Muon Capture as a Probe of $0\nu\beta\beta$ Decay - Theoretical Aspect

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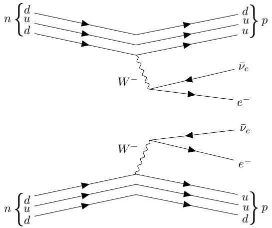
Outline

Introduction

Motivation

- Current knowledge on particles and interactions between them is based on the Standard Model (SM)
- According to the SM, neutrinos are extremely weakly interacting, massless fermions
- However, recent solar neutrino experiments have proven that neutrinos have a non-zero mass
    - Standard model's perception of neutrinos is not accurate!
    - ..which is why we are interested in $0\nu\beta\beta$ decay

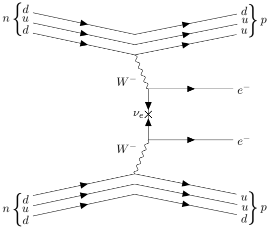
Two-Neutrino Double-Beta ($2\nu\beta\beta$) Decay



$$^A_Z\mathrm{X}_N \rightarrow {}^{\;A}_{Z+2}\,\mathrm{Y}_{N-2} + 2e^- + 2\bar{\nu}_e$$

- May happen, when β-decay is not energetically allowed
- Allowed by the Standard Model
- Measured in $\approx$ 10 isotopes
  - Half-lives of the order 10^{20} years or longer

Neutrinoless Double-Beta ($0\nu\beta\beta$) Decay

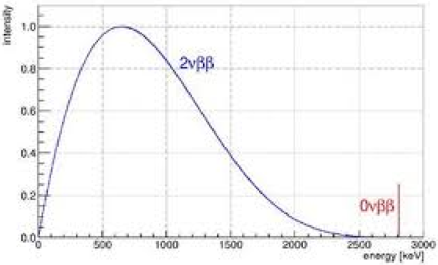


$$^{A}_{Z}\mathrm{X}_{N} \rightarrow {}^{A}_{Z+2}\,\mathrm{Y}_{N-2} + 2e^{-}$$

- Requires that the neutrino is a Majorana particle
- Violates the lepton-number conservation law by two
- $\frac{1}{t_{1/2}^{(0\nu)}} \propto |\langle m_\nu \rangle|^2$

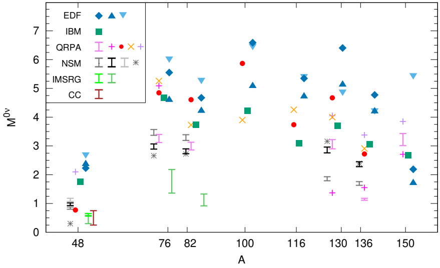
Difficulty of $0\nu\beta\beta$ Decay Searches

Challenging both experimentally...



Sketchy energy spectrum of the emitted electrons in $\beta\beta$ decays [1]

...and theoretically



Matrix elements of $0\nu\beta\beta$ decays [2]

$$t_{1/2}^{(2\nu)} \approx 10^{20}\ \mathrm{y}, \qquad t_{1/2}^{(0\nu)} \geq 10^{25}\ \mathrm{y}$$

→ We need some detours!

[1] cobra-experiment.com

[2] J. Engel and J. Menéndez, *Rep. Prog. Phys.* **80**, 046301 (2017), updated.

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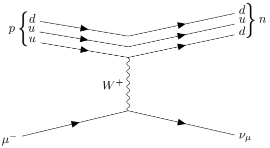
Ordinary Muon Capture as a Probe of $0\nu\beta\beta$ Decay

Ordinary Muon Capture (OMC)



$$\mu^- + ^A_Z\mathrm{X}(J_i^{\pi_i}) \rightarrow \nu_\mu + _{Z-1}^{\ A}\mathrm{Y}(J_f^{\pi_f})$$

- Muon initially bound on an atomic orbit is captured by the nucleus
- Weak interaction process with momentum transfer $q \approx 100\ \mathrm{MeV}/c^2$ due to the large mass of the captured muon, $m_\mu \approx 106\ \mathrm{MeV}/c^2$
  - Similar to $0\nu\beta\beta$ decay!
- Large m_μ also allows transitions to all J^π states up to high energies
- Both the axial vector coupling g_A and the pseudoscalar coupling g_P are involved in the process

Advantages of OMC as a Probe of $0\nu\beta\beta$ Decay

- OMC leads to transitions to all J^π states up to high energies
  - We can access the intermediate states of $0\nu\beta\beta$ decay!
- Previously intermediate states probed by charge-exchange reactions

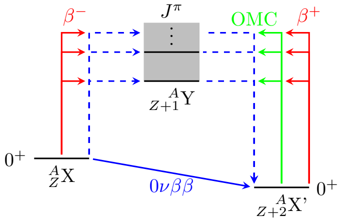
$$ {}^{a}_{z}a + {}^{A}_{Z}X \rightarrow {}^{a}_{z\pm1}b + {}^{A}_{Z\mp1}Y, $$

where (a, b) can be (p, n), $({}^{3}\mathrm{He}, t)$, ...

- Ordinary muon capture (OMC)

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

serves as a complimentary way



$\beta\beta$-decay triplet with charge-exchange reactions and ordinary muon captures to the intermediate states.

Advantages of OMC as a Probe of $0\nu\beta\beta$ Decay

- Both OMC and $0\nu\beta\beta$ decay involve couplings $g_{\rm A}$ and $g_{\rm p}$:

$$W^{(OMC)} \propto |g_{\rm A} M_{\rm A} + g_{\rm V} M_{\rm V} + g_{\rm P} M_{\rm P}|^2$$

$$M^{(0\nu)} = M_{\rm GT}^{(0\nu)}(g_{\rm A}, g_{\rm P}, g_{\rm M}) - \left(\frac{g_{\rm V}}{g_{\rm A}}\right)^2 M_{\rm F}^{(0\nu)}(g_{\rm V}) + M_{\rm T}^{(0\nu)}(g_{\rm A}, g_{\rm P}, g_{\rm M}) \ ,$$

$$[t_{1/2}^{(0\nu)}]^{-1} = g_{\rm A}^4 G_{0\nu} |M^{(0\nu)}|^2 \langle m_\nu \rangle^2$$

- ...so if
  - we know the involved nuclear structure precisely enough, and
  - OMC rates to individual nuclear states can be measured

...we can probe $g_{\rm A}$ and $g_{\rm p}$ on the relevant momentum-exchange regime for $0\nu\beta\beta$ decay

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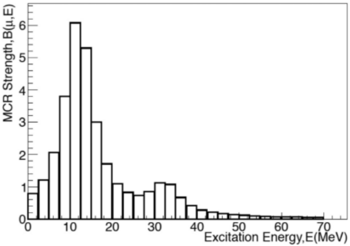
Muon Capture on ^{100}Mo

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

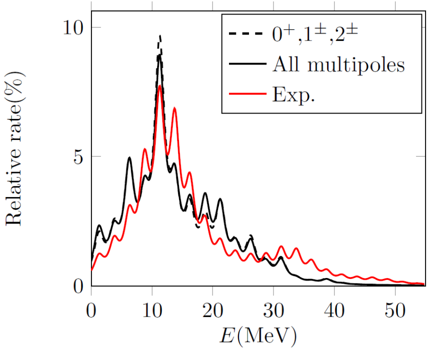
- The OMC strength distribution in ^{100}Nb [6] was studied at the MuSIC beam channel at RCNP for the first time



[6] I.H. Hashim *et al.*, *Phys. Rev. C* **97**, 014617 (2018)

Muon Capture on ^{100}Mo - Theory vs. Exp.

- We computed the OMC strength spectrum in ^{100}Nb based on the Morita-Fujii formalism [7]
- We adjusted the g_{ph} of pnQRPA to Gamow-Teller GR
- ...and compared the obtained spectrum with the observed one
  - The agreement is excellent!
- However, the total capture rate is too fast compared to the Primakoff estimate
  - We need a strongly quenched axial vector coupling g_A



Experimental vs. computed OMC strength spectra in ^{100}Nb [8]

[7] M. Morita, and A. Fujii, Phys. Rev. **118**, 606 (1960).

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

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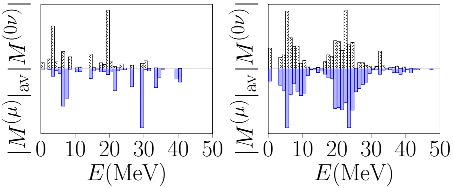
$0\nu\beta\beta$ Decay vs. Muon Capture Matrix Elements

- We studied muon capture on the daughter nuclei of $\beta\beta$-decay triplets: ^{76}Se, ^{82}Kr, ^{96}Mo, ^{100}Ru, ^{116}Sn, ^{128}Xe, ^{130}Xe, and ^{136}Ba [9]
- ...and compared the OMC matrix elements with the $0\nu\beta\beta$ matrix elements [10]
- Since the Q-values are similar, states with same E are important for both decays
- Comparison against the experiments could shed light on $0\nu\beta\beta$ decay?



(a) $J^\pi = 0^+$ **(b)** $J^\pi = 2^+$

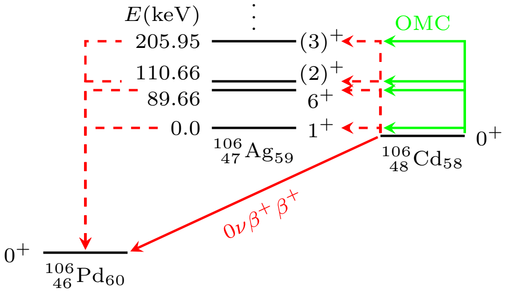
$0\nu\beta\beta$ decay and OMC NMEs in the $A = 128$ triplet.

[9] LJ and J. Suhonen, *Phys. Rev. C* **100**, 014619 (2019)

[10] LJ and J. Suhonen, *Phys. Rev. C* **102**, 024303 (2020)

Outline

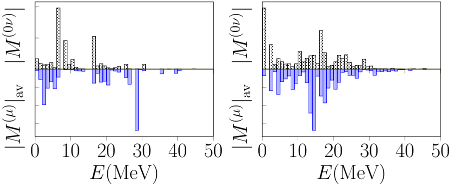
$0\nu\beta^+\beta^+$ Decay vs OMC in ^{106}Cd



- We can also study OMC on the mother nucleus of a $0\nu\beta^+\beta^+$ decay triplet
- Recently, we studied the connection between $0\nu\beta^+\beta^+$ decay and OMC in ^{106}Cd [11]

[11] LJ, J. Kotila and J. Suhonen, *Front. Phys.* **9**, 142 (2021)

- There are similarities $0\nu\beta^+\beta^+$-decay and OMC matrix elements especially for $J^\pi = 3^+, 3^-, 4^-$
  - It remains to be seen how these similarities could be utilized
- How does the $g_{\rm pp}$ parameter affect the distributions?
- How about the bound-muon wave function?

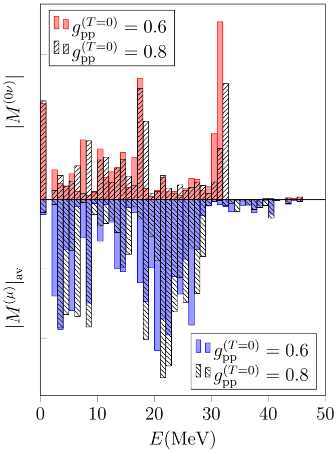


(a) $J^\pi = 0^+$ **(b)** $J^\pi = 3^+$

$0\nu\beta^+\beta^+$ decay and OMC NMEs in the ^{106}Cd triplet.

Dependence on the parameter g_{pp}

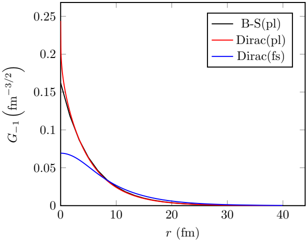
- Normally, g_{pp} is adjusted to $2\nu\beta\beta$-decay half-life
  - For ^{106}Cd, we only know that $t_{1/2}^{(2\nu)} \geq 1.7 \times 10^{21}$ y
- However, adjusting g_{pp} shifts the OMC spectrum
  - We could adjust g_{pp} to OMC giant resonance, instead?



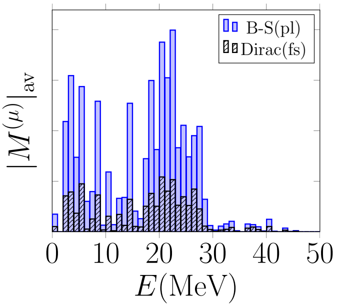
Dependence of OMC and $0\nu\beta\beta$-decay matrix elements with $J^{\pi} = 2^{+}$ on g_{pp}

Dependence on Bound-Muon Wave Functions

- Solving the exact bound-muon wave function from Dirac equations instead of the Bethe-Salpeter (B-S) point-like-nucleus approximation?



Bound muon wave functions in ^{106}Cd.



Dependence of OMC matrix elements with $J^\pi = 2^+$ on different bound-muon wave functions

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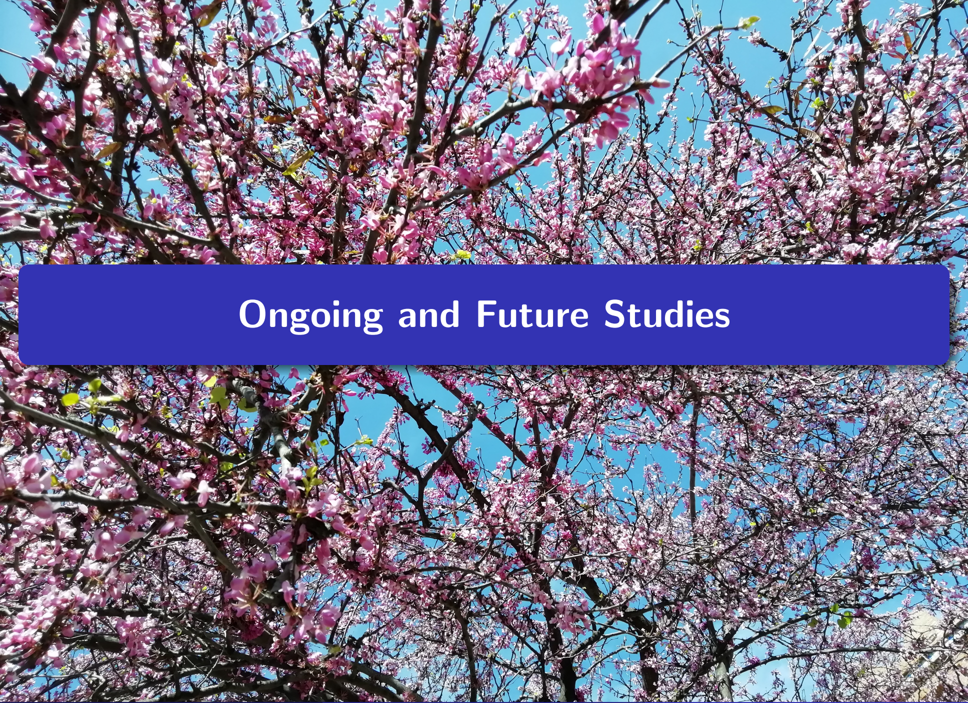
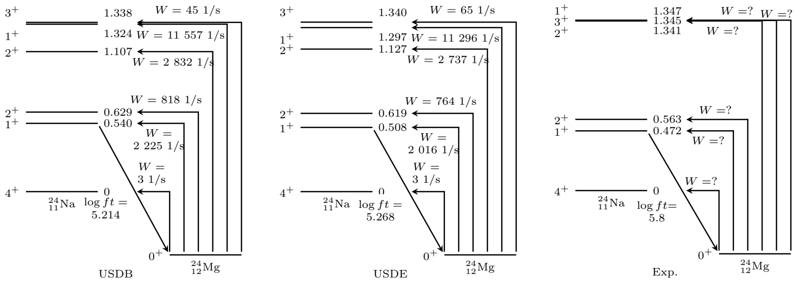


Ongoing and Future Studies

Outline

- Recently, first *ab initio* solution to g_A quenching was proposed for β-decay [12]
  - How about g_A quenching at high momentum transfer $q \approx 100$ MeV/c?
  - OMC could provide an answer!

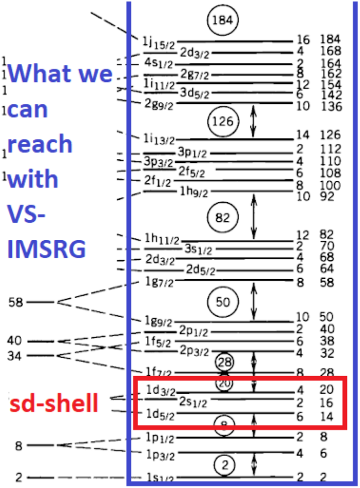


Muon capture rates to low-lying states of ^{24}Na with different shell-model interactions.

[12] P. Gysbers *et al.*, *Nature Phys.* **15**, 428 (2019)

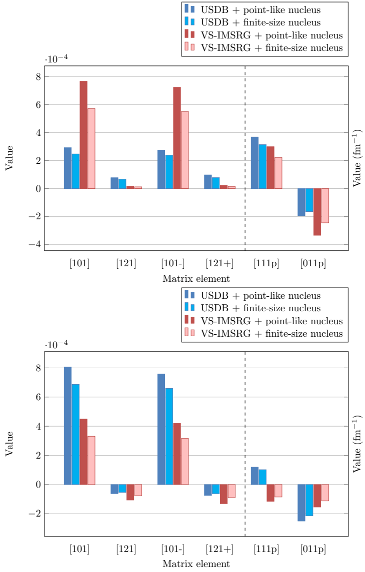
Muon Capture on ^{24}Mg from First Principles

- Muon capture in VS-IMSRG framework with T. Miyagi and J.D. Holt (TRIUMF)
- OMC rates to low-lying states of ^{24}Na in VS-IMSRG vs. shell-model (SM) frameworks
- With VS-IMSRG we can
    - include contributions outside the (*sd*) valence shell
    - include physics missing from the SM: 3*N* forces, two-body terms,...



Preliminary Results for Muon Capture on ^{24}Mg

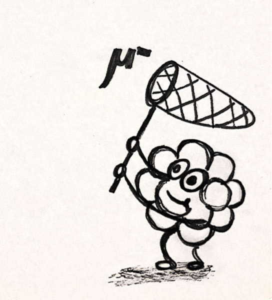
- OMC matrix elements for $\mu^- + {}^{24}\text{Mg}(0^+_{g.s.}) \rightarrow \nu_\mu + {}^{24}\text{Na}(1^+_1)$ (upper panel), and $\mu^- + {}^{24}\text{Mg}(0^+_{g.s.}) \rightarrow \nu_\mu + {}^{24}\text{Na}(1^+_2)$, (lower panel)
- We still need some additional checks
- ...but the first results should appear soon!



Muon Capture on Other Light Nuclei from First Principles

- Eventually, we plan to extend the studies to ^{32}S, ^{48}Ti and ^{56}Fe
  - Comparing the theory estimates against future experimental data, we could shed light on g_{A}-quenching at $q \approx 100$ MeV!

Stay tuned!



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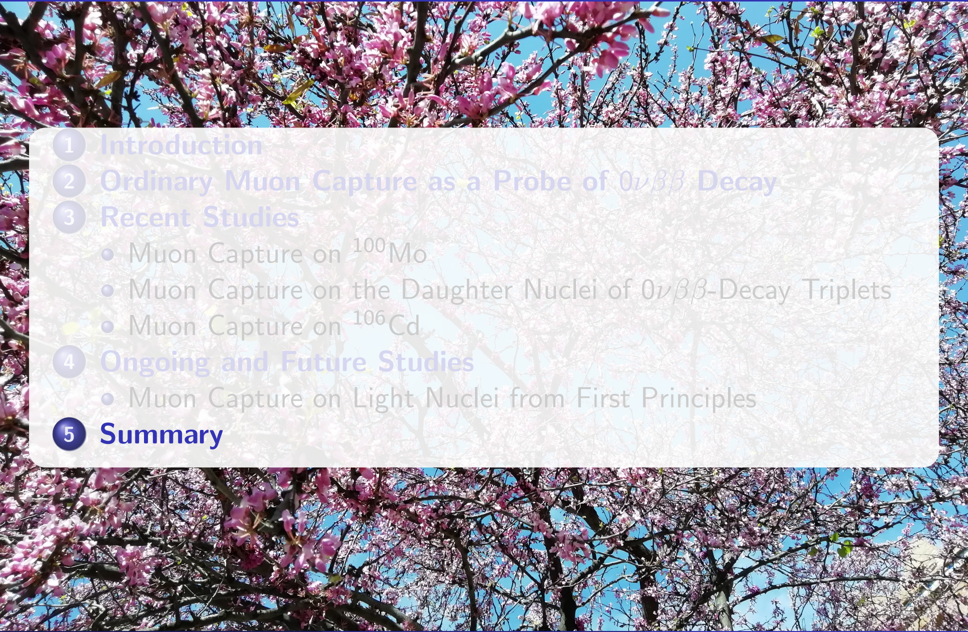

Summary

- By studying OMC we shed light on the unknown effective values of g_{A} on the momentum-exchange region relevant for $0\nu\beta\beta$ decay
- In order to probe the effective value of g_{P} we would need to have data on capture rates to individual states
- Our computations managed to reproduce the observed location of OMC giant resonance in ^{100}Nb
- However, comparing the obtained total capture rate with the Primakoff estimate suggests strongly quenched g_{A}
- There are similarities between the energy-multipole decompositions of $0\nu\beta\beta$ decay and OMC matrix elements
- First *ab initio* muon-capture studies in progress

Thank you!