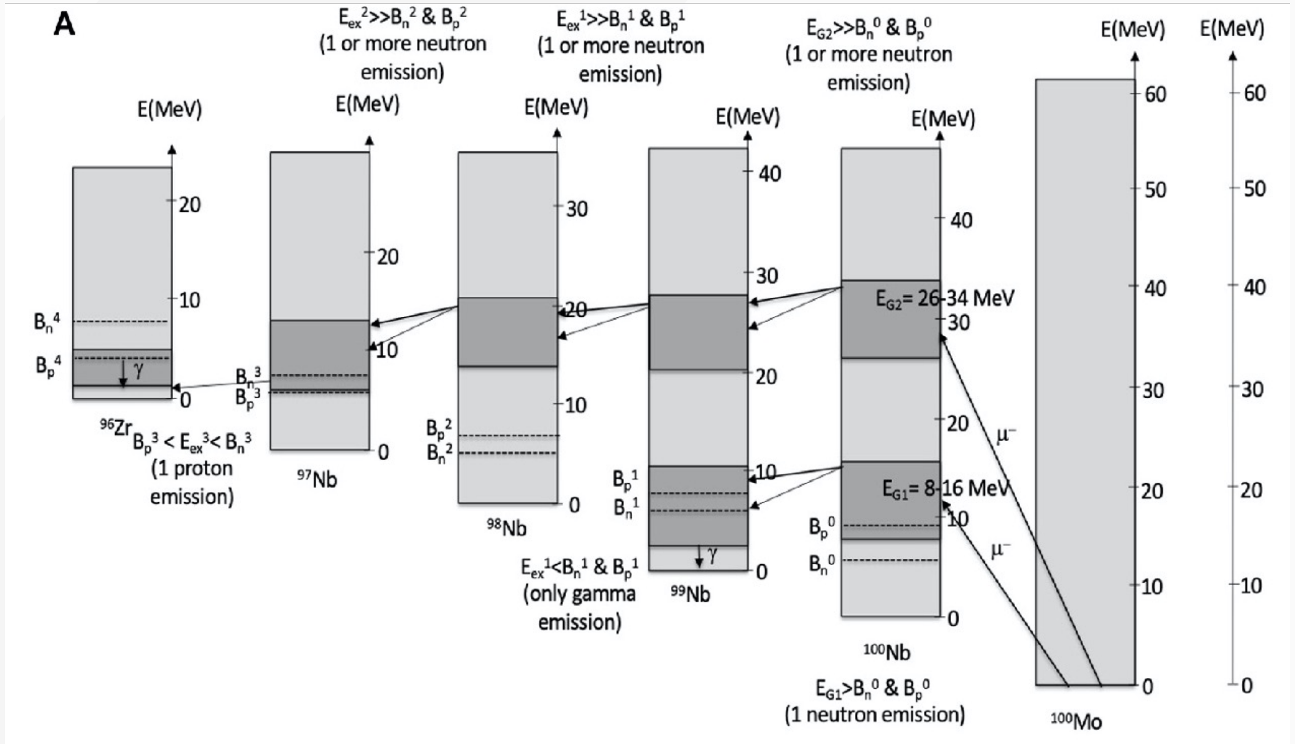
- Technically, the isotopes are not chosen randomly but the final product of DBD.
- From this observation, the intermediate nuclei nuclear structure can be evaluated and the factor effecting the uncertainty in NME can be understand.

How to relate this experimental output with the excitation region of OMC?

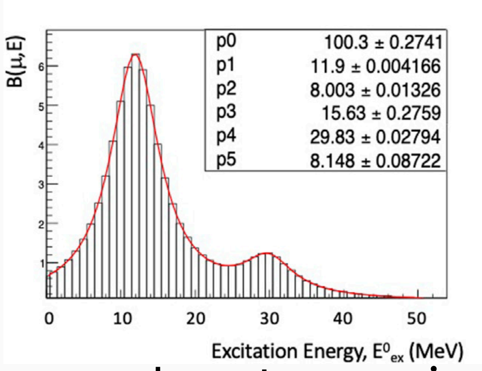
The measurement of delayed gamma for study DBDs and anti-neutrinos nuclear responses.

- In different cases, neutron are measured on time of flight (TOF) measurement.
- 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

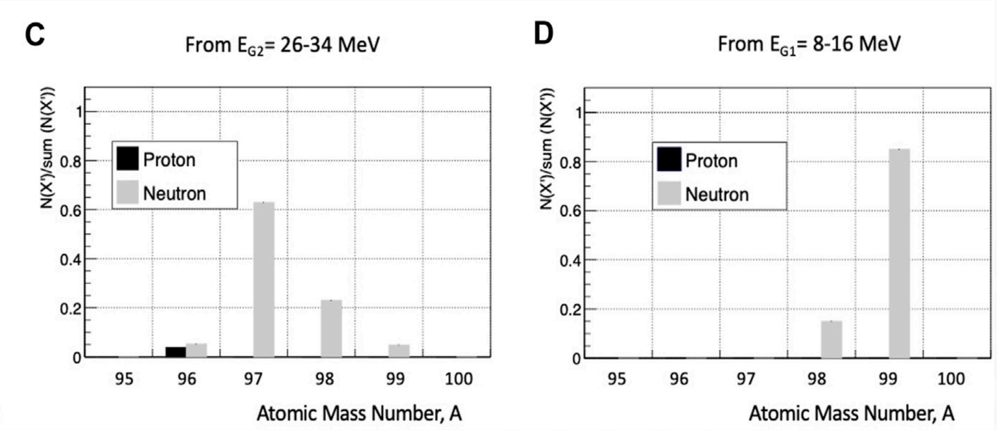
(A) PNEM layout



(B) β+ strength distribution



(C/D) Br(X') for neutron and proton emission



[17] I.H.Hashim, H.Ejiri. Front. Astron. Space Sci., 28 May 2021, Sec. High-Energy and Astroparticle Physics Volume 8 - 2021

The measurement of delayed gamma for study DBDs and anti-neutrinos nuclear responses.

Isotope	Method	E_{G1} (MeV)	E_{G2} (MeV)	Reference
^{100}Mo	Exp + NEM	12	30	[18]
^{23}Na, ^{24}Mg, ^{27}Al, ^{28}Si, ^{40}Ca, and ^{56}Ni	Exp + NEM	12-18	30-46	[19]
^{76}Se,^{106}Cd, ^{127}I, ^{150}Sm, ^{197}Au and ^{209}Bi	Exp + NEM	9.9-12.2	25.7-31.5	[20]
^{100}Mo	Exp + NEM + pn-QRPA	10.5	29.5	[21]
^{100}Mo, ^{107}Pd, ^{108}Pd, ^{127}I and ^{209}Bi.	Exp + PNEM	10-18	25-45	[22]

[18] Hashim, I.et al,. Physical Review C, 2018

[19] Muslim, N.F.H. BSc Thesis, UTM. 2018

[20] Ibrahim. F. BSc Thesis, UTM. 2018

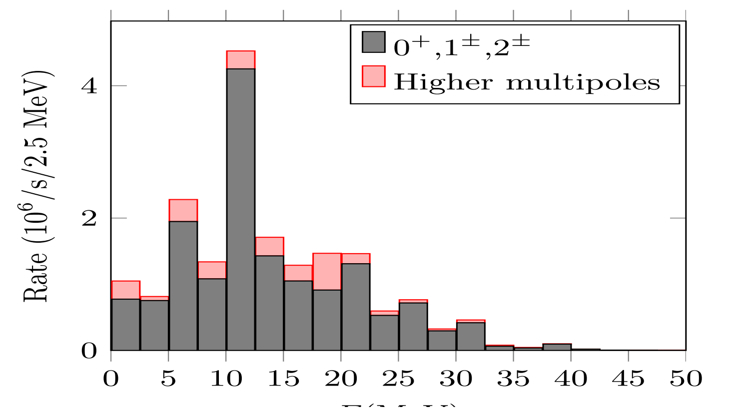
[21] Jokiniemi, L. et al. Phys Lett B, 2019

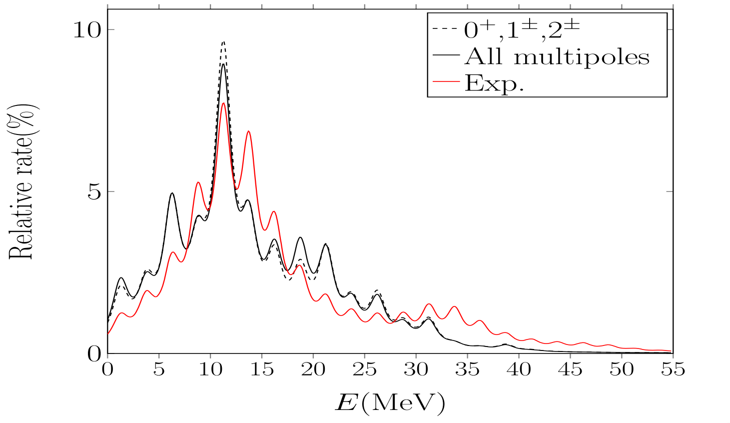
[22] Hashim, I.,et al. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2020

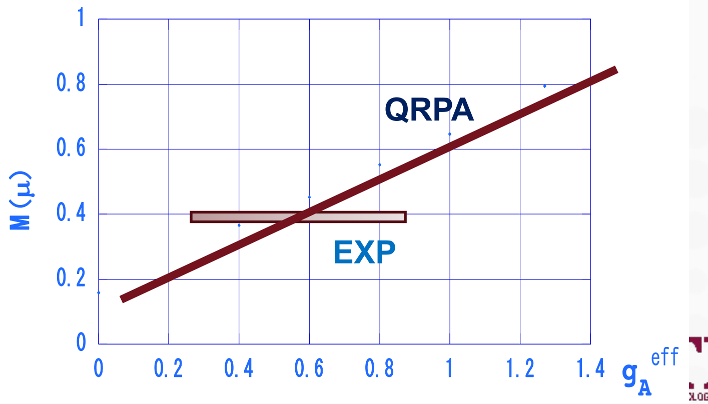
The impact of OMC results for DBDs and anti-neutrinos nuclear responses.

- Proton neutron emission model (PNEM) deduce the **experimental relative capture strength**.
- 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.

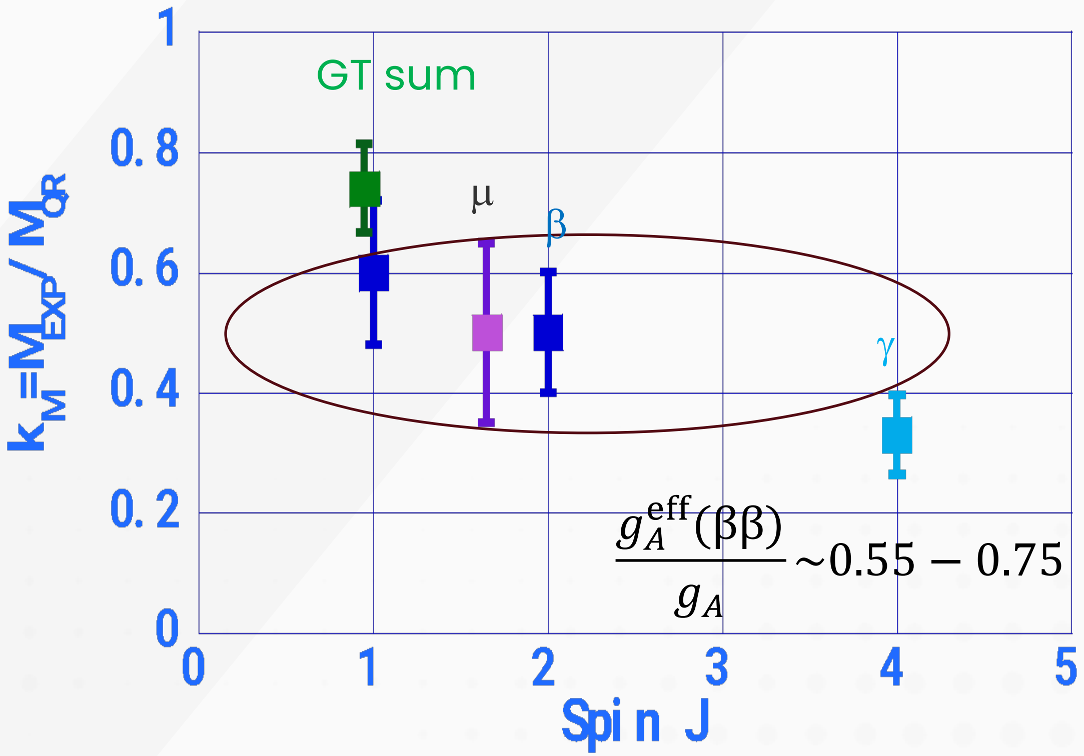
[23] L. Jokiniemi J. Suhonen. H. Ejiri and I. Hashim PL B 794 143 (2019)







The impact of OMC results for DBDs and anti-neutrinos nuclear responses.



The calculated Gamow–Teller strengths appear to reproduce most of the experimental data if the fundamental constant $g_A \approx 1.27$ characterizing the coupling of the weak interaction to a nucleon is quenched by a factor of 0.75.

- Missing nuclear correlations (that is, a lack of complexity in nuclear wavefunctions due to the limitations of nuclear models)
- neglected contributions from meson-exchange currents (that is, coupling of the weak force to two nucleons) have been proposed as possible causes of the quenching phenomenon.

[24] H, Ejiri J. Suhonen J. Phys. G. 42 2015
[25] H. Ejiri N. Soucouti, J. Suhonen PL B 729 2014 .
[26] L. Jokiniemi J. Suhonen H. Ejiri AHEP2016 ID8417598

Current status OMC on ^{136}Ba and ^{76}Se (PSI 2021 Campaign)

	^{136}Ba	^{76}Se
Sample form	metallic powder	$^{136}BaCO_3$ powder
Mass	2 g	2 g
Diameter	20 mm	20 mm
Thickness	~ 1.8 mm	~ 4 mm
Muon momentum	38 MeV/c	38 MeV/c
Irradiation time	~ 135.4 hours	~ 138 hours
Time between beam stop and offline measurement	13.5 hours	22 hours
Offline measurement time	199 hours	168.5 hours

PAUL SCHERRER INSTITUT

BV 51

PSI, Villigen
January 29, 2020

MINUTES "BESCHLUSSKONFERENZ"
OF THE USERS MEETING BV 51 AT PSI
January 27 – 29, 2020

1. Approval of Experiments

The recommendations of the BVR research committee and the μSR research committee are acknowledged (see minutes and lists in the appendix).

New Proposals

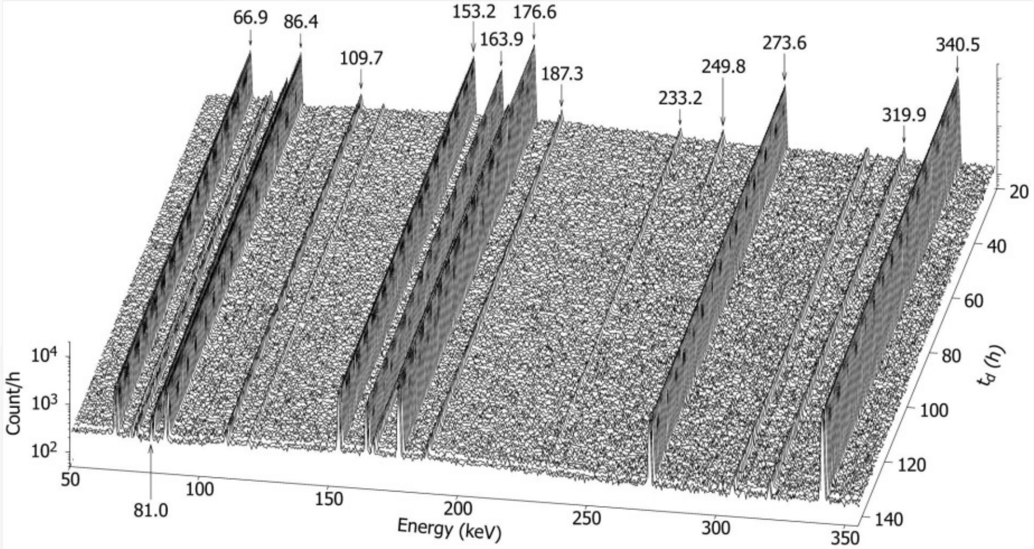
Two new proposals in particle physics have been presented:

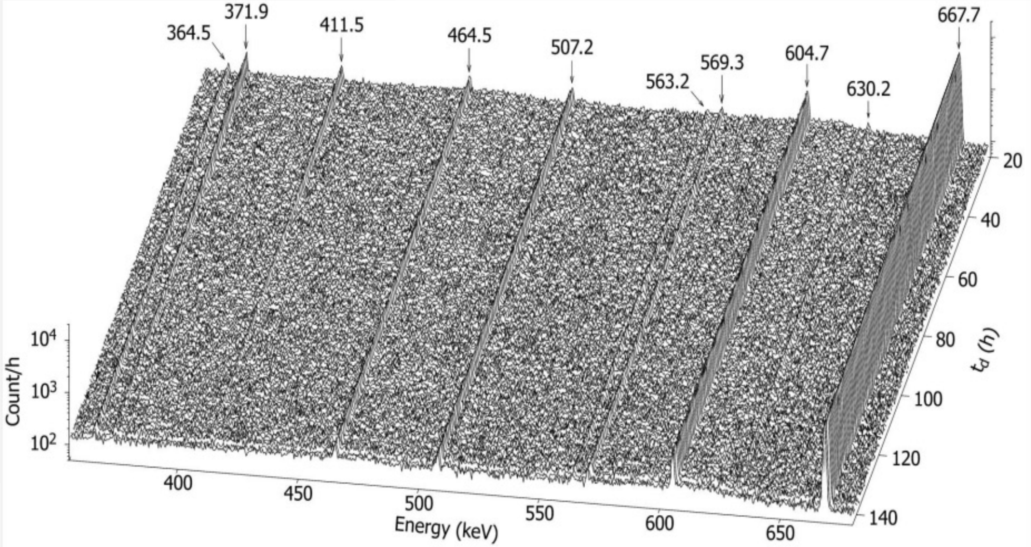
R-08-01.3 Search for muon catalyzed d^{3}He fusion, P. Kravchenko et al.

R-20-01.1 OMC4DBD: ordinary muon capture as a probe of properties of double beta decay processes, D. Zinatulinai at al.

20190166 Superconductivity formed by modification of spin-polaron in the iron-pnictide Ca10(Pt3As8)(Fe1-xPtxAs)10
Lee, Chung-Ang University
Accepted, HAL-9500, 4 days

Current status OMC on ^{136}Ba and ^{76}Se (PSI 2021 Campaign)





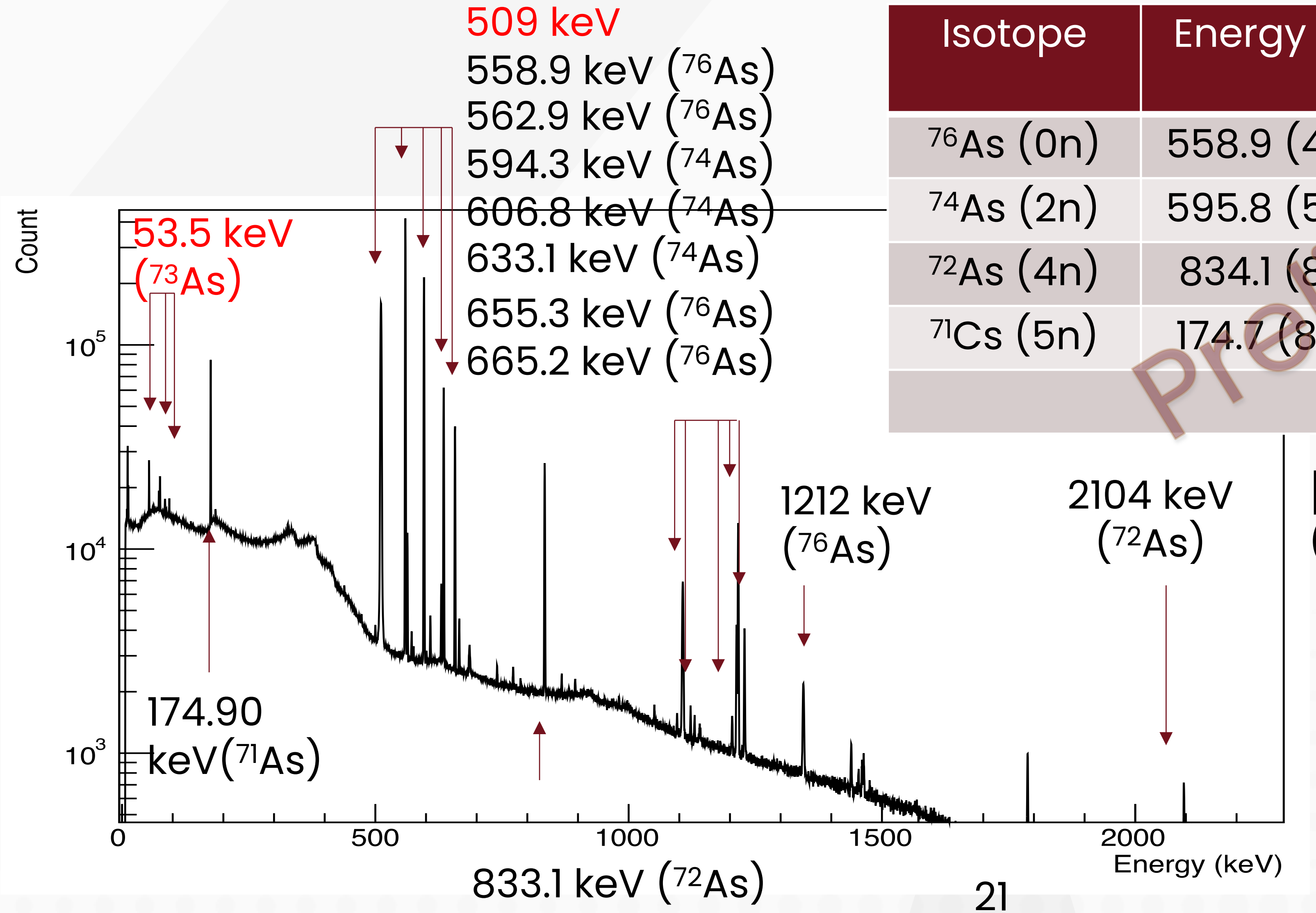
^{136}Ba

Isotope	Energy (Intensity) keV	Half-life	Br(X′) (%)
^{136}Cs (0n)	818.5 (99.7%)	13.01(5) d	5.7(4)
^{134}Cs (2n)	604.7 (97.6%)	2.0652(4) y	11.9(8)
^{132}Cs (4n)	667.7 (97.59%)	6.480(6) d	2.18(15)
^{129}Cs (7n)	371.9 (30.6%)	32.06(6) h	0.105(13)
^{135}Xe (1p)	249.8 (90%)	9.14(2) h	0.044(6)
^{133}Xe (1p2n)	81.0 (36.9%)	5.2475(5) d	0.22(2)
^{133m}Xe (1p2n)	233.2 (10.1%)	2.198(13) d	0.083(12)
^{131}I (1α1n)	364.5 (81.5%)	8.0252(6) d	0.016(2)
		Sum	20.2(9)

Preliminary

[27] Ng NPA 2023 (to be published)

Current status OMC on ^{136}Ba and ^{76}Se (PSI 2021 Campaign)



^{76}Se

Isotope	Energy (keV)	Half-life	Br(X′) (%)
^{76}As (0n)	558.9 (45.0%)	1.09(5) d	24.34(1)
^{74}As (2n)	595.8 (59.4%)	17.77(4) d	27.42(1)
^{72}As (4n)	834.1 (81.0%)	26.0(6) d	3.6 (01)
^{71}Cs (5n)	174.7 (82.4%)	65.3(6) h	0.386(17)
		Sum	55.7(21)

Preliminary

[28] I.H.Hashim et al. EPJA 2023 (to be published)

PNEM new interface 2023

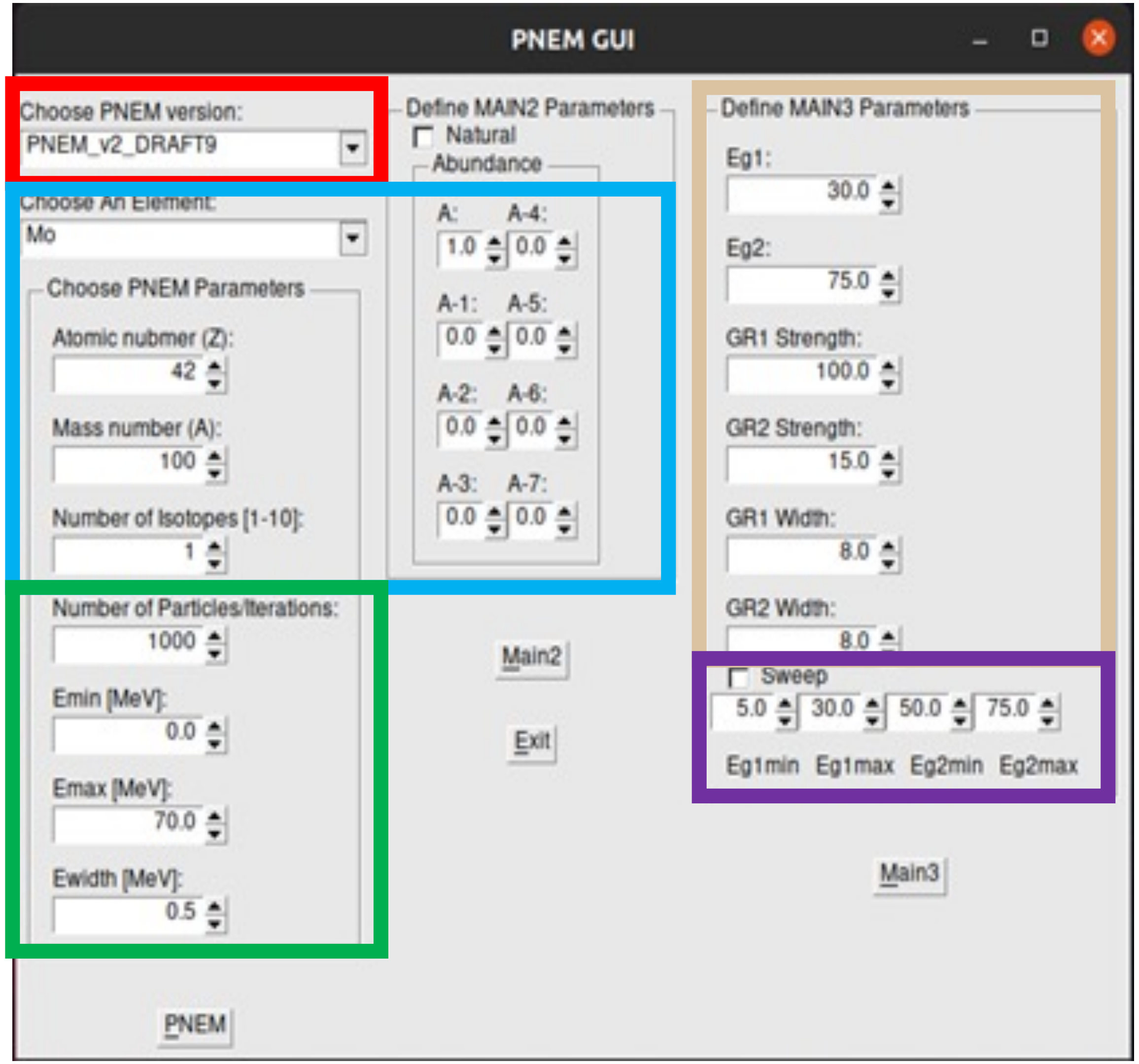
1) select version of emission model

2) select target element (enriched/natural)

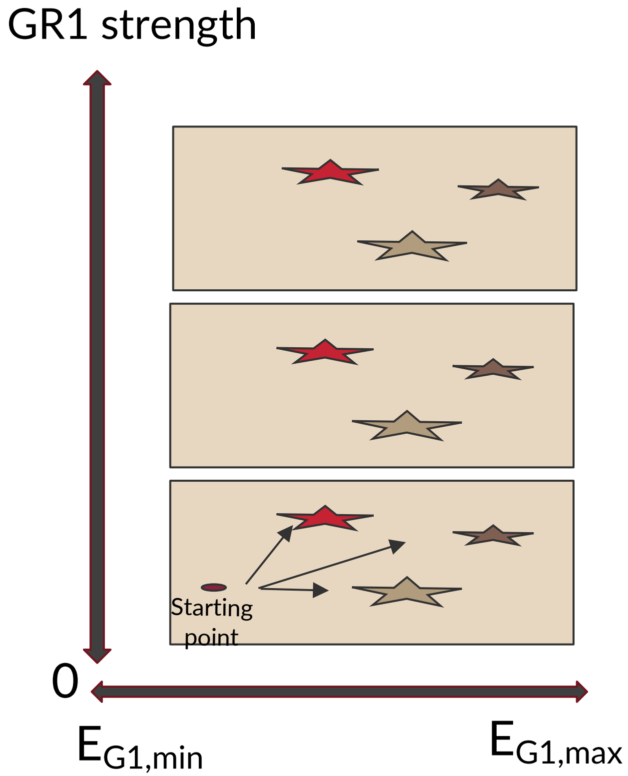
3) Define statistics/iteration

4) Initialize parameters

5) Set range for χ^2 analysis for optimization of muon capture strength based on experimental data



Recent update:
Randomly assigned GR peak for OMC based on delayed gamma rays experimental data.



- Get the highest P-value in the "area" of $(E_{G1,max}-E_{G1,min}) \times (E_{G2,max}-E_{G2,min})$
- Repeat for 3 parameters

[29] Uziel BSc Thesis 2023 UTM

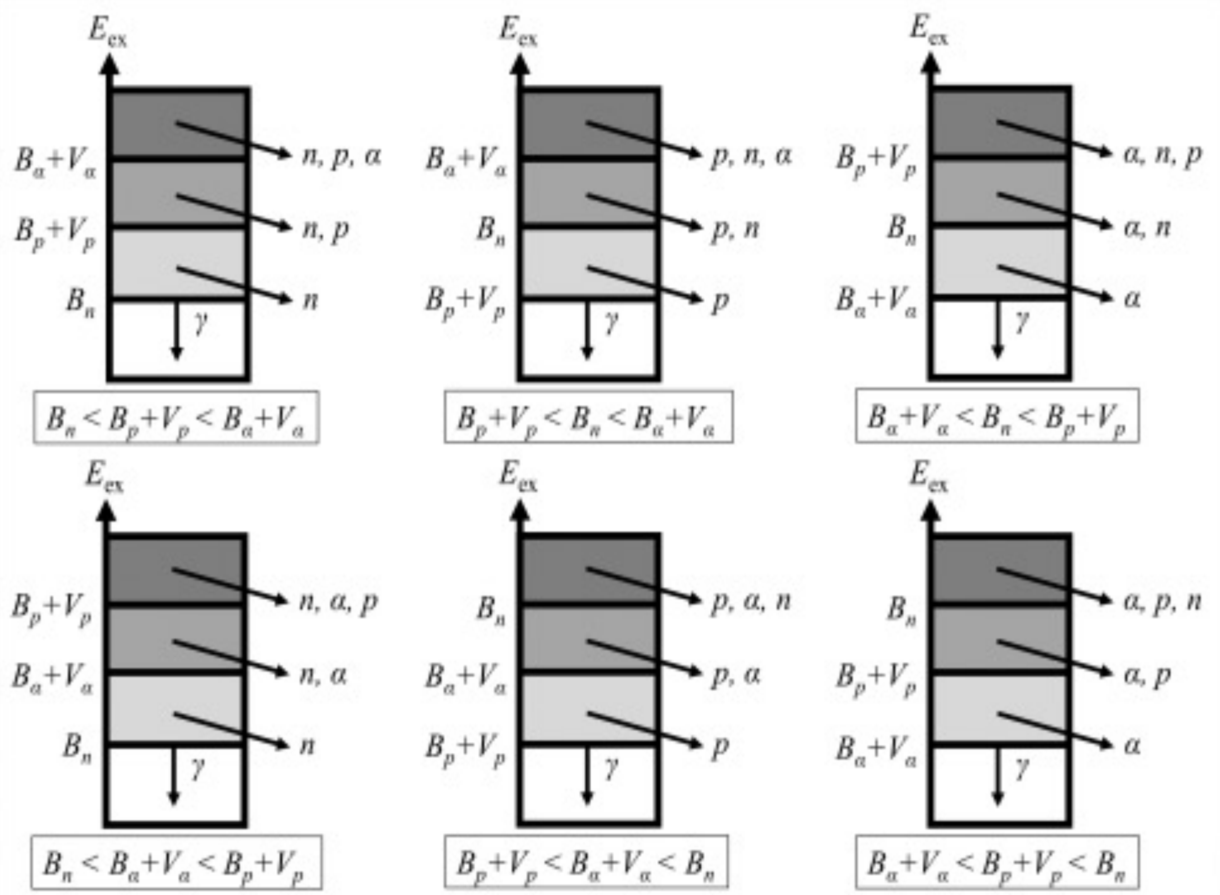
Additional alpha emission for light nuclei

Multiparticle emission model (MPEM), Inclusive of:

- emission of alpha after OMC
- Coulomb barrier effects.

Preparation for PSI Campaign 2023 if irradiation of 56Fe (light nuclei) might have more emission on alpha.

First calculation for comparison of $^{136}Ba(\mu,1\alpha 1n)$ - Next talk



Under Progress (Ng PhD Thesis)

Remarks and perspectives on OMC experiments for DBDs and anti-neutrinos nuclear responses.

- OMC can efficiently produce nuclear isotopes with the atomic number Z−1, less by one than the atomic number Z of the target isotope.
  - By using ${}^{A}_{Z}X$ target isotopes, isotopes of ${}^{A-1}_{Z-1}X$ are preferentially produced, and several isotopes with A,A−2,A−3,A−4 are also produced.
- Production of delayed gamma rays by OMC is complementary to photon capture reactions where isotopes of ${}^{A-1}_{Z}X$ are well produced.
  - Note that ppb-level nuclei (impurities) are identified by measuring gamma rays from OMC, which are characteristic of the nuclei, as explained in [1].
- The relative strength distribution of OMC on Mo isotopes show the μ-GR around E_{G1}≈12 MeV consistent with the pn-QRPA calculation.
  - The absolute strength derived from the PNEM is much smaller or about the same with the pn-QRPA [2,3]
  - Thus, suggest a similar quenching of the M_i^+ NMEs as the M_i^- NMEs derived from light-ion CERs.
- The extensive experimental programs on OMC for other nuclei of DBD and supernova anti-neutrino interests are under progress at RCNP and Paul Scherrer Institute (PSI), Switzerland, by the join group of Joint Institute for Nuclear Research (JINR), Dubna, RCNP, Osaka and Universiti Teknologi Malaysia (UTM).

OMC4DBD/MONUMENT COLLABORATION

RCNP

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TUM

ETH zürich

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VSU
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NUCLEAR AND RADIATION PHYSICS

THANK YOU

In the Name of God for Mankind