Neutrinoless double-beta decay and muon capture as a probe

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Discovery, accelerated

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Outline

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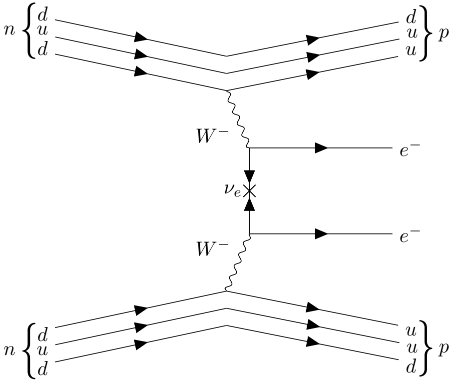
Neutrinoless double-beta decay

$$\frac{1}{t_{1/2}^{0\nu}} = g_{\mathrm{A}}^4 G^{0\nu} |\boldsymbol{M}_{\mathbf{L}}^{\boldsymbol{0\nu}}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

- **Violates lepton-number conservation**



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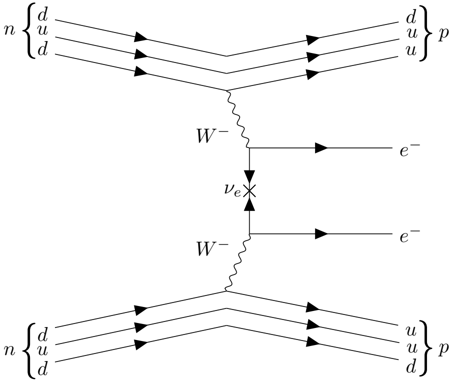
- Requires that **neutrinos are Majorana particles**



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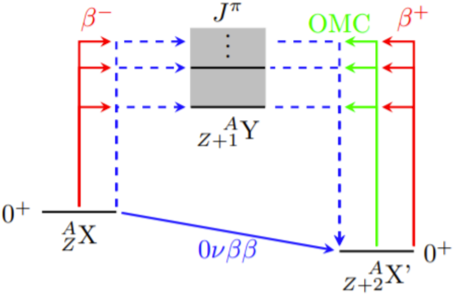

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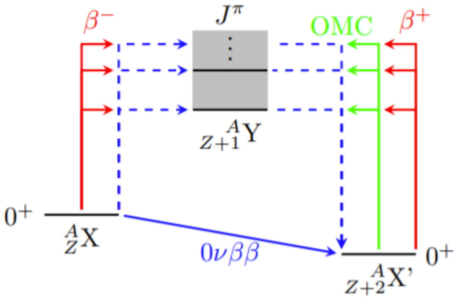

- **Violates lepton-number conservation**
- Requires that **neutrinos are Majorana particles**
- Runs virtually through **all J^π states** in the intermediate nucleus
- Momentum transfer $q \sim 100$ **MeV**

Nuclear matrix elements of neutrinoless double-beta decay

$$M^{0\nu} = \frac{R}{g_{\mathrm{A}}^2} \int \frac{\mathrm{d}\mathbf{k}}{2\pi^2} \frac{e^{i\mathbf{k}(\mathbf{x}-\mathbf{y})}}{E_\nu} \sum_n \frac{\langle f| J_\mu(\mathbf{x}) |n\rangle \langle n| J^\mu(\mathbf{y}) |i\rangle}{E_\nu + E_n - \frac{1}{2}(E_i - E_f) - \frac{1}{2}(E_1 - E_2)}$$

- Energy of the virtual neutrino $E_\nu = \sqrt{m_\nu^2 + \mathbf{k}^2} \sim |\mathbf{k}| \sim k_{\mathrm{F}} \sim 100$ **MeV** ("soft neutrinos")

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Closure approximation

Without closure approximation:

$$\sum_n \frac{\langle f| J_\mu(\mathbf{x}) |n\rangle \langle n| J^\mu(\mathbf{y}) |i\rangle}{|\mathbf{k}| + E_n - \frac{1}{2}(E_i - E_f)}$$

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- Intermediate states $|n\rangle$ **with all spin-parities J^π up to high energies**

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- Typically used **with most nuclear methods**

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Outline

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New leading-order short-range nuclear matrix element

$$\frac{1}{t_{1/2}^{0\nu}} = g_{\rm A}^4 G^{0\nu} |M_{\rm L}^{0\nu} + M_{\rm S}^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

- Previously unacknowledged contact operator was introduced

V. Cirigliano et al., Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)

Discovery, accelerated

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- The operator connects directly the initial and final nuclei

$$M_S^{0\nu} = \frac{2R}{\pi g_A^2} (0_f^+ || \sum_{m,n} \tau_m^- \tau_n^- \int j_0(qr) h_S(q^2)\, q^2 \mathrm{d}q || 0_i^+),$$

$$h_S(q^2) = 2 g_\nu^{NN} e^{-q^2/(2\Lambda^2)}$$

Discovery, accelerated

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Unknown coupling in the contact term

- Axial-vector coupling g_A known from $n \to p + e^- + \bar{\nu}_e$:

$$g_\mathrm{A} = 1.2754(11)$$

D. Dubbers, B. Märkisch, Annu. Rev. Nucl. Part. Sci. 71, 139 (2021)

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Phenomenological many-body methods

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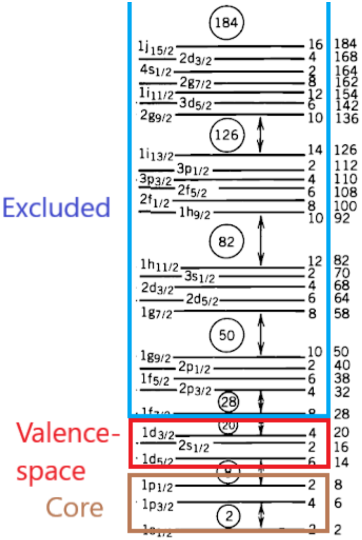

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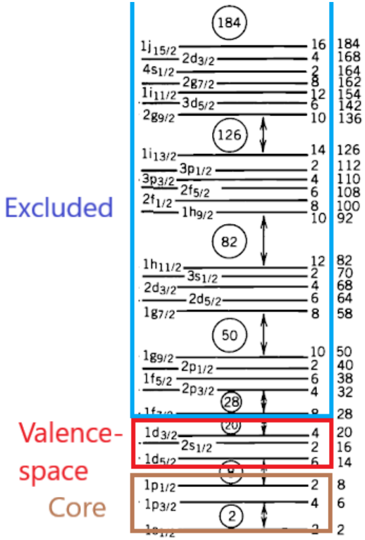

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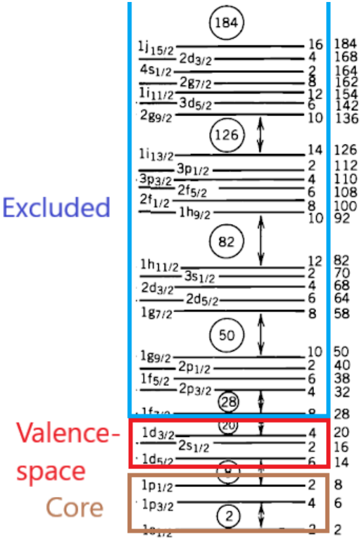

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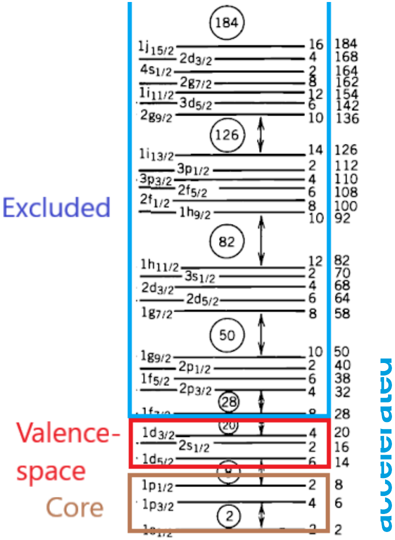

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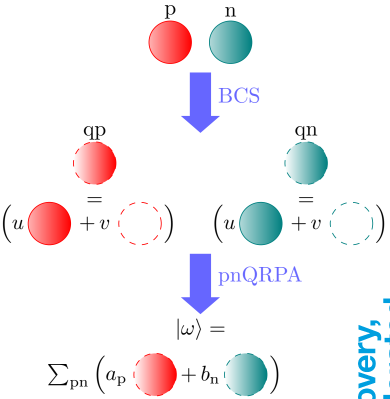

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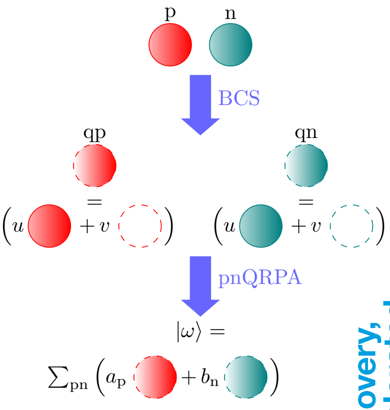

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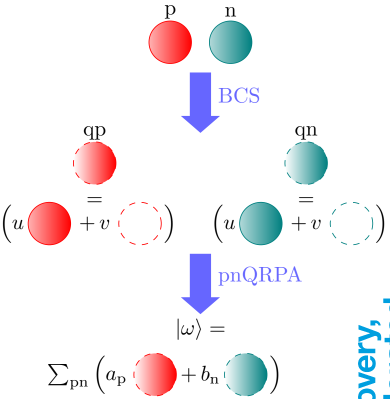

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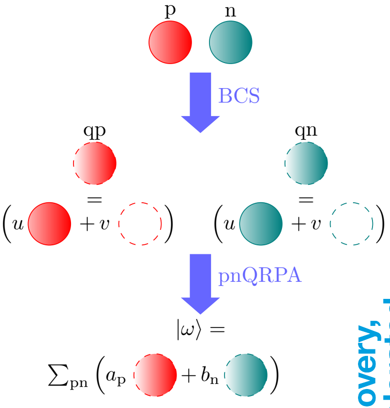

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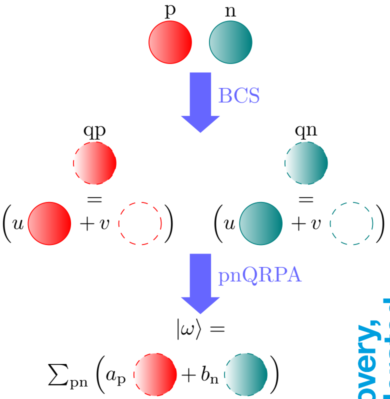

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Contact Term in pnQRPA and NSM

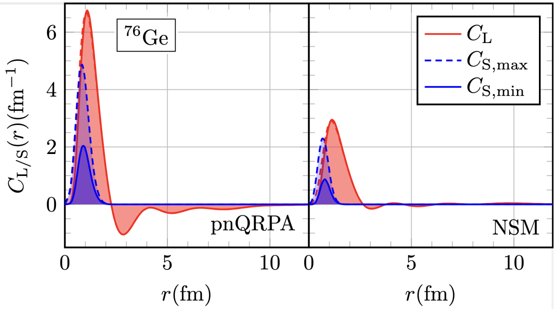
$$\int C_{\mathrm{L/S}}(r)\mathrm{d}r = M^{0\nu}_{\mathrm{L/S}}$$

In pnQRPA:

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

In NSM:

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



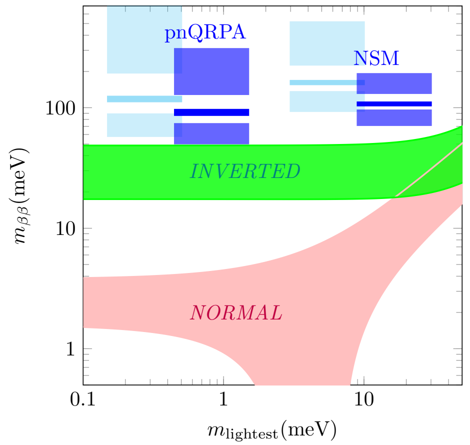
LJ, P. Soriano and J. Menéndez, Phys. Lett. B **823**, 136720 (2021)

Effective Neutrino Masses

- Effective neutrino masses combining the likelihood functions of GERDA (^{76}Ge), CUORE (^{130}Te), EXO-200 (^{136}Xe) and KamLAND-Zen (^{136}Xe)

  S. D. Biller, Phys. Rev. D ***104****, 012002 (2021)*

- Middle bands: $\boldsymbol{M_{\mathrm{L}}^{(0\nu)}}$
  Lower bands: $\boldsymbol{M_{\mathrm{L}}^{(0\nu)} + M_{\mathrm{S}}^{(0\nu)}}$
  Upper bands: $M_{\mathrm{L}}^{(0\nu)} - M_{\mathrm{S}}^{(0\nu)}$



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Outline

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Contribution of ultrasoft neutrinos

- Contribution of ultrasoft neutrinos ($|\mathbf{k}| << k_{\mathrm{F}}$) to $0\nu\beta\beta$ decay:

V. Cirigliano et al., Phys. Rev. C 97, 065501 (2018)

$$M^{0\nu}_{\mathrm{usoft}} = -\frac{\pi R}{g_{\mathrm{A}}^2} \sum_n \frac{\mathrm{d}^{d-1}k}{(2\pi)^{d-1}} \frac{1}{|\mathbf{k}|} \left[\frac{\langle f| J_\mu |n\rangle \langle n| J^\mu |i\rangle}{|\mathbf{k}| + E_2 + E_n - E_i - i\eta} + \frac{\langle f| J_\mu |n\rangle \langle n| J^\mu |i\rangle}{|\mathbf{k}| + E_1 + E_n - E_i - i\eta} \right]$$

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- Keeping only $\mathbf{k} = \mathbf{0}$ term in the current and assuming $E_1 = E_2 = Q_{\beta\beta}/2 + m_e$:

$$M^{0\nu}_{\mathrm{usoft}}(\mu_{\mathrm{us}}) = \frac{R}{2\pi} \sum_n \langle f| \sum_a \boldsymbol{\sigma}_a \tau_a^+ |n\rangle \langle n| \sum_b \boldsymbol{\sigma}_b \tau_b^+ |i\rangle \times 2(\frac{Q_{\beta\beta}}{2} + m_e + E_n - E_i) \left(\ln \frac{\mu_{\mathrm{us}}}{2(\frac{Q_{\beta\beta}}{2} + m_e + E_n - E_i)} + 1 \right)$$

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- We take $\mu_{\mathrm{us}} = m_\pi \sim k_{\mathrm{F}} \sim 100$ MeV

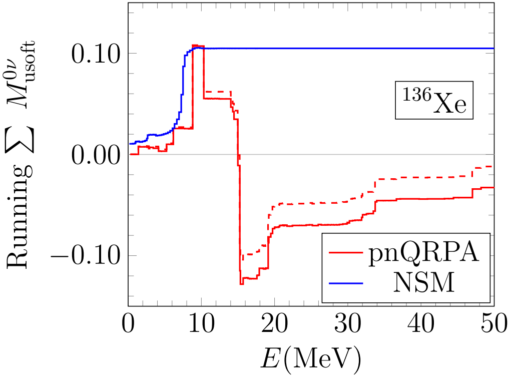
Ultrasoft neutrinos in pnQRPA and nuclear shell model

In pnQRPA:

$|M^{0\nu}_{\text{usoft}}/M^{0\nu}_{\text{L}}| \approx 1\% - 15\%$

In NSM:

$|M^{0\nu}_{\text{usoft}}/M^{0\nu}_{\text{L}}| \approx 1\% - 5\%$

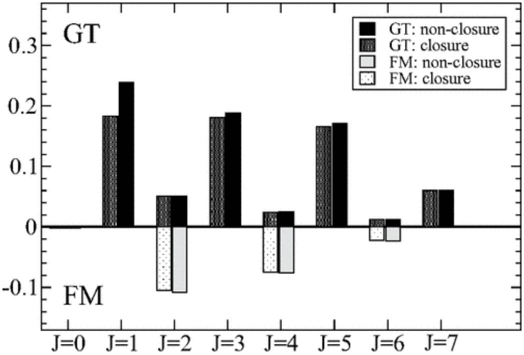


LJ, P. Soriano, J Menéndez, work in progress

Ultrasoft neutrinos as correction of the closure approximation

- In nuclear shell model, using **closure approximation typically decreases $M_{\mathrm{L}}^{0\nu}$ by $\sim 10\%$**

  R. A. Sen'kov, M. Horoi, Phys. Rev. C 88, 064312 (2013), Phys. Rev. C 93, 044334 (2016),Phys.Rev.C 89, 054304 (2014)



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Discovery, accelerated

TRIUMF

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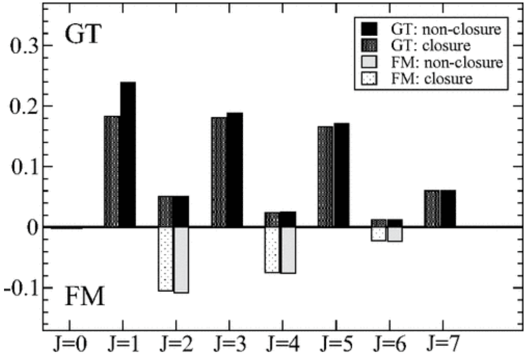

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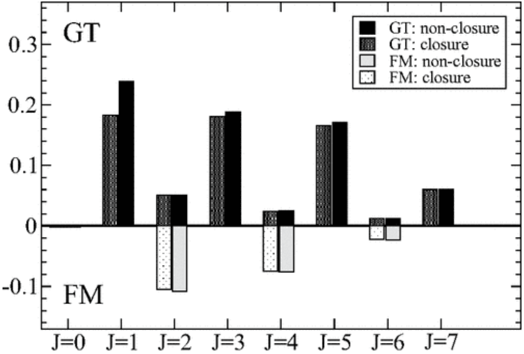

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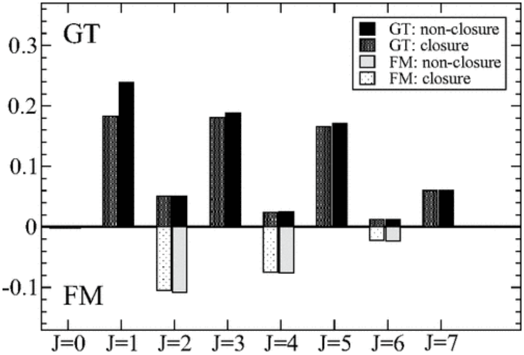
- $M_{\rm usoft}^{0\nu}$ may be considered **as closure correction**

$\rightarrow$ **TODO**: compare $M_{\rm L}^{0\nu} - M_{\rm L,cl}^{0\nu}$ with $M_{\rm usoft}^{0\nu}$ in pnQRPA



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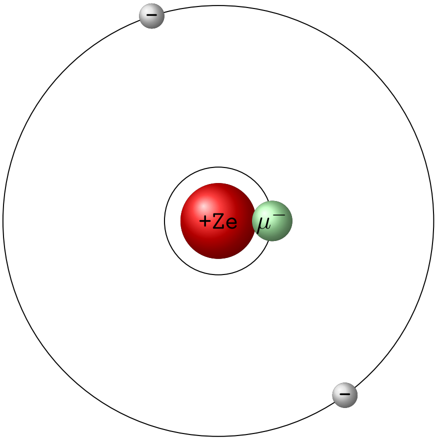
Discovery, accelerated

Outline

Ordinary Muon Capture (OMC)

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

- A muon can replace an electron in an atom, forming a *muonic atom*



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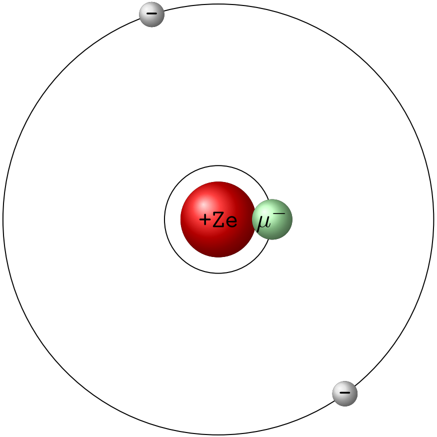

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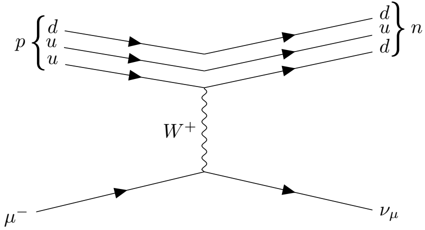

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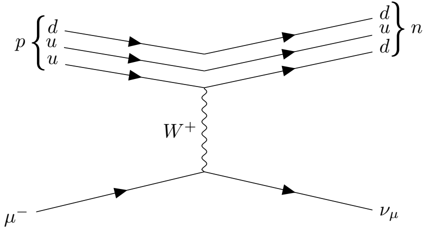
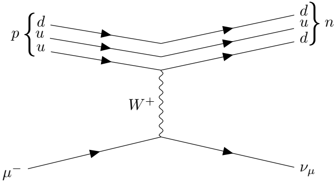
Ordinary = non-radiative

Radiative muon capture (RMC):

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



Ordinary Muon Capture (OMC) vs. $0\nu\beta\beta$



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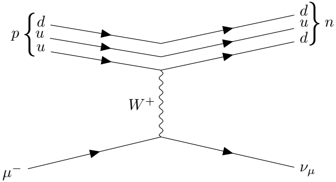

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- Weak interaction process with momentum transfer $q \approx 100\ \mathrm{MeV}/c^2$

Discovery, accelerated

TRIUMF

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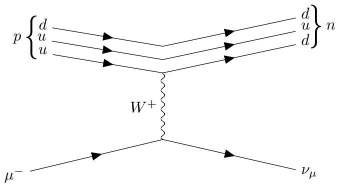

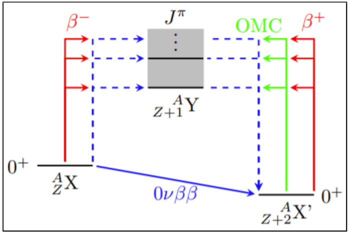

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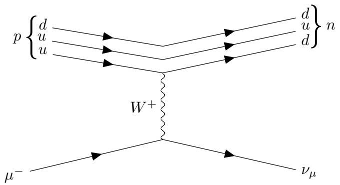

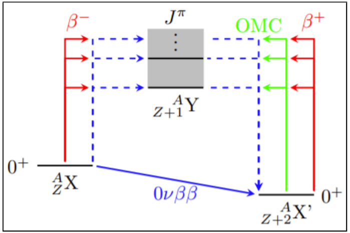

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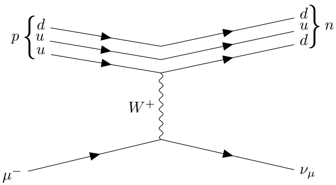

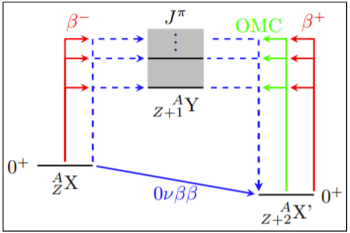

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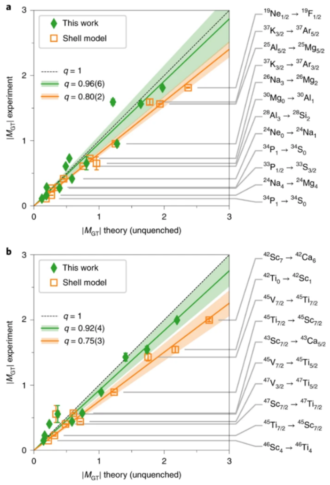
- Large m_μ allows **transitions to all J^π states** up to high energies
- **Both the axial vector coupling g_A and the pseudoscalar coupling g_P involved**
  $\rightarrow$ Similar to $0\nu\beta\beta$ decay!

Discovery, accelerated

g_A Quenching at High Momentum Exchange?

- Recently, **first *ab initio* solution to g_A quenching puzzle** was proposed for β-decay

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



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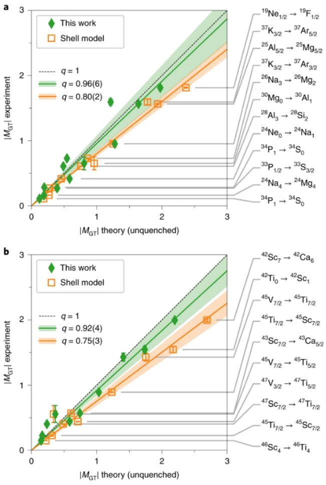

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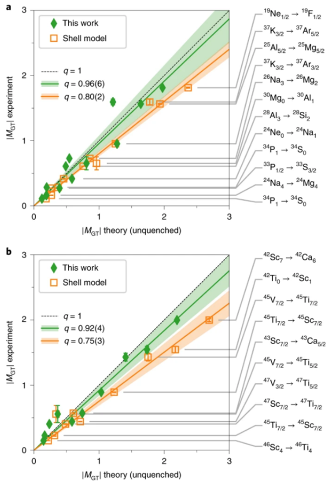

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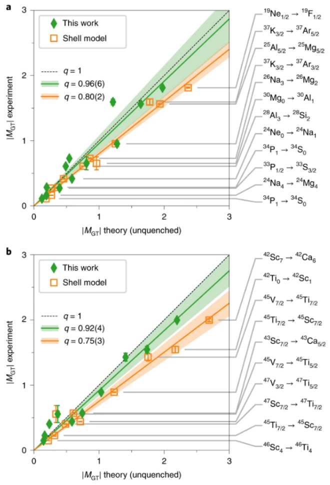

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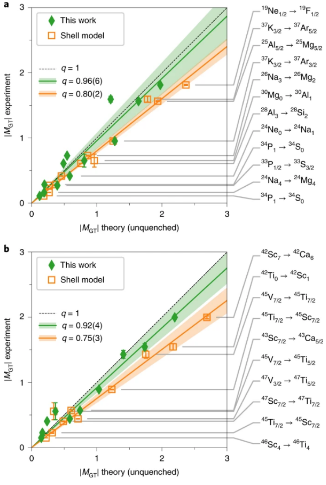
  - Solution: adding **two-body currents** and **missing correlations**
- How about **g_A quenching** at high momentum transfer **≈ 100 MeV?**
  - **OMC could provide a hint!**
- In principle, one could also access the pseudoscalar coupling g_P



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Discovery, accelerated

Muon-Capture Theory

- Interaction Hamiltonian → capture rate:

$$W(J_i \to J_f) = \frac{2J_f + 1}{2J_i + 1}\left(1 - \frac{q}{m_\mu + AM}\right) q^2 \sum_{\kappa u} \left| g_V M_V(\kappa, u) + g_M M_M(\ldots) + g_A M_A(\ldots) + g_P M_P(\ldots) \right|^2$$

PHYSICAL REVIEW VOLUME 118, NUMBER 2 APRIL 15, 1960

Theory of Allowed and Forbidden Transitions in Muon Capture Reactions*

MASATO MORITA
Columbia University, New York, New York

AND

AKIHIKO FUJII†
Brookhaven National Laboratory, Upton, Long Island, New York

(Received November 9, 1959)

TRIUMF

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- Use **realistic bound-muon wave functions**
- Add the effect of **two-body currents**

Bound-Muon Wave Functions

- Expand the muon wave function in terms of spherical spinors

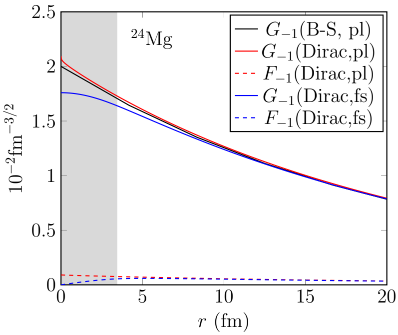
$$\psi_\mu(\kappa,\mu;\mathbf{r}) = \psi^{(\mu)}_{\kappa\mu} = \begin{bmatrix} -iF_\kappa(r)\chi_{-\kappa\mu} \\ G_\kappa(r)\chi_{\kappa\mu} \end{bmatrix} ,$$

where $\kappa = -j(j+1) + l(l+1) - \frac{1}{4}$
($\boldsymbol{\kappa = -1}$ for the $\mathbf{1s_{1/2}}$ orbit)

B-S $=$ Bethe-Salpeter: $G_{-1} = 2(\alpha Z m'_\mu)^{\frac{3}{2}} e^{-\alpha Z m'_\mu r}$

pl $=$ pointlike

fs $=$ finite size nucleus



LJ, Miyagi, Stroberg, Holt, Kotila, Suhonen, Phys. Rev. C ***107****, 014327 (2023)*

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- Solve the Dirac equations in the Coulomb potential $V(r)$:

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

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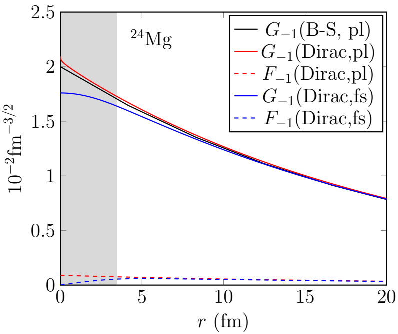

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Discovery, accelerated

TRIUMF

Axial-Vector Two-Body Currents (2BCs)

- One-body currents

$$\mathbf{J}^3_{i,1\mathrm{b}} = \frac{\tau^3_i}{2}\left(g_\mathrm{A}\boldsymbol{\sigma}_i - \frac{g_\mathrm{P}}{2m_\mathrm{N}}\mathbf{q}\cdot\boldsymbol{\sigma}_i\right)$$

+ two-body currents

$$\mathbf{J}^\mathrm{eff}_{i,2\mathrm{b}} = g_\mathrm{A}\frac{\tau^3_i}{2}\left[\delta a(\mathbf{q}^2)\boldsymbol{\sigma}_i + \frac{\delta a^P(\mathbf{q}^2)}{\mathbf{q}^2}(\mathbf{q}\cdot\boldsymbol{\sigma}_i)\mathbf{q}\right]$$

*Hoferichter, Klos, Schwenk Phys. Lett. B **746**, 410 (2015)*

Discovery, accelerated

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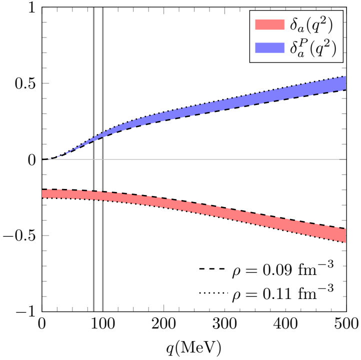
*Hoferichter, Klos, Schwenk Phys. Lett. B **746**, 410 (2015)*

- Two-body currents approximated by

$$\begin{cases} g_A \rightarrow (1+\delta_a(q^2))g_A, \\ g_P \rightarrow (1-\frac{q^2+m_\pi^2}{q^2}\delta_a^P(q^2))g_P \end{cases}$$



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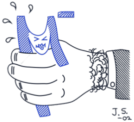
Discovery, accelerated

Muon-Capture Studies at PSI, Switzerland

- Most muon-capture experiments date back to $\sim$ 1960s – 1990s



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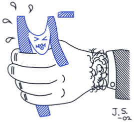

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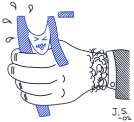

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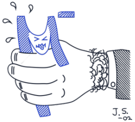

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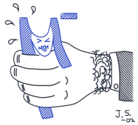
  - Muon-capture in $\beta\beta$-decay triplets, e.g. $\mathbf{^{136}Ba}$, ^{48}Ti
  - Potentially partial capture rates for $\mathbf{^{12}C}$, ^{13}C



Outline

Introduction

Corrections to $0\nu\beta\beta$-decay nuclear matrix elements
- The contact term
- Contribution of ultrasoft neutrinos

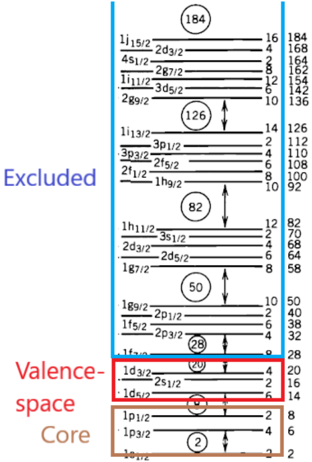
Muon capture as a probe of $0\nu\beta\beta$ decay
- VS-IMSRG Study on Muon Capture on ^{24}Mg
- No-Core Shell-Model Studies on Muon Capture on Light Nuclei
- Phenomenological study on muon capture on ^{136}Ba

Summary and Outlook

TRIUMF

Valence-Space In-Medium Similarity Renormalization Group (VS-IMSRG)

- We choose a Hamiltonian based on the chiral EFT with EM 1.8/2.0 interaction



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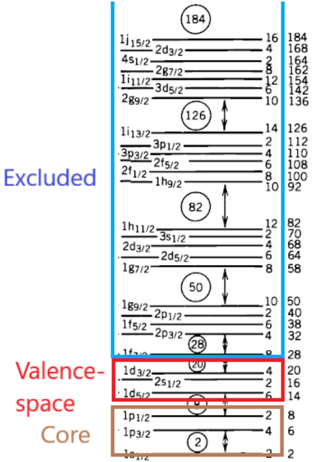

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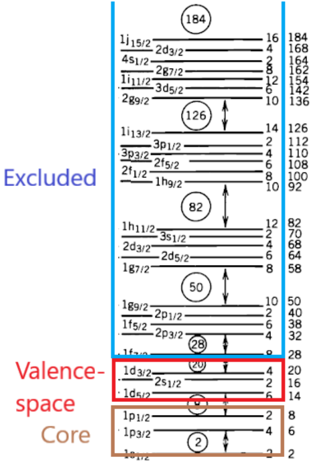

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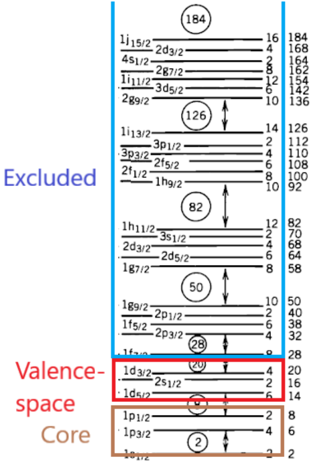

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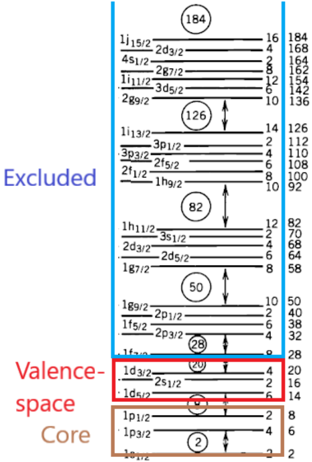

TRIUMF

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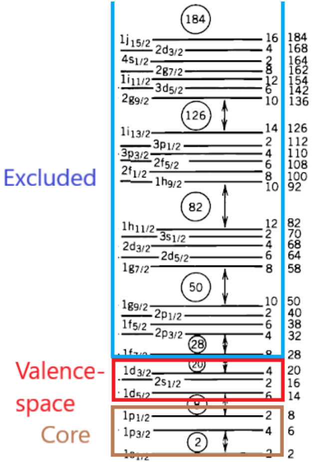
→ **First case: OMC on ^{24}Mg**



Discovery, accelerated

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

J_i^π	E_{exp} (MeV)	Rate (10^3 1/s)				
		Exp.[1]	NSM		VS-IMSRG	
			1bc	1bc+2bc	1bc	1bc+2bc
1_1^+	0.472	(21.0 ± 6.6)	4.0	3.0	22.3	15.2
1_2^+	1.347	17.5 ± 2.3	32.7	21.3	7.7	4.9
Sum(1^+)		38.5 ± 8.9	36.7	24.5	30.0	20.0
2_1^+	0.563	17.5 ± 2.1	1.0	0.7	0.5	0.3
2_2^+	1.341	3.4 ± 0.5	3.1	2.5	1.0	0.9
Sum(2^+)		20.9 ± 2.6	4.1	3.2	1.5	1.2

*LJ, Miyagi, Stroberg, Holt, Kotila, Suhonen, Phys. Rev. C **107**, 014327 (2023)*

[1] Gorringe *et al.*, *Phys. Rev. C* **60**, 055501 (1999)

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LJ, Miyagi, Stroberg, Holt, Kotila, Suhonen, Phys. Rev. C ***107****, 014327 (2023)*

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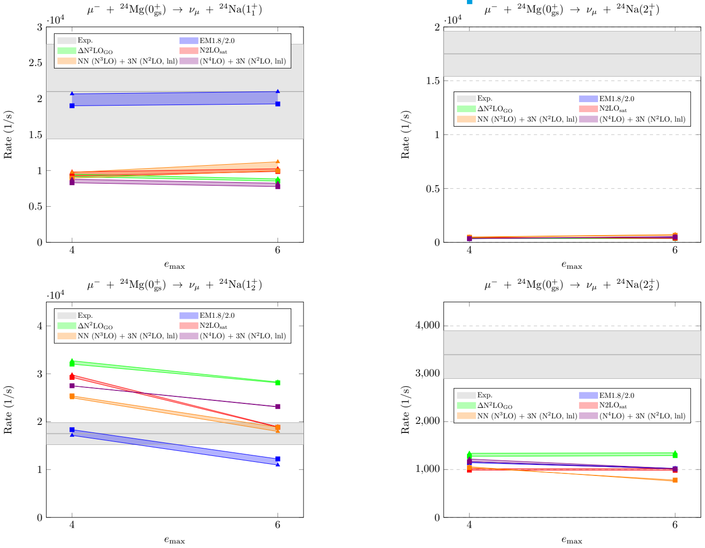
Discovery, accelerated

TRIUMF

Interaction Dependence

- Rates are sensitive to the interaction



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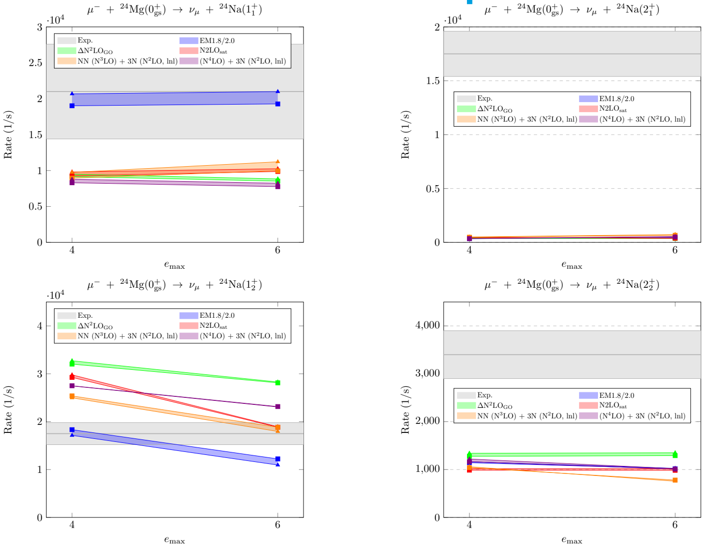
Interaction Dependence

- Rates are sensitive to the interaction
- It does not explain the poor agreement with the measured rates to the 2^+ states (on the right)



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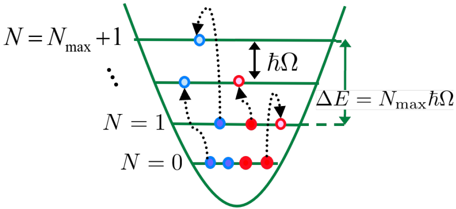
Discovery, accelerated

Outline

No-Core Shell Model (NCSM)

- OMC operators and one-body transition densities computed in large harmonic-oscillator (HO) basis



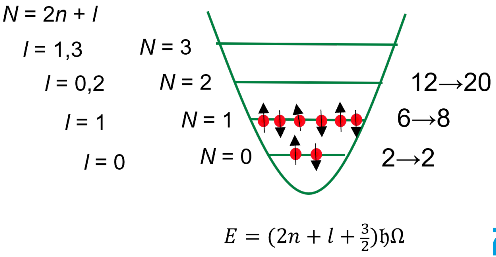


Figure courtesy of P. Navrátil

No-Core Shell Model (NCSM)

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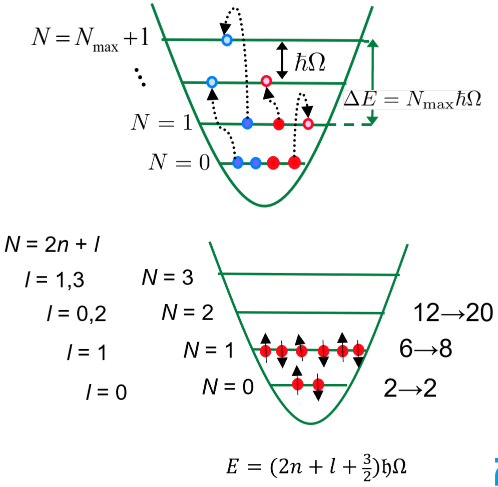
  - **HO basis truncated with N_{max}**



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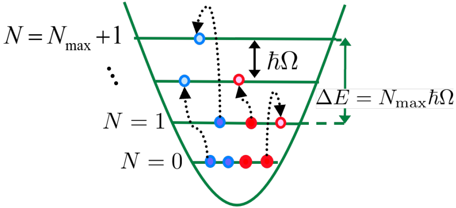

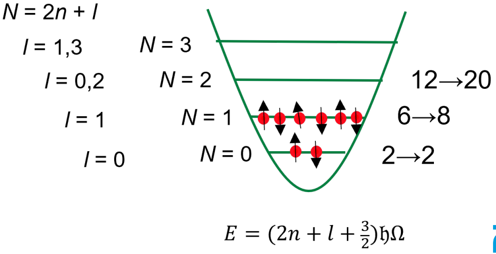

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Discovery, accelerated

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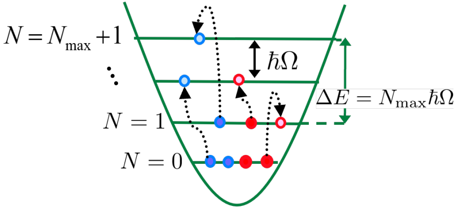

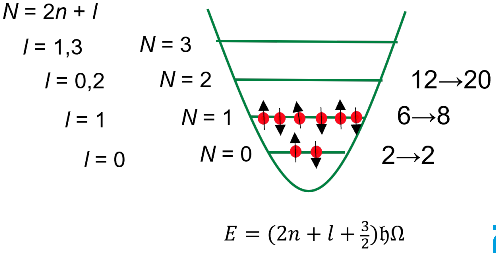

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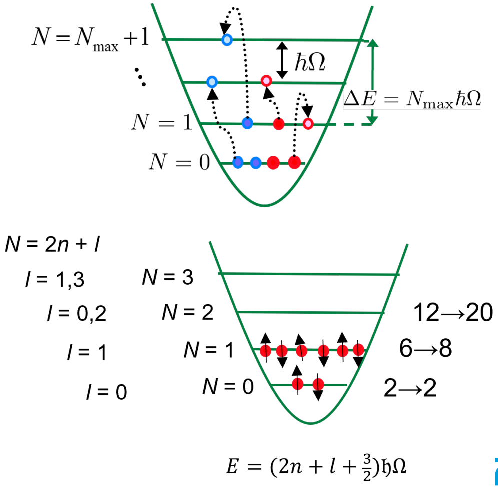

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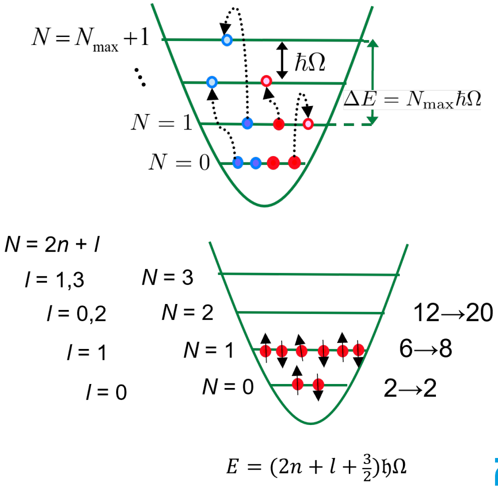

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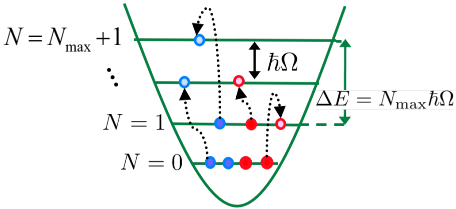
→ **OMC on ^{6}Li, ^{12}C and ^{16}O**



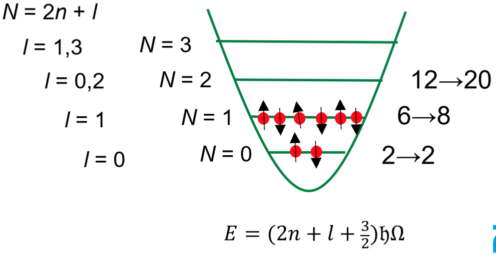
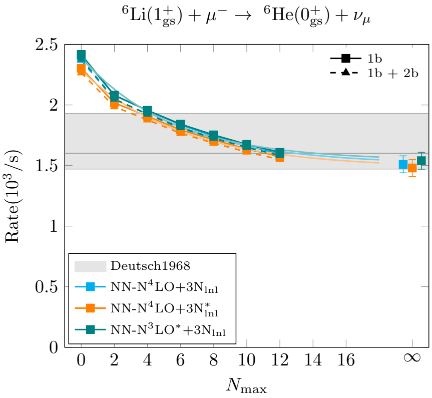


Figure courtesy of P. Navrátil

Discovery, accelerated

Capture Rates to the Ground State of ^{6}He

- NCSM in keeping with experiment



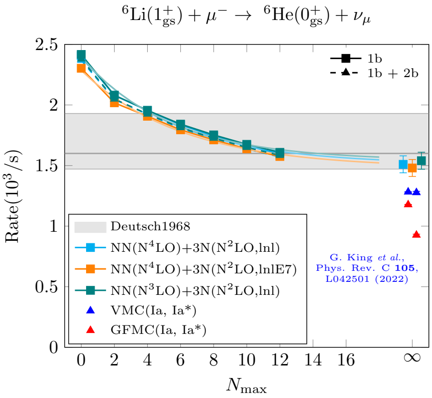
LJ, Navrátil, Kotila, Kravvaris,

work in progress

Capture Rates to the Ground State of ^{6}He

- NCSM in keeping with experiment
- The rates can be compared with the variational (VMC) and Green's function Monte-Carlo (GFMC) calculations

King *et al.*, Phys. Rev. C **105**, L042501 (2022)



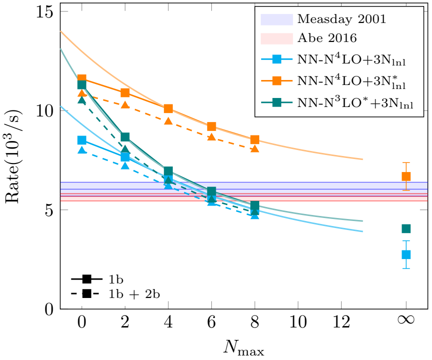
LJ, Navrátil, Kotila, Kravvaris,

work in progress

Capture Rates to the Ground State of ^{12}B

- Interaction dependence

$$^{12}\mathrm{C}(0^+_{\mathrm{gs}}) + \mu^- \rightarrow \ ^{12}\mathrm{B}(1^+_{\mathrm{gs}}) + \nu_\mu$$



LJ, Navrátil, Kotila, Kravvaris,

work in progress

TRIUMF

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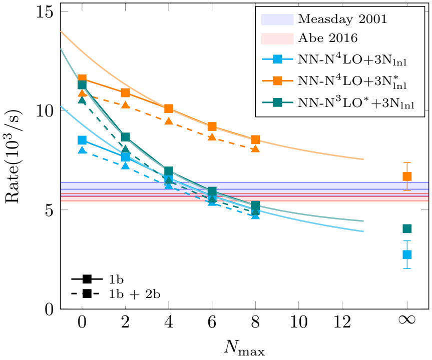

LJ, Navrátil, Kotila, Kravvaris,

work in progress

Discovery, accelerated

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- Converge slow (clustering effects?)

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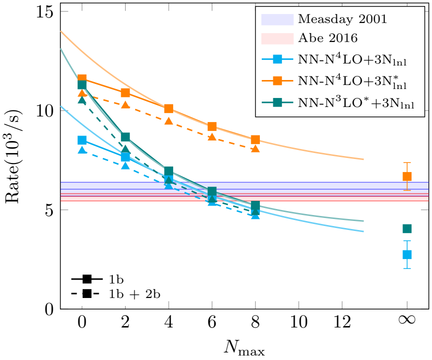

LJ, Navrátil, Kotila, Kravvaris, work in progress

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Hayes *et al.*, *Phys. Rev. Lett.* **91**, 012502 (2003)

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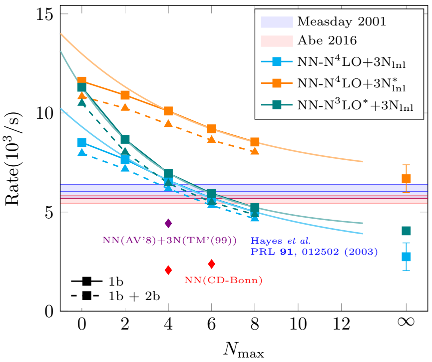

LJ, Navrátil, Kotila, Kravvaris,

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Discovery, accelerated

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- 3-body forces essential to reproduce the measured rate

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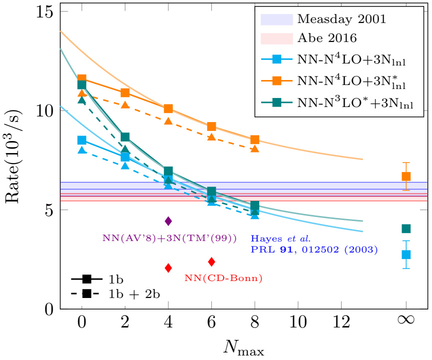


LJ, Navrátil, Kotila, Kravvaris,

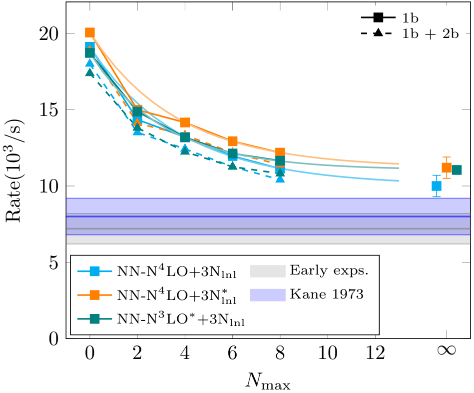
work in progress

Discovery, accelerated

Capture Rates to the ground state of ^{16}N

- NCSM describes well the complex systems ^{16}O and ^{16}N

$$^{16}\mathrm{O}(0^+_{\mathrm{gs}}) + \mu^- \to \, ^{16}\mathrm{N}(2^-_{\mathrm{gs}}) + \nu_\mu$$



LJ, Navrátil, Kotila, Kravvaris,

work in progress

TRIUMF

Capture Rates to the ground state of ^{16}N

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- Less sensitive to the interaction than $^{12}\mathrm{C}(\mu^-, \nu_\mu)^{12}\mathrm{B}$

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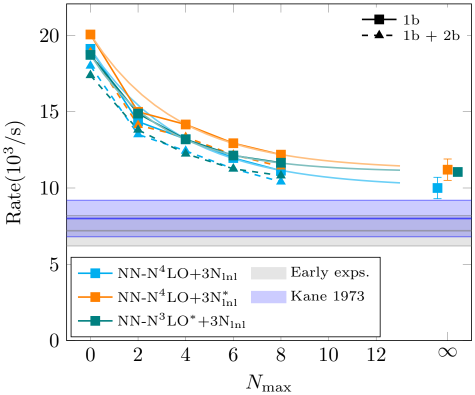

LJ, Navrátil, Kotila, Kravvaris, work in progress

Discovery, accelerated

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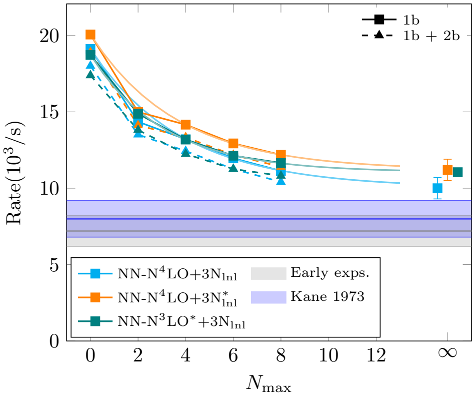
→ Forbidden β decay $^{16}N(2^-_{gs}) \rightarrow {}^{16}O(0^+_{gs}) + e^- + \bar{\nu}_e$ for beyond-standard model studies

$^{16}O(0^+_{gs}) + \mu^- \rightarrow {}^{16}N(2^-_{gs}) + \nu_\mu$



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→ Forbidden β decay $^{16}\mathrm{N}(2^-_{\mathrm{gs}}) \rightarrow {}^{16}\mathrm{O}(0^+_{\mathrm{gs}}) + e^- + \bar{\nu}_e$ for beyond-standard model studies

  - Ongoing experiment at SARAF, Israel

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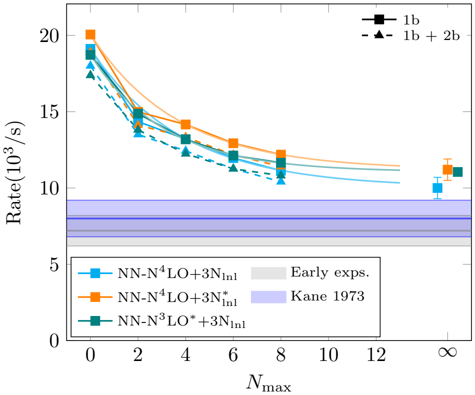

LJ, Navrátil, Kotila, Kravvaris,

work in progress

Discovery, accelerated

TRIUMF

Capture Rates to the ground state of ^{16}N

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  → Theory estimates based on NCSM

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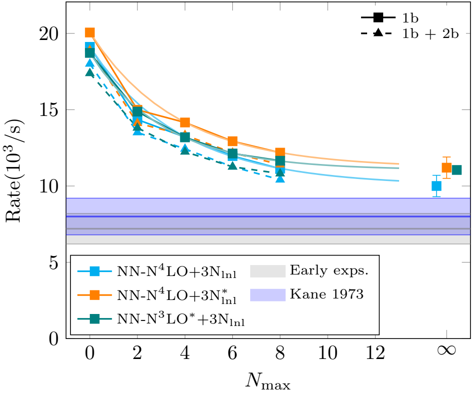

LJ, Navrátil, Kotila, Kravvaris,

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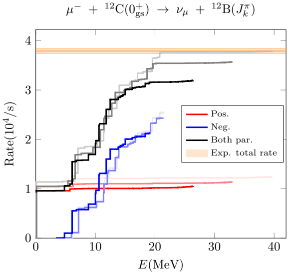
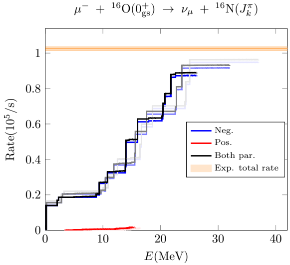
Total Muon-Capture Rates in ^{12}B and ^{16}N

- Color gradient: increasing $N_{\max}$ (3,5,7 for ^{12}C and 2,4,6 for ^{16}O)





LJ, Navrátil, Kotila, Kravvaris, work in progress

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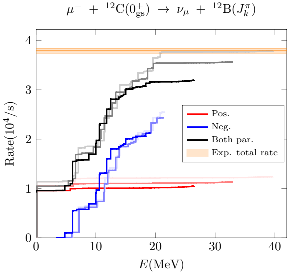

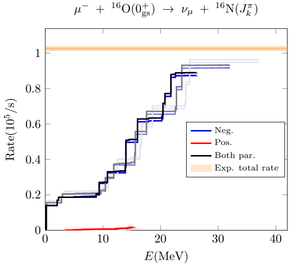

LJ, Navrátil, Kotila, Kravvaris, work in progress

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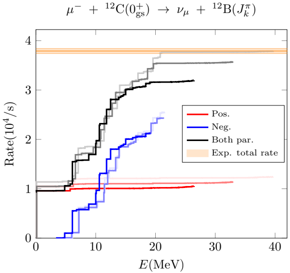
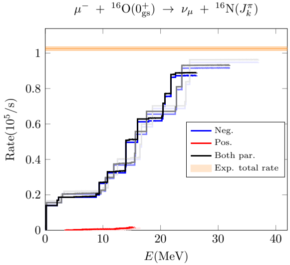
- Summing up **the rates up to ~ 20 MeV**, we capture **$\sim 85\%$ of the total rate** in both ^{12}B and ^{16}N





LJ, Navrátil, Kotila, Kravvaris, work in progress

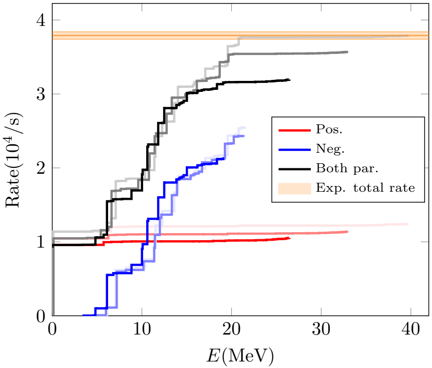
Discovery, accelerated

TRIUMF

Total Muon-Capture Rates

Calculation:

$$\mu^- + {}^{12}\mathrm{C}(0^+_{gs}) \rightarrow \nu_\mu + {}^{12}\mathrm{B}(J^\pi_k)$$



Experiment:

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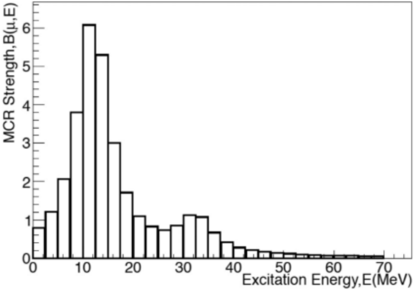

*Hashim et al., Phys. Rev. C **97**, 014617 (2018)*

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TRIUMF

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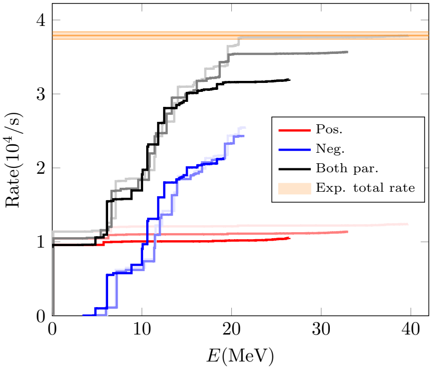

Missing potentially important contribution from high energies

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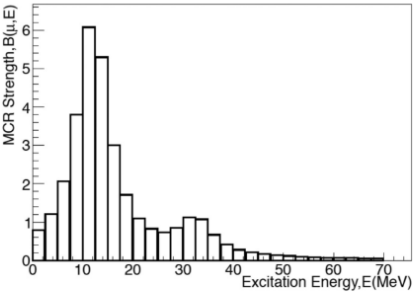

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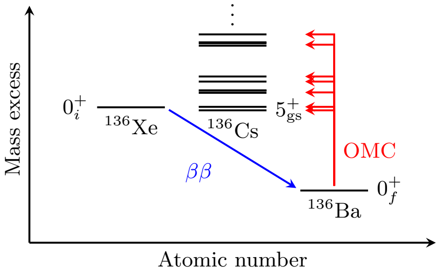
Discovery, accelerated

Outline

Muon capture on ^{136}Ba

- OMC on ^{136}Ba one of the candidates to be measured by the MONUMENT collaboration



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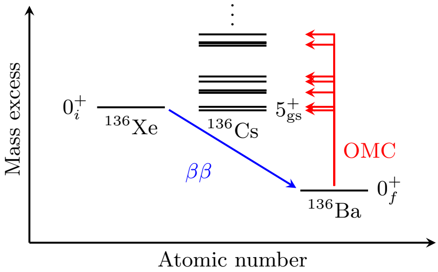

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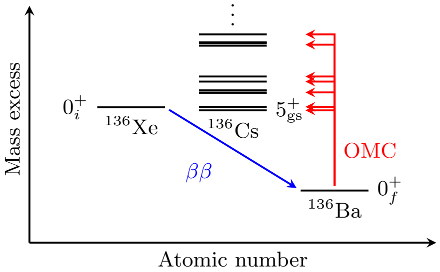

Discovery, accelerated

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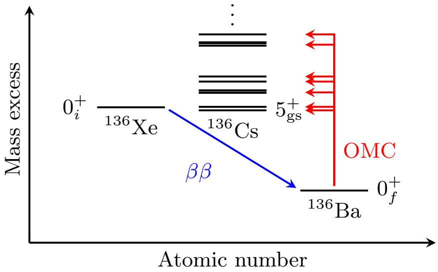

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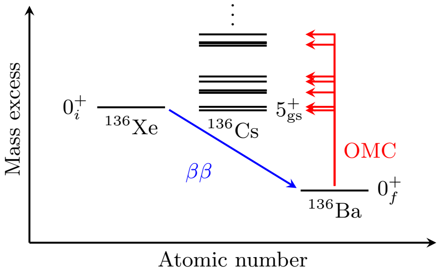
- Solution: (phenomenological) **nuclear shell model and proton-neutron QRPA**



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TRIUMF

Excitation energies in ^{136}Cs ($J \leq 5$)

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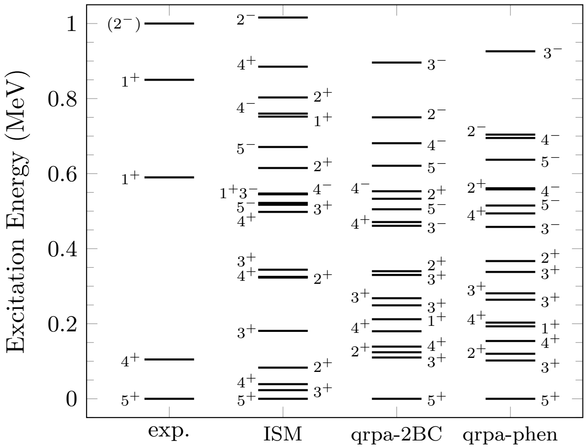

P. Gimeno, LJ, J. Kotila, M. Ramalho, J. Suhonen,

10.20944/preprints202304.0899.v1 (submitted to Universe)

Discovery, accelerated

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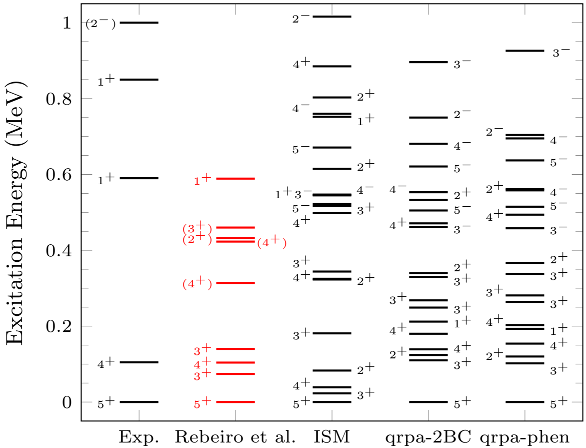
B. M. Rebeiro *et al.*, arXiv:2301.11371 (2023)



***P. Gimeno**, LJ, J. Kotila, M. Ramalho, J. Suhonen,*

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Discovery, accelerated

Muon capture rates to low-lying states in ^{136}Cs

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P. Gimeno, LJ, J. Kotila, M. Ramalho, J. Suhonen, 10.20944/preprints202304.0899.v1 (submitted to Universe)

	Rate (1b)$(10^3 1/s)$	Rate (1b+2b)$(10^3 1/s)$	Rate (1b+2b) / Total rate
NSM	248	$150 - 174$	$1.4 - 1.5\%$
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TRIUMF

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Discovery, accelerated

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Discovery, accelerated

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Discovery, accelerated

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- Similar study ongoing for OMC on ^{128,130}Xe

TRIUMF

Outline

Introduction

Corrections to $0\nu\beta\beta$-decay nuclear matrix elements

- The contact term
- Contribution of ultrasoft neutrinos

Muon capture as a probe of $0\nu\beta\beta$ decay

- VS-IMSRG Study on Muon Capture on ^{24}Mg
- No-Core Shell-Model Studies on Muon Capture on Light Nuclei
- Phenomenological study on muon capture on ^{136}Ba

Summary and Outlook

Discovery, accelerated

Summary

- Newly introduced contact term significantly enhances the $0\nu\beta\beta$-decay NMEs

TRIUMF

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Discovery, accelerated

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Discovery, accelerated

TRIUMF

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- Phenomenological methods still needed for heavy/difficult systems

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Outlook

- Study the effect of **vector two-body currents** (one-pion-exchange & pion-in-flight) on OMC rates

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TRIUMF

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Discovery, accelerated

TRIUMF

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Discovery, accelerated

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  - **^{12}C and ^{16}O** are both of interest in **neutrino-scattering experiments**

$$\left(\nu_\mu + {}^{12}\mathrm{C} \rightarrow \mu^- + {}^{12}\mathrm{N} \right)$$

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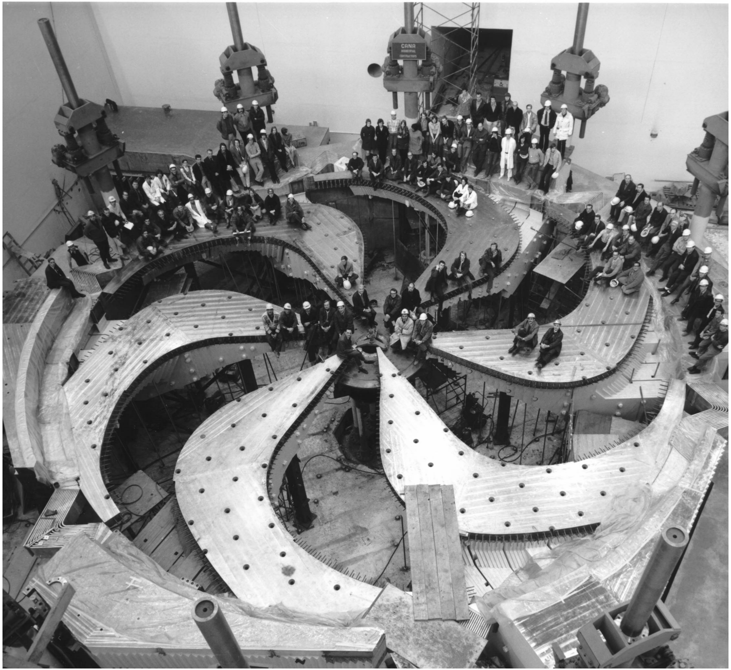
Thank you

Merci



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TRIUMF

OMC operators

- Rates written in terms of reduced one-body matrix elements:

$$(\Psi_f||\sum_{s=1}^{A}\hat{O}_{kwux}(\mathbf{r}_s,\mathbf{p}_s)||\Psi_i) = \frac{1}{\sqrt{2u+1}}\sum_{pn}(n||\hat{O}_{kwux}(\mathbf{r}_s,\mathbf{p}_s)||p)(\Psi_f||[a_n^\dagger \tilde{a}_p]_u||\Psi_i)$$

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Morita, Fujii, *Phys. Rev.* **118**, 606 (1960)

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TRIUMF

Axial-Vector Two-Body Currents (2BCs)

- One-body (1b) axial-vector currents given by

$$\mathbf{J}^3_{i,1\mathrm{b}} = \frac{\tau^3_i}{2}\left(g_\mathrm{A}\boldsymbol{\sigma}_i - \frac{g_\mathrm{P}}{2m_\mathrm{N}}\mathbf{q}\cdot\boldsymbol{\sigma}_i\right) ,$$

where $g_\mathrm{P} = (2m_\mathrm{N}q/(q^2+m_\pi^2))g_\mathrm{A}$

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- Additional **pion-exchange, pion-pole, and contact** two-body (2b) currents

Hoferichter, Klos, Schwenk *Phys. Lett. B* **746**, 410 (2015)

$$\begin{aligned}\mathbf{J}^3_{12} = &-\frac{g_\mathrm{A}}{2F_\pi^2}[\tau_1\times\tau_2]^3\left[c_4\left(1-\frac{\mathbf{q}}{\mathbf{q}^2+M_\pi}\mathbf{q}\cdot\right)(\boldsymbol{\sigma}_1\times\mathbf{k}_2)+\frac{c_6}{4}(\boldsymbol{\sigma}_1\times\mathbf{q})+i\frac{\mathbf{p}_1+\mathbf{p}_1'}{4m_\mathrm{N}}\right]\frac{\boldsymbol{\sigma}_2\cdot\mathbf{k}_2}{M_\pi^2+k_2^2}\\ &-\frac{g_\mathrm{A}}{F_\pi^2}\tau_2^3\left[c_3\left(1-\frac{\mathbf{q}}{\mathbf{q}^2+M_\pi}\mathbf{q}\cdot\right)\mathbf{k}_2+2c_1M_\pi^2\frac{\mathbf{q}}{\mathbf{q}^2+M_\pi^2}\right]\frac{\boldsymbol{\sigma}_2\cdot\mathbf{k}_2}{M_\pi^2+k_2^2}\\ &-d_1\tau_1^3\left(1-\frac{\mathbf{q}}{\mathbf{q}^2+M_\pi^2}\mathbf{q}\cdot\right)\boldsymbol{\sigma}_1+(1\leftrightarrow 2)-d_2(\tau_1\times\tau_2)^3(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\left(1-\cdot\mathbf{q}\frac{\mathbf{q}}{\mathbf{q}^2+M_\pi^2}\right)\end{aligned}$$

where $\mathbf{k}_i = \mathbf{p}_i' - \mathbf{p}_i$ and $\mathbf{q} = -\mathbf{k}_1 - \mathbf{k}_2$

Discovery, accelerated

Axial-Vector Two-Body Currents (2BCs)

- Approximate 2BCs by normal-ordering w.r.t. spin-isospin–symmetric reference state with $\rho = 2k_{\mathrm{F}}^3/(3\pi^2)$:

Hoferichter, Menéndez, Schwenk, *Phys. Rev. D* **102**,074018 (2020)

$$\mathbf{J}_{i,2\mathrm{b}}^{\mathrm{eff}} = \sum_j (1 - P_{ij}) \mathbf{J}_{ij}^3$$

TRIUMF

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$$\rightarrow \boxed{\mathbf{J}_{i,2\mathrm{b}}^{\mathrm{eff}} = g_\mathrm{A} \frac{\tau_i^3}{2} \left[\delta a(\mathbf{q}^2) \boldsymbol{\sigma}_i + \frac{\delta a^P(\mathbf{q}^2)}{\mathbf{q}^2} (\mathbf{q} \cdot \boldsymbol{\sigma}_i) \mathbf{q} \right]} ,$$

where

$$\delta_a(\mathbf{q}^2) = -\frac{\rho}{F_\pi^2} \left[\frac{c_4}{3} [3 I_2^\sigma(\rho, \mathbf{q}) - I_1^\sigma(\rho, |\mathbf{q}|)] - \frac{1}{3} \left(c_3 - \frac{1}{4m_\mathrm{N}} \right) I_1^\sigma(\rho, |\mathbf{q}|) - \frac{c_6}{12} I_{c6}(\rho, |\mathbf{q}|) - \frac{c_D}{4 g_A \Lambda_\chi} \right] ,$$

$$\delta_a^P(\mathbf{q}^2) = \frac{\rho}{F_\pi^2} \left[-2(c_3 - 2c_1) \frac{m_\pi^2 \mathbf{q}^2}{(m_\pi^2 + \mathbf{q}^2)^2} + \frac{1}{3} \left(c_3 + c_4 - \frac{1}{4m_\mathrm{N}} \right) I^P(\rho, |\mathbf{q}|) - \left(\frac{c_6}{12} - \frac{2}{3} \frac{c_1 m_\pi^2}{m_\pi^2 + \mathbf{q}^2} \right) I_{c6}(\rho, |\mathbf{q}|) \right.$$
$$\left. - \frac{\mathbf{q}^2}{m_\pi^2 + \mathbf{q}^2} \left(\frac{c_3}{3} [I_1^\sigma(\rho, |\mathbf{q}|) + I^P(\rho, |\mathbf{q}|)] + \frac{c_4}{3} [I_1^\sigma(\rho, |\mathbf{q}|) + I^P(\rho, |\mathbf{q}|) - 3 I_2^\sigma(\rho, |\mathbf{q}|)] \right) - \frac{c_D}{4 g_A \Lambda_\chi} \frac{\mathbf{q}^2}{m_\pi^2 + \mathbf{q}^2} \right]$$

Discovery, accelerated

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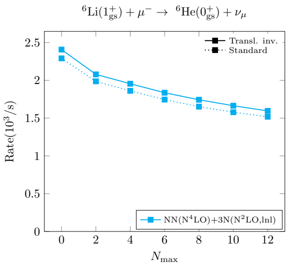
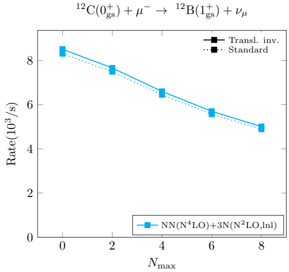
  - Working with A single-particle coordinates and separating the center-of-mass motion:

$$\Psi_{\text{SD}}^A = \sum_{N=0}^{N_{\max}} \sum_i c_{Nj}^{\text{SD}} \Phi_{\text{SD}\ Nj}^{\text{HO}}(\mathbf{r}_1, \mathbf{r}_2, ..., \mathbf{r}_A) = \Psi^A \Psi_{\text{CM}}(\mathbf{R}_{\text{CM}})$$

Removing Spurious Center-of-Mass Motion

- OMC operators depend on single-particle coordinates $\mathbf{r_s}$ and $\mathbf{p_s}$ w. r. t. the center of mass





LJ, Navrátil, Kotila and Kravvaris, in progress

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Navrátil, *Phys. Rev. C* **104**, 064322 (2021)

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$$= \frac{1}{\sqrt{2u+1}} \times \sum_{pnp'n'} (n' || \hat{O}_s \left(-\sqrt{\frac{A-1}{A}} \boldsymbol{\xi}_s, -\sqrt{\frac{A-1}{A}} \boldsymbol{\pi}_s \right) || p')$$

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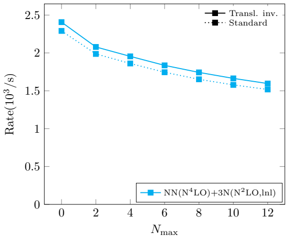
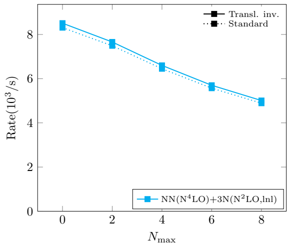


$^{12}\mathrm{C}(0^+_{\mathrm{gs}}) + \mu^- \to {}^{12}\mathrm{B}(1^+_{\mathrm{gs}}) + \nu_\mu$



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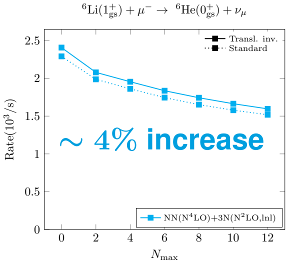

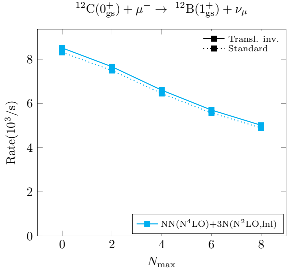

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Discovery, accelerated

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Navrátil, *Phys. Rev. C* **104**, 064322 (2021)

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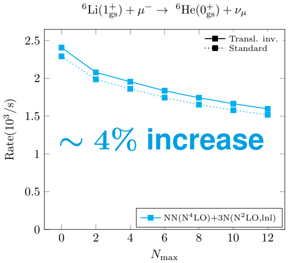

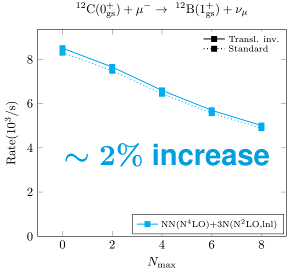

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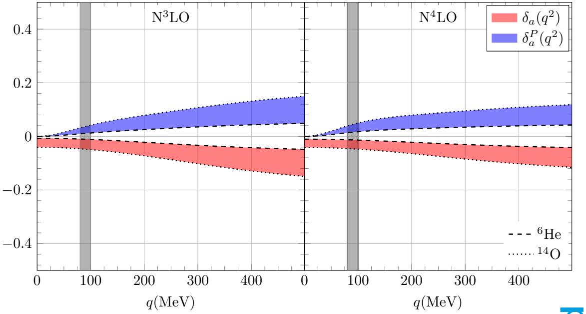
TRIUMF

Two-Body Currents

- Fermi-gas density ρ adjusted so that $\delta_a(0)$ reproduces the effect of exact two-body currents in

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



LJ, Navrátil, Kotila and Kravvaris, work in progress

Discovery, accelerated

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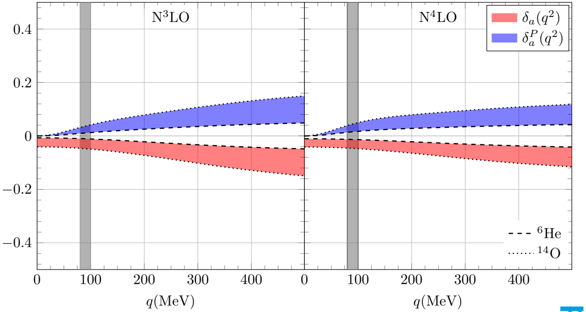

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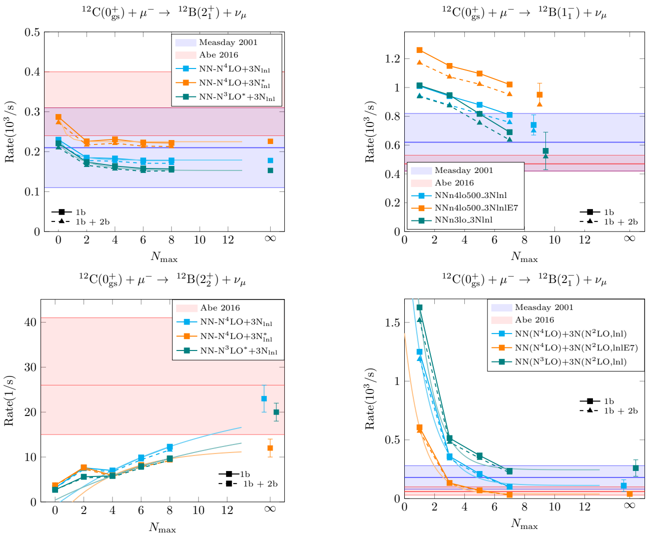
Capture Rates to Low-Lying States in ^{12}B

- Interaction dependence



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TRIUMF

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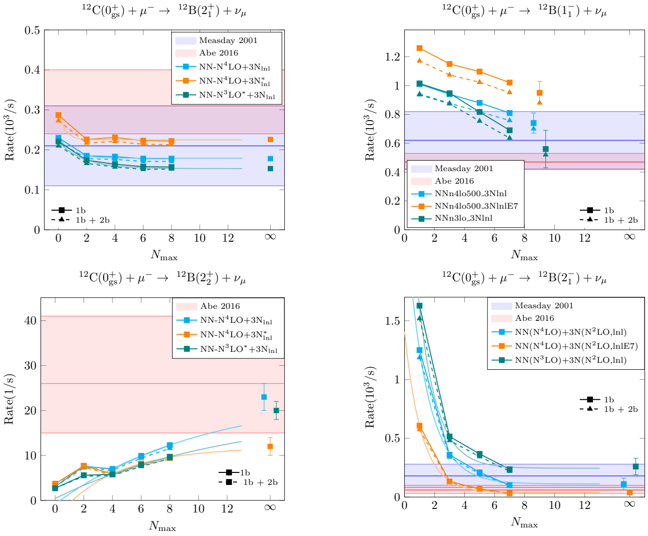
- Adding the E_7 spin-orbit term improves agreement with experiment



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Discovery, accelerated

Capture Rates to Low-Lying States in ^{16}N

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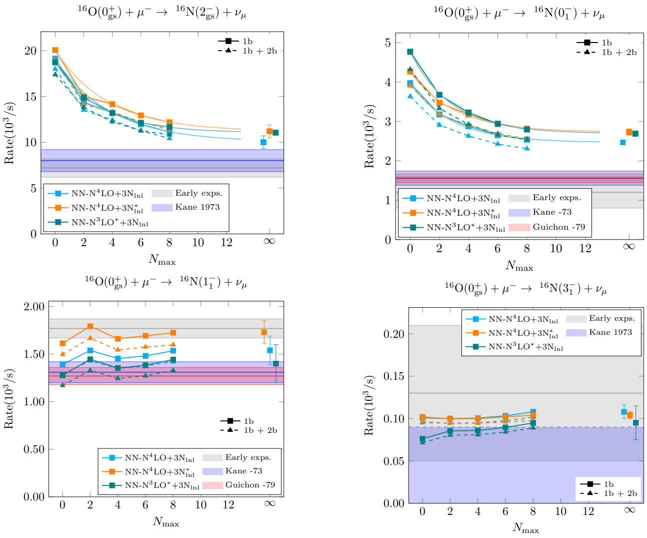

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Discovery, accelerated

TRIUMF

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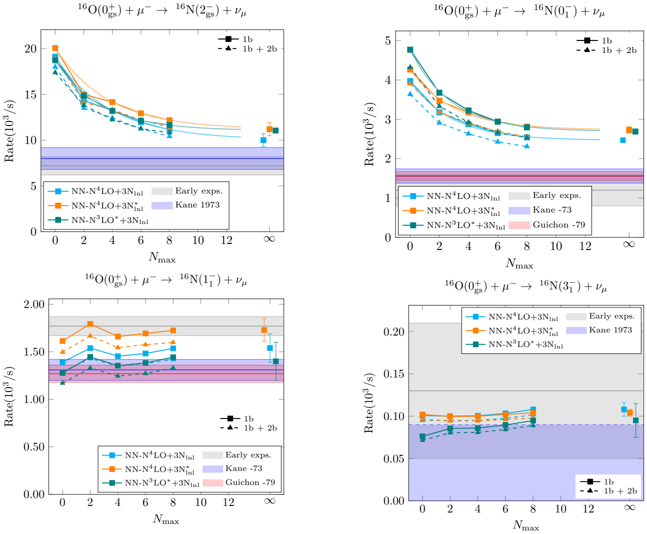

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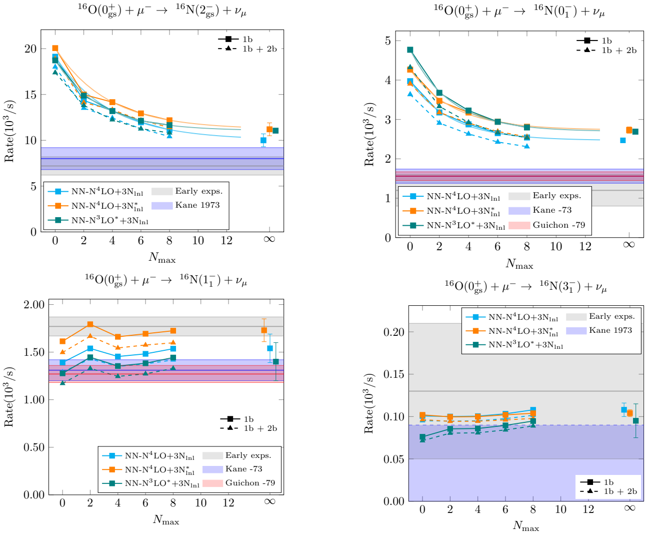

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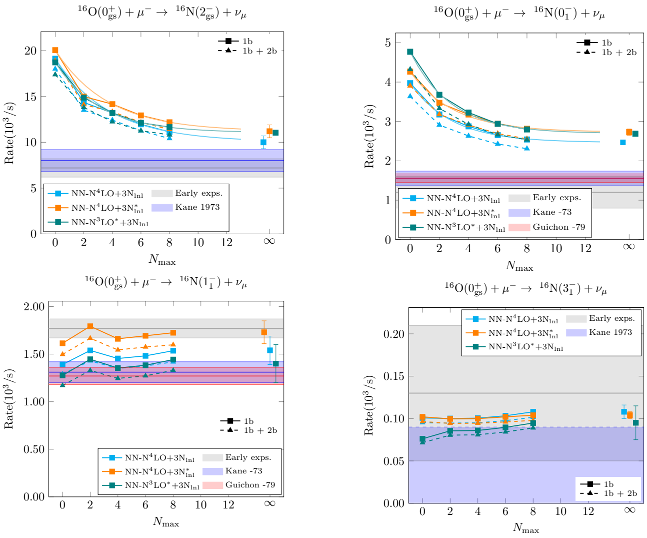

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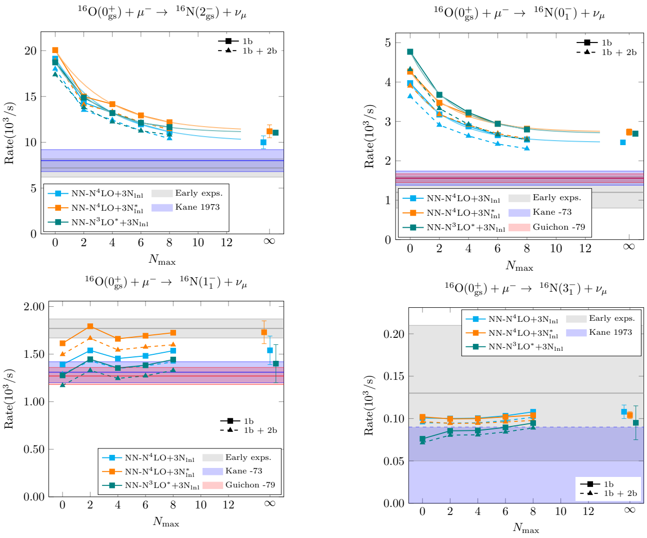

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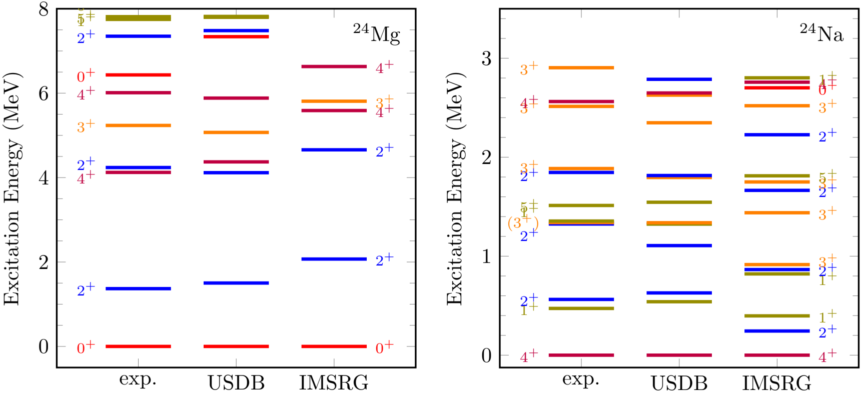
TRIUMF

Excitation Energies in the $A = 24$ Systems



Discovery, accelerated

Electromagnetic Moments in the $A = 24$ Systems

Nucleus	J_i^π	$E(\mathrm{MeV})$			$\mu(\mu_\mathrm{N})$			$Q(e^2\mathrm{fm}^2)$		
		exp.	NSM	IMSRG	exp.	NSM	IMSRG	exp.	NSM	IMSRG
^{24}Mg	2^+	1.369	1.502	1.981	1.08(3)	1.008	1.033	$-29(3)$	-19.346	-12.9
^{24}Mg	4^+	4.123	4.372	5.327	1.7(12)	2.021	2.096	-		
^{24}Mg	2^+	4.238	4.116	4.327	1.3(4)	1.011	1.085	-		
^{24}Mg	4^+	6.010	5.882	6.347	2.1(16)	2.015	2.089	-		
^{24}Na	4^+	0.0	0.0	0.0	1.6903(8)	1.533	1.485	-		
^{24}Na	1^+	0.472	0.540	0.397	$-1.931(3)$	-1.385	-0.344	-		

β Decays of the $A = 24$ Systems

Nucleus	$J_i \to J_f$	log ft		
		exp.	NSM	IMSRG
^{24}Na	$1_1^+ \to 0_1^+$	5.80	5.188–5.223	4.448–4.545
^{24}Na	$4_{gs}^+ \to 4_1^+$	6.11	5.416–5.461	5.795–5.866
^{24}Na	$4_{gs}^+ \to 3_1^+$	6.60	5.727–5.773	6.342–6.422

TRIUMF

Excitation Energies of ^{12}B

J_i^π	Interaction	$E_{\text{exc.}}$ (MeV)			
		$N_{\text{max}} = 4$	$N_{\text{max}} = 6$	$N_{\text{max}} = 8$(IT)	Exp.
1_1^+	NN(N^4LO)-3Nlnl	0.0	0.0	0.0	0.0
	NN(N^4LO)-3NlnlE7	0.135	0.000	0.000	
2_1^+	NN(N^4LO)-3Nlnl	0.251	0.465	0.538	0.953
	NN(N^4LO)-3NlnlE7	0.000	0.027	0.097	
0_1^+	NN(N^4LO)-3Nlnl	2.073	1.831	1.713	2.723
	NN(N^4LO)-3NlnlE7	3.306	2.909	2.761	
2_2^+	NN(N^4LO)-3Nlnl	3.816	3.490	3.344	3.760
	NN(N^4LO)-3NlnlE7	4.919	4.463	4.281	

Discovery,
accelerated

TRIUMF

Excitation Energies of ^{16}N

J_i^π	Interaction	$E_{\text{exc.}}$ (MeV) $N_{\max}=4$	$N_{\max}=6$	$N_{\max}=8$(IT)	Exp.
2_1^-	NN(N^{4}LO)-3NlnL	0.154	0.087	0.064	0.0
	NN(N^{4}LO)-3NlnlE7	0.214	0.146	0.133	
0_1^-	NN(N^{4}LO)-3Nlnl	2.245	1.487	1.010	0.120
	NN(N^{4}LO)-3NlnlE7	2.807	2.065	1.606	
3_1^-	NN(N^{4}LO)-3Nlnl	0.000	0.000	0.000	0.298
	NN(N^{4}LO)-3NlnlE7	0.000	0.000	0.000	
1_1^-	NN(N^{4}LO)-3Nlnl	2.561	1.833	1.363	0.397
	NN(N^{4}LO)-3NlnlE7	2.985	2.310	1.869	

Discovery, accelerated