Neutrino nuclear response for DBDs and astro-antineutrino responses by muon capture reactions and the isotope productions

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Outline

- Neutrino nuclear responses for double beta decays and astro-antineutrino responses.
- Ordinary muon capture for nuclear transmutation and isotope production.
- First Joint program UTM-RCNP-JINR
- Muon absolute lifetime and total capture rate
- Conclusion and remarks

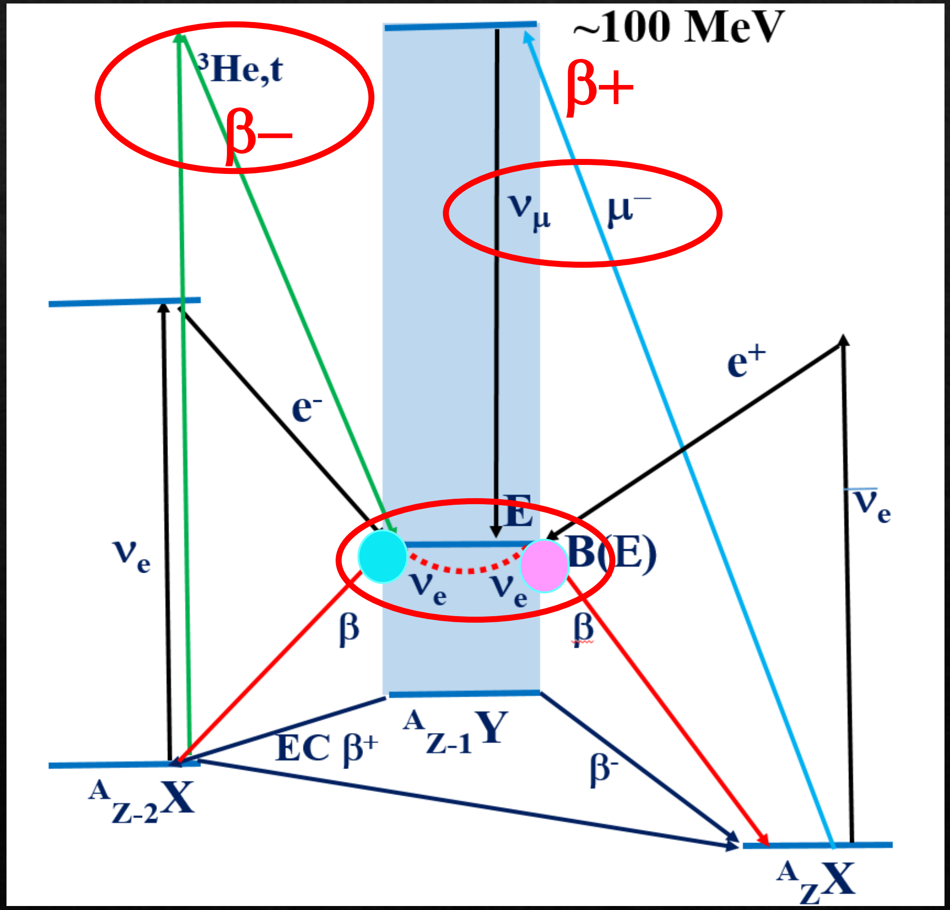
Neutrino nuclear responses for double beta decays and astro-antineutrino responses

- The fundamental properties of neutrinos have been observed in various experiment including double beta decay (DBD), inverse beta decay(IBD) and single beta decay(SBD).
  - In DBD (2νββ or 0νββ), nuclear matrix element is important in extracting the absolute mass of neutrino. However, DBD involves transformation from parent to daughter nucleus through intermediate nucleus measurement of NME from the final 2 transitions causes suppression to NME value due to the nuclear structures of the intermediate nuclei.
  - In IBD and SBD (EM, weak and nuclear probe), simpler way to understand nuclear structure and each probe type investigates different region of interest for nuclear structure studies produces neutrino nuclear response which is the square root of NME.

[1] H. Ejiri, Proc. CNNP2017, Catania 2017, IOP Conf. Series, 1056 (2018) 012019.
[2] J. Vergados, H. Ejiri, and F. Simkovic, Rep. Prog. Phys. 75 (2012) 106301.

Nuclear & lepton (μ) CERs for CC ν responses

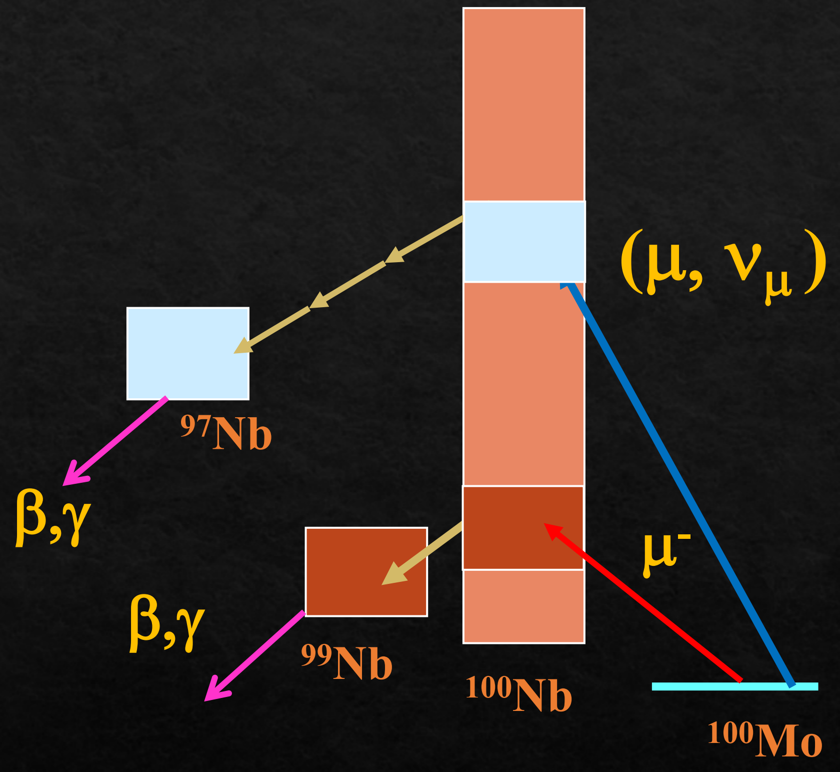
- (^{3}He,t) β- side ν, and (μ,n_μ) β+ side anti-ν CCs associated with DBD ν-exchange responses, and with astro ν and anti-ν responses
- Nuclear and μ CERs cover the large E & P regions as DBD & astro-ν
- P=100-50 MeV/c
- E=0-50 MeV



Muon CER (μ, ν_μ, xnγ)

E+P~100 MeV/c E = 5-50 MeV, P = 95-50 MeV

- 1-50 MeV input
- Represents the β+ side of DBD NME.
- It is difficult to measure neutrino due to its unknown characteristics and it is very fast.
- Neutron evaporation with energy of a few MeV.
- Number of neutrons emission gives the excitation energy in ^{100}Nb.
- Experimentally we can either measure neutrons or gamma ray the accompanying neutron emission.



H. Ejiri Proc. e-γ conference Sendai 1972,
H. Ejiri et al., JPSJ 2013
I. H. Hashim H. Ejiri et al., PRC 97 (2018) 014617

Ordinary muon capture for nuclear transmutation and isotope production.

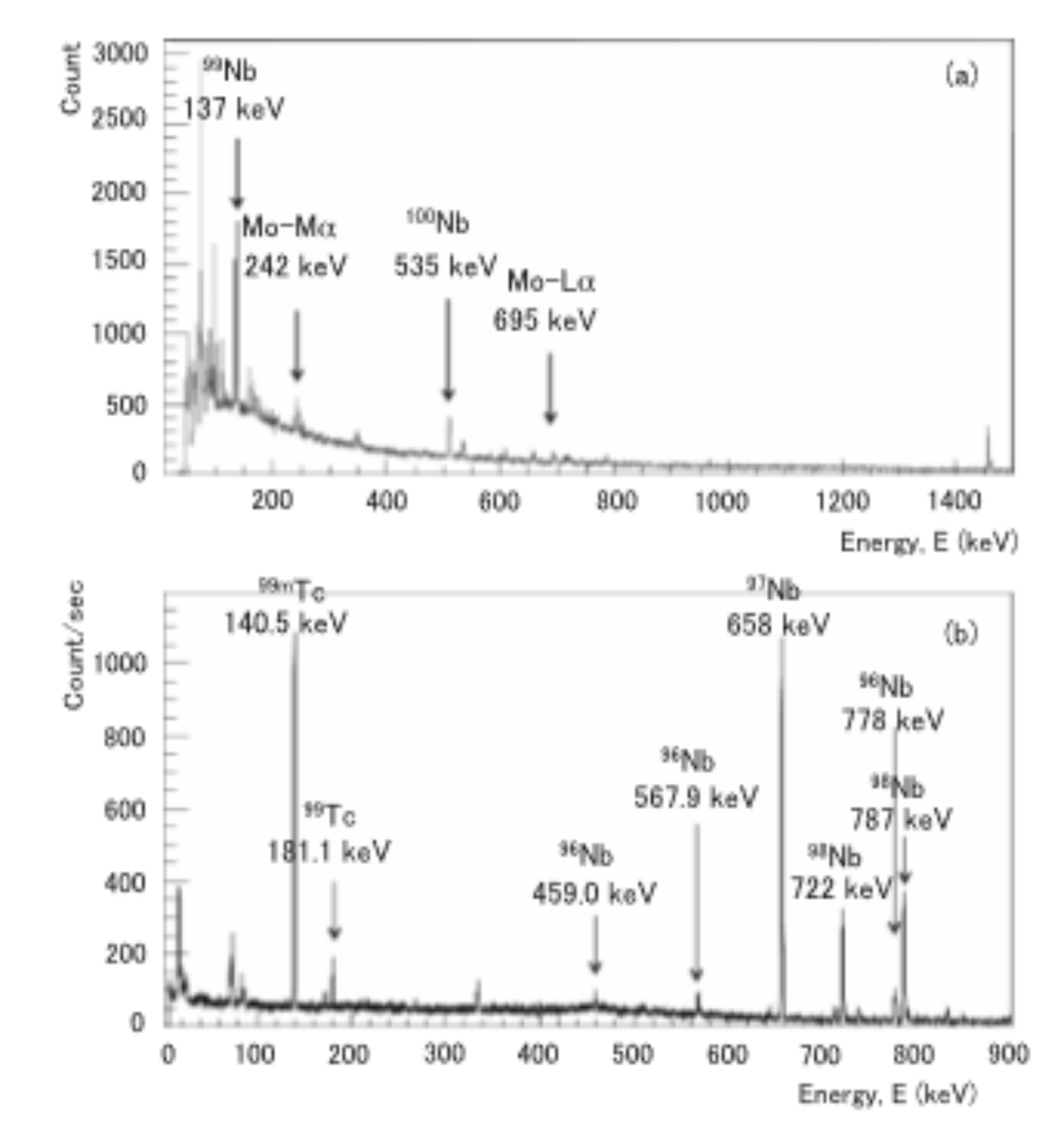
$$\mu + {}^{A}_{Z}X \longrightarrow \nu_{\mu} + {}_{Z-1}{}^{A}X^{*}$$

- Produces nuclear isotopes with high sensitivity and to efficiently produce specific radioisotopes (RIs), especially for environmental and biomedical applications

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

[1] H. Ejiri, I. H. Hashim, et al. J. Phys. Soc. Japan, 82 (2013) 044202.
[2] I.H.Hashim, H Ejiri, AAPPS Bulletin (June 2019)

MCER RIs detection and production on ^{100}Mo



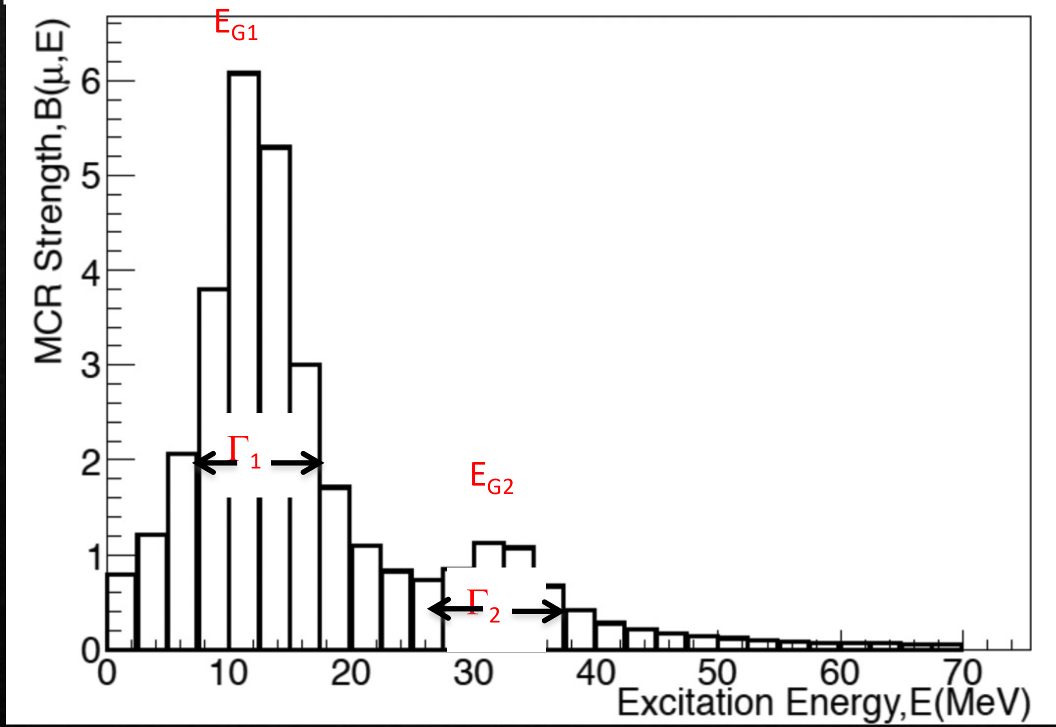
Isotope	lifetime	Energy(keV)
^{100}Nb	2.99 s	535.0
^{99}Nb	2.6 min	137.0
^{99}Mo	66.0 h	181.1, 739.5
^{99m}Tc	6 h	140.5
^{98}Nb	1.23 h	722.0, 787.0
^{97}Nb	0.85 h	657.9
^{96}Nb	23.3 h	459.0, 568.7, 778.0
^{95}Nb	34.9 d	765.0
^{94}Nb	51.8 min	75.5, 366.9, 891.7
^{93}Nb	6.85 h	2424.9

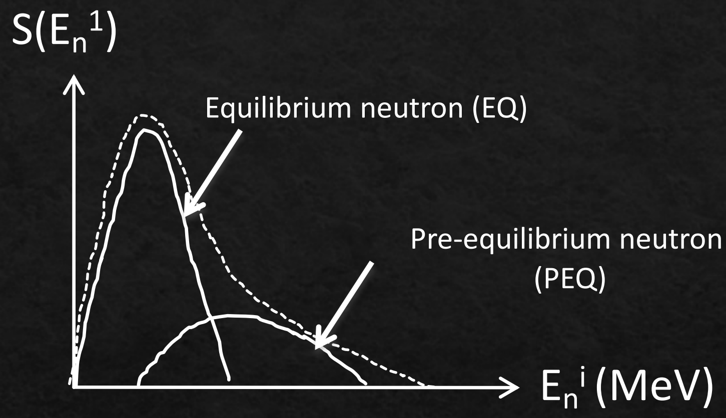
(a) Online spectrum for the γ rays with half-lived 0 to 1.5 hours.
(b) Off-line spectrum for the delayed γ rays with half-lived 0.5 hours onwards.

1. I. H. Hashim PhD Thesis Osaka 2015.
2. I. H. Hashim H. Ejiri , 2015. MXG16,
3. I. H. Hashim H. Ejiri , et al PR C 97 2018

OMC response B(μ,E) was derived by exp. and theory

μ response(strength) distribution





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

{EQ} {PEQ}

Neutron emitted in both equilibrium (EQ) and pre -equilibrium (PEQ) where the ratio of PEQ to EQ is set to 25% based on comparison with neutron spectrum on various nuclei.

$$B(\mu,E) = B_1(\mu,E) + B_2(\mu,E),$$

$$B_i(\mu,E) = \frac{B_i(\mu)}{(E - E_{Gi})^2 + (\Gamma_i/2)^2},$$

I.H.Hashim, H. Ejiri, et al. PRC 97(2018) 014617 (J-PARC 2014)

Particles emission for light nuclei after OMC

Reaction	Observed γ-ray yield	Estimated ground-state transition	Missing yields	Total yield
$^{27}Al(\mu^-, \nu)^{27}Mg$	10(1)	0	3	13
$^{27}Al(\mu^-, \nu n)^{26}Mg$	53(5)	4	4	61
$^{27}Al(\mu^-, \nu 2n)^{25}Mg$	7(1)	3	2	12
$^{27}Al(\mu^-, \nu 3n)^{24}Mg$	2	3	1	6
$^{27}Al(\mu^-, \nu pxn)^{26\text{-}23}Na$	2	2	1	5
$^{27}Al(\mu^-, \nu\alpha xn)^{23\text{-}21}Ne$	1	2	0	3
Total	75(5)	14	11	100

Reaction	Observed	Ground state	Missing	Total
$^{40}Ca(\mu^-,\nu)^{40}K$	12	-	15	27
$^{40}Ca(\mu^-,\nu n)^{39}K$	20	8	15	43
$^{40}Ca(\mu^-,\nu 2n)^{38}K$	0.7	0.3	2	3
$^{40}Ca(\mu^-,\nu p)^{39}Ar$	6	4	-	10
$^{40}Ca(\mu^-,\nu pn)^{38}Ar$	7	4	-	11
$^{40}Ca(\mu^-,\nu p2n)^{37}Ar$	1	2	-	3
$^{40}Ca(\mu^-,\nu\alpha xn)Cl$	2	1	-	3
Total	**49**	**19**	**32**	**100**

Most experimental work could not observed proton emission after muon capture.

Reaction	Observed γ ray yield	Estimated ground-state transition	Missing yields	Total yield
$^{28}Si(\mu^-, \nu)^{28}Al$	16.6(12)	0.4	9	26
$^{28}Si(\mu^-, \nu n)^{27}Al$	28(2)	19	2	49
$^{28}Si(\mu^-, \nu 2n)^{26}Al$	2.8(5)	1	2.2	6
$^{28}Si(\mu^-, \nu 3n)^{25}Al$	<0.5	1	–	1
$^{28}Si(\mu^-, \nu p)^{27}Mg$	2.5(4)	0.5	–	3
$^{28}Si(\mu^-, \nu pn)^{26}Mg$	8.4(8)	2	−1.4	9
$^{28}Si(\mu^-, \nu p2n)^{25}Mg$	1.5(1)	1	–	2.5
$^{28}Si(\mu^-, \nu p3n)^{24}Mg$	<0.5	0.5	–	0.5
$^{28}Si(\mu^-, \nu\alpha)^{24}Na$	0.5(5)	0.5	–	1
$^{28}Si(\mu^-, \nu\alpha n)^{23}Na$	0.5(5)	0.5	1	2
Total	60.8	26.4	12.8	100

Reaction	Observed	Ground state	Missing	Total
$^{56}Fe(\mu^-,\nu)^{56}Mn$	-	-	17	17
$^{56}Fe(\mu^-,\nu n)^{55}Mn$	36	12	9	57
$^{56}Fe(\mu^-,\nu 2n)^{54}Mn$	8	3	-	11
$^{56}Fe(\mu^-,\nu 3n)^{53}Mn$	2.2	1.6	5	9
$^{56}Fe(\mu^-,\nu pxn)Cr$	2	1	1	4
$^{56}Fe(\mu^-,\nu\alpha xn)V$	-	1	1	2
Total	**48**	**19**	**33**	**100**

[1] D.F. Measday, Phys. Rev. C 76 (2007) 035504.
[2] D.F. Measday, Phys. Rev. C 75 (2007) 045501.
[3] D.F. Measday and T.J. Stocki, AIP Conference Proceedings 947 (2007) 253.

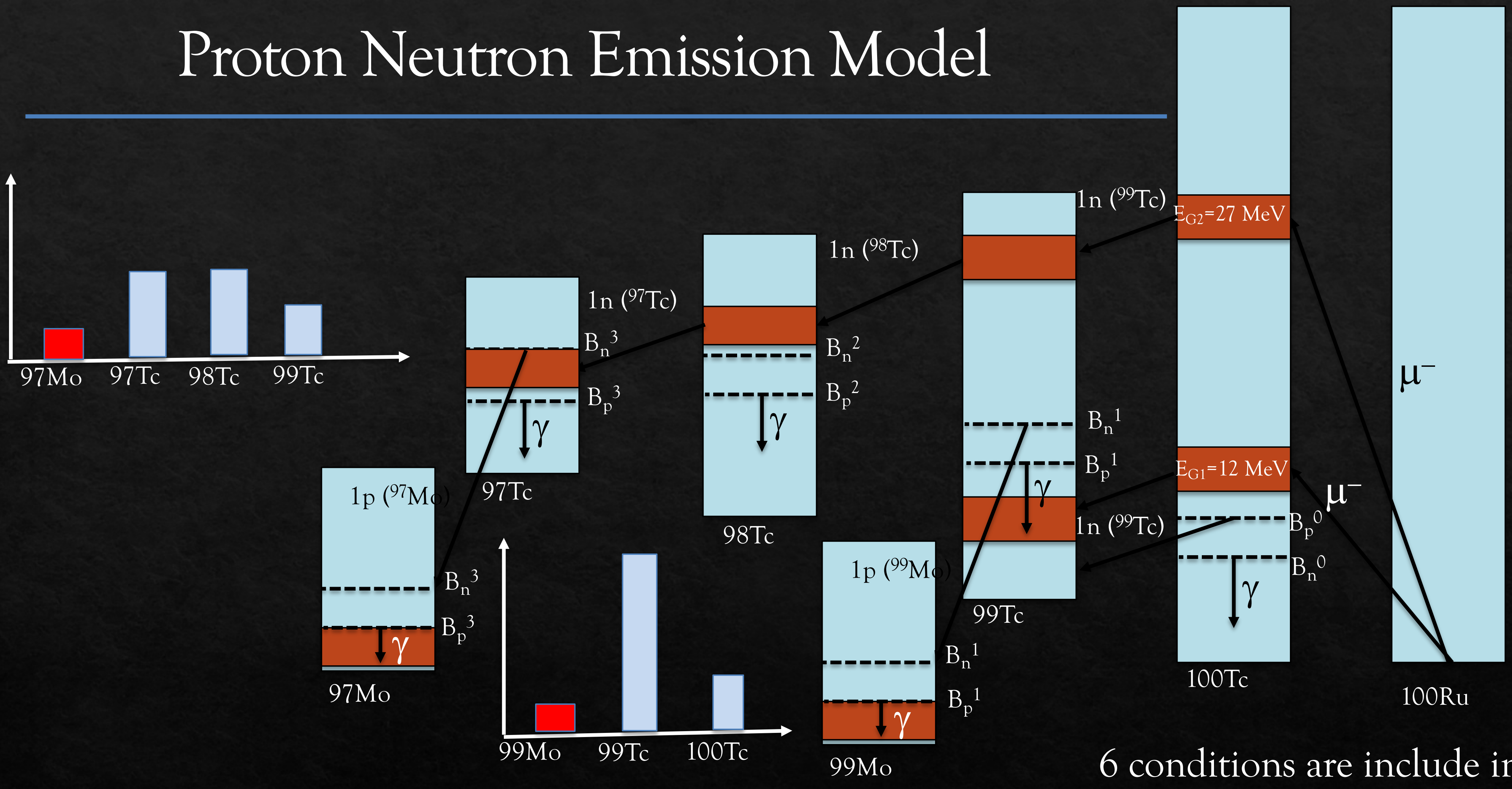
Particles emission for medium-heavy nuclei after OMC

Reaction	N	Al	Si	Ca	Ni	I	Pb	Bi
(μ^-, ν)	9	13	26	27	31	8	8	5
$(\mu^-, \nu n)$	46	61	49	43	59	52	44	47
$(\mu^-, \nu 2n)$	27	12	6	3	7	18	37	29
$(\mu^-, \nu 3n)$	4	6	1	0	1	14	11	9
$(\mu^-, \nu 4n)$	0	0	0	0	0	5	0.3	5
$(\mu^-, \nu p)$	2	0	3	10	0.2	0.03	0.01	0.01
$(\mu^-, \nu pn)$	6	5	9	11	1.5	0.3	0.1	0.1
$(\mu^-, \nu p2n)$	3	0	2.5	3	1.1	0.2	0.2	0.06
$(\mu^-, \nu \alpha xn)$	3	3	3	3	0.4	0	0	0

- RI Production rates by OMC [1]
  - Performed at Muon channel, CERN Synchrocyclotron on Mg, Al, Fe, Co, Ni, Mn, Fe and Co targets.
  - Observed up to 3 neutron emission on Fe (0n: 15-30%, 1n: 50-60%, 2n: 10-20% and 3n: 0.5-10%).
- Consideration seems small for medium-heavy nuclei but for light nuclei > 10% [2]

[1] G. Heusser and T. Kirsten. Nuc. Phys. A (1972) 369-378
[2] D. F. Measday and T. J. Stocki. AIP Conference Proceedings 947, 253 (2007)

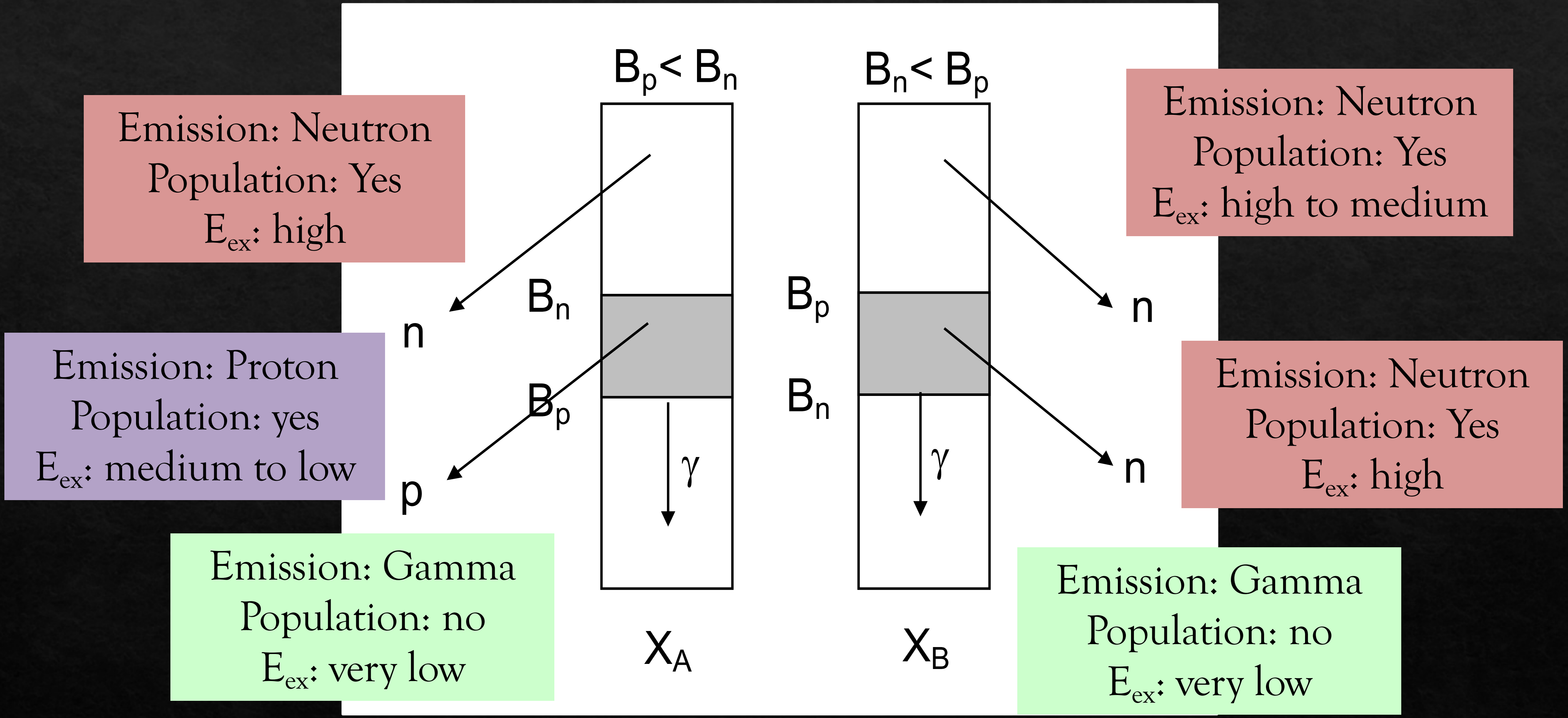
Proton Neutron Emission Model



6 conditions are include in current PNEM.

[1] H. Ejiri, I.H. Hashim. Private Comm. 2018
[2] I.H. Hashim. F.Soberi, F.Ibrahim, F.Othman. Private Comm. 2019
[3] I. H. Hashim et al, Nucl. Instr. Method. A, Mar 2020

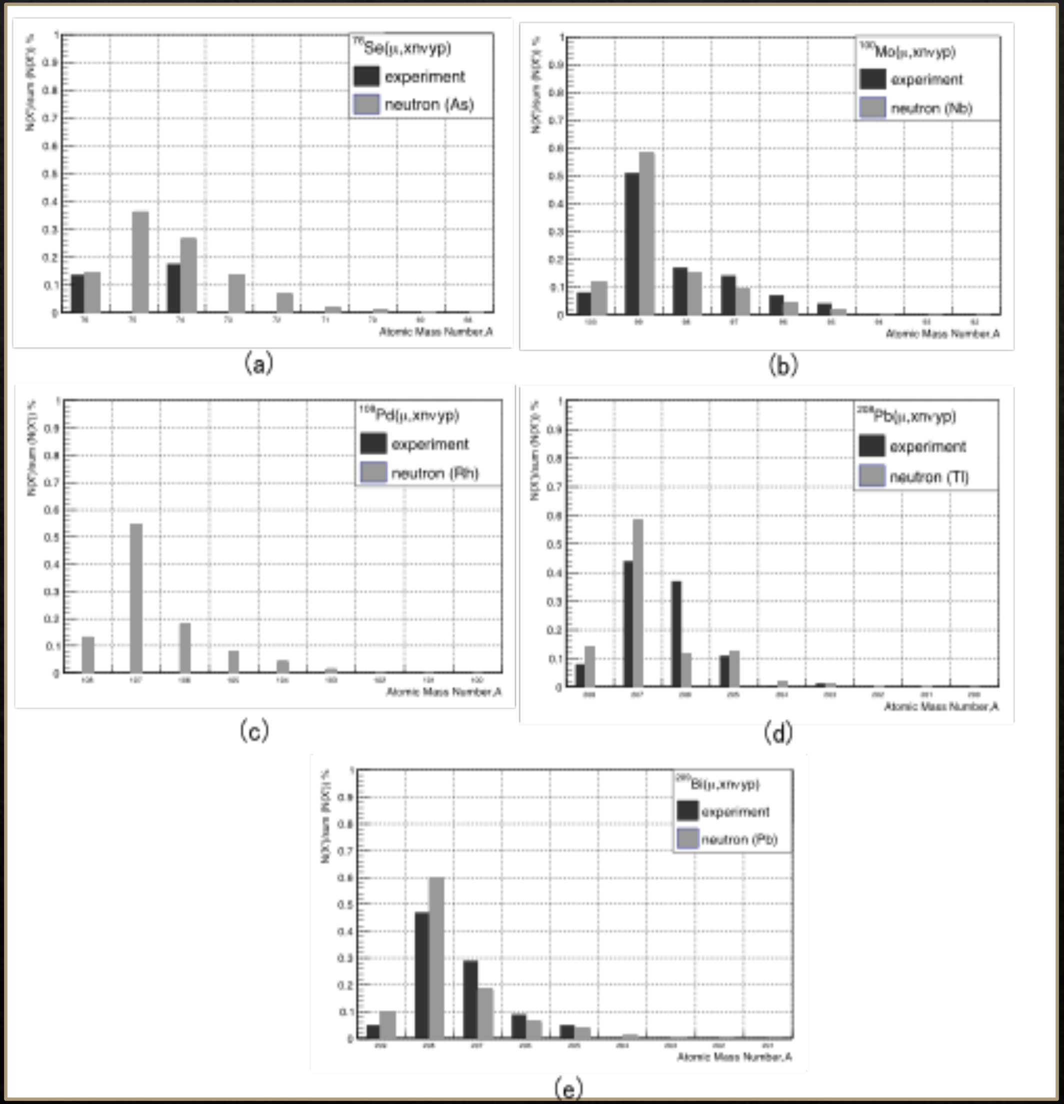
Setup Conditions for PNEM



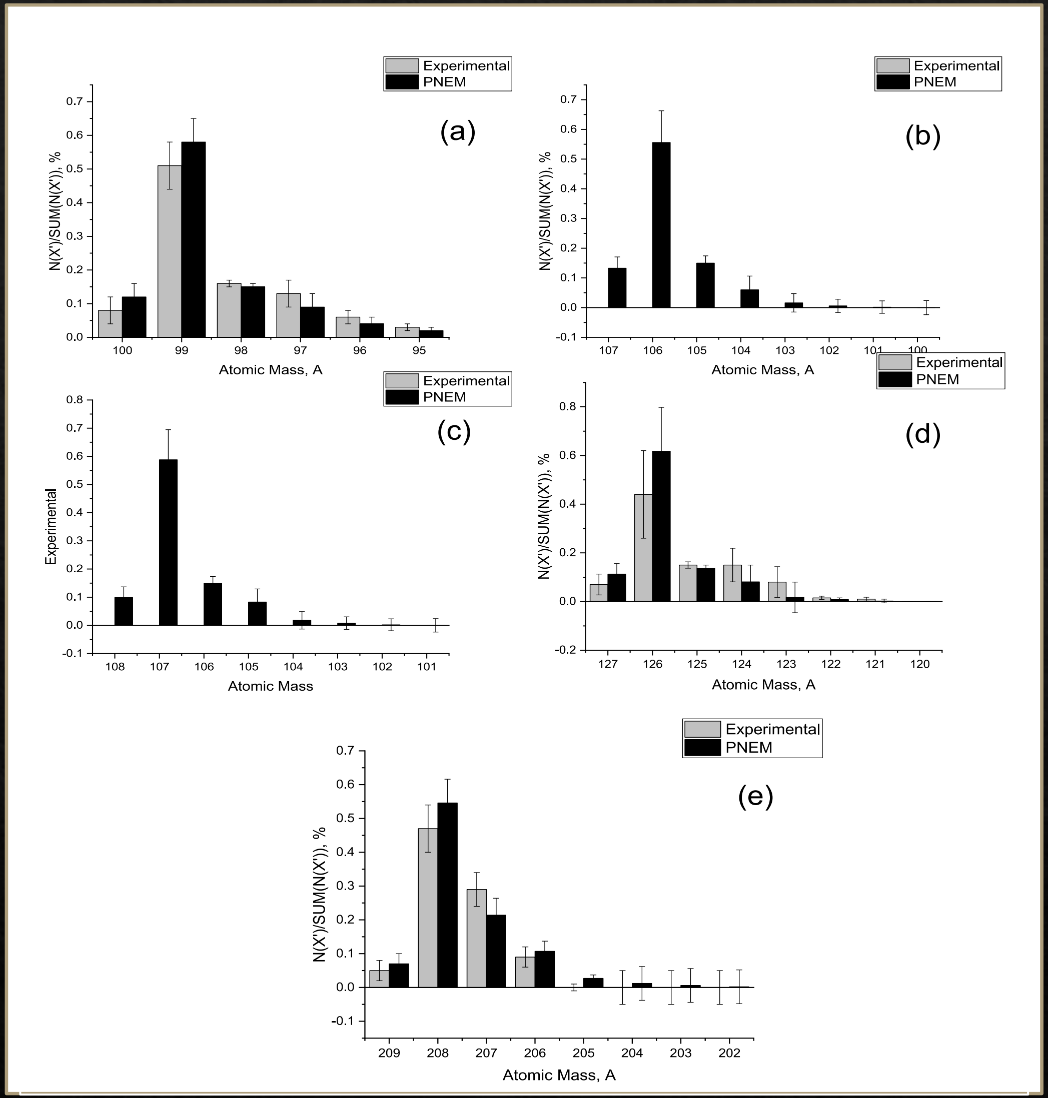
I. H. Hashim et al, Nucl. Instr. Method. A, Mar 2020

Proton neutron emission model for OMC

Neutron emission model 2014 [1]



Proton neutron emission model 2020 [2]



Using these model, more particle emission after OMC can be expected.

[1] I. H. Hashim PhD Thesis Osaka 2015.

[2] I. H. Hashim et al, Nucl. Instr. Method. A, Mar 2020

Calculation with Natural Mo target

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)	$N(X')\times10^8$	γ rays (keV)	calc. $N(X')\times10^8$
^{100}Nb	^{100}Mo	$^{100}Mo(\mu,0n)$	4.4×10^{-3}	0.6 ± 0.1	535.6[a]	0.35 ± 0.26
^{99}Mo	^{99m}Tc	$^{100}Mo(\mu,n\beta^-)$	66	3.8 ± 0.4	140.5, 181.0, 739.5	2.91 ± 1.02
^{98}Nb	^{98}Mo	$^{100}Mo(\mu,2n)$	7.1×10^{-3}, 0.855	3.0 ± 0.8	734.7[a] , 787.4	2.08 ± 1.01
^{97}Nb	^{97}Mo	$^{98}Mo(\mu,1n)$	1.2	8.8 ± 1.5	658.1	8.51 ± 0.83
^{97}Zr	^{97}Nb	$^{98}Mo(\mu,p)$	16.9	0.05 ± 0.02	743.5	–
^{96}Nb	^{96}Mo	$^{97}Mo(\mu,1n)$	23.4	4.5 ± 1.0	568.8, 778.2, 1091.3	7.02 ± 1.37
^{95}Nb	^{95}Mo	$^{96}Mo(\mu,1n)$	1205	6.7 ± 1.0	765.8	7.52 ± 2.16
^{94}Nb	^{94}Mo	$^{98}Mo(\mu,1n)$	1.75×10^8	8.62 ± 1.0[b]	–	8.29 ± 1.13
^{93}Nb	^{93}Nb	$^{94}Mo(\mu,1n)$	1.41×10^5	5.26 ± 1.0[b]	–	5.06 ± 1.35
^{92}Nb	^{92}Zr	$^{94}Mo(\mu,2n)$	244.8	3.0 ± 0.15	934.5	2.78 ± 1.17
^{91}Nb	^{91}Zr	$^{92}Mo(\mu,1n)$	6×10^6	5.19 ± 1.0[b]	–	5.00 ± 1.17
^{90}Nb	^{90}Zr	$^{92}Mo(\mu,2n)$	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.

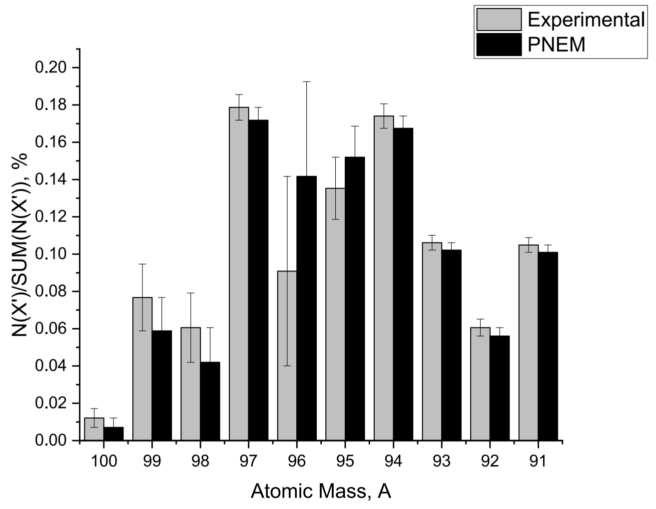


Fig. 6. Isotope mass distributions of RIs produced by MuCIP on ^{Nat}Mo.

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

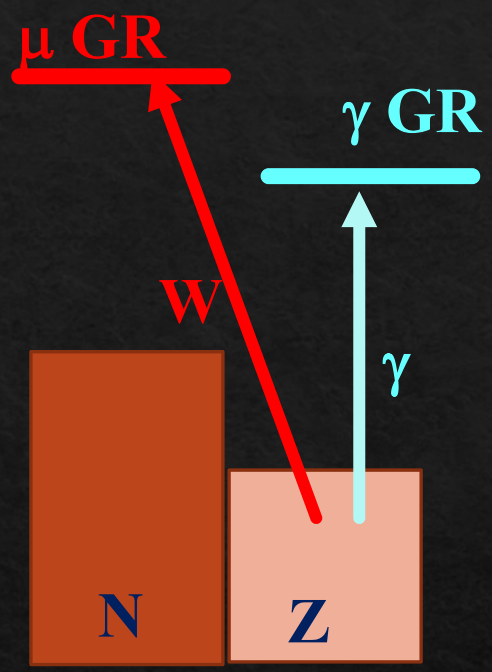
μ-GR (Giant resonance)

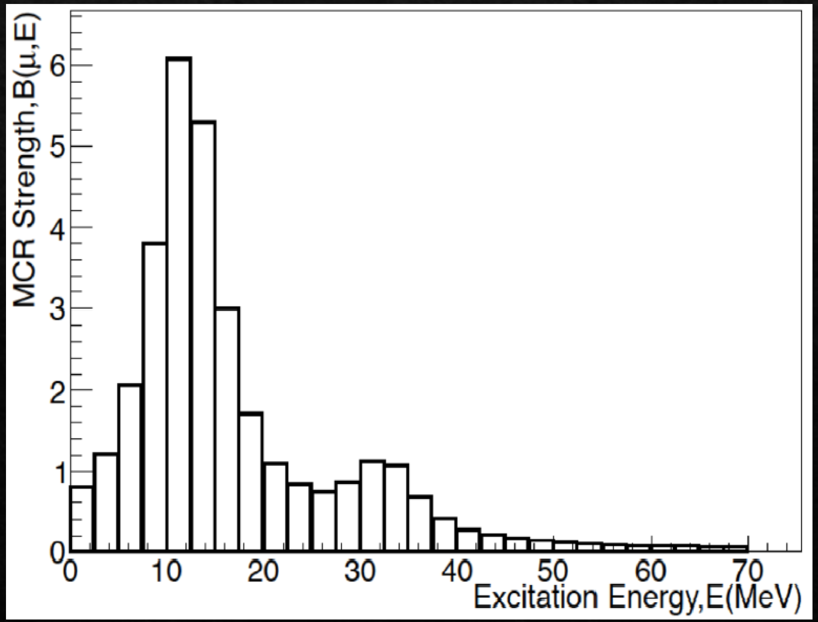
- Muon transition rate as a function of the excitation E was derived from the residual isotope mass distribution.
- μ-GR around 12-14 MeV was found for ^{100}Mo.
- The OMC rate : 6.7 ±1.3x10^6/sec.
- Relationship between GR peak energy with A.

$$E_{G1} = 30\ A^{-1/5}$$

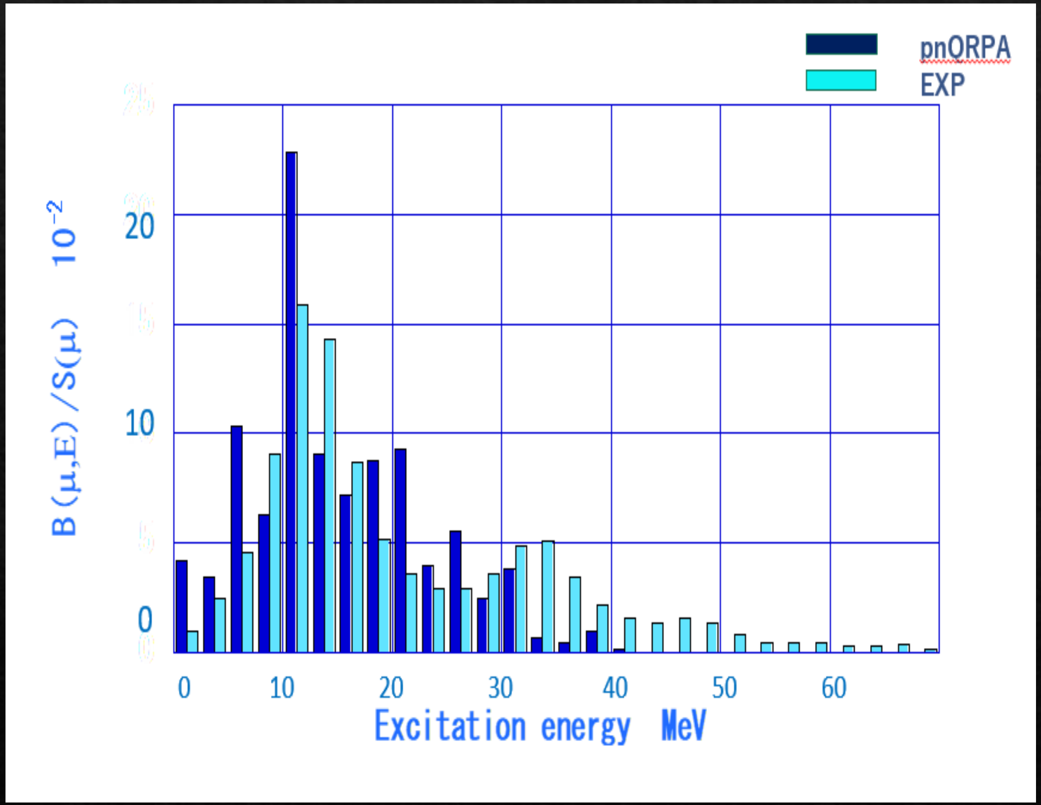
$$E_{G2} = 75\ A^{-1/5}$$

I.H. Hashim H. Ejiri et al., Phys. Rev. C 97 014617 2018
I. H. Hashim et al, Nucl. Instr. Method. A, Mar 2020
I.H. Hashim H. Ejiri et al., DBD workshop RCNP 2020





OMC response B(μ,E) was derived by exp. and theory



Muon capture rates based on Morita-Fujii formalism:

$$W = 8\left(\frac{Z_{eff}}{Z}\right)^4 P(\alpha Z m'_\mu)^3 \frac{2J_f+1}{2J_i+1}\left(1-\frac{q}{m_\mu+AM}\right)q^2$$

$$= G^\mu \frac{2J_f+1}{2J_i+1}$$

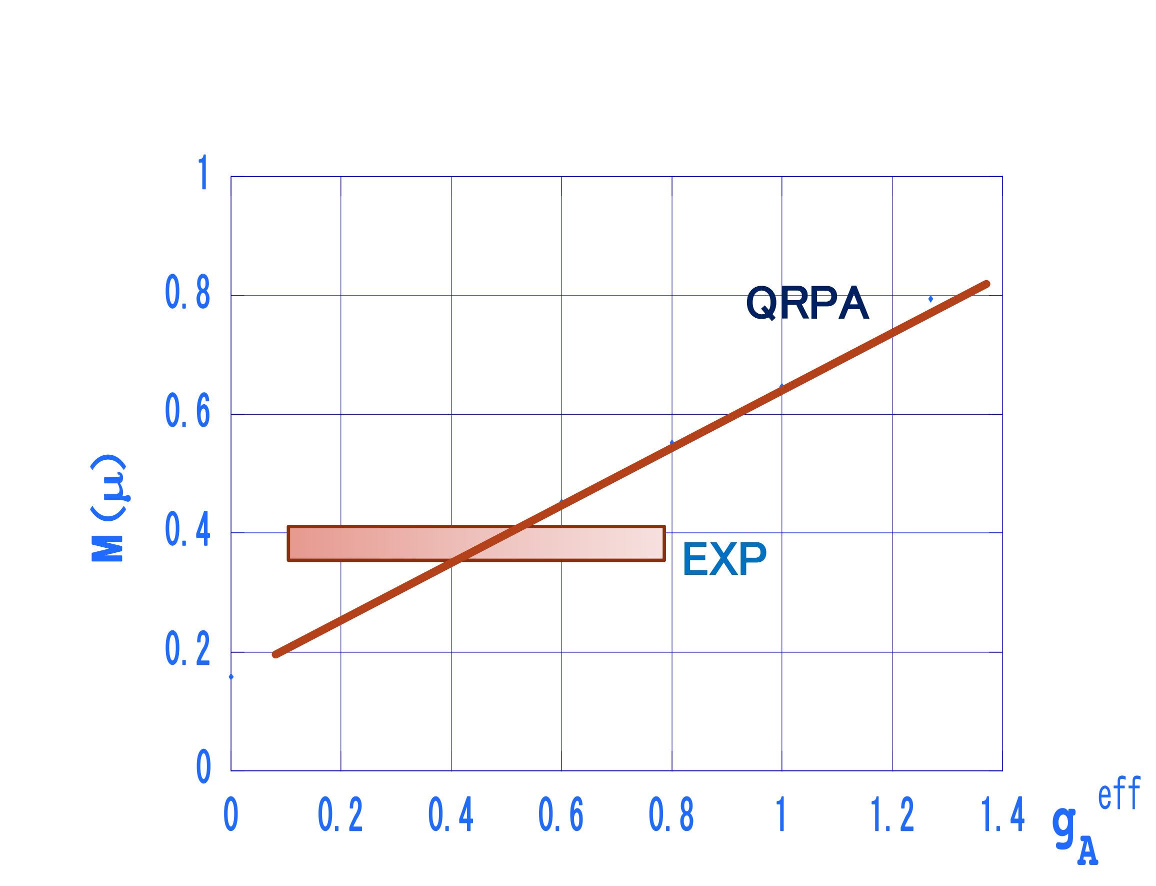
where P term has a complex structure containing all nuclear matrix element as well as weak couplings, some geometric factors and Racah coefficients.

$$R(\mu,E) = C_V^2 G^\mu B(\mu,E)$$

$$B(\mu,E) = \frac{M(E)^2}{2J_i+1}$$

H. Ejiri, L. Jokiniemi, J. Suhonen, AIP Proceedings 2020

OMC response B(μ,E) was derived by exp. and theory



Exp. summed strength and NME

$S(\mu) = \int B(\mu,E)\, dE = 0.146 \pm 0.03$

$M(\mu) = S(\mu)^{1/2} = 0.38 \pm 0.04$

Comparison of experiment and pn-QRPA, L. Jokiniemi S(μ) suggests a quenched g_A^{eff} ~0.5 , i.e. g_A^{eff}/g_A~0.4

L. Jokiniemi et al. PLB 2019

Renormalization of axial vector couplings A=100 (Mo)

$M_{EXP} = k_{NM} M_{QRPA}$

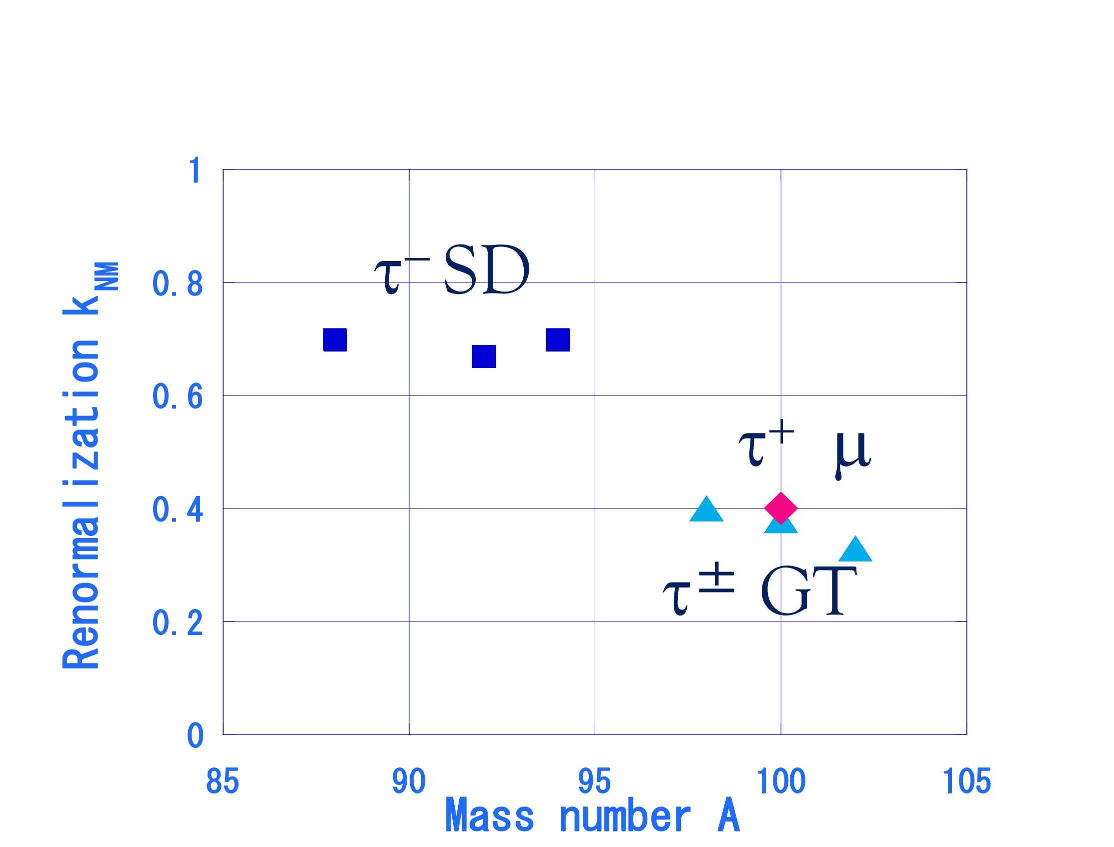
k_{NM} is the renormalization by non-nucleonic and nuclear medium effects, that are not in QRPA.

μ-renormalization (quenching)

$k_{NM} = g_A^{eff}/g_A \sim 0.4$,

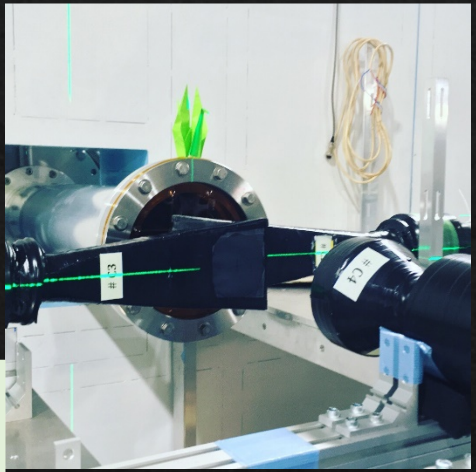
as SD, GT NMEs*.

DBD and astro-ν NMEs are reduced, depending on the ratio of the axial to vector NMEs.



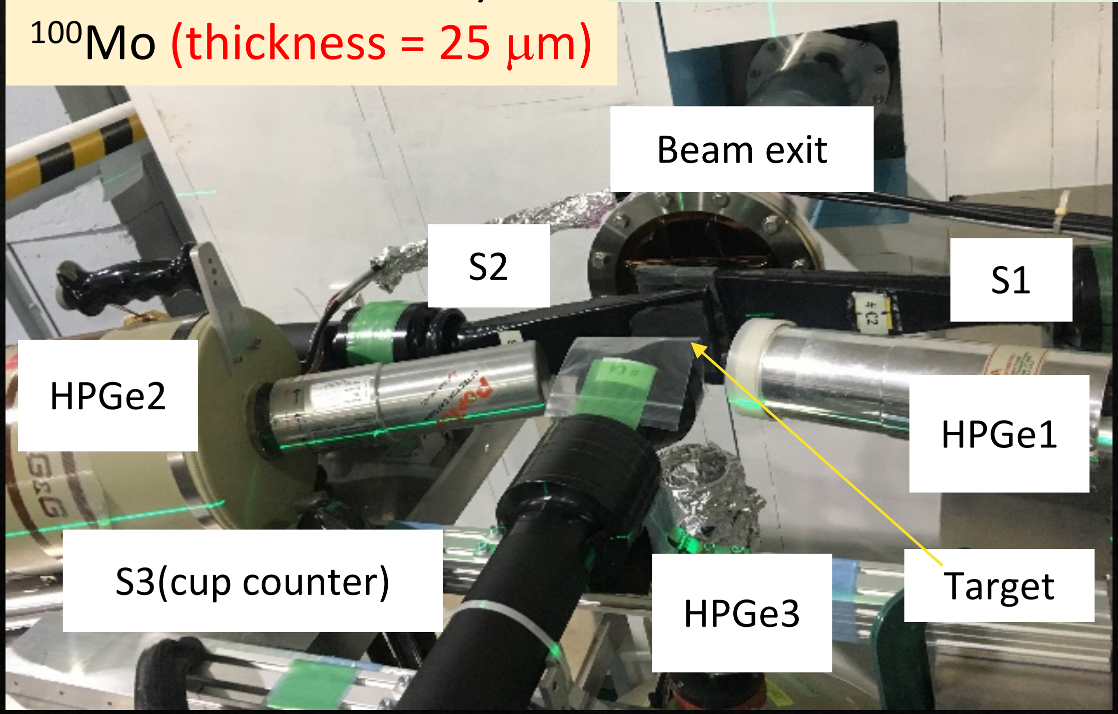
*H. Ejiri, N. Soukouti, J. Suhonen PL B 729 27 2014
*H. Ejiri, J. Suhonen J. Phys. G 42 055201 2015,

UTM-RCNP-JINR First Joint Program



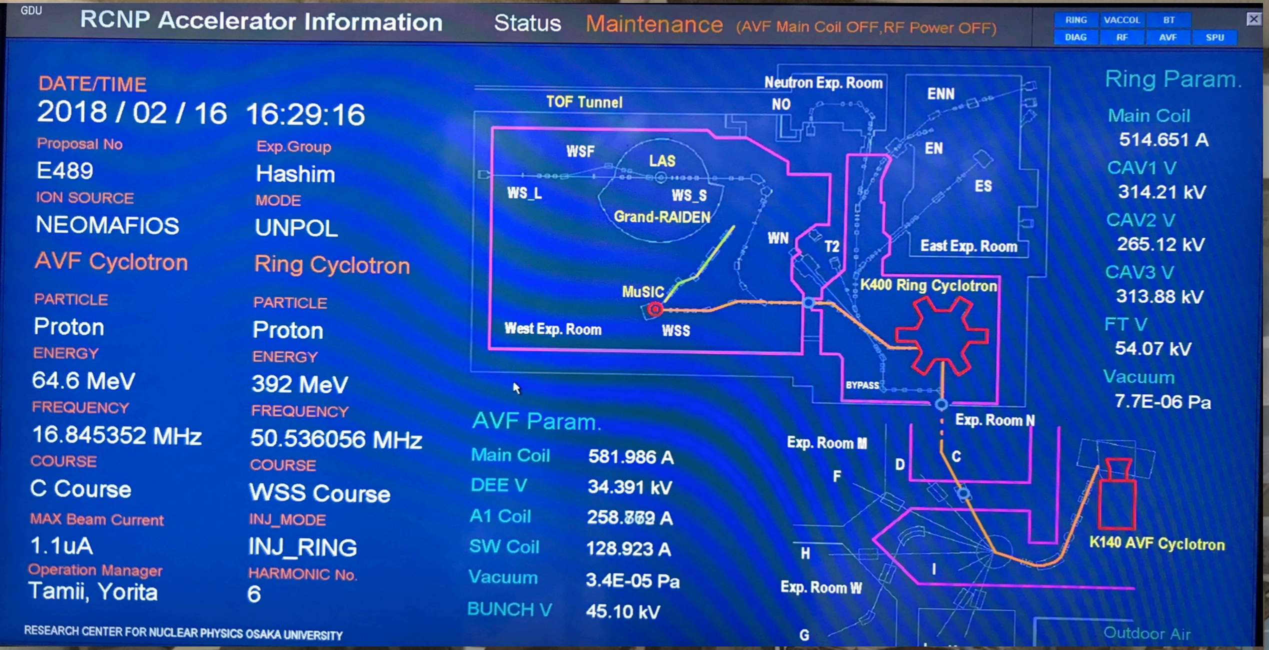
Negative muon momentum: 45 MeV/c for ^{100}Mo (thickness = 25 μm)

Irradiation time:
100Mo (15hours)



- Officially established in September 2018.
- E489 Beamtime at Osaka University (Feb 2018).

^{100}Mo	Natural Ruthenium
Natural Molybdenum	Natural Selenium



RCNP

BEAM LINE: MuSIC

BEAM REQUIREMENTS:

Type of particle proton
Beam energy 400 MeV
Beam intensity 1 μA

Type of particle muon
Muon momentum 50 MeV/c
Beam intensity 1 μA

Muon absolute lifetime and total capture rate

- The lifetime of positive muon muon is measured quite accurately in two most precise experiments, Saclay and TRIUMF, the value is known as 2197.03 ns.
- The lifetime of the negative muon is more difficult to determine because if the μ^- stops in a material, it will undergo capture when it reaches the 1s muonic state.
- The lifetime of the muon is a key property to determine the muon capture rates in nuclei and the best way to determines the leptonic coupling of the weak interactions since its principle decay does not include hadrons.

$$\Lambda_T = \frac{1}{\tau_\mu} = 0.995610 \frac{G_F^2 m_\mu^5 c^4}{192\pi^3 \hbar^7}$$

where G_F is the Fermi constant that closely related to other weak coupling constant associates with nuclear structure.

D.F. Measday. Physics Reports 354 (2001) 243–409

Muon absolute lifetime and total capture rate

- Total capture rates for negative muons [1,3]
  - Total capture rates for 50 elements and 8 isotopes have been deduced and compared to various calculations.

$$\Lambda_T = \frac{1}{\tau} = \Lambda_{Capture} + H\Lambda_{decay}$$

where H is the Huff Factor, $\Lambda_{capture}$ and Λ_{decay} are the μ-capture rate and muon decay rate (0.4552×10^6 $s^{-1}=1/\tau^{+}$).

- Calculation of total capture rate [2,3]

$$\Lambda_c(A,Z)=Z_{\mathrm{eff}}^4 X_1\left[1-X_2\left[\frac{A-Z}{2A}\right]\right]$$

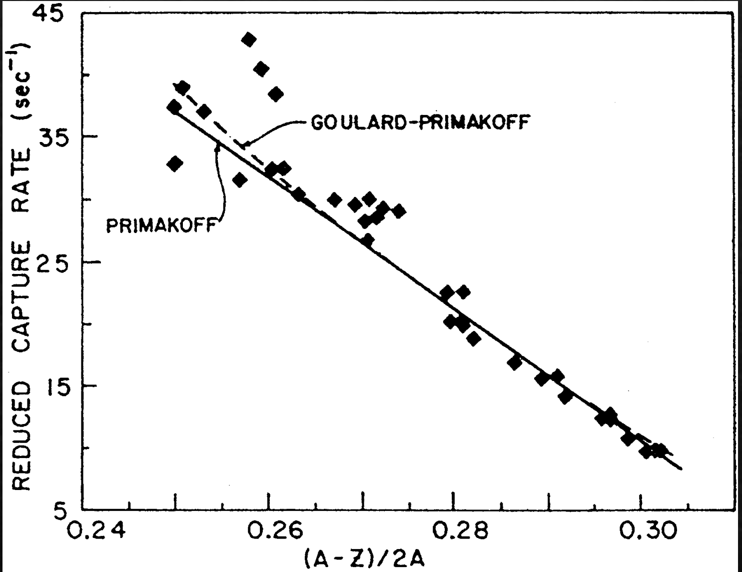
Where X = 170 and X' = 3.125

For heavy elements higher order Pauli corrections become necessary.

$$\Lambda_c(A,Z)=Z_{\mathrm{eff}}^4 G_1\left[1+G_2\frac{A}{2Z}-G_3\frac{A-2Z}{2Z}-G_4\left(\frac{A-Z}{2A}+\frac{A-2Z}{8AZ}\right)\right]$$

[1] T. Suzuki, D.F Measday and J.P.Roalsvig. Phys. Rev. C 35 6 (1987) 2212
[2] H. Primakoff, Rev of Modern Physics 31 3 (1959) 802
[3] D.F. Measday. Physics Reports 354 (2001) 243–409

Muon absolute lifetime and total capture rate



$$\Lambda(\text{reduced}) = \frac{\Lambda_c^{\exp} Z}{Z_{\text{eff}}^4}$$

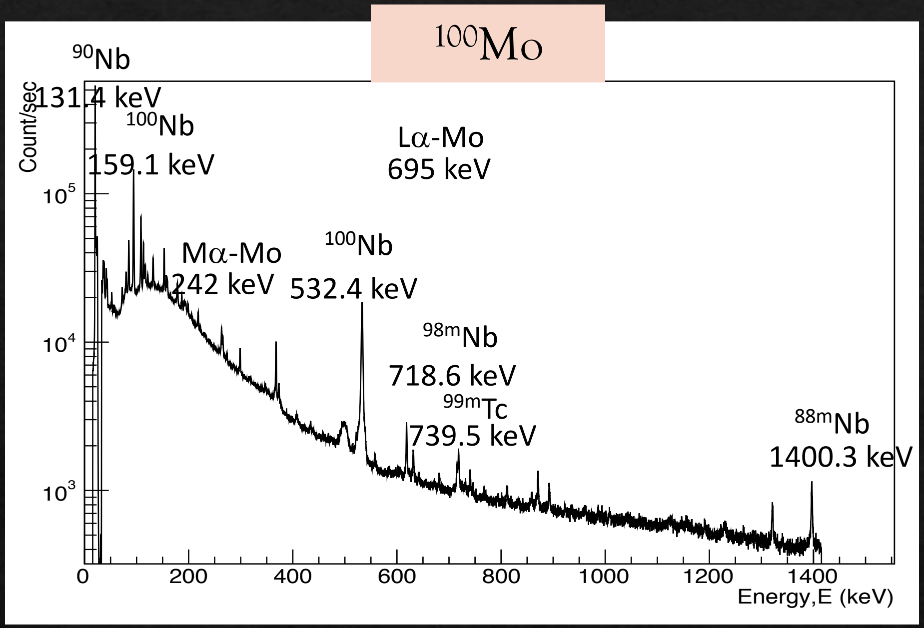
Table 4.4
Comparison of some experimental total capture rates with some illustrative calculations by Mukhopadhyay et al. [261], Chiang et al. [262], Cannata et al. [263], Walecka and Foldy [249], and Auerbach et al. [264–266]. All values are given in units of $10^3\ \mathrm{s}^{-1}$

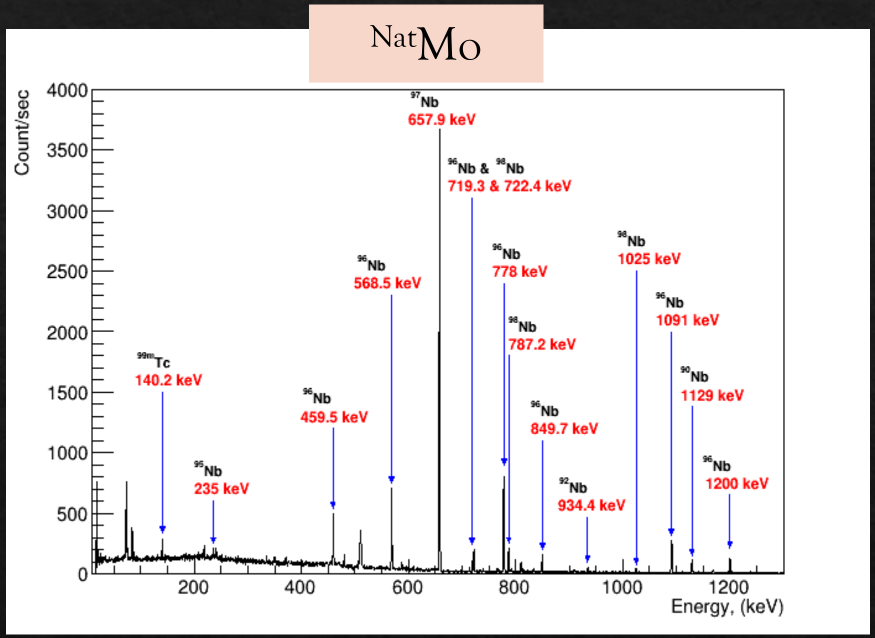
Nuclide	Experiment	Eq. (4.53)	[261]	[262]	[263]	[249]	[265,266]
^{4}He	0.356 (26)	0.59			0.300	0.278	
^{6}Li	4.68 (12)	3.01	4.68	4.73			
^{7}Li	2.26 (12)	1.48	3.4	3.4			
^{9}Be	6.1 (6)	5.6	8.84	10.6			
^{12}C	37.9 (5)	40	36	49	34[a]	36	34
^{13}C	35.0 (20)	29	30	38			
^{14}N	66 (4)	71	87	88			
^{16}O	102.5 (10)	117	116	146	98	107	102.5
^{18}O	88.0 (14)	71	90	115			
^{40}Ca	2546 (20)	2530		2771	2520	3180	2480
^{90}Zr	8630 (80)	9644		7194			9290
^{208}Pb	12985 (70)	12399		15338			13930

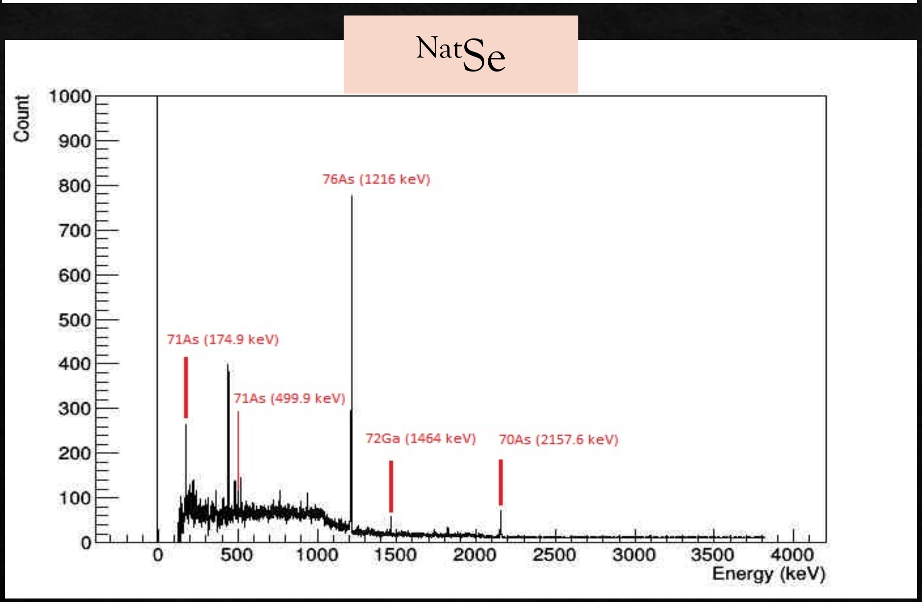
[a] We have added $6000\ \mathrm{s}^{-1}$ to the published calculation to take account of the ground-state transition and to compare more fairly with Walecka's value.

D.F. Measday. Physics Reports 354 (2001) 243–409

E489 short lived and delayed gamma



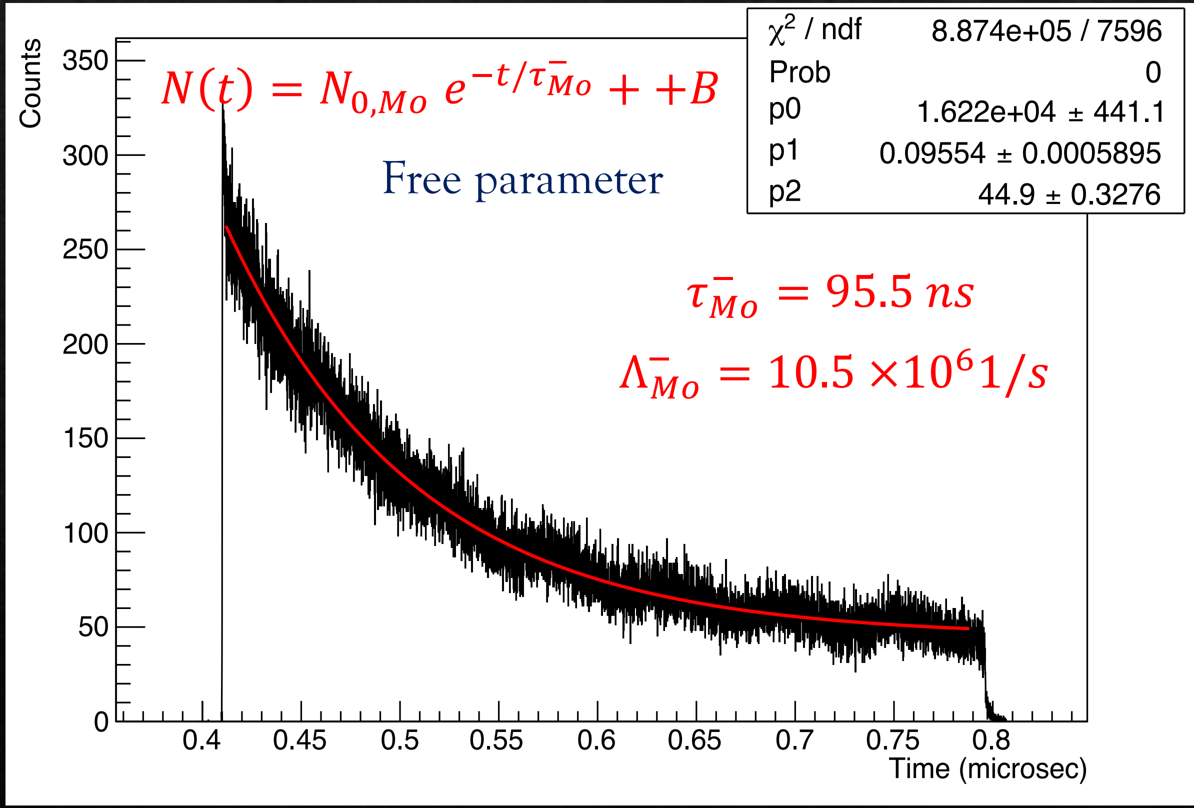




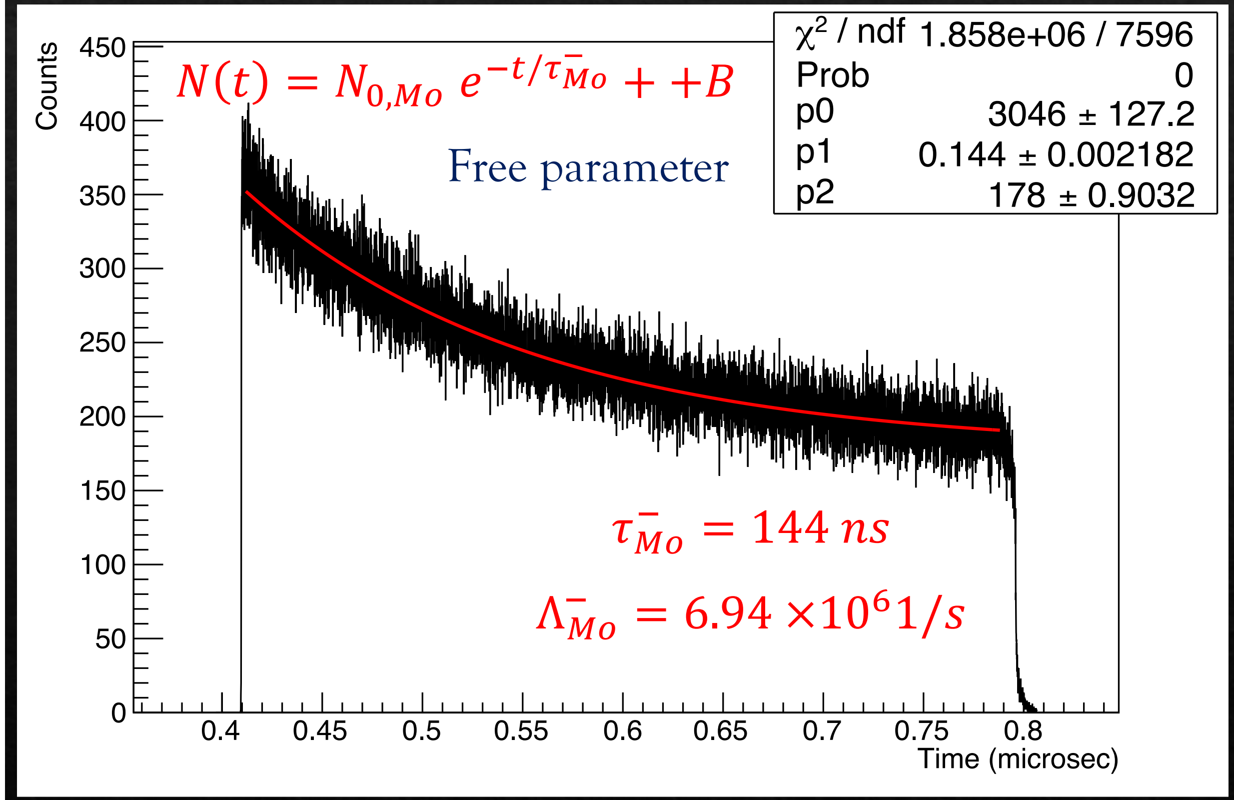
- Short lived isotope after OMC are observed. Most of them are from 0n and 1n emission.
- Delayed gamma ray from long lived isotope are measured in off beam measurement. Most of them are from 1n, 2n, 3n, 4n and 5n emission.

E489 muon to electron decay spectrum

^{Nat}Mo



^{100}Mo



- The effect of the Al degrader placed in front of the ^{100}Mo target was too small and almost negligible.

Mean lifetime and capture rate (Primakoff1959)

- Primakoff estimates ^{100}Mo lifetime is larger by a factor 1.3 than the lifetime of ^{Nat}Mo.
- Our experiment shows that ^{100}Mo lifetime is 144 ns and the lifetime of ^{Nat}Mo is 95.5 ns (about a factor of 1.5).

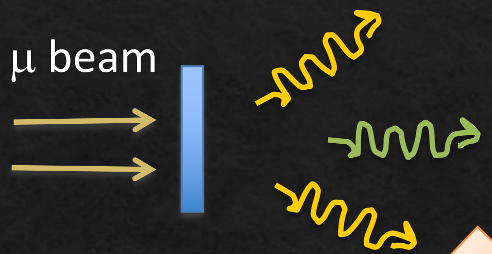
A	Z	Zeff	Capture rate	Meanlife (ns)
100	42	26.37	7.71E+06	130
98	42	26.37	8.81E+06	114
96	42	26.37	9.95E+06	100
95	42	26.37	10.5E+06	94.8
94	42	26.37	11.1E+06	89.7
92	42	26.37	12.4E+06	80.7

Meanlife (ns)
[Suzuki 1987]
105 ns
103.5 ns
99.6 ns

[1] T. Suzuki, D.F Measday and J.P.Roalsvig. Phys. Rev. C 35 6 (1987) 2212
[2] H. Primakoff, Rev of Modern Physics 31 3 (1959) 802
[3] D.F. Measday. Physics Reports 354 (2001) 243–409

Overview

1.0 Muon Irradiation experiment



muonic X-ray, electrons, prompt γ-rays, short-lived and delayed γ-rays

1.1 Measurement of short-lived and delayed γ-rays

$^{100}Mo + \mu^- \rightarrow Nb^* + \nu_\mu + xn$

$\quad \rightarrow Nb^* + \beta^- + \bar{\nu}_e + \gamma$

Exp. data give the RIs production rate of the final nuclei after neutron and proton emission.

1.2 Measurement of absolute lifetime

$$\lambda_T = 1/\tau = \lambda_C + H\lambda_{free}$$

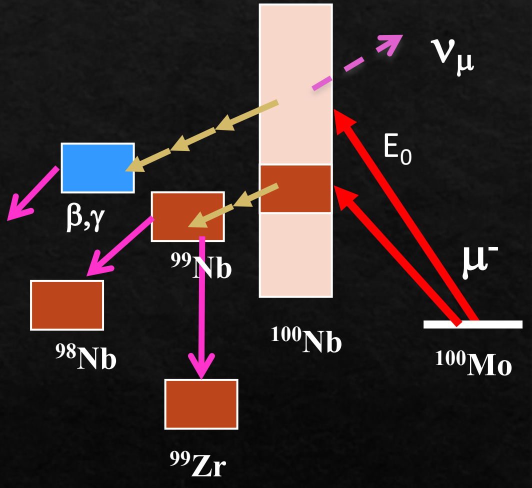
Exp. data give the muon to electron decay curve and calculate the total capture rate

- Improve missing gamma rays from neutron and proton emission

2.0 Proton and neutron emission model

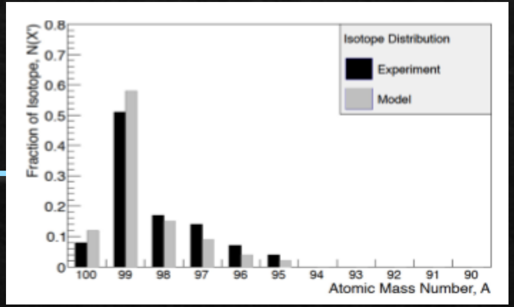
Reproduces the Ris production rate distribution

- Adjust the PEQ and EQ neutron emission process
- Adjust the probability of neutron and proton emission
- Provides μ capture strength ^{100}Nb after muon capture

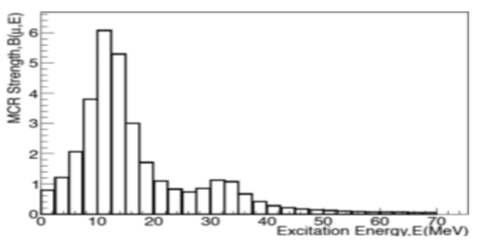


compare

Output 1: RI Production Rates



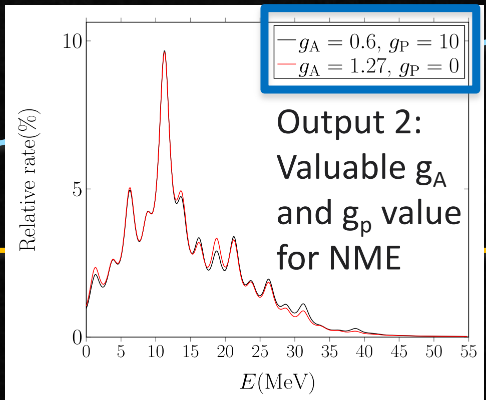
Output 2: Muon Capture Strength



Absolute capture strength

compare

Output 1: Muon Capture Strength



Output 2: Valuable g_A and g_p value for NME

3.0 pn-QRPA calculation

Reproduces the μ capture strength from experiment using pn-QRPA.

- Adjust the pn-QRPA with g_A, g_p and g_A/g_p ratio can reproduce the μ capture strength.

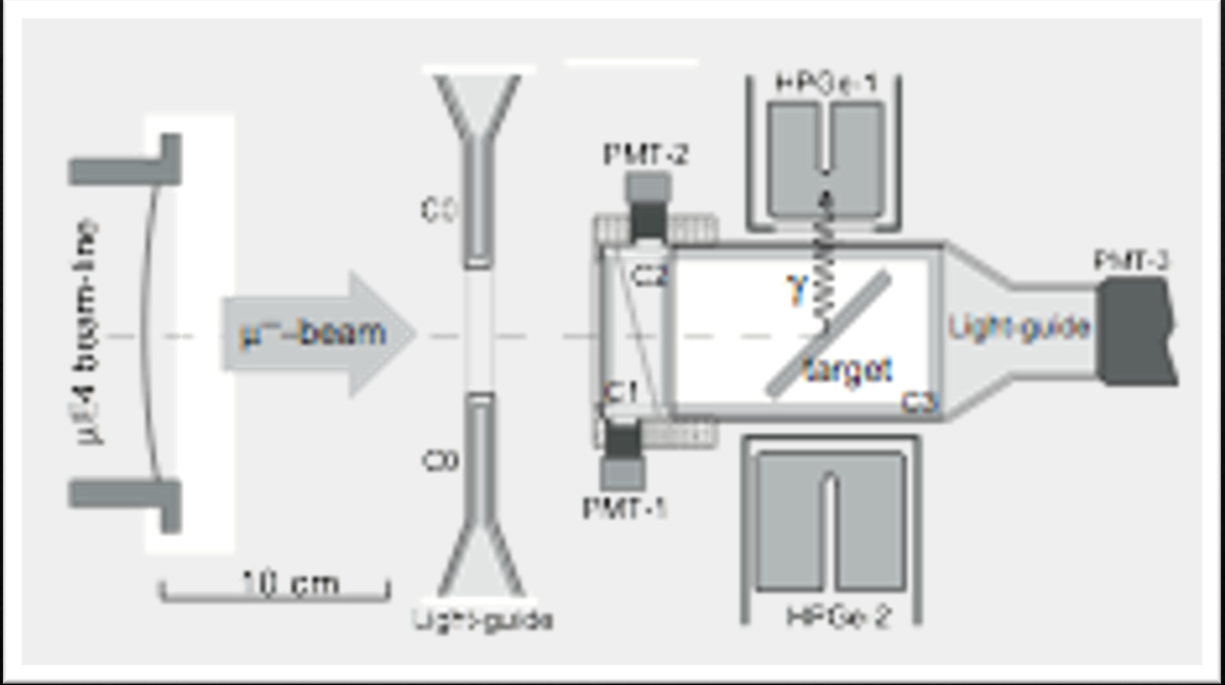
Repeat experiment with other nuclei to understand the effect of

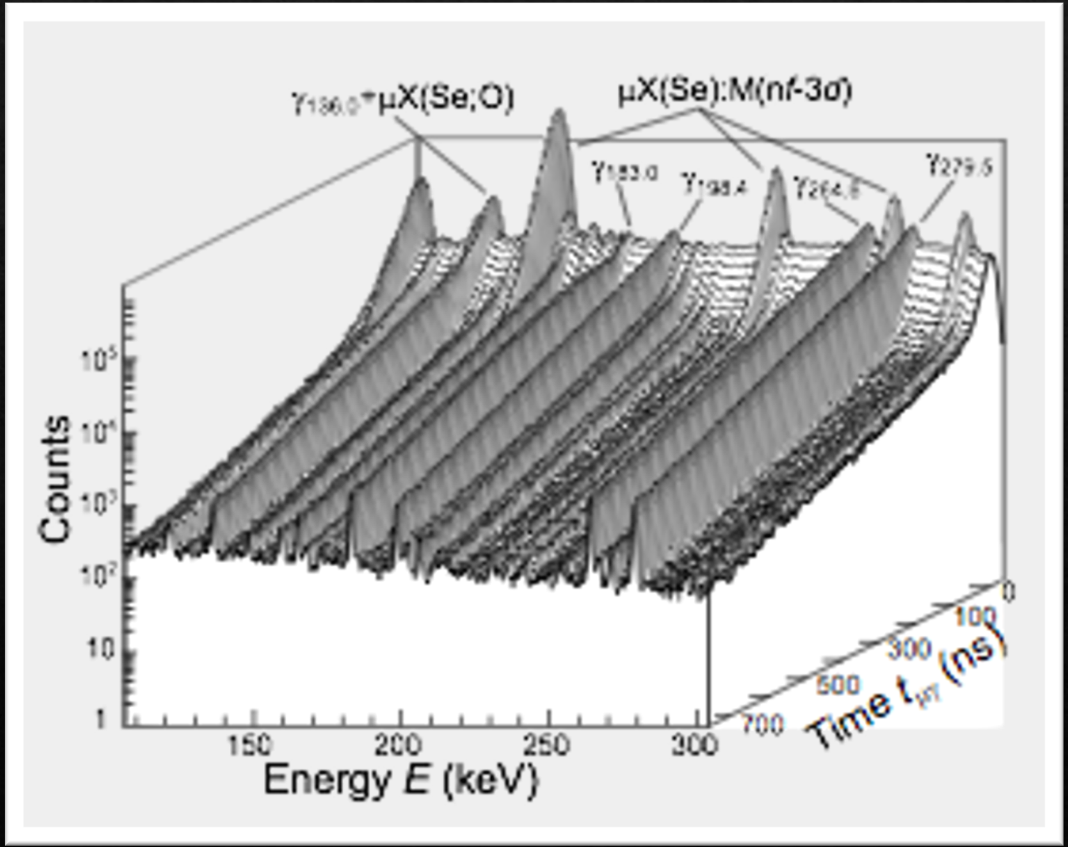
1. GR peak in μ capture strength,
2. g_A and g_p parameter on nuclear structure.

Nuclear matrix element (NME) for DBD

Future Plan at PSI and RCNP (2021/2022)

Muon capture on double beta decay nuclei of ^{133}Ba, ^{76}Se and ^{100}Mo to study neutrino nuclear responses





[1] D. Zinatulina et al. Phys. Rev. C 99 (2019) 024327.

Conclusion

- OMC is a lepton-sector charge exchange reaction via the weak boson and is shown to be used to study neutrino nuclear responses relevant to $0\nu\beta\beta$ and astro-neutrino reactions.
- OMC is crucial for isotope detection and production of RI for biomedical and environmental applications.
- Proton and neutron emission model is developed to reproduce the absolute strength from OMC on nuclei. Improved from previous neutron emission model.
- The lifetime measurement is in progress to experimentally confirmed the absolute strength (square of absolute NME).
- The muon absolute response, together with the strength distribution, help theories to evaluate the $0\nu\beta\beta$ NMEs and astro-neutrino synthesis/interaction NMEs.