Nuclear Responses for Double Beta Decay and Muon Capture

& ν Nuclear Responses by Nuclear and Lepton (μ) Charge-Exchange Reactions (CERs)

Lotta Jokiniemi (& Hiro Ejiri)

CNNP2020, South Africa, February 28, 2020

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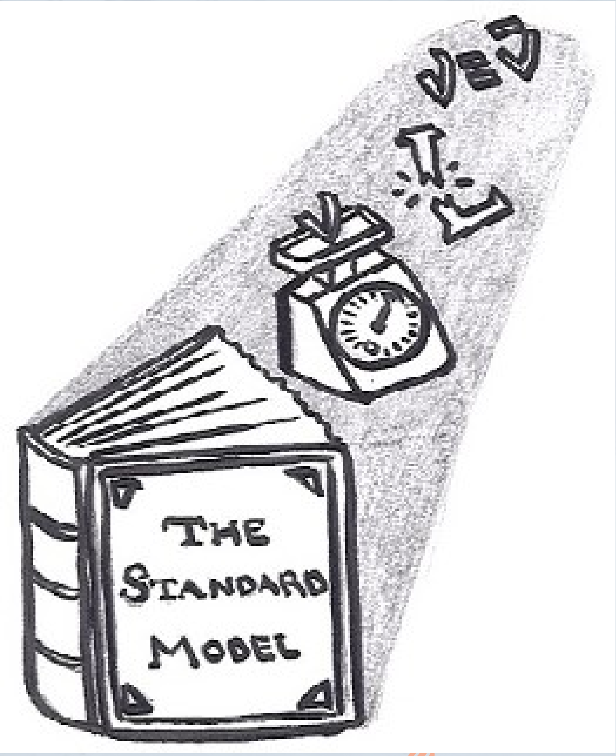
Motivation

- $0\nu\beta\beta$ decays challenging to study
  $\rightarrow$ Ordinary muon capture (OMC) serves as a detour.



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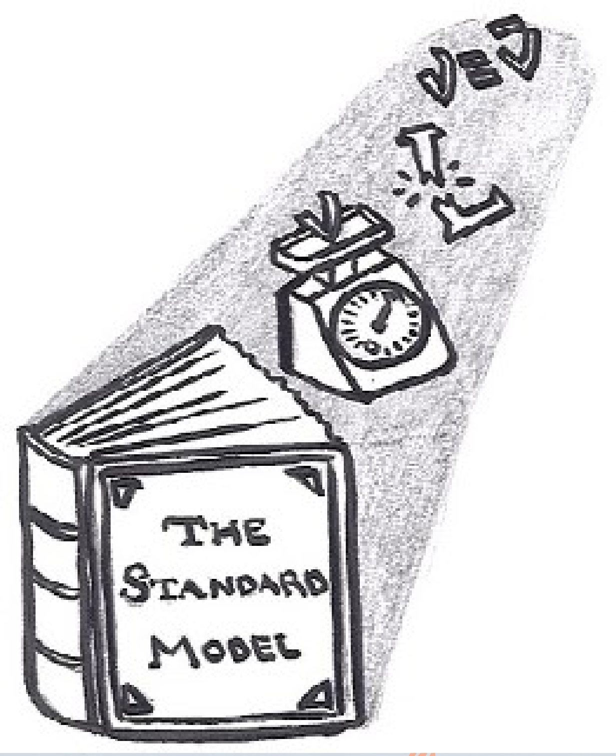

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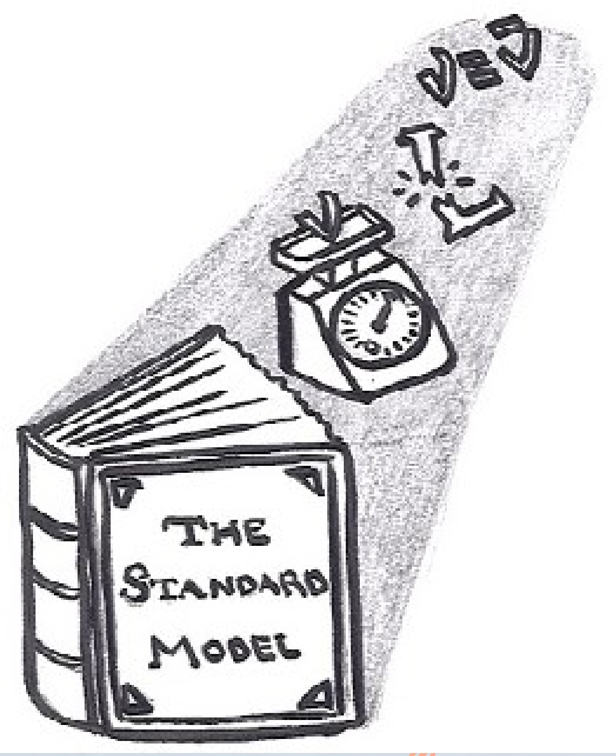
  $\rightarrow$ Ordinary muon capture (OMC) serves as a detour.
- Reliable description of the intermediate states essential for probing the half-lives of $0\nu\beta\beta$-decay.
- Connections between OMC rates and $0\nu\beta\beta$ decay could shed light on unknown effective values of g_A and g_P.



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Ordinary Muon Capture (OMC)

OMC

$\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z-1)$

- Weak interaction process with high energy release and large momentum transfer (quite like $0\nu\beta\beta$ decay!).

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- Energy release is about 100 MeV, of which the largest fraction is donated to the neutrino.
- Large mass of the captured muon allows forbidden transitions and high excitation energies of the final state.

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Muon Capture Formalism

- OMC rates based on Morita-Fujii formalism [1].

[1] M. Morita, and A. Fujii, Phys. Rev. **118**, 606 (1960).
[2] H. Primakoff, Rev. Mod. Phys. **31**, 802 (1959).
[3] L. Jokiniemi, and J. Suhonen, Phys. Rev. C **100**, 014619 (2019).

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Muon Capture Formalism

- OMC rates based on Morita-Fujii formalism [1].
- Muon wave function computed using point-like nucleus approximation.
- Muonic screening taken into account by the Primakoff method [2].
- Capture rate to a J^π final state can be written as [3]

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

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Theoretical vs. Experimental Muon Capture Spectra in ^{100}Nb

OMC on ^{100}Mo

$$\mu^- + \ ^{100}\mathrm{Mo}(0^+_{\mathrm{g.s.}}) \to \nu_\mu + \ ^{100}\mathrm{Nb}(J^\pi)$$

- For the first time, OMC giant resonance was observed in ^{100}Nb [1].

[1] I. H. Hashim *et al.*, *Phys. Rev. C*, **97**, 014617 (2018).
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- OMC rate distribution to the excited states of ^{100}Nb computed and compared with the experimental strength distribution [2].
- Involved nuclear wave functions computed with pnQRPA with large no-core single-particle bases.

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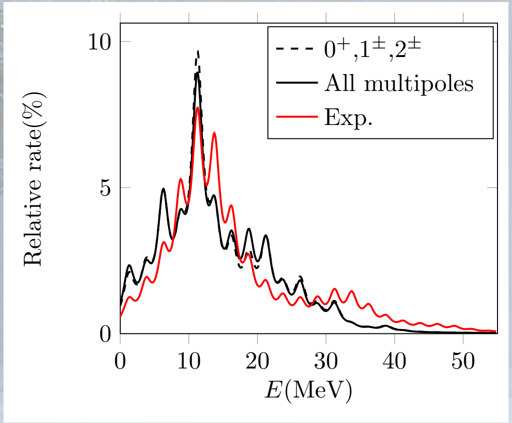

Figure 1: pnQRPA relative OMC rate distribution compared with the experimental distribution [1].

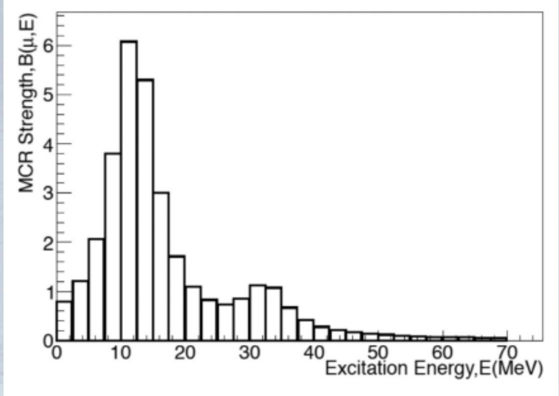

Figure 2: Experimental muon capture strength distribution in ^{100}Nb.[2]

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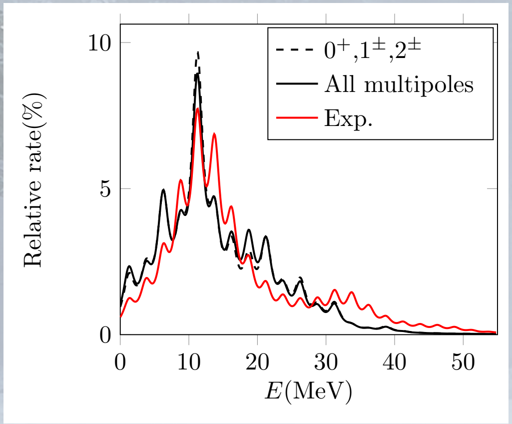

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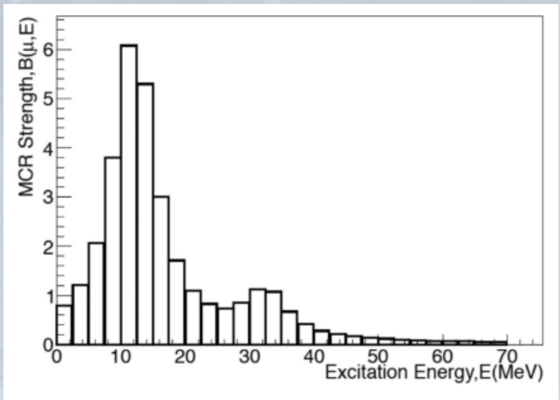

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→ Both distributions show giant resonance at around 12 MeV!

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Total Muon Capture Rate in ^{100}Nb

- Primakoff estimate for the total muon capture rate

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

where $X_1 = 170\ 1/\mathrm{s}$ and $X_2 = 3.125$, gives
$W_{\mathrm{Pr.}}(^{100}\mathrm{Mo}) = 7.7 \times 10^6$ 1/s.

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- Total OMC rate value obtained from pnQRPA calculations (with $g_{\mathrm{A}} = 0.8$ and $g_{\mathrm{P}} = 10$) was $W_{\mathrm{tot}} = 17.7 \times 10^6$ 1/s [1]
  $\rightarrow$ This suggests for quenched $g_{\mathrm{A}} \approx 0.5$!

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- Comparing the total OMC strengths suggests for similar effective value of g_A. This is also in keeping with the β decay results (see Prof. Ejiri's contribution).

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[1] L. Jokiniemi, J. Suhonen, H. Ejiri, and I. H. Hashim, *Phys. Lett. B* **794**, 143 (2019).

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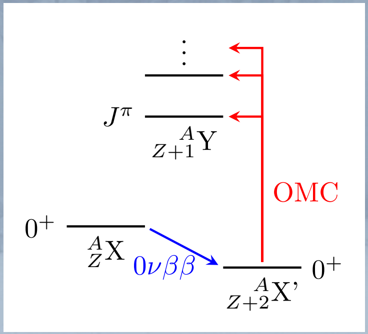

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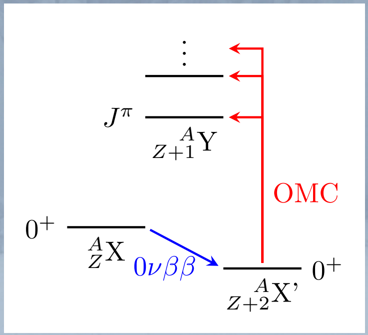

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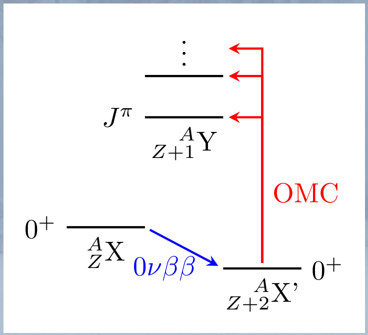
- The corresponding OMC (capture-rate) strength functions have been analyzed in terms of multipole decompositions.
- The computed low-energy OMC-rate distribution to ^{76}As is compared with the available data of Zinatulina *et al.*[2]



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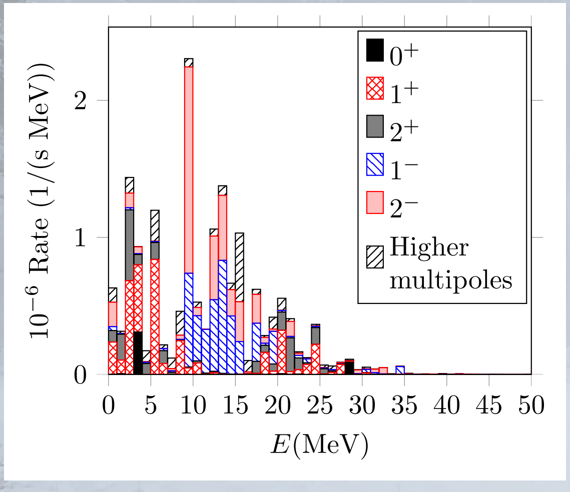

Figure 3: OMC rate distribution for $^{76}\text{Se}(0^+_{\text{g.s.}}) + \mu^- \rightarrow {}^{76}\text{As}(J^\pi) + \nu_\mu$ [1].

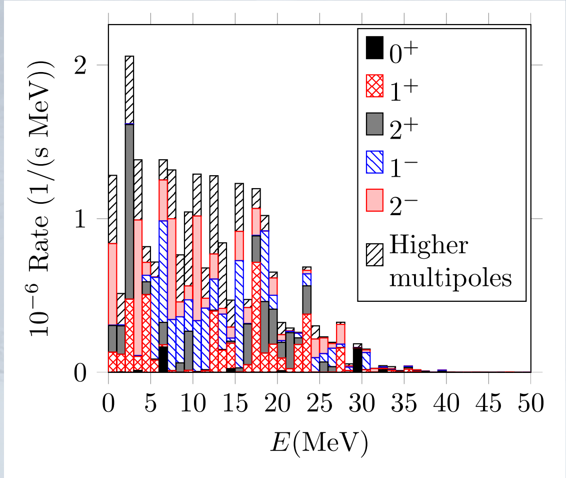

Figure 4: OMC rate distribution for $^{130}\text{Xe}(0^+_{\text{g.s.}}) + \mu^- \rightarrow {}^{130}\text{I}(J^\pi) + \nu_\mu$ [1].

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OMC Rates to the Lowest States of ^{76}As

Table 1: Experimental OMC rates [1] below 1.1 MeV in ^{76}As compared with the pnQRPA-computed rates [2]. 'g.s.': transitions to the ground state.

J^{π}	OMC rate (1/s) Exp.	pnQRPA
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

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OMC vs. $0\nu\beta\beta$ in ^{76}As

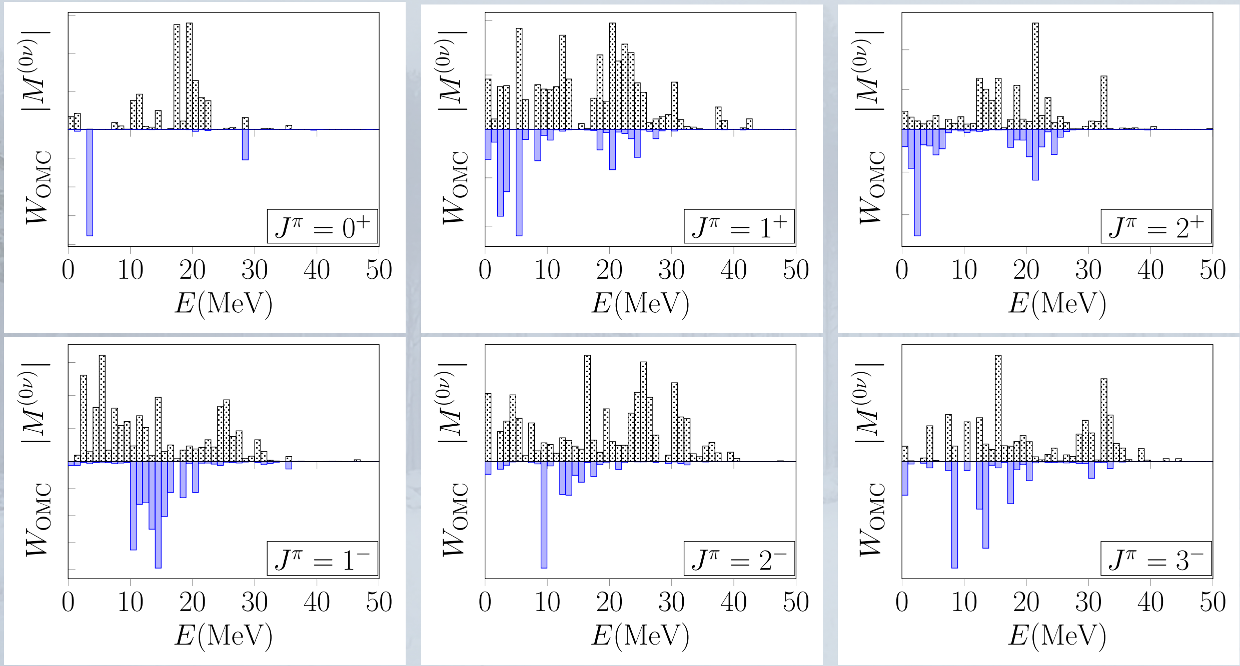

Figure 5: $0\nu\beta\beta$ matrix elements vs. OMC rates to the daughter nucleus of $0\nu\beta\beta$ decay in the A=76 system [1]. J^π refers to the angular momentum of the virtual states of the intermediate nucleus of $0\nu\beta\beta$ decay.

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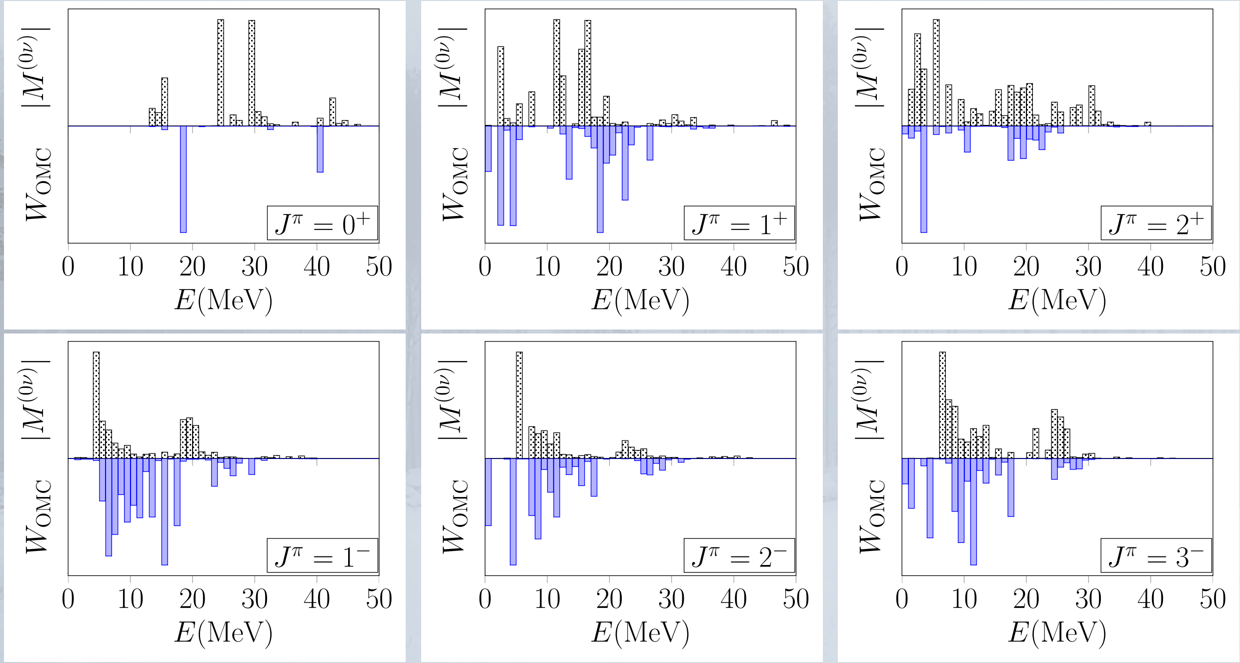

Figure 6: $0\nu\beta\beta$ matrix elements vs. OMC rates to the daughter nucleus of $0\nu\beta\beta$ decay in the A=136 system [1]. J^π refers to the angular momentum of the virtual states of the intermediate nucleus of $0\nu\beta\beta$ decay.

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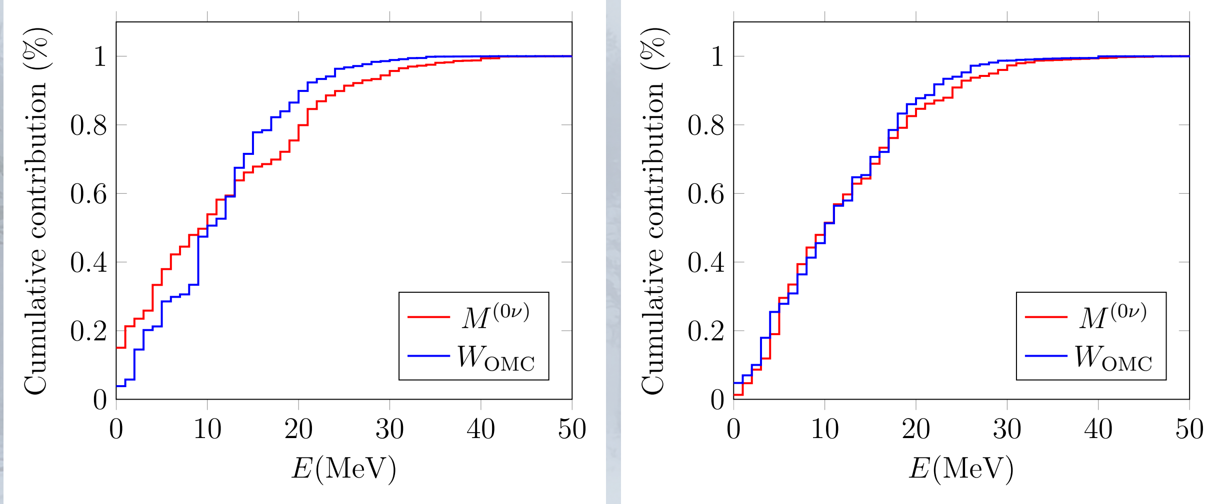
OMC vs. $0\nu\beta\beta$ Cumulative distributions



(a) A=76 **(b)** A=136

Figure 7: Normalized cumulative OMC rates and normalized $0\nu\beta\beta$ decay NMEs as functions of energy in the intermediate nuclei ^{76}As and ^{136}Cs of the $A = 76$ and $A = 136$ $0\nu\beta\beta$ decay triplets [1].

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Contributions from Different Multipoles

Table 2: Contributions (in percentages) from different multipoles to $0\nu\beta\beta$-decay NMEs and OMC rates. The presented values are normalized ratios $M = M^{(0\nu)}(J^\pi)/M^{(0\nu)}$ and $W = W_{\mathrm{OMC}}(J^\pi)/W_{\mathrm{OMC}}$.

Case / J^π	$A = 76$ M	$A = 76$ W	$A = 136$ M	$A = 136$ W
0^+	2	3	0.9	2
1^+	7	23	7	17
1^-	16	25	9	22
2^+	13	13	14	16
2^-	10	24	6	20
3^+	5	9	7	12
3^-	11	2	9	6
4^+	7	0.2	9	1
4^-	5	1	5	4
Σ	76	100	67	100

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Next: Improved Bound Muon Wave Functions

- So far we have used point-like-nucleus approximation [1]

$$G_{-1} = 2(\alpha Z m'_\mu)^{\frac{3}{2}} e^{-\alpha Z m'_\mu r} \ , \qquad (3)$$
$$F_{-1} = 0$$

for the bound muon wave function

$$\psi_\mu(\kappa, \mu; \mathbf{r}) = \psi_{\kappa\mu}^{(\mu)} = \begin{pmatrix} iF_\kappa \chi_{-\kappa\mu} \\ G_\kappa \chi_{\kappa\mu} \ , \end{pmatrix} \qquad (4)$$

[1] H. A. Bethe and E. E. Salpeter, *Quantum Mechanics of One- and Two-Electron Atoms* (1959).

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- In reality, nuclei are not point-like. How good is the approximation?

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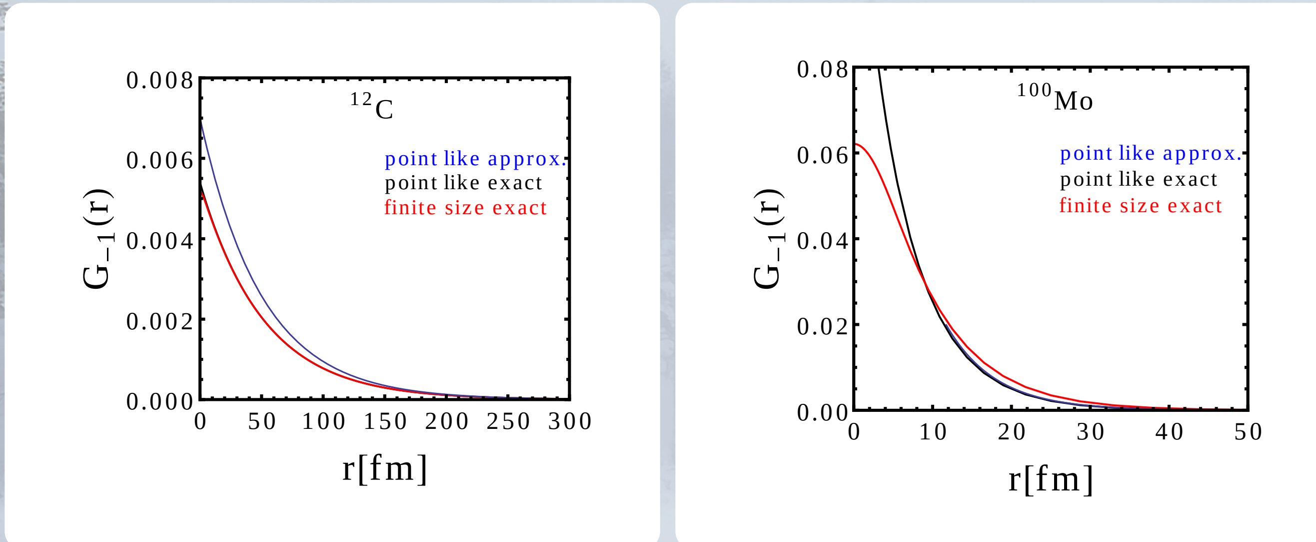

(a) ^{12}C. **(b)** ^{100}Mo.

Figure 8: Wave functions of a muon bound in extended Coulomb fields created by the nucleus of ^{12}C and ^{100}Mo. The point-like-nucleus approximation is compared with more realistic wave function taking into account the finite size of the nucleus. Muon wave functions by J. Kotila.

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Very Preliminary Results: OMC to lowest states of ^{12}B

Table 3: OMC rates to the lowest states of ^{12}B obtained using exact bound muon wave function or point-like-nucleus approximation.

J_i^π	Rate(1/s) Exact	Rate(1/s) Point-like approx.	Ratio
1_{gs}^+	7.5×10^3	13.1×10^3	0.57
2_1^+	500	890	0.57
2_1^-	3	5	0.67
1_1^-	1.1×10^3	1.8×10^3	0.58
0_1^+	0.1	0.2	0.56
3_1^-	14	22	0.64

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- There are correspondences between the multipole decompositions of $0\nu\beta\beta$ decay NMEs and OMC rates, and overall the cumulative behavior of the $0\nu\beta\beta$ decay NMEs and OMC rates is quite similar.

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Summary

- Nuclear muon capture serves as a useful way to improve the accuracy of $0\nu\beta\beta$ decay calculations.
- So far, the theoretical muon capture giant resonances and low-energy OMC rates seem to match the experimental ones.
- Comparing the total capture rates with Primakoff estimates suggests for strongly quenched g_{A} value.
- There are correspondences between the multipole decompositions of $0\nu\beta\beta$ decay NMEs and OMC rates, and overall the cumulative behavior of the $0\nu\beta\beta$ decay NMEs and OMC rates is quite similar.
- The bound muon wave function may partly explain the quenching of g_A?

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ν nuclear responses by nuclear and lepton (μ) charge exchange reactions (CERs)

Collaboration with

H. Ejiri RCNP, I. Hashim UTM,

L. Jokiniemi , J. Suhonen Jyvaskyla, D. Zinatulina JINR

ν nuclear responses (nucl. matrix element NME)^2 are crucial for $\beta\beta$ decays & astro ν interactions.

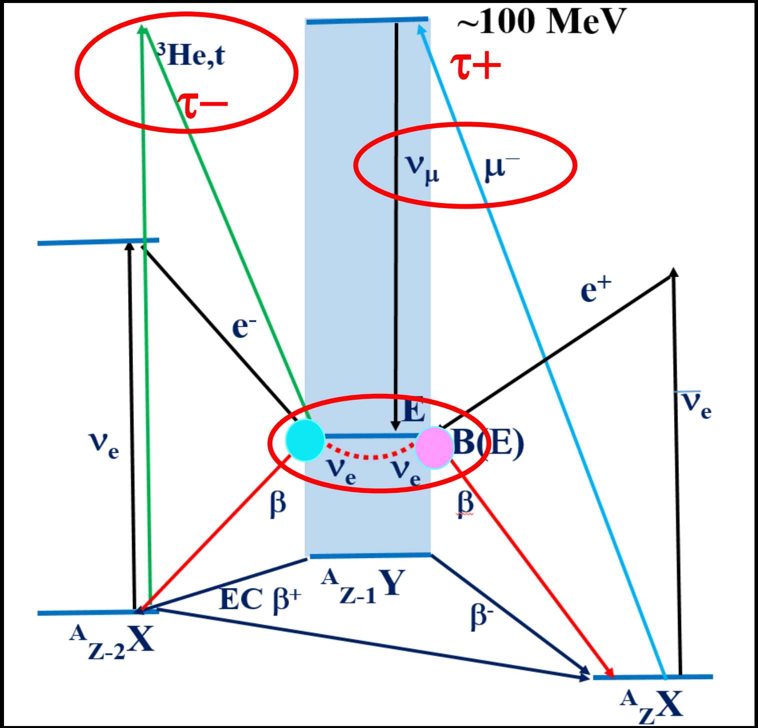
H. Ejiri, J. Suhonen, K. Zuber Physics Report 797 1 2019

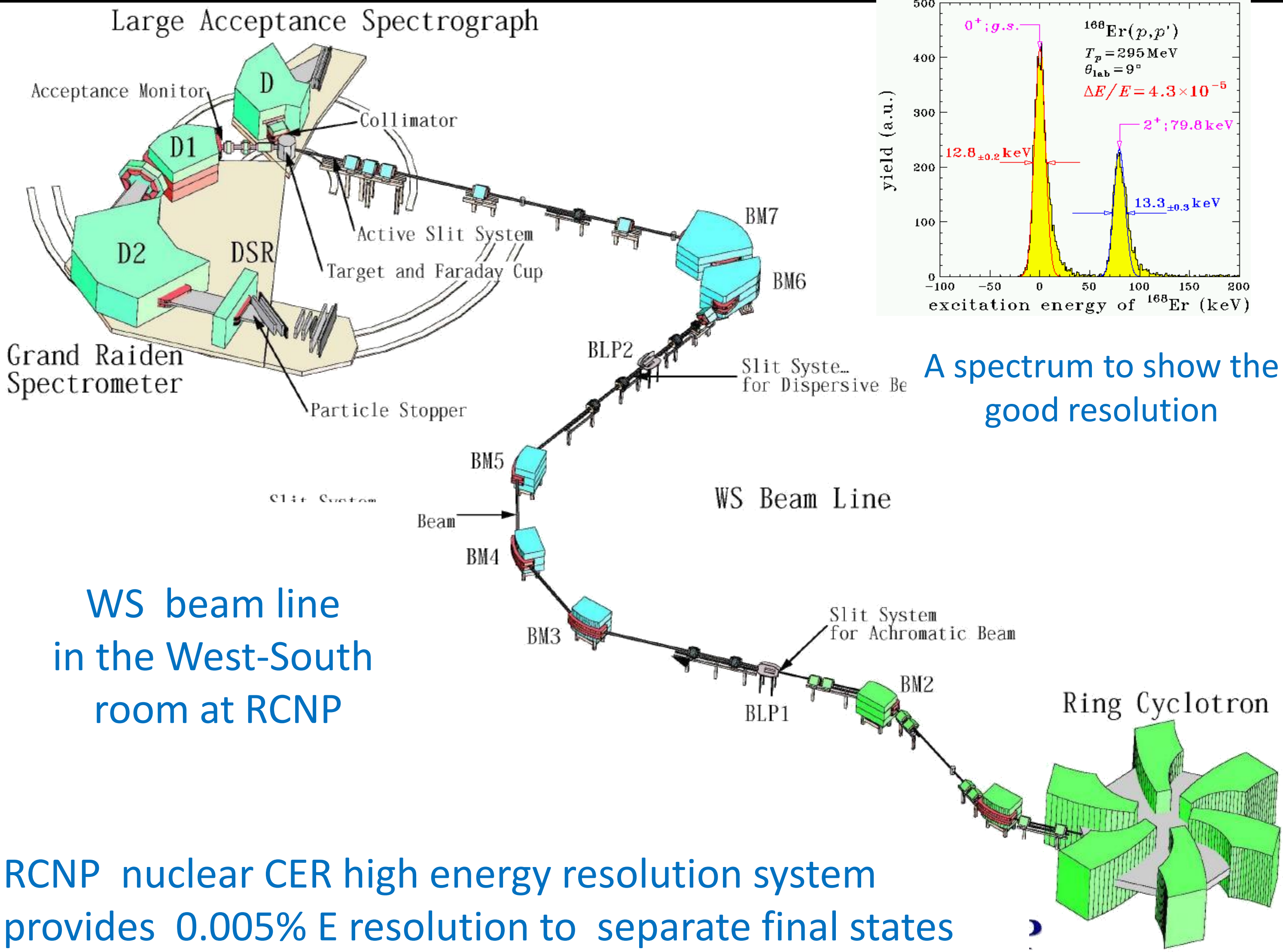
H. Ejiri thanks the organizers for that this talk is presented by his collaborator, L. Jokiniemi.

Nuclear & lepton (μ) CERs for CC ν responses

(^{3}He,t) τ- side ν, and (μ,ν_μ) τ+ 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





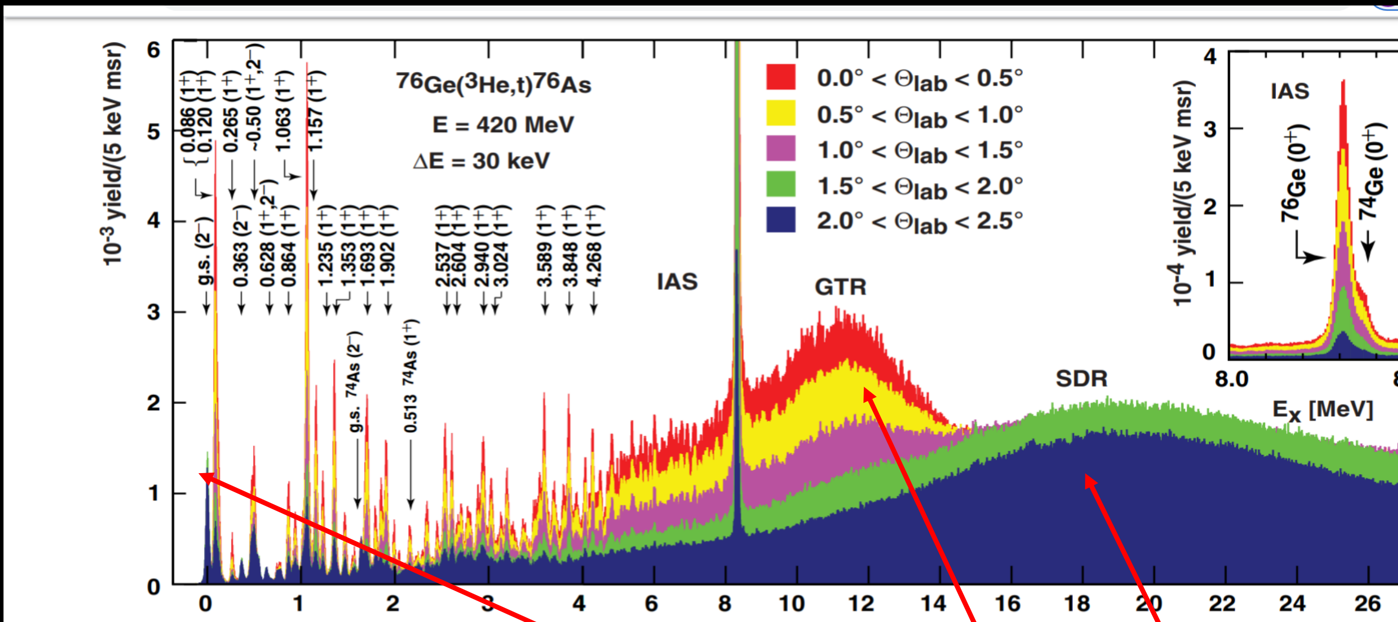
A spectrum to show the good resolution

WS beam line
in the West-South
room at RCNP

RCNP nuclear CER high energy resolution system provides 0.005% E resolution to separate final states

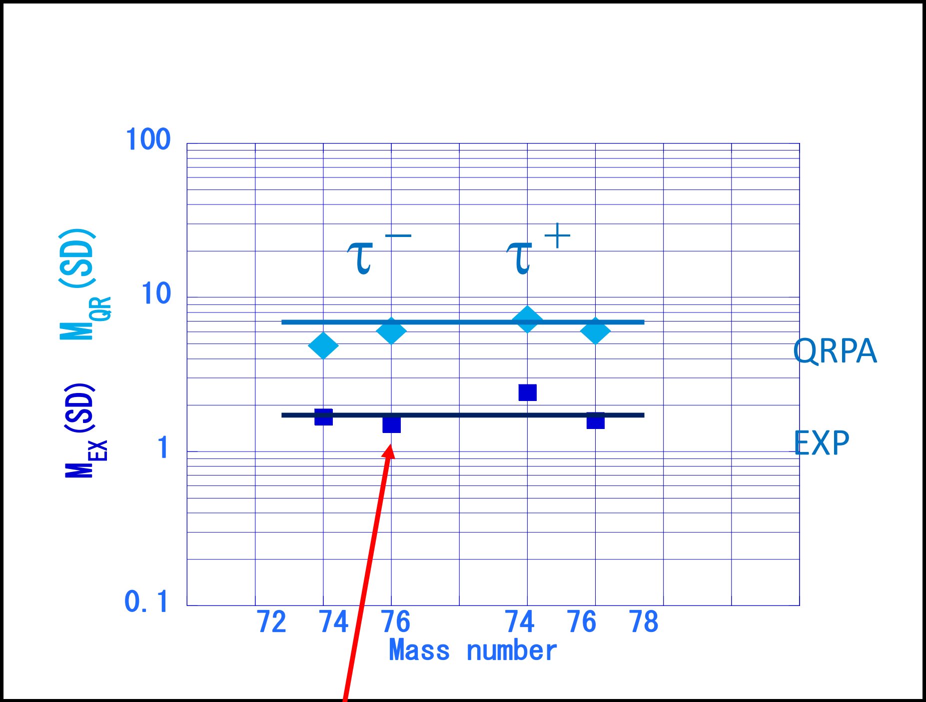
^{74,76}Ge (^{3}He,t) CER at RCNP Osaka JP G 2020

H. Ejiri , in collaboration Catania C. Agodi, F. Cappuzzello, et al , KVI, Konan, et al., and J.H. Thies PR 2012 et al



τ⁻ (^{76}Ge to ^{76}As) SD (2-) blue, the major component of DBD NME , was clearly excited in addition to GT and SD GRs

^{74,76} Ge (^{3}He,t) CER at RCNP Osaka JP G 2020



The NME is M(SD)=1.50 10^{-3} n.u. (natural unit) like other SD NMEs. They are smaller than the pnQRPA NME (Suhonen) by the coefficient of g_A^{eff}/g_A~0.35 – 0.4

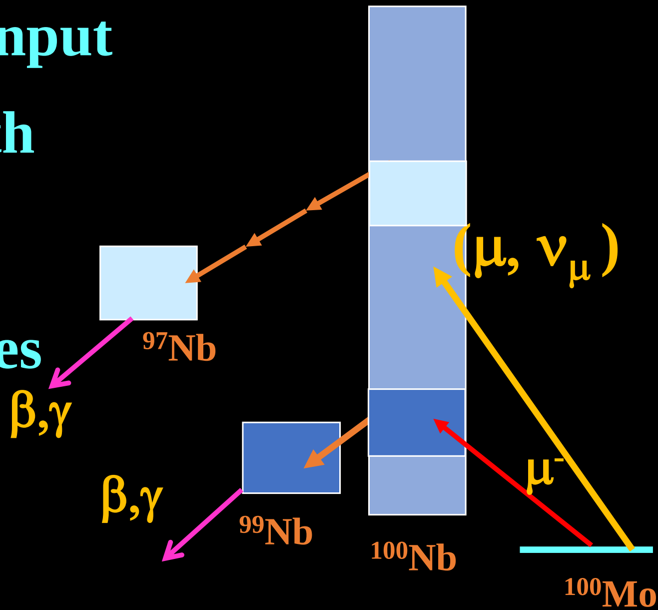
CER $(\mu, \nu_\mu, xn\ \gamma)$

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

Muon capture: 1-50 MeV input

Neutron evaporation with E~a few MeV

Number of neutrons gives the excitation energy in ^{100}Nb



H. Ejiri Proc. e-γ conference Sendai 1972,
H. Ejiri et al., JPSJ 2014
I. Hashim H. Ejiri et al., PRC 97 (2018) 014617

μ–GR (Giant resonance)

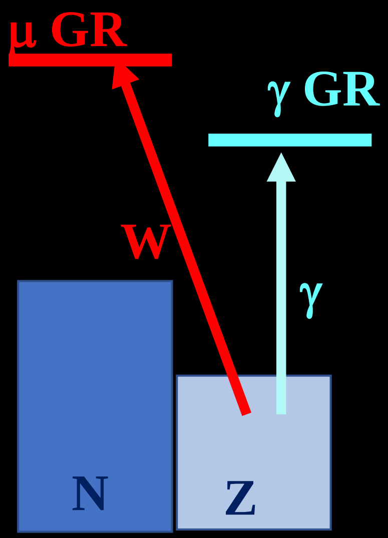
Muon transition rate as a function of the excitation E was derived from the residual isotope mass distribution .

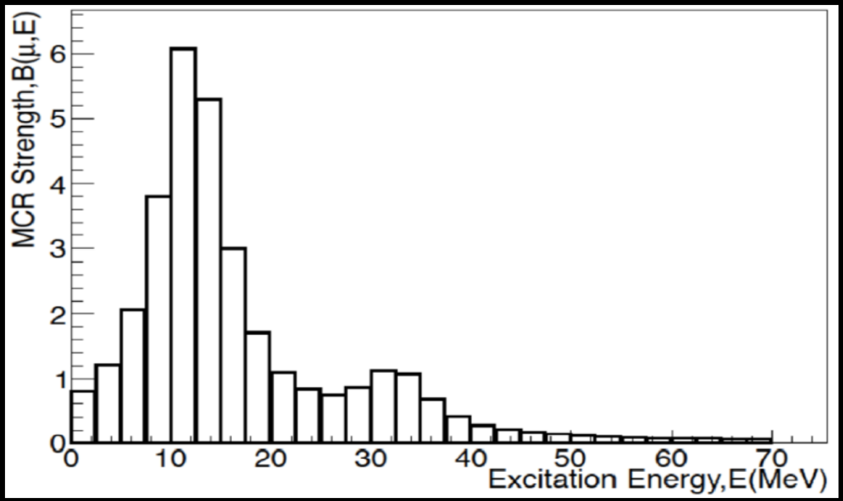
μ-GR around 12-14 MeV was found .

The OMC rate : 6.7 ±1.3 10^6/sec.

I, Hashim H. Ejiri et al., Phys. Rev. C 97 014617 2018

I. Hashim H. Ejiri et al., DBD workshop RCNP 2020 .





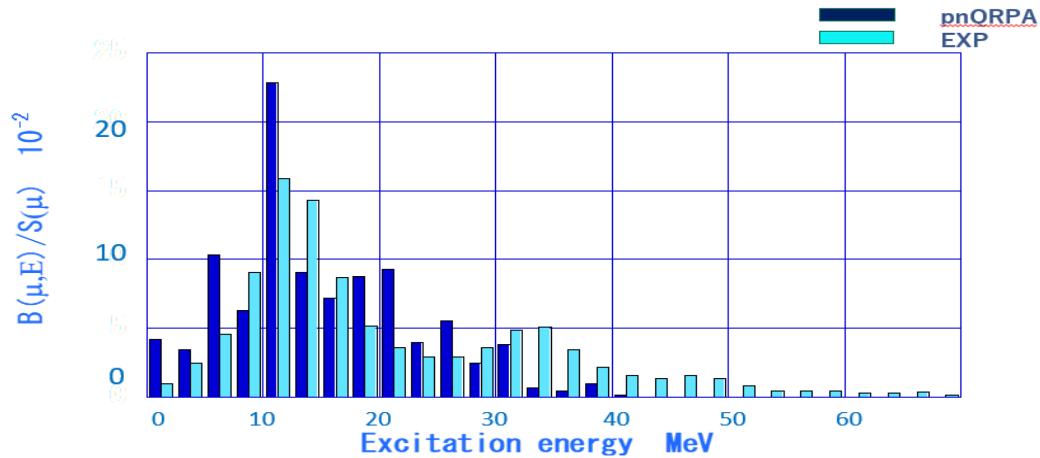
OMC response (B(μ,E) was derived by exp. and theory.

$$\mu + {}^A_Z \mathrm{X} \rightarrow \nu_\mu + {}^A_{Z-1} \mathrm{X}^*,$$

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

$$G^\mu = 8(\frac{Z^{eff}}{Z})^4 (\alpha Z m_\mu)^3 (1 - \frac{q}{m_\mu + AM}) q^2,$$

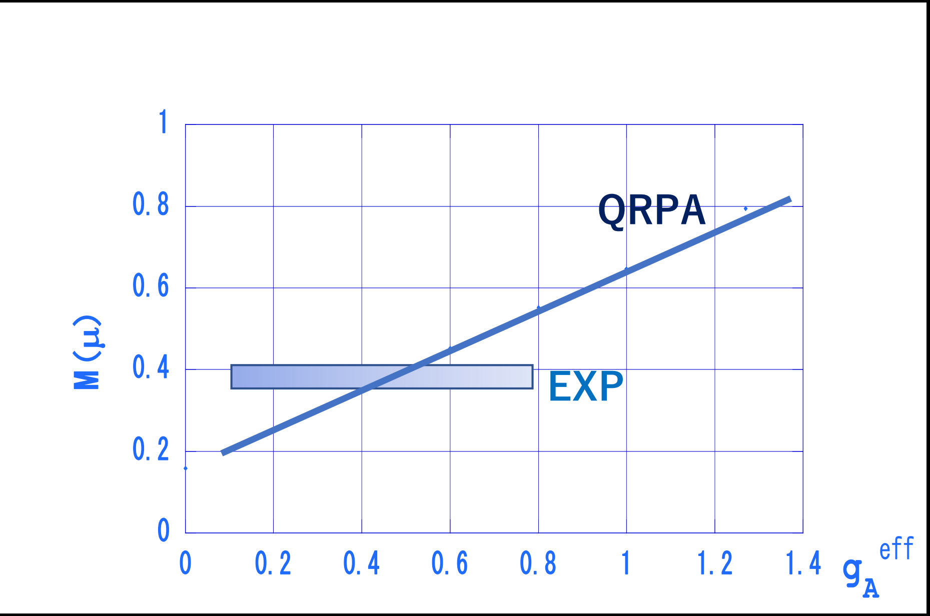
$$B(\mu, E) = \frac{M(E)^2}{2J_i + 1},$$



H. Ejiri L. Jokiniemi J. Suhonen 2020

Exp. summed strength: and NME

$S(\mu)=\int B(\mu,E)dE=0.146\pm 0.03 \quad M(\mu)= S(\mu)^{1/2}= 0.38 \pm 0.04$



Comparison of experiment and pnQRPA $S(\mu)$ (L. Jokiniemi et al.) suggests a quenched g_A^{eff} ~0.5 , i.e. g_A^{eff}/g_A~0.4

Renormalization of axial vector couplings A=100 (Mo)

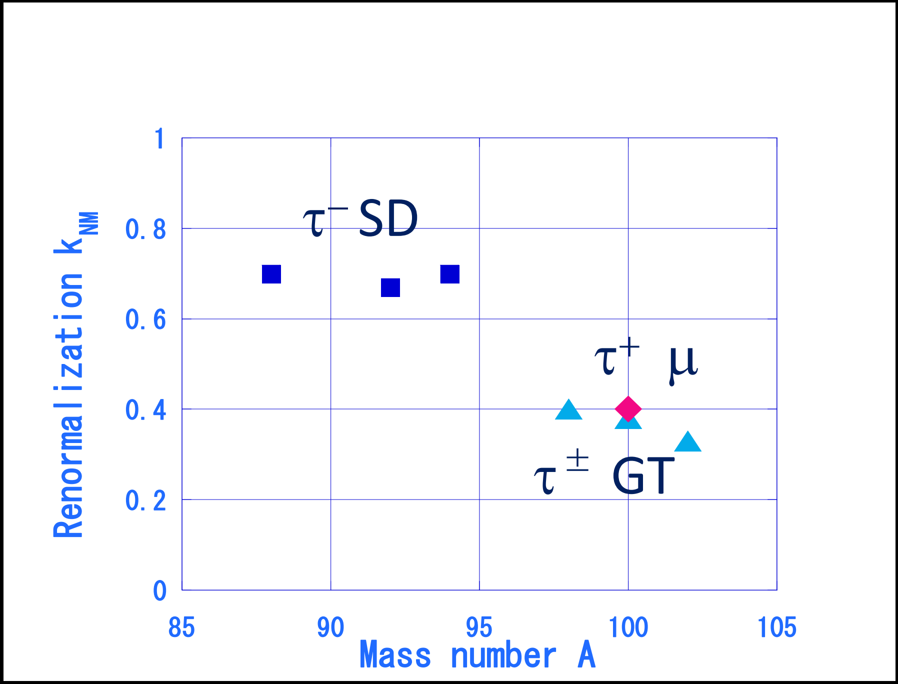
$M_{EXP}=k_{NM}\ M_{QRPA}$, k_{NM} =renormalization by non-nucleonic and nuclear medium effects, that are not in QRPA.

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,

Concluding Remarks

1. Charge exchange nuclear & muon reactions provide τ- ν & τ+ anti-ν responses in a wide E and P .
2. The high E resolution nuclear CER gives the SD NME for ^{76}Ge, M=1.5 10^{-3} n.u. The SD NMEs in A~74-78 are quenched by 0.35-0.4 with respect to pnQRPA NMRs.
3. μ-CER (OMC) rate on ^{100}Mo shows GR at around 20 MeV from ^{100}Mo (E~12-14 MeV from ^{100}Nb)).
Rate= 6.7 10^6/sec = $\Sigma G\,|M|^2$ with the phase space $G \sim kq^2$.
M is extracted for the first time as M=0.38.
4. QRPA reproduces the experimental μ-GR.
Ratio of Exp NME to QRPA NME based on a point -like nucleus for μ gives $g^{eff}_A/g_A \sim 0.4$.
5. The quenching coefficients for $\tau^{\pm}$ NMEs lead a severe (0.3~0.5) quenching for DBD and astro neutrino NMEs

Comparison of Different Bound Muon Wave Functions

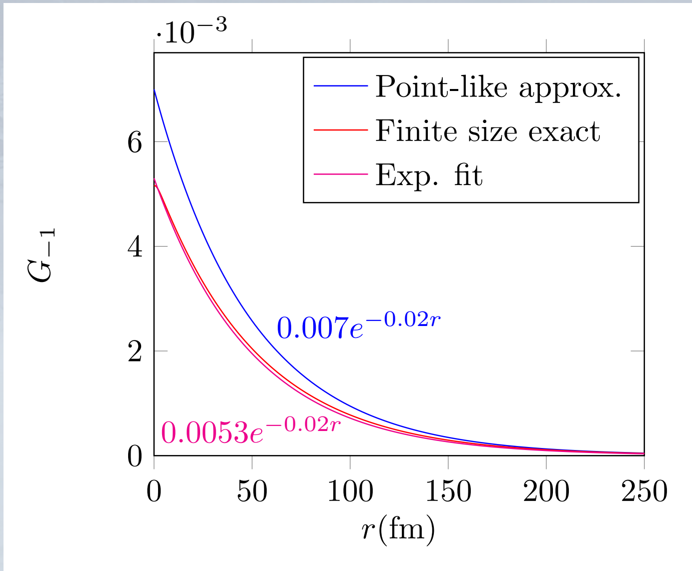
- If $G_{-1} = C_1 e^{-C_2 r}$, then $W \propto C_1^2$.
- For point-like approx:

$$G_{-1} = 0.007 e^{-0.02r}$$

- For finite size exact:

$$G_{-1} \approx 0.0053 e^{-0.02r}$$

$\rightarrow \frac{W_{finite}}{W_{poin-tlike}} \propto \frac{0.0053^2}{0.007^2} \approx 0.57$



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Spin isospin GR s on ^{100}Mo