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Ab initio studies on muon capture to probe neutrinoless double-beta decay

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TRIUMF, Theory Department

Celebrating 75 Years of the Nuclear Shell Model and Maria Goeppert-Mayer,
Argonne National Laboratory 20/07/2024

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Discovery, accelerated

Collaboration

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Outline

Introduction to double-beta decay

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

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

Summary and Outlook

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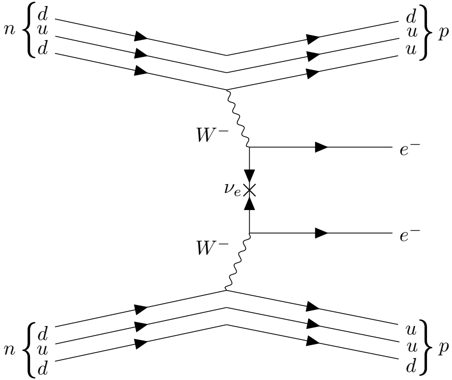
Neutrinoless double-beta decay via light neutrino exhange

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

- **Violates lepton-number conservation**



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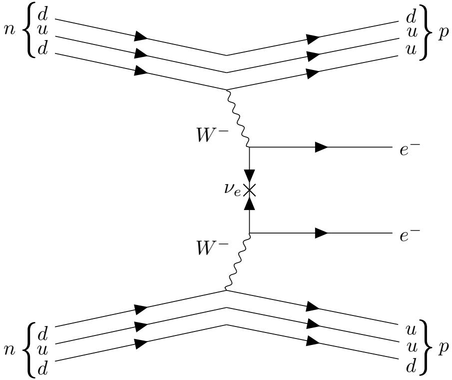
- Requires that **neutrinos are Majorana particles**



Discovery, accelerated

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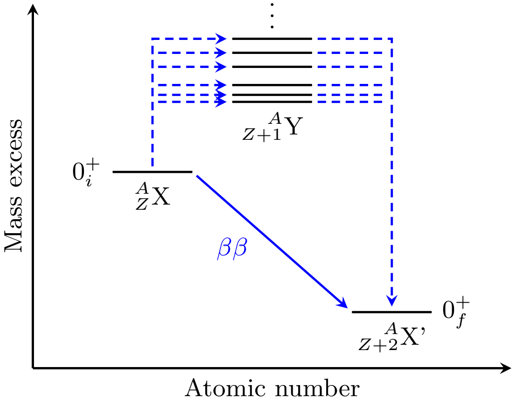

Discovery, accelerated

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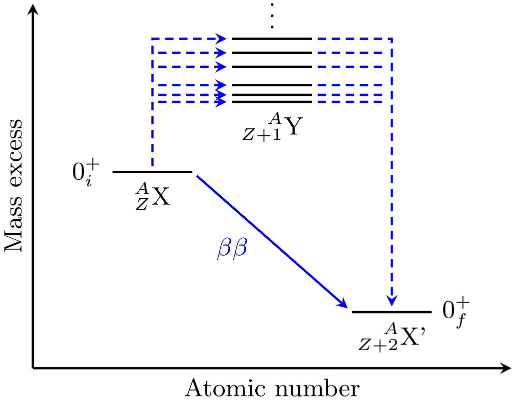

Discovery, accelerated

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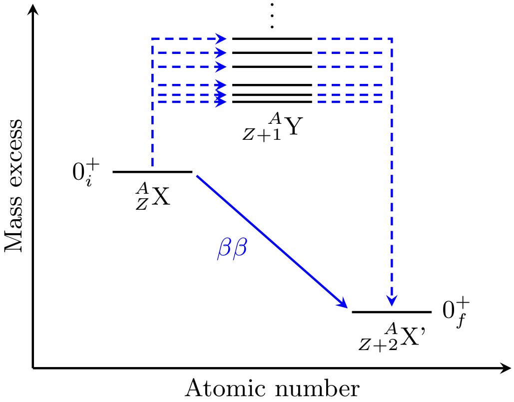

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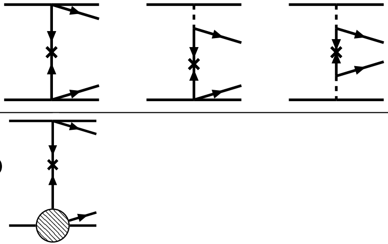
Effective-field-theory corrections to $0\nu\beta\beta$ decay

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

V. Cirigliano et al., Phys. Rev. C 97, 065501 (2018), Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)

LO

N^{2}LO



Effective-field-theory corrections to $0\nu\beta\beta$ decay

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M_L^{0\nu} + M_S^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

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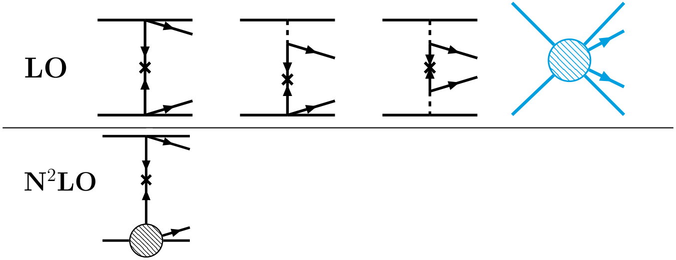

Effective-field-theory corrections to $0\nu\beta\beta$ decay

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M_L^{0\nu} + M_S^{0\nu} + M_{usoft}^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

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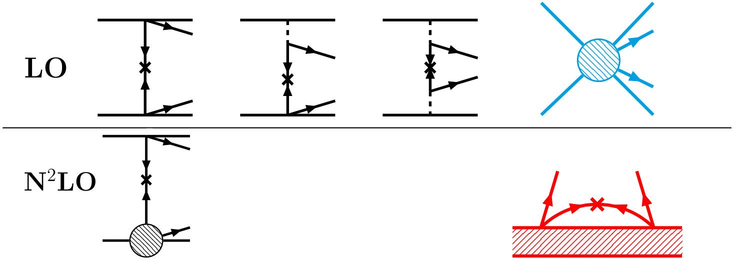

Effective-field-theory corrections to $0\nu\beta\beta$ decay

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} \left| M_L^{0\nu} + M_S^{0\nu} + M_{usoft}^{0\nu} + M_{loops}^{0\nu} \right|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2$$

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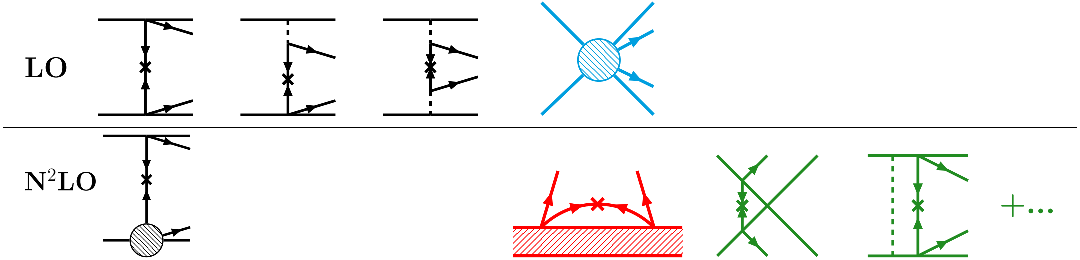

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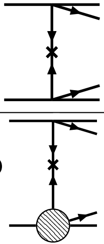
LO

N^{2}LO



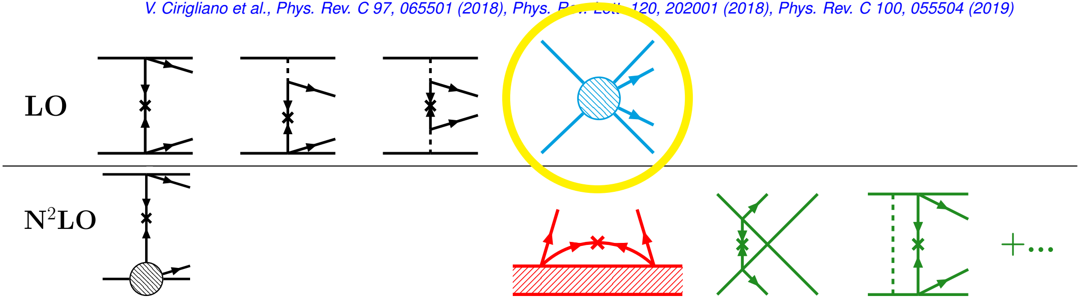
$$M_L^{0\nu} \propto \int \frac{d\mathbf{k}}{2\pi^2} \frac{\langle f | J_\mu(\mathbf{x}) J^\mu(\mathbf{y}) | i \rangle}{|\mathbf{k}|}$$

Discovery, accelerated

Leading-order short-range contribution to $0\nu\beta\beta$ decay

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} \left| M_L^{0\nu} + M_S^{0\nu} + M_{\text{usoft}}^{0\nu} + M_{N^2LO}^{0\nu} \right|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2$$

V. Cirigliano et al., Phys. Rev. C 97, 065501 (2018), Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)



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Contact Term in pnQRPA and NSM

- The contact term reads

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

with

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

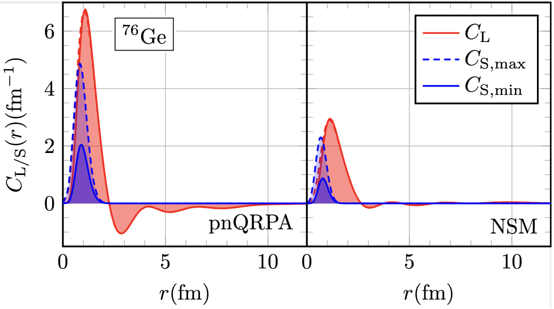
$$\int C_{L/S}(r)\mathrm{d}r = M_{L/S}^{0\nu}$$

In pnQRPA:

$M_S/M_L \approx 30\% - 80\%$

In NSM:

$M_S/M_L \approx 15\% - 50\%$

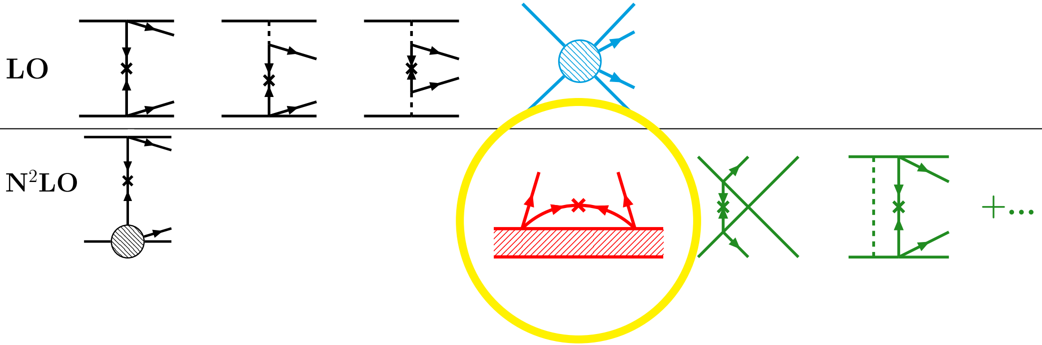


LJ, P. Soriano and J. Menéndez, Phys. Lett. B **823**, 136720 (2021)

Ultrasoft-neutrino contribution to $0\nu\beta\beta$ decay

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} \left| M_L^{0\nu} + M_S^{0\nu} + M_{usoft}^{0\nu} + M_{N^2LO}^{0\nu} \right|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

V. Cirigliano et al., Phys. Rev. C 97, 065501 (2018), Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)

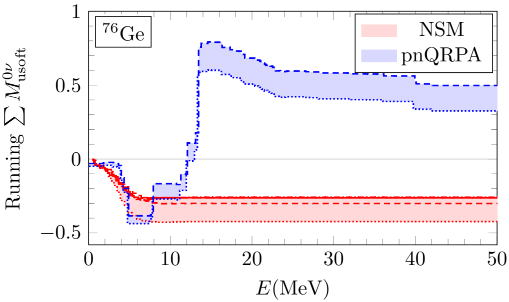


Ultrasoft neutrinos in pnQRPA and nuclear shell model

- Contribution of ultrasoft neutrinos ($|\mathbf{k}| << k_{\mathrm{F}} \approx 100$ **MeV**) to $0\nu\beta\beta$ decay:

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

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



LJ, D. Castillo, P. Soriano, J. Menéndez, in preparation

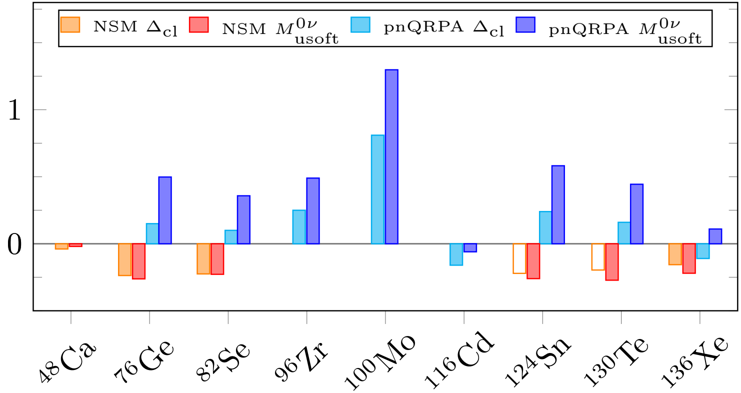
In pnQRPA:

$|M^{0\nu}_{\mathrm{usoft}}/M^{0\nu}_{\mathrm{L}}| \leq 30\%$

In NSM:

$|M^{0\nu}_{\mathrm{usoft}}/M^{0\nu}_{\mathrm{L}}| \leq 10\%$

Ultrasoft Neutrinos as Closure Correction



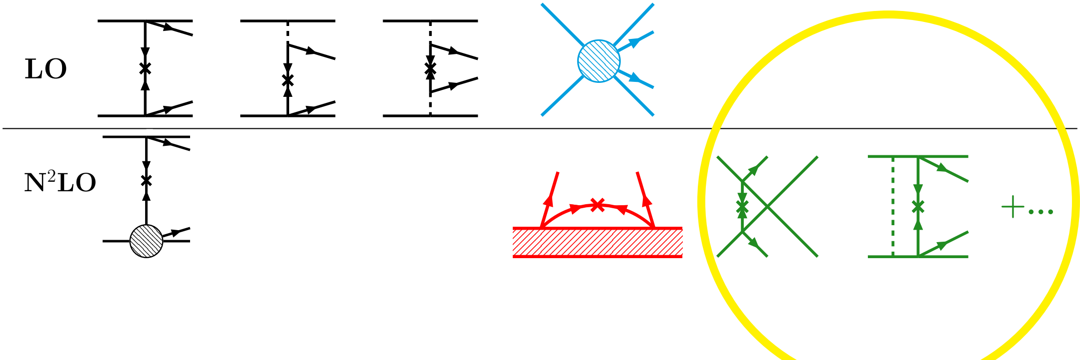
$$\Delta_{\rm cl} = M^{0\nu}_{\rm non-cl} - M^{0\nu}_{\rm cl}$$

LJ, D. Castillo, P. Soriano, J. Menéndez, in preparation

Genuine N^{2}LO corrections to $0\nu\beta\beta$ decay

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M_L^{0\nu} + M_S^{0\nu} + M_{\text{usoft}}^{0\nu} + M_{\text{N}^2\text{LO}}^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

V. Cirigliano et al., Phys. Rev. C 97, 065501 (2018), Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)



Genuine N^2LO Loop Corrections

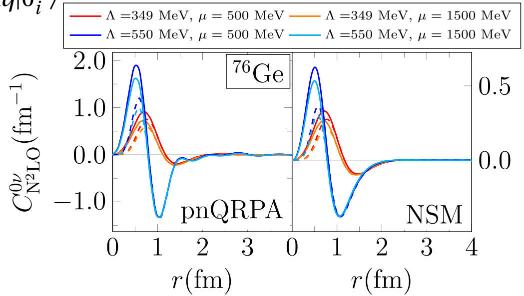
- The genuine N^2LO loop corrections read as

$$M^{0\nu}_{\text{loops}} = \frac{4R}{\pi g_A^2}\langle 0_f^+|\sum_{m,n}\tau_m^-\tau_n^-\int e^{-\frac{q^2}{2\Lambda^2}} j_u(qr)\, V_{\nu,2}^{(m,n)}\, q^2 dq|0_i^+\rangle$$

with

$$V_{\nu,2}^{(m,n)} = V_{\text{VV}}^{(m,n)} + V_{\text{AA}}^{(m,n)} + \ln\frac{m_\pi^2}{\mu_{\text{us}}^2} V_{\text{us}}^{(m,n)} + V_{\text{CT}}^{(m,n)}$$

$$\int C^{0\nu}_{\text{N}^2\text{LO}}(r)\,\mathrm{d}r = M^{0\nu}_{\text{loops}}$$



LJ, D. Castillo, P. Soriano, J Menéndez, in preparation

In pnQRPA:

$|M_{\text{N}^2\text{LO}}/M_{\text{L}}| \approx 2\% - 10\%$

In NSM:

$|M_{\text{N}^2\text{LO}}/M_{\text{L}}| \approx 4\% - 10\%$

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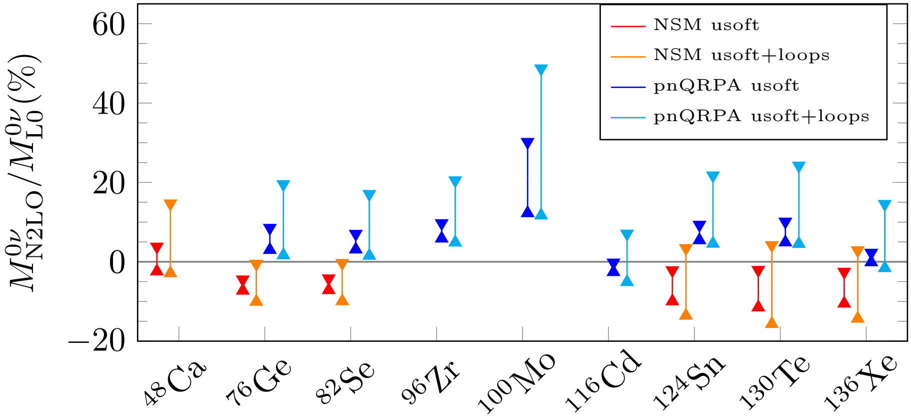
Complete N^2LO Corrections



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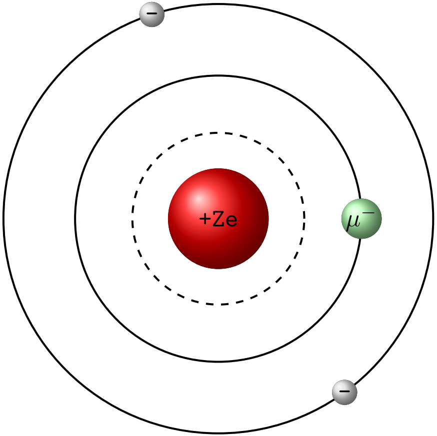
Ordinary Muon Capture (OMC)

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



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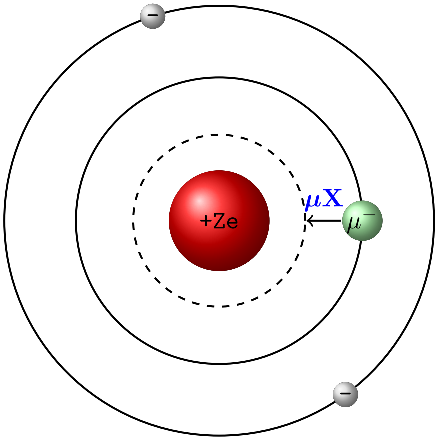

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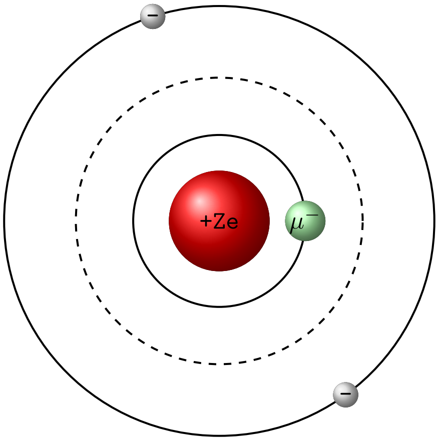

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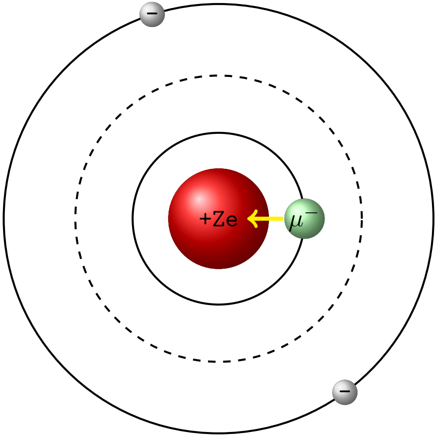
- The *muon can then be captured* by the nucleus

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



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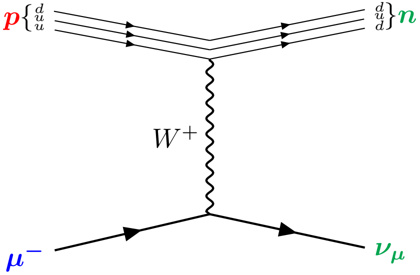

Discovery, accelerated

Ordinary Muon Capture (OMC)

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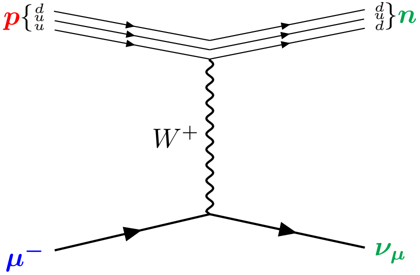


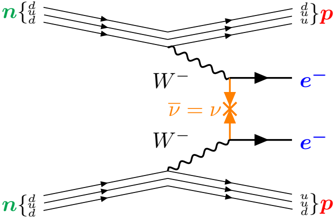
Ordinary = non-radiative

(Radiative muon capture (RMC):

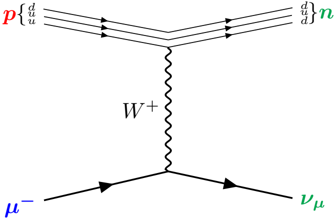
$$\mu^- + {}^{A}_{Z}\mathrm{X}(J_i^{\pi_i}) \rightarrow \nu_\mu + {}^{A}_{Z-1}\mathrm{Y}(J_f^{\pi_f}) + \gamma$$
)

Discovery, accelerated

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



$$ {}^{A}_{Z}\mathrm{X}(J_i^{\pi_i}) \rightarrow {}^{A}_{Z+2}\mathrm{X}'(J_f^{\pi_f}) + 2e^- $$



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

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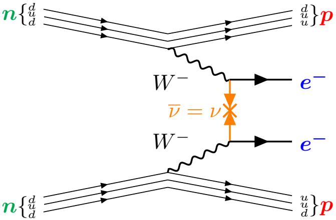
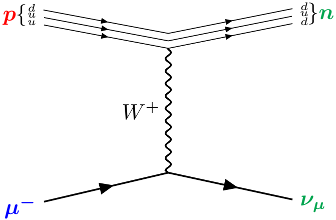
$0\nu\beta\beta$ Decay vs. Muon Capture



$${}^{A}_{Z}\mathrm{X}(J_i^{\pi_i}) \rightarrow {}^{\quad A}_{Z+2}\mathrm{X}'(J_f^{\pi_f}) + 2e^-$$



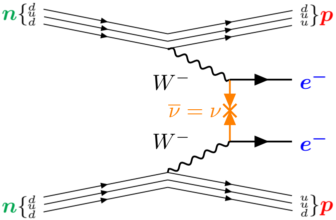
$$\mu^- + {}^{A}_{Z}\mathrm{X}(J_i^{\pi_i}) \rightarrow \nu_\mu + {}^{\quad A}_{Z-1}\mathrm{Y}(J_f^{\pi_f})$$

Both involve hadronic current:

$$\langle \boldsymbol{p} | j^{\alpha\dagger} | \boldsymbol{p} \rangle = \bar{\Psi}\left[g_{\mathrm{V}}(q^2)\gamma^\alpha - g_{\mathrm{A}}(q^2)\gamma^\alpha\gamma_5 - g_{\mathrm{P}}(q^2)q^\alpha\gamma_5 + i g_{\mathrm{M}}(q^2)\frac{\sigma^{\alpha\beta}}{2m_p}q_\beta \right]\tau^\pm\Psi$$

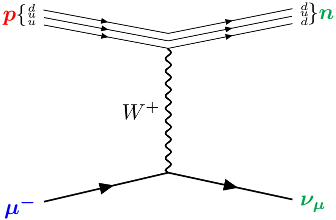
Discovery, accelerated

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



$$^{A}_{Z}\mathrm{X}(J_i^{\pi_i}) \rightarrow \; _{Z+2}{}^{A}\mathrm{X}'(J_f^{\pi_f}) + 2e^-$$

- $q \approx 1/|\mathbf{r}_1 - \mathbf{r}_2| \approx 100 - 200$ MeV



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

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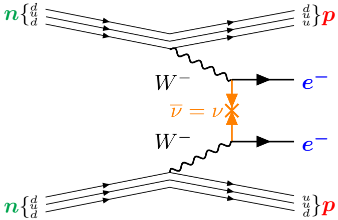
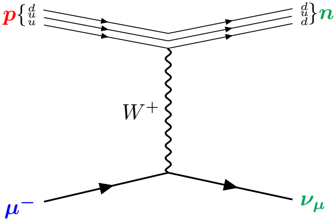
$0\nu\beta\beta$ Decay vs. Muon Capture



$$ {}^A_Z X(J_i^{\pi_i}) \rightarrow {}^{\;\;A}_{Z+2}X'(J_f^{\pi_f}) + 2e^- $$

- $\boldsymbol{q} \approx \mathbf{1/|r_1 - r_2| \approx 100-200}$ **MeV**



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

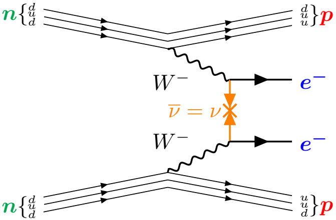
- $\boldsymbol{q} \approx m_\mu + M_i - M_f - m_e - E_X \approx \mathbf{100}$ **MeV**

Both involve hadronic current:

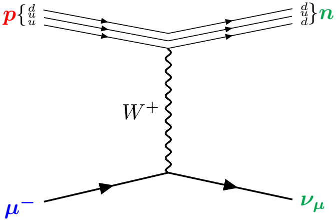
$$ \langle \boldsymbol{p} | j^{\alpha\dagger} | \boldsymbol{p} \rangle = \bar{\Psi} \left[g_V(q^2)\gamma^\alpha - g_A(q^2)\gamma^\alpha\gamma_5 - g_P(q^2)q^\alpha\gamma_5 + i g_M(q^2)\frac{\sigma^{\alpha\beta}}{2m_p}q_\beta \right] \tau^\pm \Psi $$

Discovery, accelerated

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



$$ {}^{A}_{Z}\mathrm{X}(J_i^{\pi_i}) \rightarrow \; {}^{\;\;\;A}_{Z+2}\mathrm{X}'(J_f^{\pi_f}) + 2e^- $$



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

- $q \approx 1/|\mathbf{r}_1 - \mathbf{r}_2| \approx 100 - 200$ **MeV**
- **Yet hypothetical**

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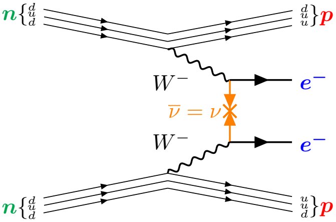

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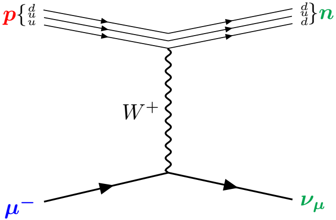

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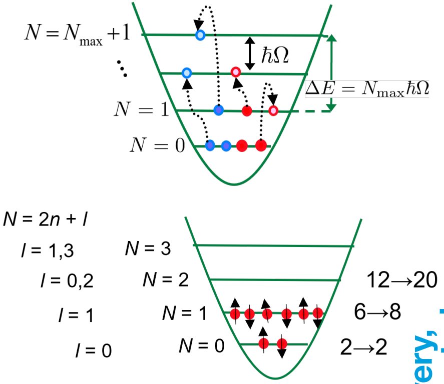
Discovery, accelerated

Ab initio No-Core Shell Model (NCSM)

- Solve nuclear many-body problem

$$H^{(A)}\Psi^{(A)}(\mathbf{r}_1,\mathbf{r}_2,\ldots,\mathbf{r}_A) = E^{(A)}\Psi^{(A)}(\mathbf{r}_1,\mathbf{r}_2,\ldots,\mathbf{r}_A)$$



$$E = (2n + l + \tfrac{3}{2})\hbar\Omega$$

Figure courtesy of P. Navrátil

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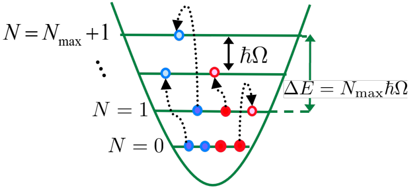
- **Two- (NN)** and **three-nucleon (3N)** forces from χEFT

$$H^{(A)} = \sum_{i=1}^{A}\frac{p_i^2}{2m} + \sum_{i<j=1}^{A} V^{NN}(\mathbf{r}_i - \mathbf{r}_j) + \sum_{i<j<k=1}^{A} V_{ijk}^{3N}$$



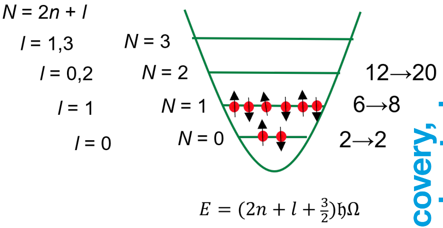


Figure courtesy of P. Navrátil

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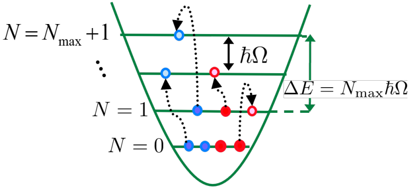
- Expansion in harmonic oscillator (HO) basis

$$\Psi^{(A)} = \sum_{N=0}^{N_{\max}}\sum_{j} c_{Nj}\Phi^{\mathrm{HO}}_{Nj}(\mathbf{r}_1,\mathbf{r}_2,\ldots,\mathbf{r}_A)$$



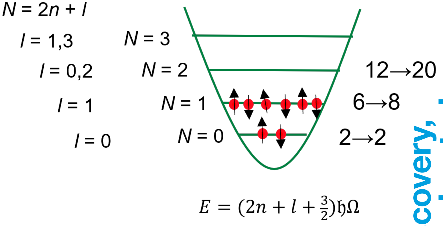


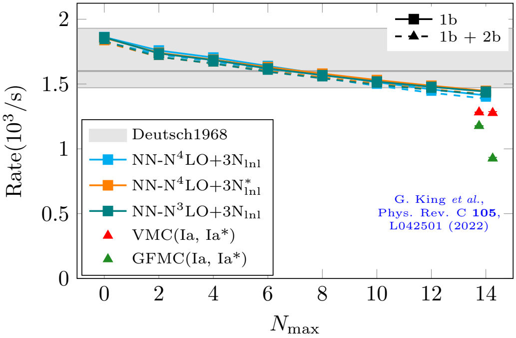
Figure courtesy of P. Navrátil

Discovery, accelerated

Muon Capture on ^{6}Li

- NCSM slightly underestimating experiment

$$^6\mathrm{Li}(1^+_{\mathrm{gs}}) + \mu^- \rightarrow \; ^6\mathrm{He}(0^+_{\mathrm{gs}}) + \nu_\mu$$



LJ, Navrátil, Kotila, Kravvaris,

Phys. Rev. C 109, 065501 (2024)

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

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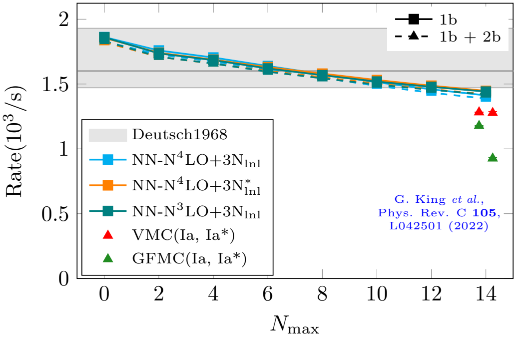

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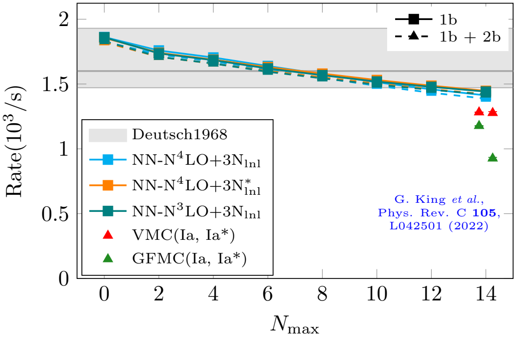

LJ, Navrátil, Kotila, Kravvaris, Phys. Rev. C 109, 065501 (2024)

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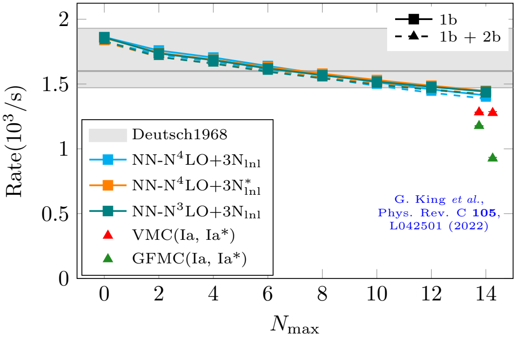
- Slow convergence due to cluster-structure?
  - **NCSM with continuum (NCSMC) might give better results?**



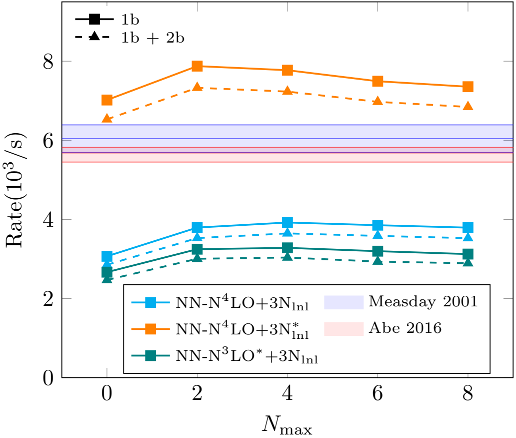
LJ, Navrátil, Kotila, Kravvaris, Phys. Rev. C 109, 065501 (2024)

TRIUMF

Muon capture on ^{12}C

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

- The **NN-N^{4}LO+3N$^*_{\mathrm{lnl}}$** interaction with the additional spin-orbit 3N-force term most consistent with experiment



LJ, Navrátil, Kotila, Kravvaris,

Phys. Rev. C 109, 065501 (2024)

Discovery, accelerated

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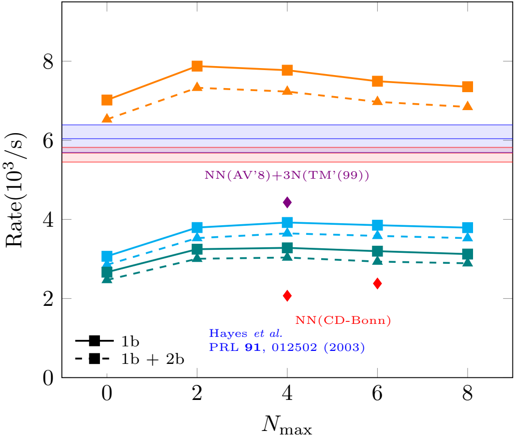
Hayes *et al.*, *Phys. Rev. Lett.* **91**, 012502 (2003)



LJ, Navrátil, Kotila, Kravvaris, Phys. Rev. C 109, 065501 (2024)

Discovery, accelerated

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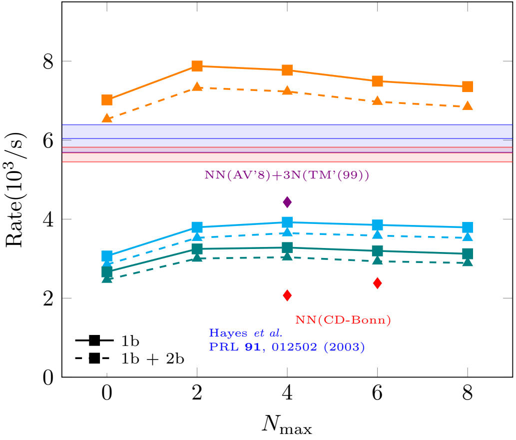
- 3N-forces essential to reproduce the measured rate



LJ, Navrátil, Kotila, Kravvaris,
Phys. Rev. C 109, 065501 (2024)

Discovery, accelerated

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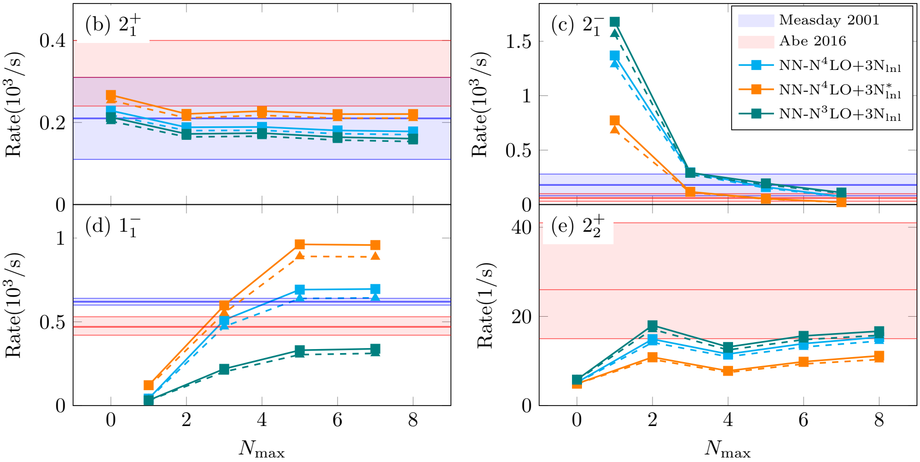
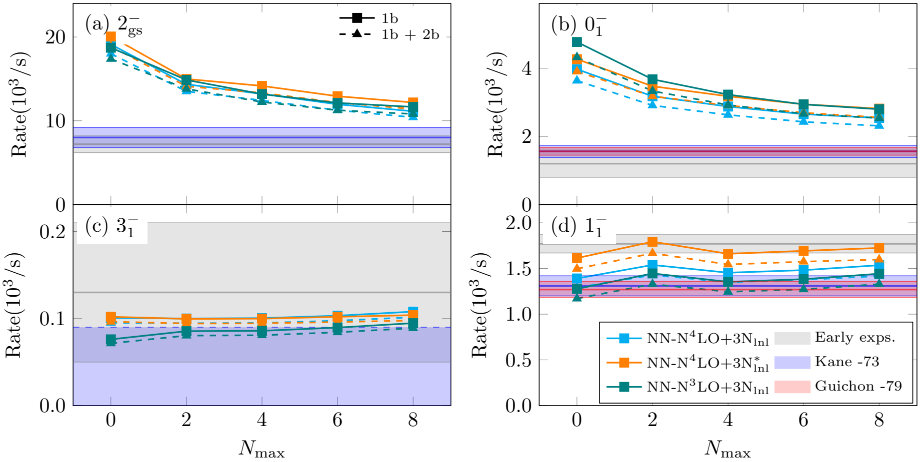


LJ, Navrátil, Kotila, Kravvaris, Phys. Rev. C 109, 065501 (2024)

TRIUMF

Muon capture on ^{16}O

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

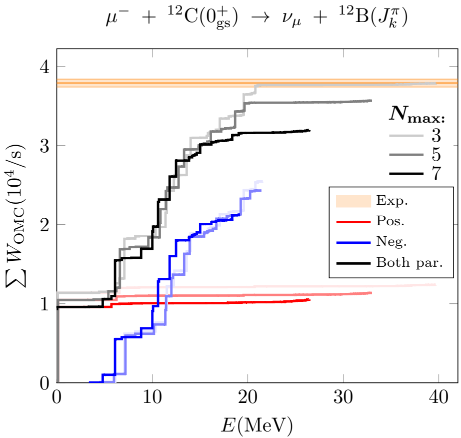


LJ, Navrátil, Kotila, Kravvaris, Phys. Rev. C 109, 065501 (2024)

Discovery, accelerated

Total Muon-Capture Rates

- Rates obtained summing over ~ 50 final states of each parity



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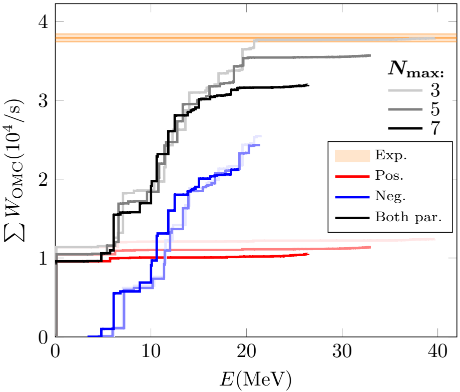

TRIUMF

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- Better estimation with the Lanczos strength function method underway

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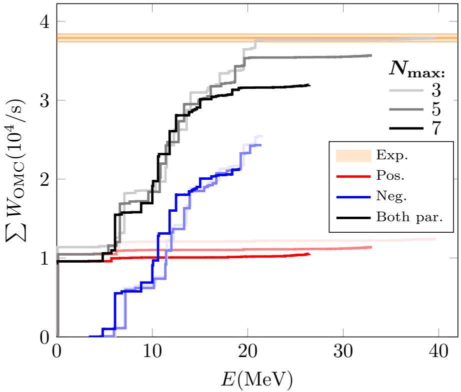

Discovery, accelerated

Outline

Discovery, accelerated

Summary

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TRIUMF

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- The no-core shell model describes well the muon-capture rates in light nuclei, ^{6}Li, ^{12}C and ^{16}O

TRIUMF

Outlook

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

Discovery, accelerated

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Discovery, accelerated

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Discovery, accelerated

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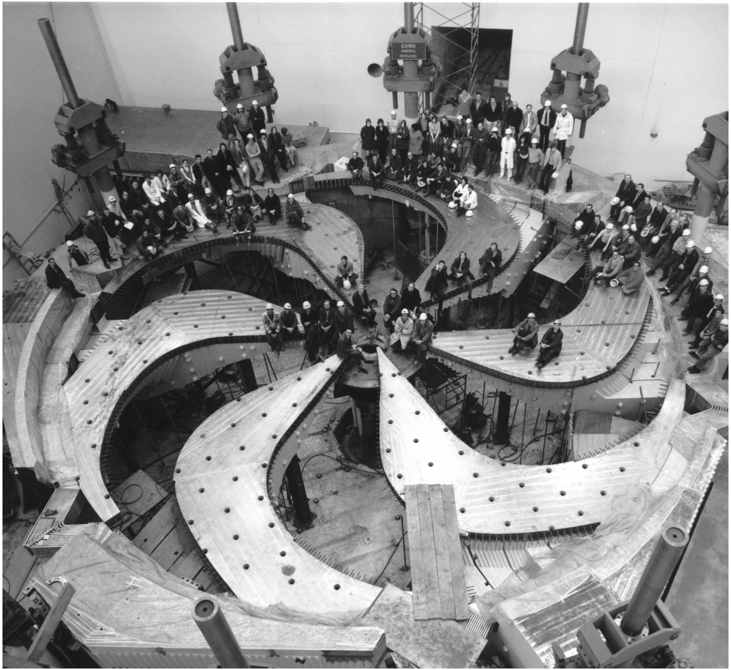
  - **^{16}N** potential candidate for **forbidden β-decay** studies (**ongoing**)
  - **^{12}C and ^{16}O** are both of interest in **neutrino-scattering experiments**

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

TRIUMF

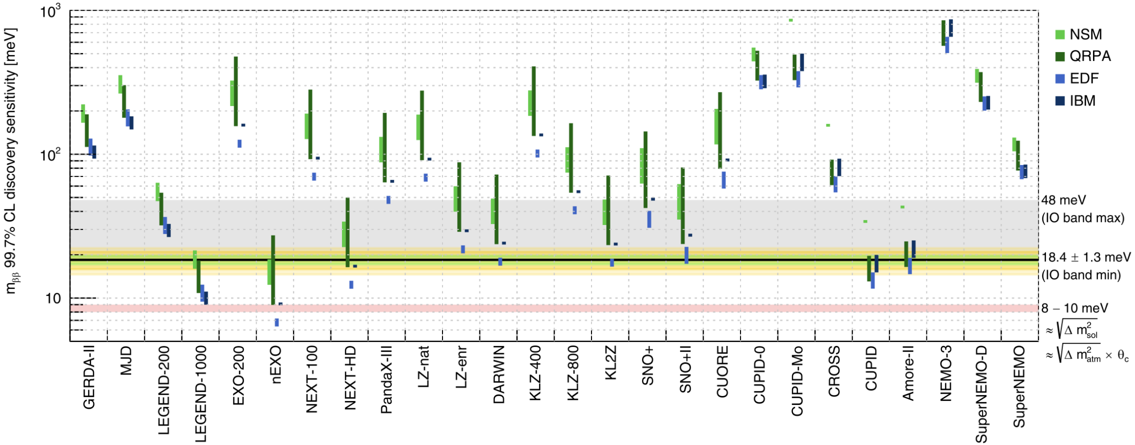
Thank you
Merci



Discovery, accelerated

TRIUMF

Next generation experiments



M. Agostini et al., Rev. Mod. Phys. ***95****, 025002 (2023)*

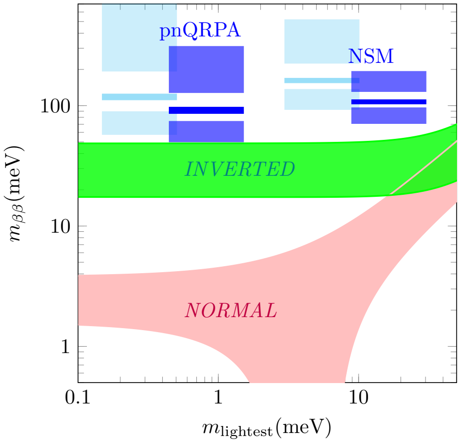
Disc accelerated

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: $M_L^{(0\nu)}$
  Lower bands: $M_L^{(0\nu)} + M_S^{(0\nu)}$
  Upper bands: $M_L^{(0\nu)} - M_S^{(0\nu)}$



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

TRIUMF

OMC operators

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

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

NME	$\hat{O}_{kwux}(\mathbf{r}_s,\mathbf{p}_s)$
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Morita, Fujii, *Phys. Rev.* **118**, 606 (1960)

Discovery, accelerated

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$\mathcal{M}[1\,w\,u\pm]$	$[j_w(qr_s)G_{-1}(r_s)\mp\frac{1}{q}j_{w\mp1}(qr_s)\frac{d}{dr_s}G_{-1}(r_s)]\mathcal{Y}_{1wu}^{M_f-M_i}(\hat{\mathbf{r}}_s,\boldsymbol{\sigma}_s)$
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Morita, Fujii, *Phys. Rev.* **118**, 606 (1960)

Dependency on the Harmonic-Oscillator Frequency

$$\Psi^{(A)} = \sum_{N=0}^{N_{\text{max}}} \sum_{j} c_{Nj} \Phi_{Nj}^{\text{HO}}(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_A)$$

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TRIUMF

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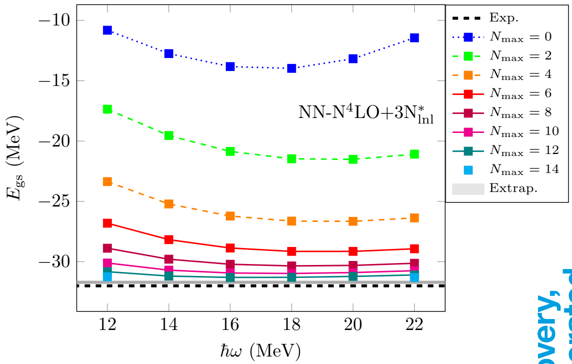
- The expansion depends on the HO frequency because of the $N_{\max}$ truncation
  - **Increasing $N_{\max}$ leads towards convergenced results**

Ground-state energy of ^{6}Li

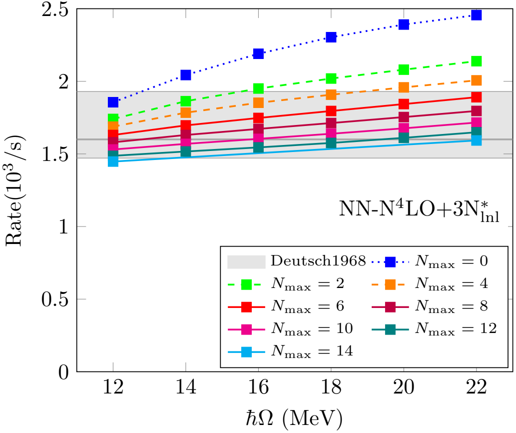


LJ, Navrátil, Kotila, Kravvaris, arXiv:2403.05776

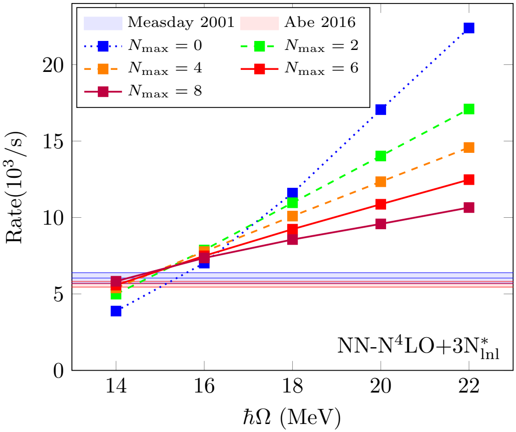
Discovery, accelerated

Harmonic-Oscillator Frequency Dependence of Muon Capture

$^{6}\mathrm{Li}(1^+_{\mathrm{gs}}) + \mu^- \rightarrow\ ^{6}\mathrm{He}(0^+_{\mathrm{gs}}) + \nu_\mu$



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



LJ, Navrátil, Kotila and Kravvaris, arXiv:2403.05776

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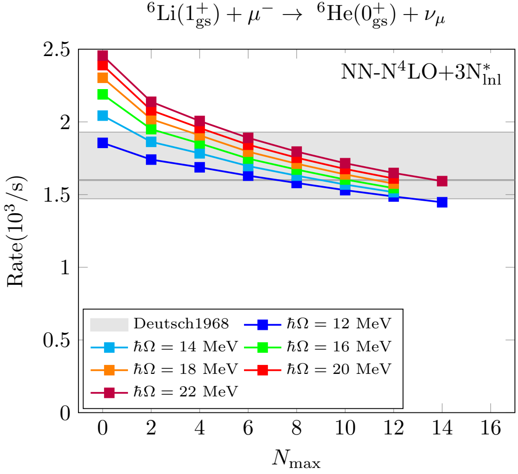

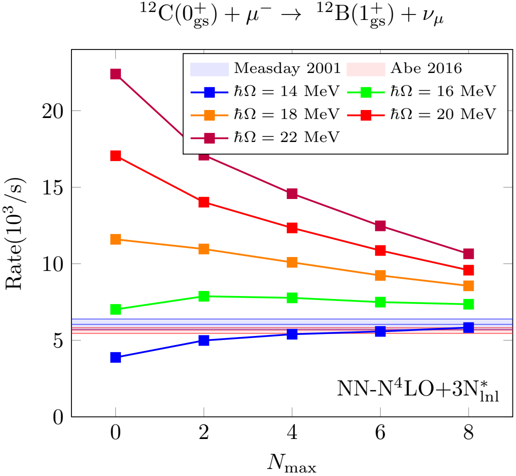

LJ, Navrátil, Kotila and Kravvaris, arXiv:2403.05776

Discovery, accelerated

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)

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

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

TRIUMF

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)

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

Discovery, accelerated

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

where

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

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

TRIUMF

Axial-Vector Two-Body Currents (2BCs)

- One-body currents

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

+ two-body currents

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

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

Discovery, accelerated

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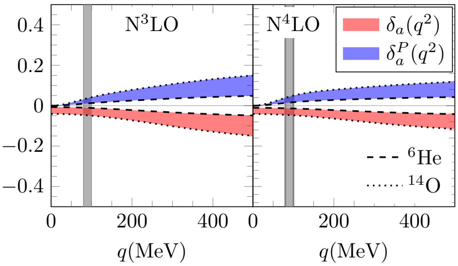
*Hoferichter, Klos, Schwenk Phys. Lett. B **746**, 410 (2015)*

- Two-body currents approximated by

$$\begin{cases} g_\mathrm{A}(q^2, 2\mathrm{b}) \to g_\mathrm{A}(q^2) + g_\mathrm{A}\boldsymbol{\delta_a(q^2)}, \\ g_\mathrm{P}(q^2, 2\mathrm{b}) \to g_\mathrm{P}(q^2) - \frac{2m_\mathrm{N} g_\mathrm{A}}{q} \boldsymbol{\delta^P_a(q^2)} \end{cases}$$



LJ, Navrátil, Kotila, Kravvaris, arXiv:2403:05776 (accepted to PRC)

Translationally invariant wave function

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TRIUMF

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Discovery, accelerated

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  - Working with $A-1$ Jacobi coordinates $\boldsymbol{\xi}_s = -\sqrt{A/(A-1)}(\mathbf{r}_s - \mathbf{R}_{\mathrm{CM}})$:

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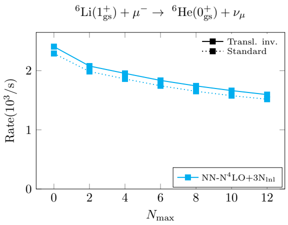
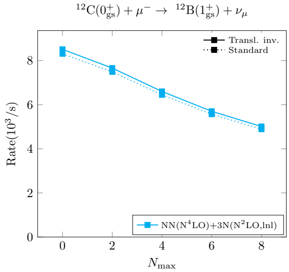
  - Working with A single-particle coordinates and separating the center-of-mass motion:

$$\Psi^A_{\rm SD} = \sum_{N=0}^{N_{\rm max}} \sum_i c^{\rm SD}_{Nj} \Phi^{\rm HO}_{{\rm SD}\; Nj}(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_A) = \Psi^A \Psi_{\rm CM}(\mathbf{R}_{\rm CM})$$

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





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

$$(\Psi_f||\sum_{s=1}^{A}\hat{O}_s(\mathbf{r}_s-\mathbf{R}_{\rm CM},\mathbf{p}_s-\mathbf{P})||\Psi_i)$$
$$=\frac{1}{\sqrt{2u+1}}\times\sum_{pnp'n'}(n'||\hat{O}_s\left(-\sqrt{\frac{A-1}{A}}\boldsymbol{\xi}_s,-\sqrt{\frac{A-1}{A}}\boldsymbol{\pi}_s\right)||p')$$
$$\times(M^u)^{-1}_{n'p',np}(\Psi_f|||[a^\dagger_n\tilde{a}_p]_u||\Psi_i)\,,$$

where

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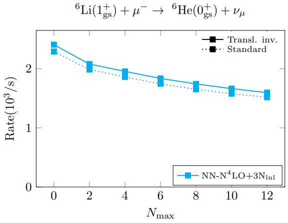

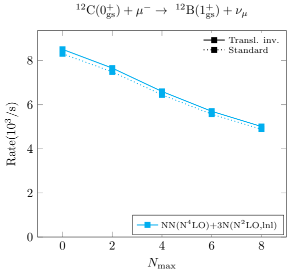

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Discovery, accelerated

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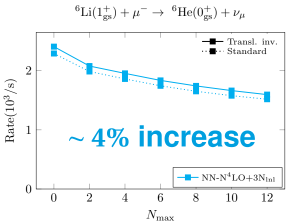

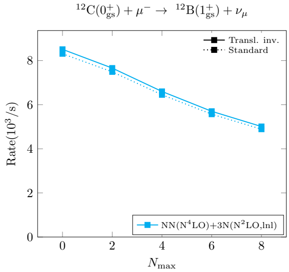

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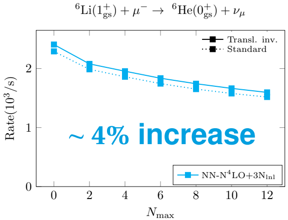

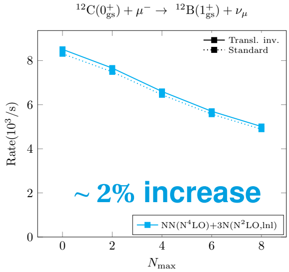

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