NEWS on Ordinary Muon Capture and Double Beta Decay

Lotta Jokiniemi

University of Barcelona, Spain

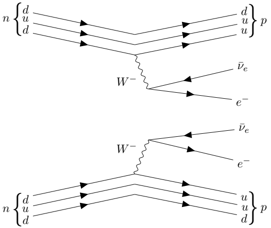
RCNP NEWS Colloquim, 24.06.2021

Outline

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!
  - What could we learn from $0\nu\beta\beta$ decay?

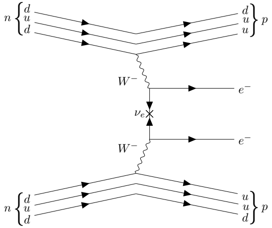
Two-Neutrino Double-Beta ($2\nu\beta\beta$) Decay



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

- Transition runs through 1^+ virtual states of the intermediate nucleus ${}^A_{Z+1}\mathrm{X'}_{N-1}$
- May happen, when β-decay is not energetically allowed
- Allowed by the Standard Model
- Measured in ≈ 10 isotopes
  - Half-lives of the order 10^{20} years or longer

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

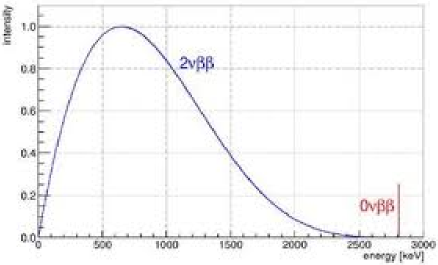


$$^{A}_{Z}\mathrm{X}_{N} \rightarrow {}^{A}_{Z+2}\,\mathrm{Y}_{N-2} + 2e^{-}$$

- Transition runs through all J^{π} virtual states of the intermediate nucleus ${}^{A}_{Z+1}\mathrm{X}'_{N-1}$
- Requires that the neutrino is a Majorana particle, meaning its own antiparticle
- Violates the lepton-number conservation law by two units
- $\frac{1}{t^{(0\nu)}_{1/2}} \propto \left|\frac{m_{\beta\beta}}{m_e}\right|^2, \quad m_{\beta\beta} = \sum_i^{\mathrm{light}} U_{ei}^2 m_i$

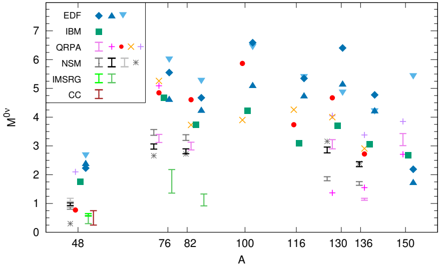
Difficulty of $0\nu\beta\beta$ Decay Searches

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]

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

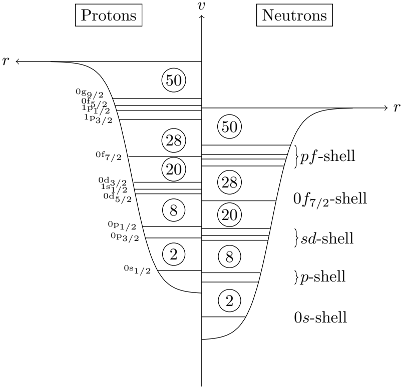
→ We need some detours!

[1] cobra-experiment.com

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

Proton-Neutron Quasiparticle Random-Phase Approximation (pnQRPA)

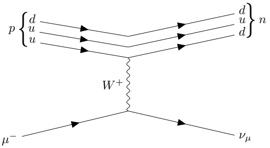
- Describes nuclear excitations in odd-odd nuclei as proton-neutron quasiparticle pairs
- Relies on the nuclear mean-field
  - Strongly interacting fermions → Non-interacting particles in an external potential
- Allows the use of large single-particle bases with reasonable computational effort
  - Wide excitation-energy regions in medium-heavy/heavy nuclei
- Adjustable parameters g_{ph} and g_{pp}



Woods-Saxon -based mean field potentials for protons and neutrons.

Outline

Ordinary Muon Capture (OMC)



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

- Muon initially bound on an atomic orbit is captured by the nucleus
- Weak interaction process with momentum transfer $q \approx 100\ \mathrm{MeV}/c^2$
  - Similar to $0\nu\beta\beta$ decay!
- Large m_μ 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
  - Can access the intermediate states of $0\nu\beta\beta$ decay!
- Previously intermediate states probed by charge-exchange reactions

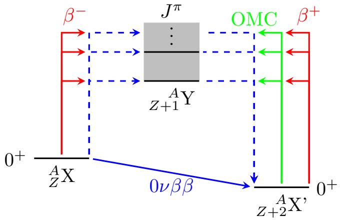
$$ {}^{a}_{z}a + {}^{A}_{Z}X \rightarrow {}^{a}_{z\pm1}b + {}^{A}_{Z\mp1}Y, $$

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 probe



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 $g_{\rm p}$:

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

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

$$[t_{1/2}^{(0\nu)}]^{-1} = g_{\rm A}^4 G_{0\nu} |M^{(0\nu)}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

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

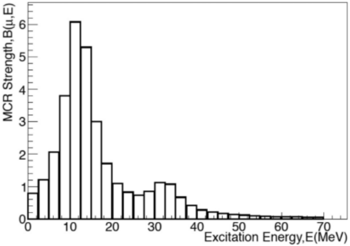
...we can probe $g_{\rm A}$ and $g_{\rm p}$ on the relevant momentum-exchange regime for $0\nu\beta\beta$ decay

Outline

Strength Functions - Theory Agrees with Experiment

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

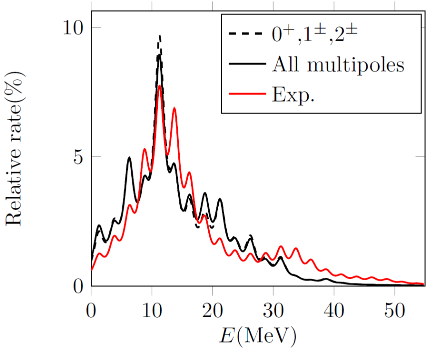
- The OMC strength distribution in ^{100}Nb [3] was studied at the MuSIC beam channel at RCNP for the first time



[3] 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 [4]
- ...and compared the obtained spectrum with the observed one
  - The agreement is excellent!



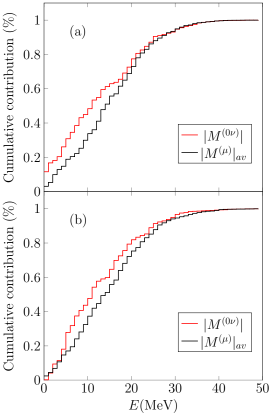
Experimental vs. computed OMC strength spectra in ^{100}Nb [5]

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

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

Similarities of OMC and $0\nu\beta\beta$ Decay

- In the above-mentioned setup the final nucleus of OMC = intermediate nucleus of $0\nu\beta\beta$-decay
- Same excitation-energy regions are important
- Transitions to/through multipoles with $1 \leq J \leq 3$ dominate both $0\nu\beta\beta$ decay and OMC

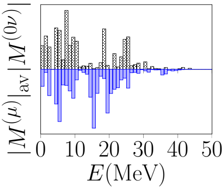


Cumulative $0\nu\beta\beta$-Decay and OMC NMEs of (a) A=76 and (b) A=136 triplets [6]

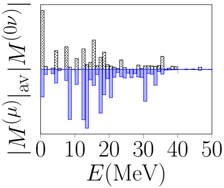
[6] LJ and J. Suhonen, *Phys. Rev. C* **102**, 024303 (2020)

Correlations between OMC and $0\nu\beta\beta$ Matrix Elements

- Similarities between $0\nu\beta\beta$-decay and OMC matrix elements both on the $\beta^-\beta^-$ and the $\beta^+\beta^+$ sides

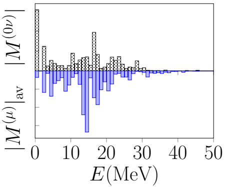


(a) $J^\pi = 3^+$

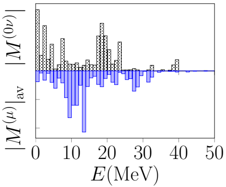


(b) $J^\pi = 3^-$

$0\nu\beta^-\beta^-$ decay vs. OMC NMEs in the ^{76}Ge triplet[7].



(a) $J^\pi = 3^+$



(b) $J^\pi = 3^-$

$0\nu\beta^+\beta^+$ decay vs. OMC NMEs in the ^{106}Cd triplet[8].

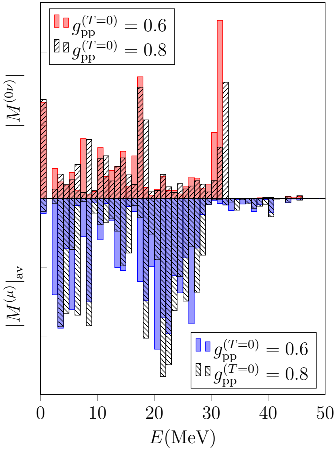
---

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

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

Both OMC and $0\nu\beta\beta$ Decay are Sensitive to g_{pp}

- The particle-particle parameter g_{pp} is normally adjusted to $2\nu\beta\beta$-decay half-life, where possible
- Adjusting g_{pp} shifts both the OMC and the $0\nu\beta\beta$ spectra
    - 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} [9]

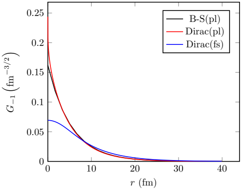
[9] LJ, J. Suhonen and J. Kotila, *Front. Phys.* **9**, 142 (2021)

OMC Matrix Elements Depend on Bound-Muon Wave Functions

- Dirac equations

$$\begin{cases} \frac{\mathrm{d}}{\mathrm{d}r} G_{-1} + \frac{1}{r} G_{-1} = \frac{1}{\hbar c}(mc^2 - E + V(r))F_{-1} \\ \frac{\mathrm{d}}{\mathrm{d}r} F_{-1} - \frac{1}{r} F_{-1} = \frac{1}{\hbar c}(mc^2 + E - V(r))G_{-1} \end{cases},$$

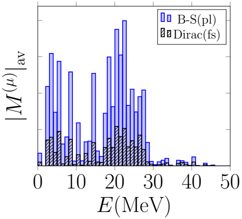
where $V(r)$ is the potential created by finite-size/point-like nucleus



[Front. Phys. ***9****, 142 (2021)]*

- Bethe-Salpeter (B-S) approx.

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



OMC matrix elements with $J^\pi = 2^+$ with different wave functions

OMC Matrix Elements Depend on Bound-Muon Wave Functions

- Dirac equations

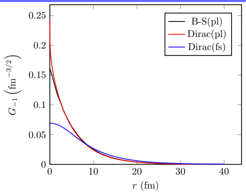
$$\begin{cases} \frac{\mathrm{d}}{\mathrm{d}r} G_{-1} + \frac{1}{r} G_{-1} = \frac{1}{\hbar c}(mc^2 - E + V(r))F_{-1} \\ \frac{\mathrm{d}}{\mathrm{d}r} F_{-1} - \frac{1}{r} F_{-1} = \frac{1}{\hbar c}(mc^2 + E - V(r))G_{-1} \end{cases},$$

where $V(r)$ is the potential created

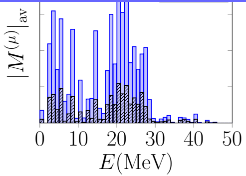
- Bethe-Salpeter (B-S) approx.

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

Finite-size effect: $W(\mathrm{fs}) \approx \left(\frac{Z_{\mathrm{eff}}}{Z}\right)^4 W(\mathrm{pl})$

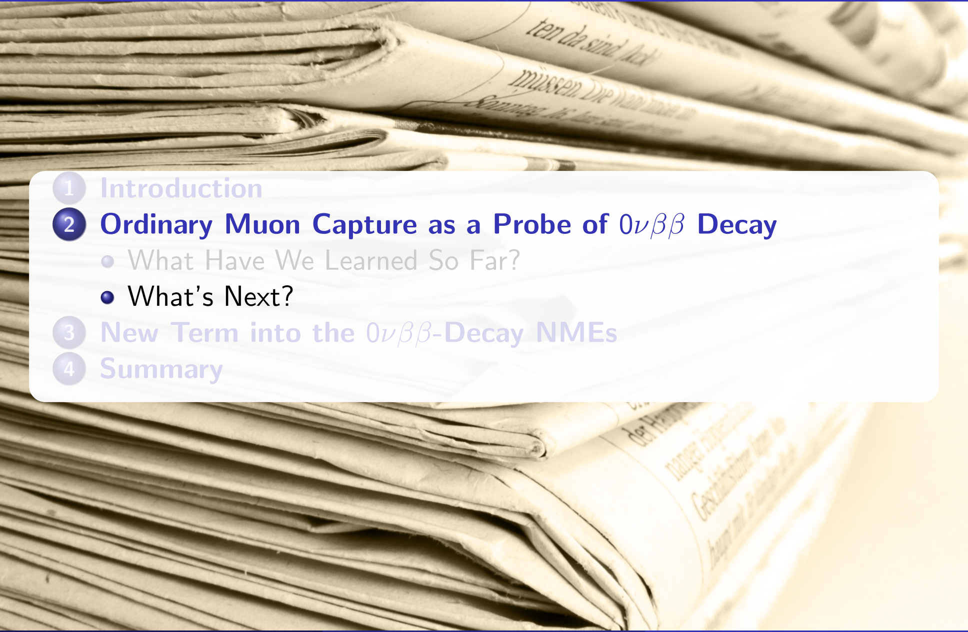


[Front. Phys. **9**, 142 (2021)]



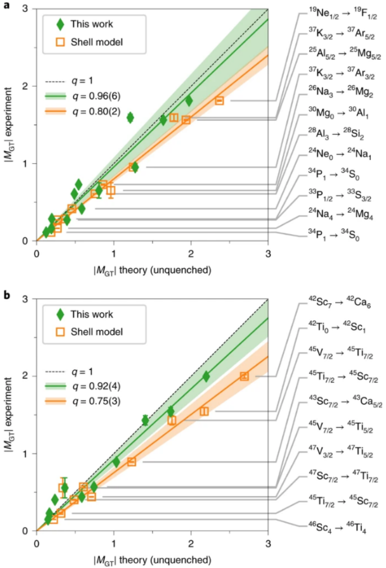
OMC matrix elements with $J^\pi = 2^+$ with different wave functions

Outline



Muon Capture on Light Nuclei from First Principles

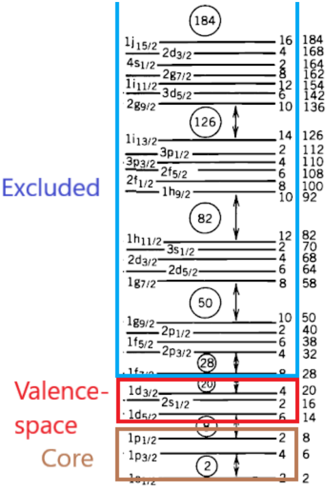
- Recently, first *ab initio* solution to g_A quenching puzzle was proposed for β-decay [10]
  - Solution: missing correlations and two-body currents from the NSM
- How about g_A quenching at high momentum transfer $q \approx 100$ MeV/c?
  - OMC could provide an answer!



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

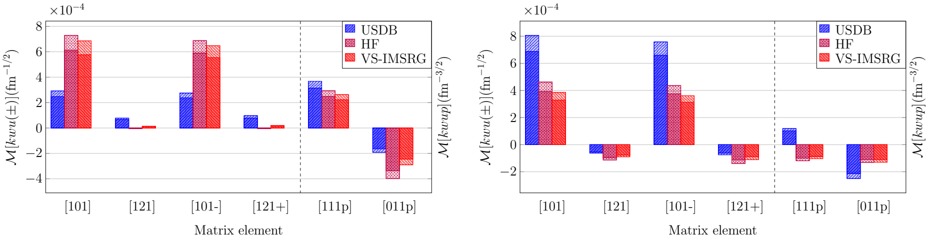
Muon Capture on ^{24}Mg from First Principles

- Muon capture matrix elements evaluated in VS-IMSRG framework
  - Hamiltonian based on the chiral EFT
  - Valence-space Hamiltonian and OMC operators decoupled from complimentary space with a unitary transformation
  - include physics missing from the NSM: 3N forces, two-body matrix elements,...



- OMC matrix elements for

$$\mu^- + \,^{24}\mathrm{Mg}(0^+_{g.s.}) \rightarrow \nu_\mu + \,^{24}\mathrm{Na}(J^\pi_n)$$



$J^\pi_n = 1^+_1$ $\qquad$ $J^\pi_n = 1^+_2$

[L.J., T. Miyagi, J.D. Holt, J. Kotila and J. Suhonen, *in preparation*]

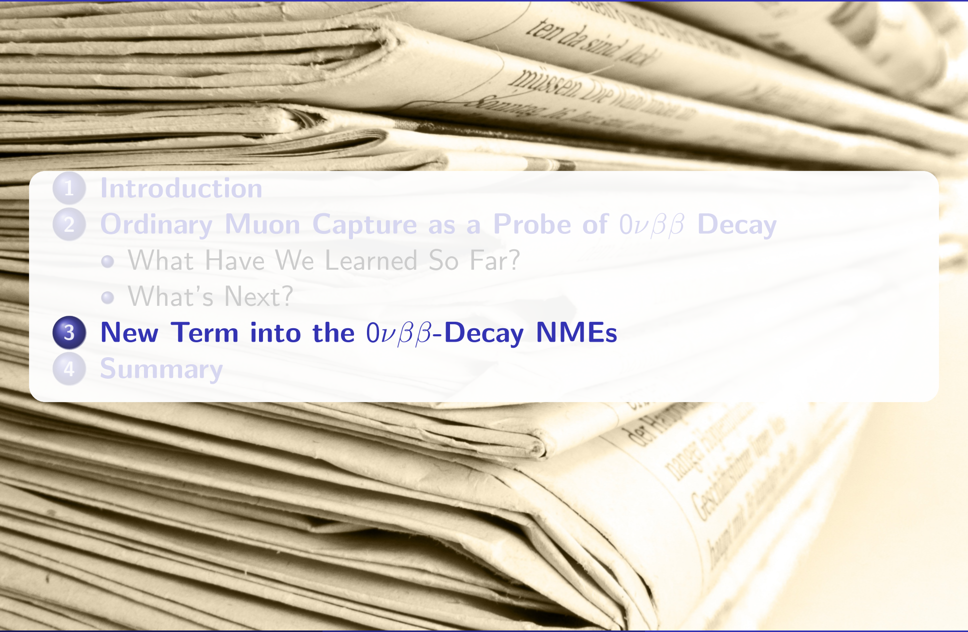
Capture Rates on Low-Lying States in ^{24}Na

- Comparing the VS-IMSRG and nuclear shell model (NSM) results against experimental data could shed light on the values of g_{A} and g_{P}

J_i^π	E (MeV)			Rate (1/s)	
	Exp.	USDB	Vs-IMSRG	USDB	VS-IMSRG
$4^+_{\mathrm{g.s.}}$	0.0	0.0	0.0	2	2
1^+_1	0.472	0.540	0.397	3 000	18 000
2^+_1	0.563	0.629	0.244	800	400
2^+_2	1.341	1.107	0.865	2 000	800
3^+_1	1.345	1.338	0.915	90	4
1^+_2	1.347	1.324	0.821	26 000	6 000

[L.J., T. Miyagi, J.D. Holt, J. Kotila and J. Suhonen, in preparation]

Outline



$0\nu\beta\beta$-Decay Nuclear Matrix Elements

- Assuming the standard light-neutrino exchange is the dominant mechanism of $0\nu\beta\beta$ decay

$$[t_{1/2}^{0\nu}]^{-1} = g_{\mathrm{A}}^4 G_{0\nu} |M_{\mathrm{L}}^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

- The matrix element can be written as

$$M_{\mathrm{L}}^{0\nu} = M_{\mathrm{GT}}^{0\nu} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M_{\mathrm{F}}^{0\nu} - M_{\mathrm{T}}^{0\nu}$$

- However, there seems to be something missing...

The Contact Term

PHYSICAL REVIEW LETTERS **120,** 202001 (2018)

Editors' Suggestion   Featured in Physics

New Leading Contribution to Neutrinoless Double-β Decay

Vincenzo Cirigliano,[1] Wouter Dekens,[1] Jordy de Vries,[2] Michael L. Graesser,[1]
Emanuele Mereghetti,[1] Saori Pastore,[1] and Ubirajara van Kolck[3,4]
[1]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[2]*Nikhef, Theory Group, Science Park 105, 1098 XG Amsterdam, The Netherlands*
[3]*Institut de Physique Nucléaire, CNRS/IN2P3, Université Paris-Sud, Université Paris-Saclay, 91406 Orsay, France*
[4]*Department of Physics, University of Arizona, Tucson, Arizona 85721, USA*

(Received 1 March 2018; revised manuscript received 28 March 2018; published 16 May 2018)

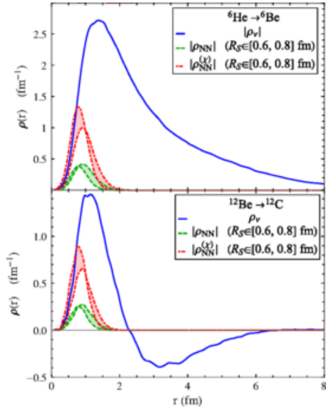
Within the framework of chiral effective field theory, we discuss the leading contributions to the neutrinoless double-beta decay transition operator induced by light Majorana neutrinos. Based on renormalization arguments in both dimensional regularization with minimal subtraction and a coordinate-space cutoff scheme, we show the need to introduce a leading-order short-range operator, missing in all current calculations. We discuss strategies to determine the finite part of the short-range coupling by matching to lattice QCD or by relating it via chiral symmetry to isospin-breaking observables in the two-nucleon sector. Finally, we speculate on the impact of this new contribution on nuclear matrix elements of relevance to experiment.

The Contact Term - First ab initio Results

- Contact term enhances the NMEs by [12]

$$\begin{cases} 5 \sim 15\% & \text{for } ^{6}\mathrm{He} \\ 20 \sim 80\% & \text{for } ^{12}\mathrm{Be} \end{cases}$$

- Study of the lightest $0\nu\beta\beta$-candidate ^{48}Ca shows a 43(7)% enhancement [13]
  - Good news for the experiments!



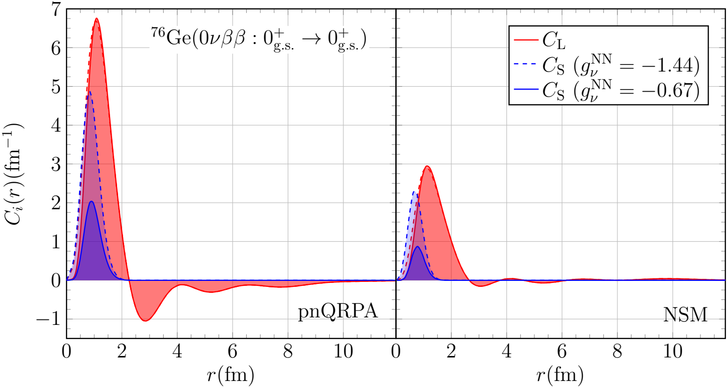
[V. Cirigliano et al., Phys. Rev. Lett. **120***,202001 (2018)]*

[12] V. Cirigliano et al., PRC **100**, 055504 (2019), PRL **120**, 202001 (2018)
[13] M. Wirth, J. M. Yao and H. Hergert, arXiv:2105.05415 [nucl-th] (2021)

Contact Terms in pnQRPA and NSM

In pnQRPA: $M_{\mathrm{S}}/M_{\mathrm{L}} \approx 30-80\%$

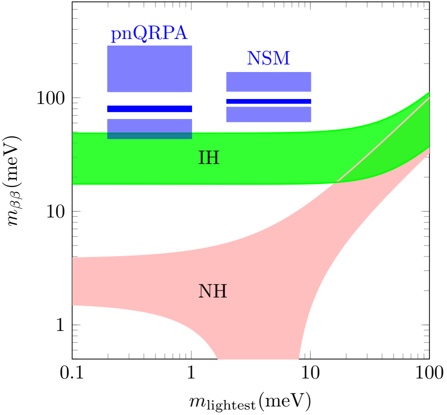
In NSM: $M_{\mathrm{S}}/M_{\mathrm{L}} \approx 15-50\%$



[LJ, P. Soriano and J. Menéndez, in preparation]

Effective Neutrino Masses

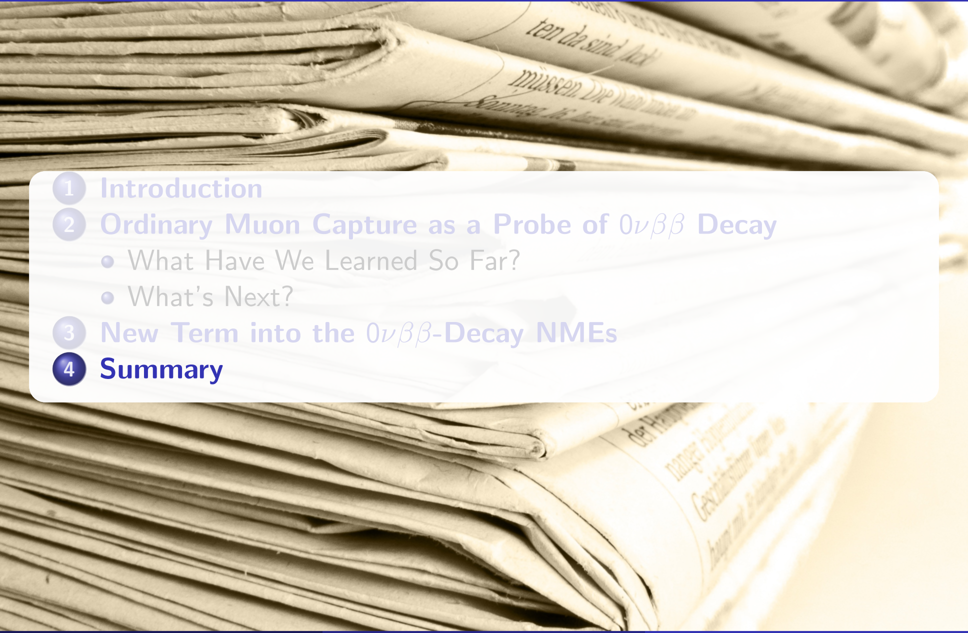
- Effective neutrino masses from combined likelihood functions of GERDA (^{76}Ge), CUORE (^{130}Te), EXO-200 (^{136}Xe) and KamLAND-Zen (^{136}Xe), method proposed in [14]
- Middle bands correspond to the computed values of $M_{\mathrm{L}}^{(0\nu)}$, upper bands to $M_{\mathrm{L}}^{(0\nu)} - M_{\mathrm{S}}^{(0\nu)}$ and the lower bands to $M_{\mathrm{L}}^{(0\nu)} + M_{\mathrm{S}}^{(0\nu)}$



[LJ, P. Soriano and J. Menéndez, in preparation]

[14] S. D. Biller, arXiv:2103.06036 [hep-ex] (2021), *accepted in PRD*

Outline



Summary

- OMC is a useful tool to probe $0\nu\beta\beta$ decay
- Our computations managed to reproduce the observed location of OMC giant resonance in ^{100}Nb
- We found similarities between of $0\nu\beta\beta$ decay and OMC matrix elements
- First *ab initio* muon-capture studies in progress
- Adding a new short-range term into the $0\nu\beta\beta$ NMEs changes the values of NMEs by $\approx 30\%$ in NSM and by $\approx 50\%$ in pnQRPA
- If the sign of the contact term is positive, pnQRPA already reaches the inverted-hierarchy region of neutrino masses

Thank you!