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

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PAINT2024 Workshop
29/02/2024

Discovery, accelerated

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Collaboration

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J. Kotila

Lawrence Livermore National Laboratory
K. Kravvaris

Outline

Introduction

Muon Capture from No-Core Shell Model

Results

- Muon capture on ^{6}Li
- Muon capture on ^{12}C
- Muon capture on ^{16}O

Summary

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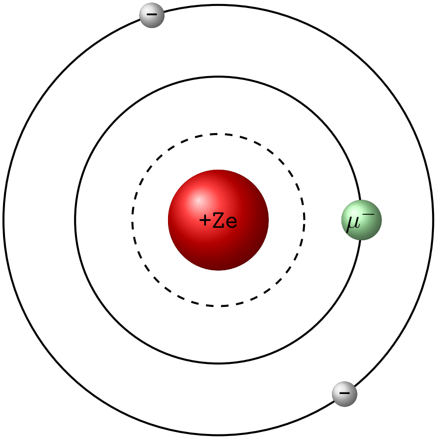
Ordinary Muon Capture (OMC)

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



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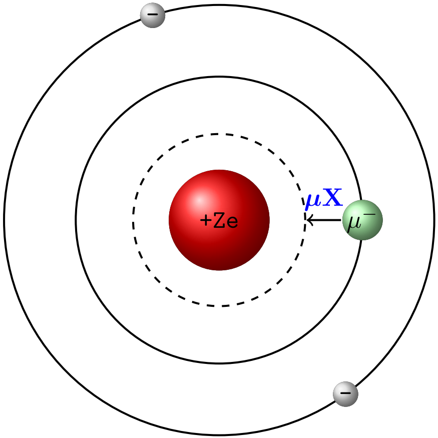

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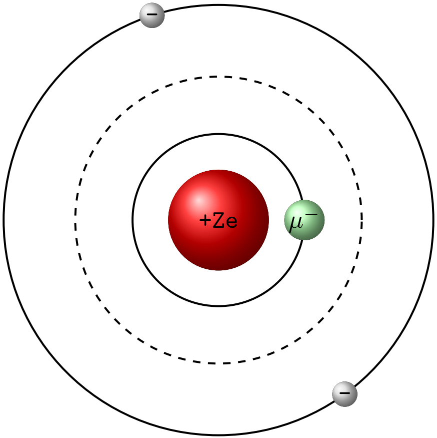
  - Eventually bound on **the $1s_{1/2}$ orbit**



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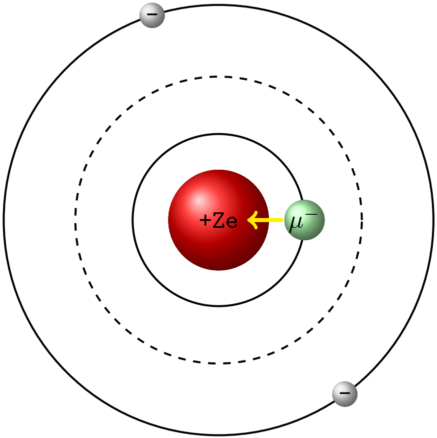

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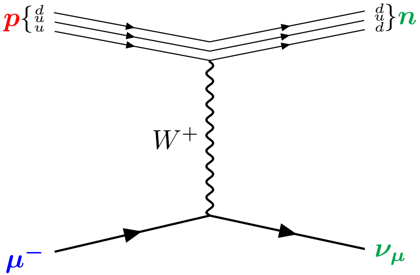

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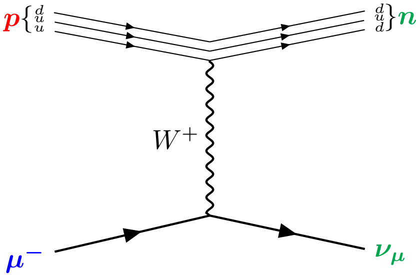
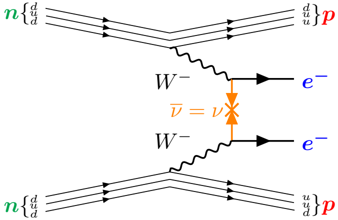


Ordinary = non-radiative

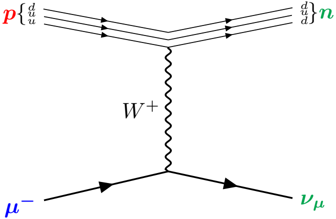
$$\left(\begin{array}{c}\text{Radiative muon capture (RMC):}\\ \mu^- + {}^A_Z\mathrm{X}(J_i^{\pi_i}) \rightarrow \nu_\mu + {}_{Z-1}^{\ \ A}\mathrm{Y}(J_f^{\pi_f}) + \gamma\end{array}\right)$$

Discovery, accelerated

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



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



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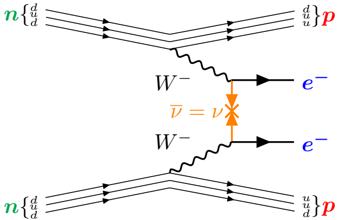

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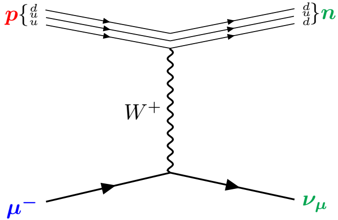

$$\boxed{\mu^- + {}^{A}_{Z}\mathrm{X}(J_i^{\pi_i}) \to \nu_\mu + {}^{A}_{Z-1}\mathrm{Y}(J_f^{\pi_f})}$$

Both involve hadronic current:

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

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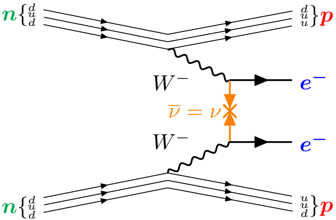

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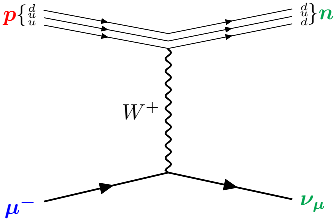

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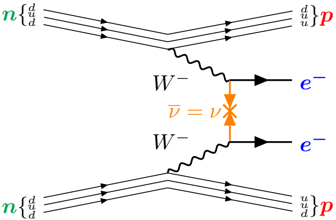

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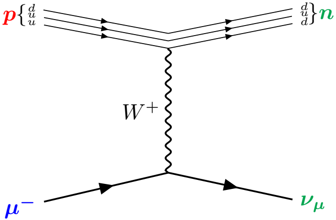

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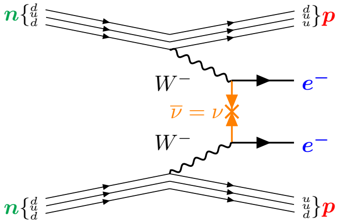

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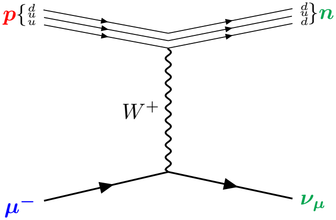
- **Yet hypothetical**



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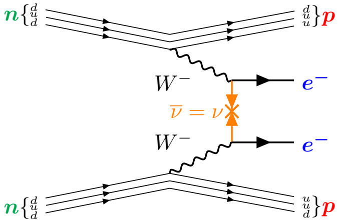

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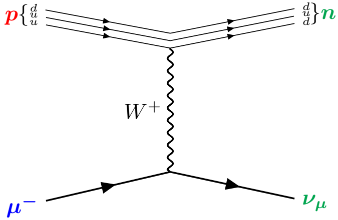

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- **Has been measured!**

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Muon-Capture Theory

- Interaction Hamiltonian → capture rate:

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

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†
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(Received November 9, 1959)

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+ Approximate **two-body currents** via normal-ordering

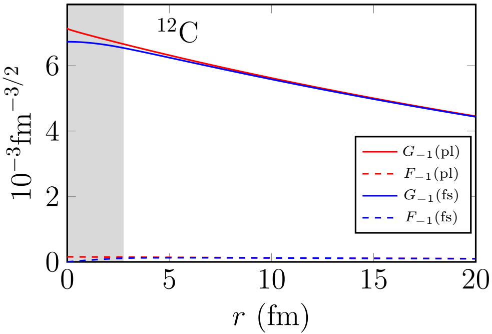
Bound-Muon Wave Functions

- Expand the muon wave function in terms of spherical spinors

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

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

pl = pointlike
fs = finite size nucleus



LJ, Navrátil, Kotila, Kravvaris, work in progress

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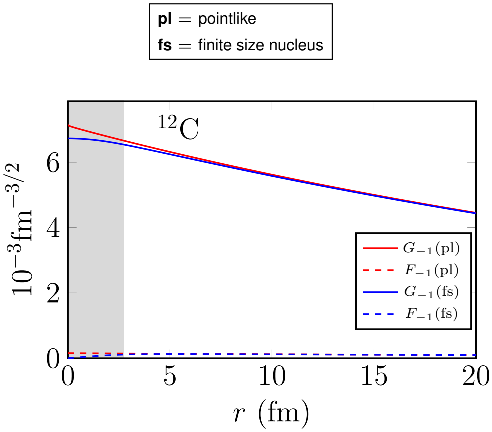
- Solve the Dirac equations in the Coulomb potential $V(r)$:

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



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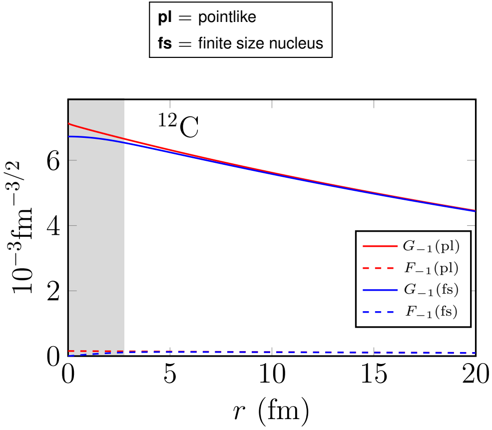
$\rightarrow (J_f || \sum_{s=1}^{A} G_{-1}(r_s) \mathcal{O}_s(q_s, r_s, \boldsymbol{\sigma}_s) || J_i)$

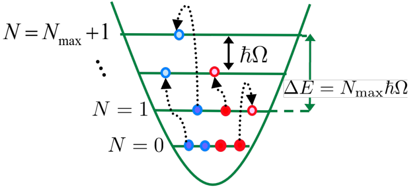


Ab initio No-Core Shell Model (NCSM)

B. R. Barrett, P. Navrátil, J. P. Vary, Progr. Part. Nucl. Phys. ***69****, 131 (2013)*

- Solve nuclear many-body problem

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



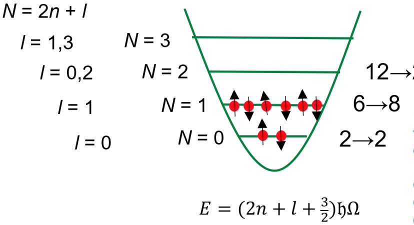


Figure courtesy of P. Navrátil

Discovery, accelerated

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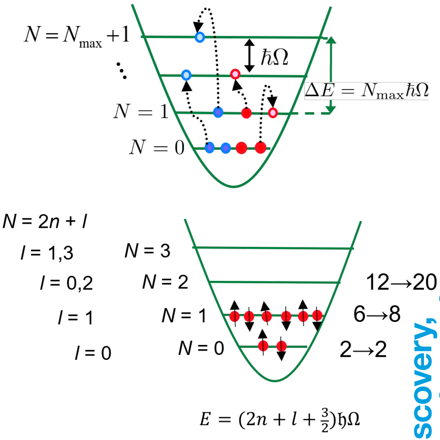
$$H^{(A)} = \sum_{i=1}^{A} \frac{p_i^2}{2m} + \sum_{i<j=1}^{A} \boldsymbol{V^{2b}(\mathbf{r}_i - \mathbf{r}_j)} + \sum_{i<j<k=1}^{A} \boldsymbol{V^{3b}_{ijk}}$$



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- A-nucleon wave functions expanded in harmonic oscillator (HO) basis

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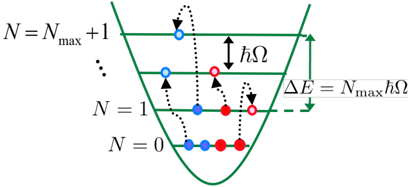

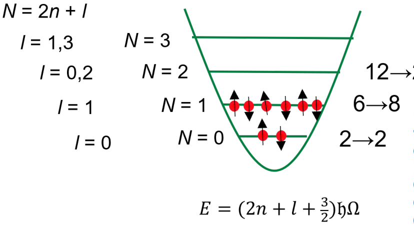

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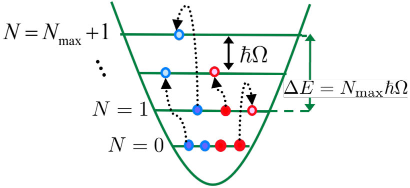
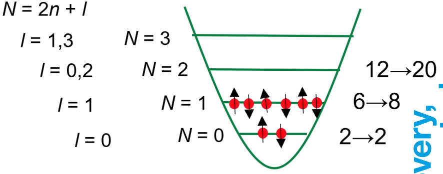




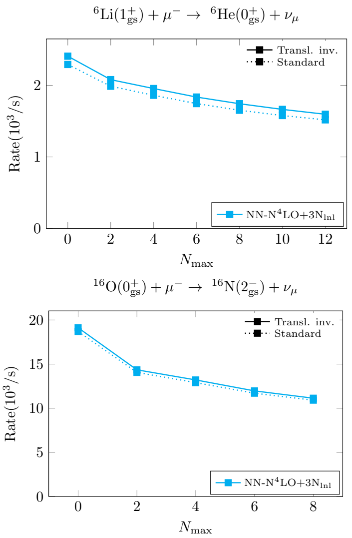
$E = (2n + l + \frac{3}{2})\hbar\Omega$

Figure courtesy of P. Navrátil

Discovery, accelerated

Translationally Invariant Operators

- Operators depend on coordinates $\mathbf{r_s}$ and $\mathbf{p_s}$ w.r.t. the center of mass (CM) of the HO potential



LJ, Navrátil, Kotila and Kravvaris, in progress

Discovery, accelerated

TRIUMF

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

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

$$\times\ (M^u)^{-1}_{n'p',np}\frac{-1}{\sqrt{2u+1}}(\Psi_f||[a^\dagger_n\tilde{a}_p]_u||\Psi_i)\ ,$$

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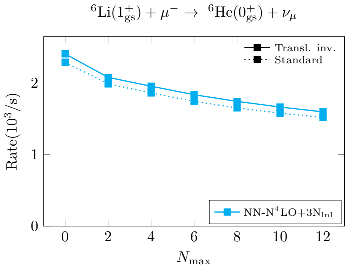
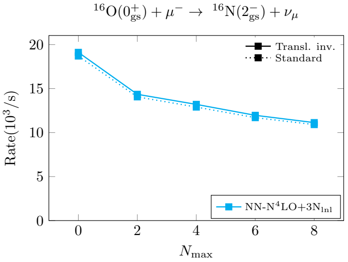
$$\boldsymbol{\xi}_s = -\sqrt{A/(A-1)}(\mathbf{r}_s - \mathbf{R}_{\rm CM})\ ;\ \boldsymbol{\pi}_s = -\sqrt{A/(A-1)}(\mathbf{p}_s - \mathbf{P})$$





LJ, Navrátil, Kotila and Kravvaris, in progress

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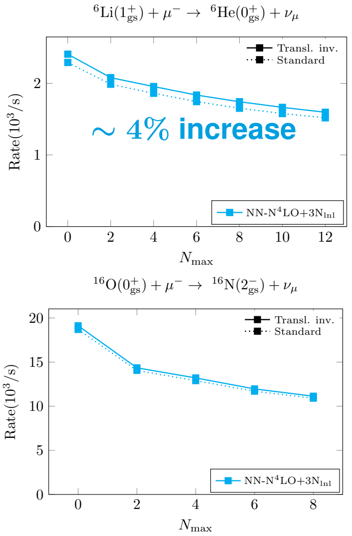

LJ, Navrátil, Kotila and Kravvaris, in progress

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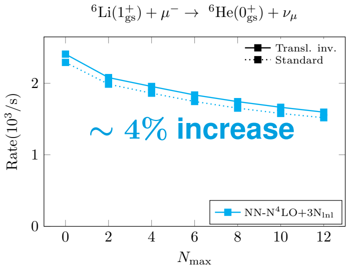

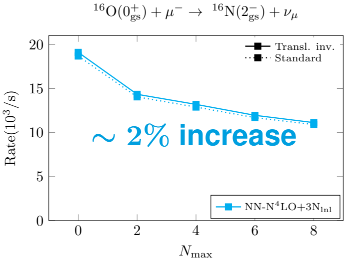

LJ, Navrátil, Kotila and Kravvaris, in progress

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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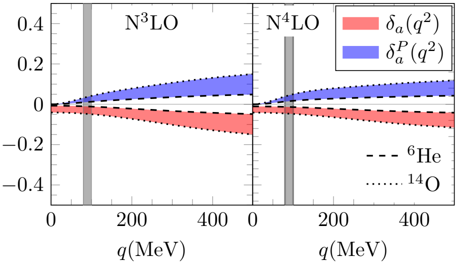

LJ, Navrátil, Kotila, Kravvaris, work in progress

- Two-body currents approximated by

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

Discovery, accelerated

Dependency on the Harmonic-Oscillator Frequency

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

- The expansion depends on the HO frequency because of the N_{max} truncation

Discovery, accelerated

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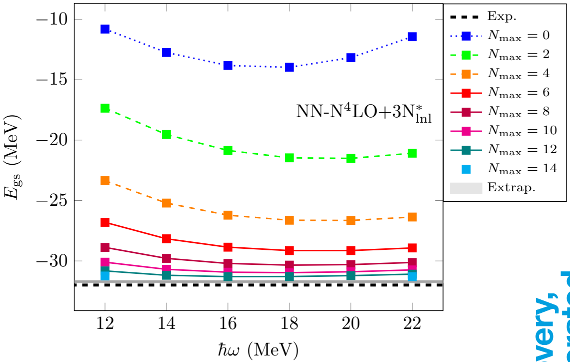
  - **Increasing $N_{\max}$ leads towards convergenced results**

Ground-state energy of ^{6}Li



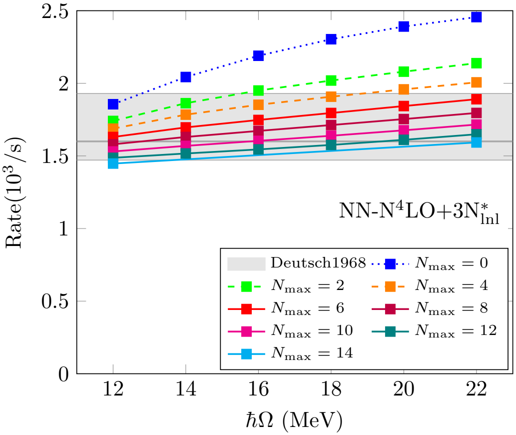
LJ, Navrátil, Kotila, Kravvaris, work in progress

Discovery, accelerated

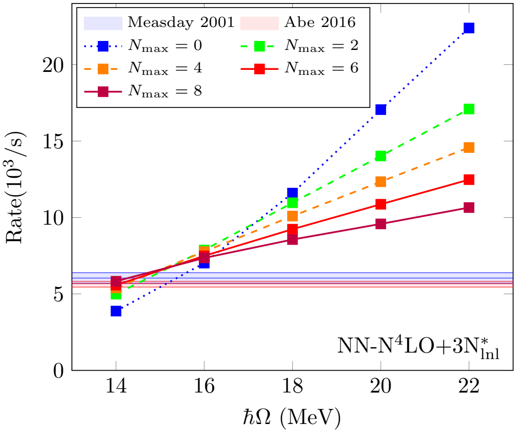
TRIUMF

Harmonic-Oscillator Frequency Dependence of Muon Capture

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



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



LJ, Navrátil, Kotila and Kravvaris, in progress

Discovery, accelerated

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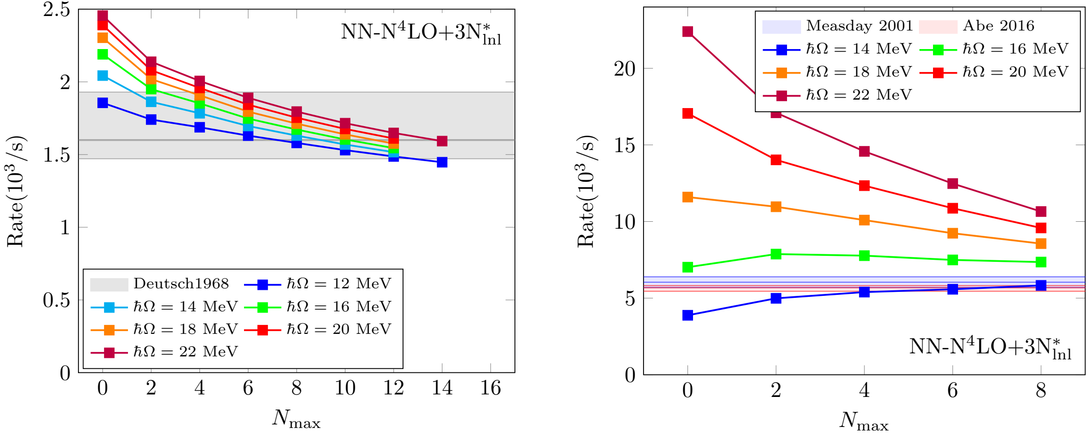


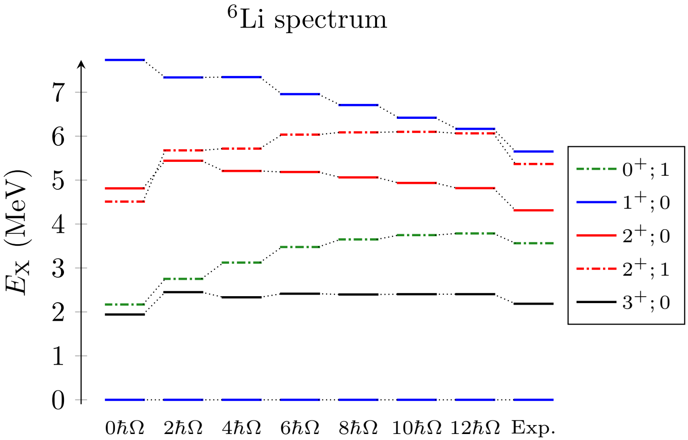
LJ, Navrátil, Kotila and Kravvaris, in progress

Discovery, accelerated

Outline

Outline

Energy spectrum of ^{6}Li



LJ, Navrátil, Kotila, Kravvaris, in preparation

TRIUMF

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

- NCSM slightly underestimating experiment

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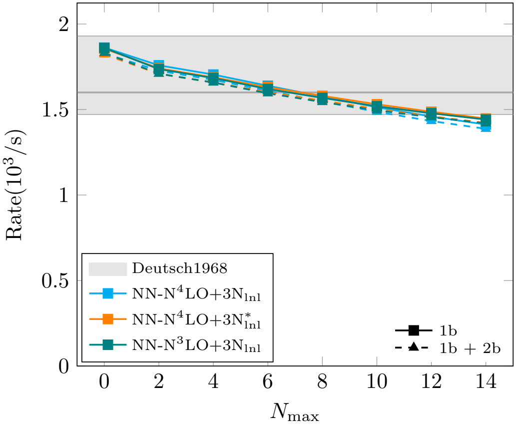

LJ, Navrátil, Kotila, Kravvaris, in preparation

Discovery, accelerated

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

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- The results are consistent with the variational (VMC) and Green's function Monte-Carlo (GFMC) calculations

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

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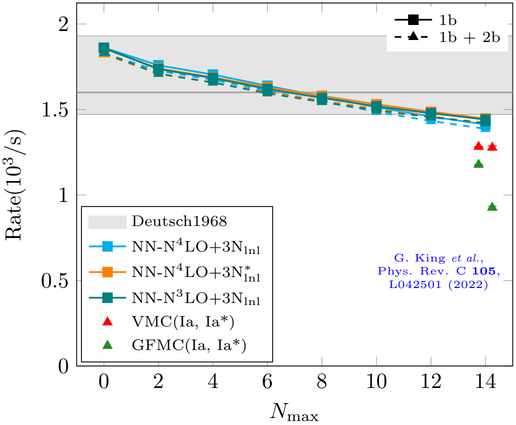

LJ, Navrátil, Kotila, Kravvaris, in preparation

TRIUMF

Discovery, accelerated

TRIUMF

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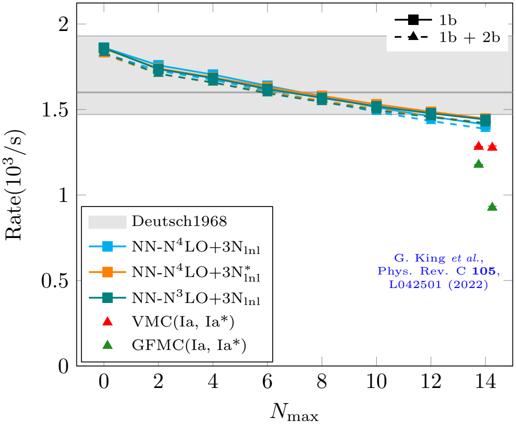
  - Slow convergence likely due to cluster-structure



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Discovery, accelerated

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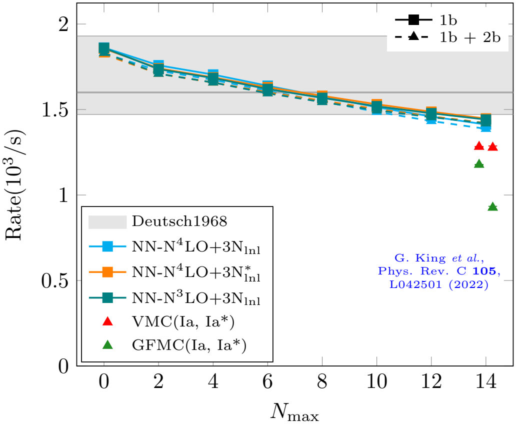
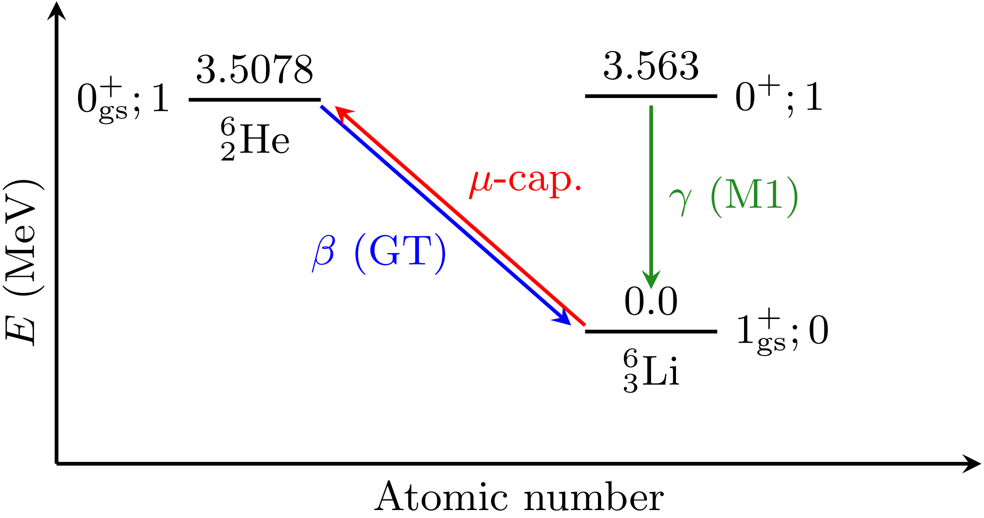
  King *et al.*, Phys. Rev. C **105**, L042501 (2022)

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



LJ, Navrátil, Kotila, Kravvaris, in preparation

Correlations with Other Observables



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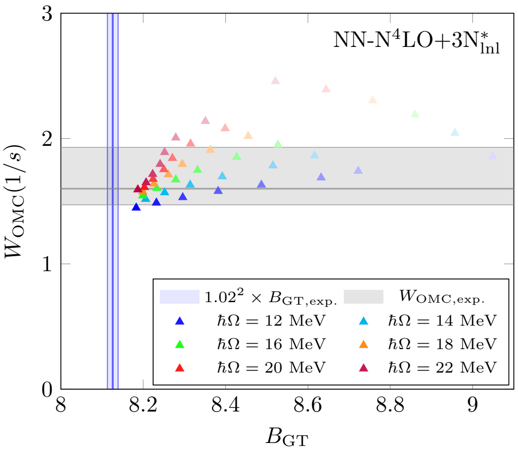
GT β decay:



LJ, Navrátil, Kotila and Kravvaris, in preparation

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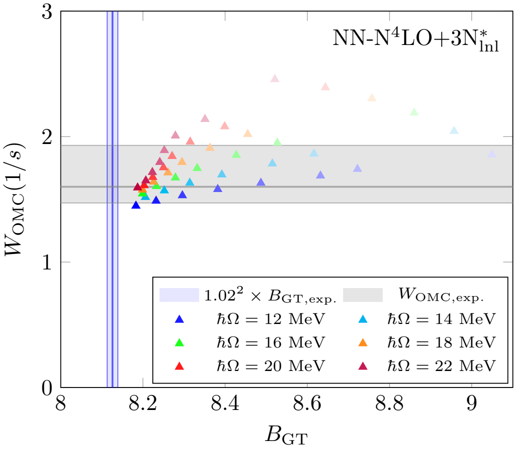
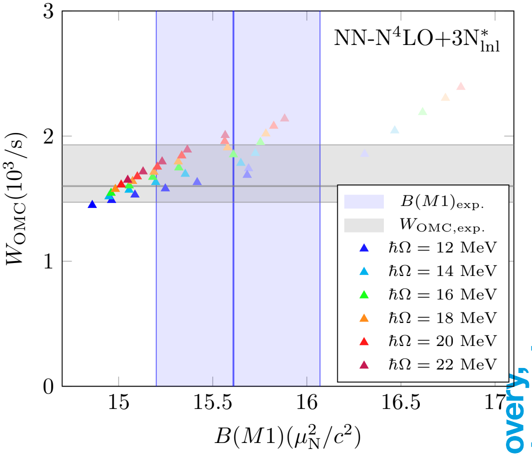


M1 γ decay:



LJ, Navrátil, Kotila and Kravvaris, in preparation

Outline

Introduction

Muon Capture from No-Core Shell Model

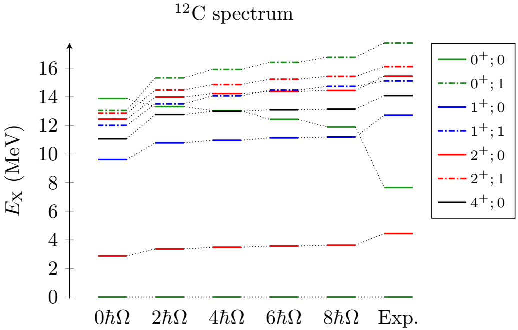
Results

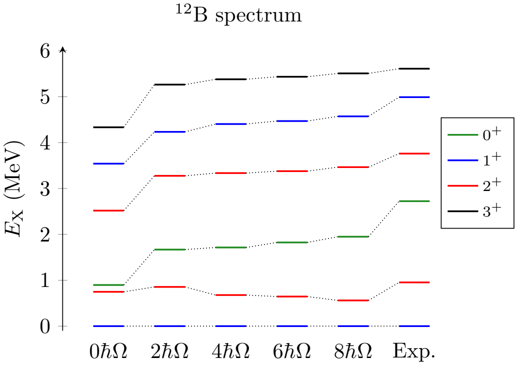
- Muon capture on ^{6}Li
- Muon capture on ^{12}C
- Muon capture on ^{16}O

Summary

Discovery, accelerated

Energy spectra of ^{12}C and ^{12}B





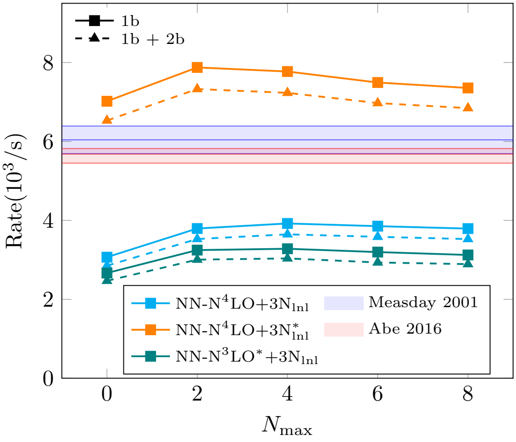
LJ, Navrátil, Kotila, Kravvaris, in preparation

Discovery, accelerated

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

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

- Significant interaction dependence



LJ, Navrátil, Kotila, Kravvaris, in preparation

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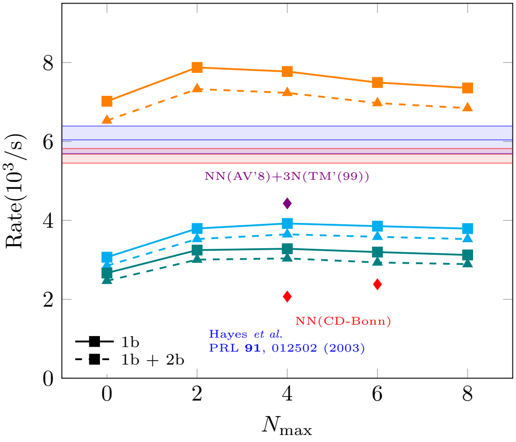
  - The **NN-N^{4}LO+3N$^*_{\mathrm{lnl}}$** interaction with the additional spin-orbit term most consistent with experiment



LJ, Navrátil, Kotila, Kravvaris, in preparation

Discovery, accelerated

TRIUMF

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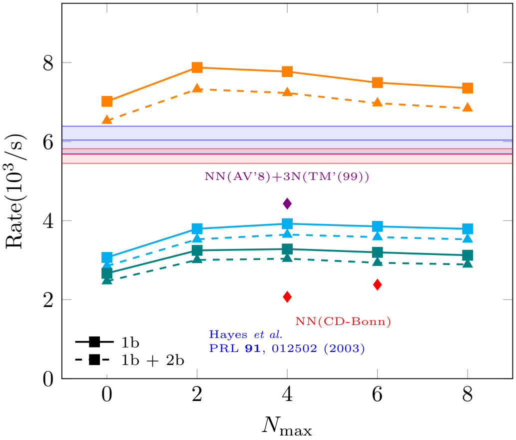
- The results can be compared against earlier NCSM calculations with phenomenological interactions

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



LJ, Navrátil, Kotila, Kravvaris, in preparation

Discovery, accelerated

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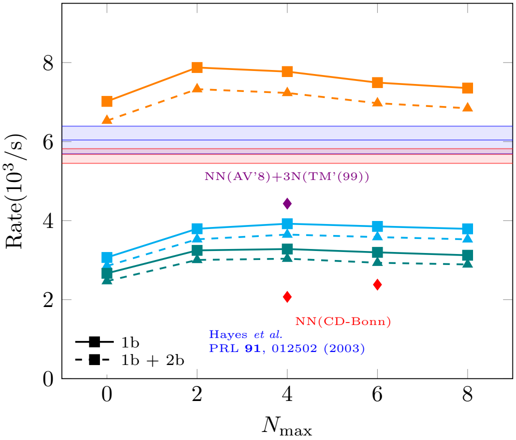
  Hayes *et al.*, *Phys. Rev. Lett.* **91**, 012502 (2003)
- 3-body forces essential to reproduce the measured rate



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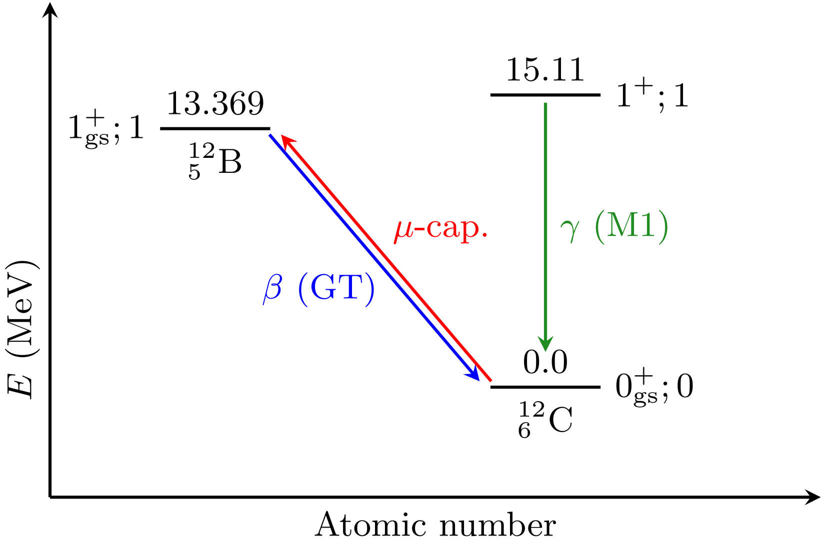
Discovery, accelerated

Correlations with Other Observables



Discovery, accelerated

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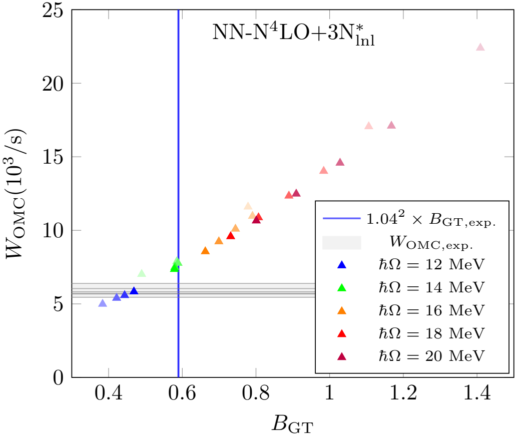

LJ, Navrátil, Kotila and Kravvaris, in progress

Discovery, accelerated

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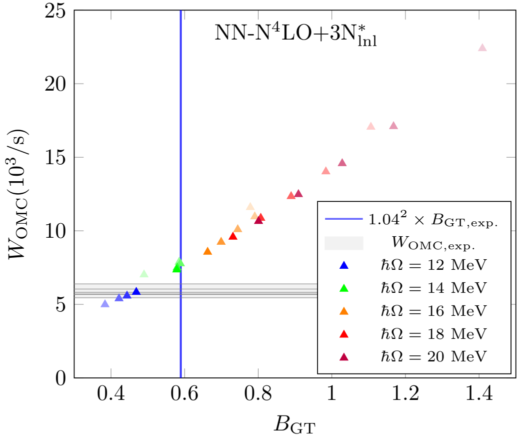

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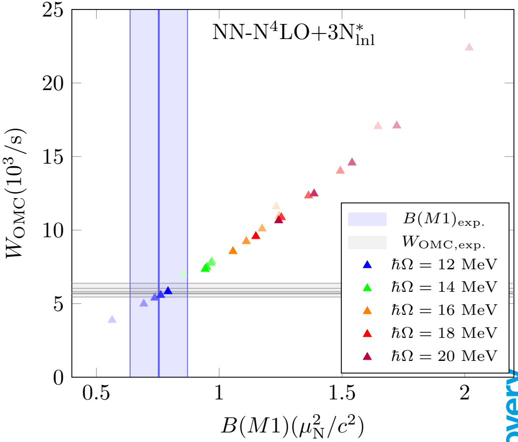

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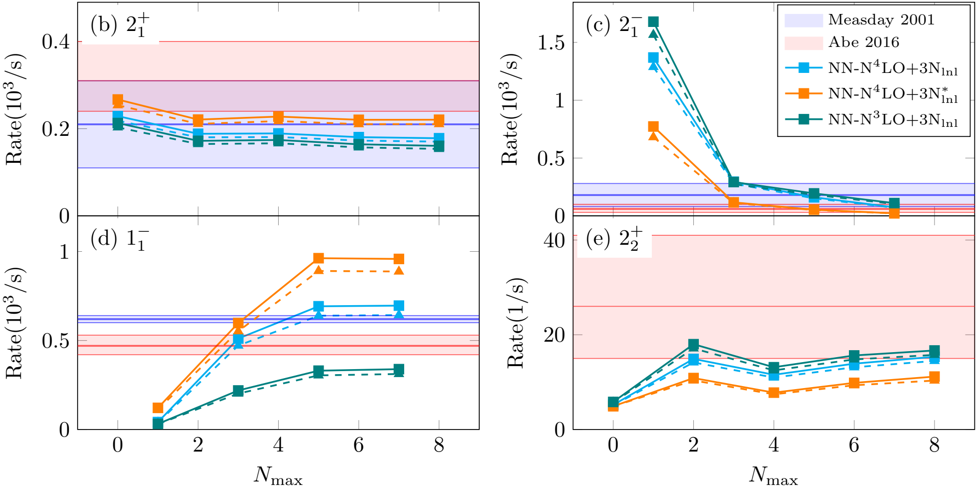
TRIUMF

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



LJ, Navrátil, Kotila, Kravvaris, in preparation

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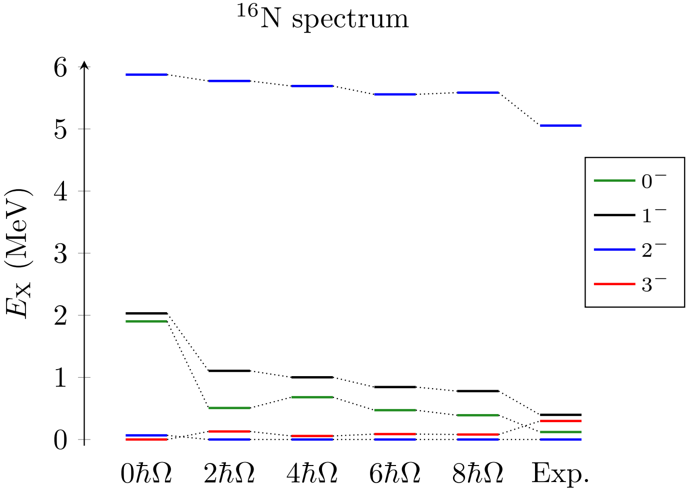
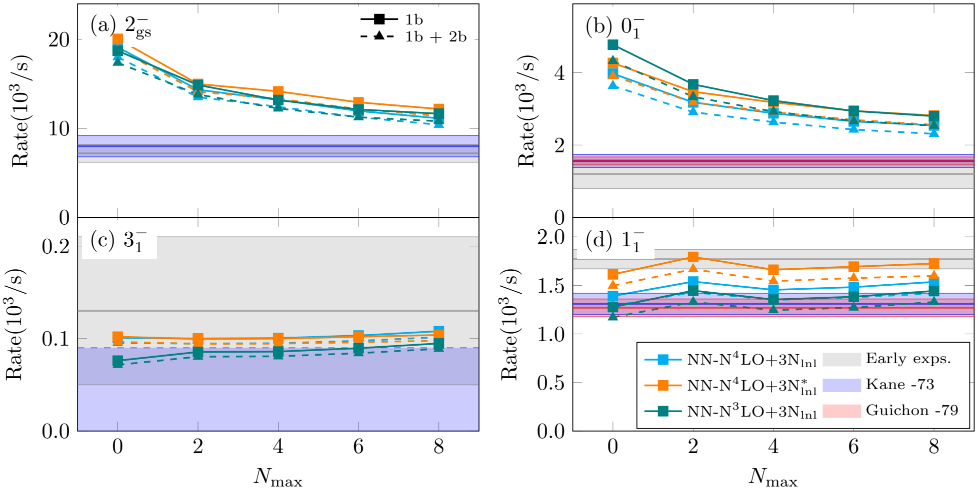
Outline

Energy spectra of ^{16}N



LJ, Navrátil, Kotila, Kravvaris, in preparation

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



LJ, Navrátil, Kotila, Kravvaris, in preparation

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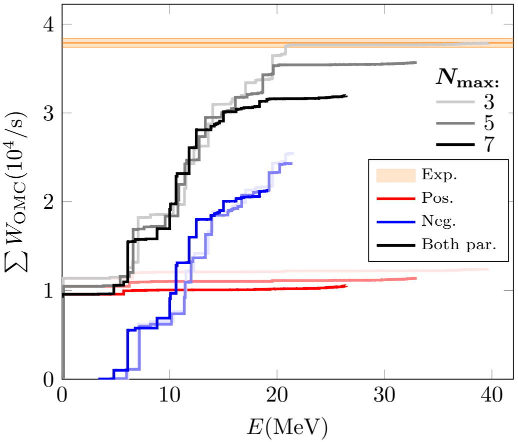
TRIUMF

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

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

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



LJ, Navrátil, Kotila, Kravvaris, in preparation

Discovery, accelerated

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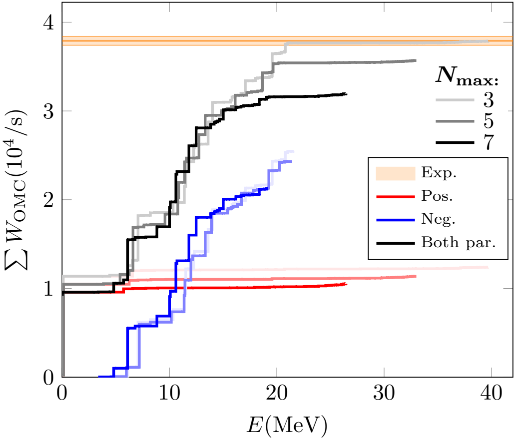

LJ, Navrátil, Kotila, Kravvaris, in preparation

Discovery, accelerated

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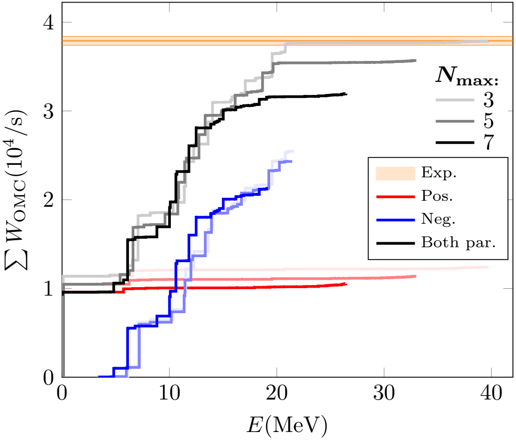
- Better estimation with the Lanczos strength function method ongoing (**see poster by D. Araujo**)



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Discovery, accelerated

Outline

TRIUMF

Summary

- *Ab initio* muon-capture studies could shed light on nuclear electroweak currents at finite momentum exchange regime

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- No-core shell-model describes well partial muon-capture rates in light nuclei ^{6}He, ^{12}B and ^{16}N

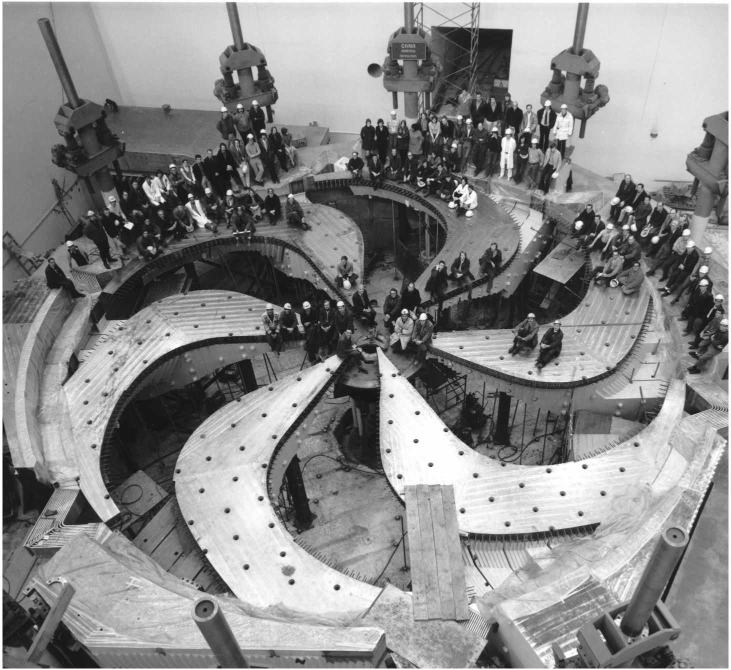
Summary

- *Ab initio* muon-capture studies could shed light on nuclear electroweak currents at finite momentum exchange regime
- No-core shell-model describes well partial muon-capture rates in light nuclei ^{6}He, ^{12}B and ^{16}N
- Calculation of total capture rates currently in progress in NCSM

Discovery, accelerated

TRIUMF

Thank you
Merci



Discovery, accelerated

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	$\hat{O}_{kwux}(\mathbf{r}_s, \mathbf{p}_s)$
$\mathcal{M}[0\,w\,u]$	$j_w(qr_s)G_{-1}(r_s)\mathcal{Y}_{0wu}^{M_f-M_i}(\hat{\mathbf{r}}_s)\delta_{wu}$
$\mathcal{M}[1\,w\,u]$	$j_w(qr_s)G_{-1}(r_s)\mathcal{Y}_{1wu}^{M_f-M_i}(\hat{\mathbf{r}}_s, \boldsymbol{\sigma}_s)$
$\mathcal{M}[0\,w\,u\,\pm]$	$[j_w(qr_s)G_{-1}(r_s) \mp \frac{1}{q} j_{w\mp1}(qr_s)\frac{d}{dr_s}G_{-1}(r_s)]\mathcal{Y}_{0wu}^{M_f-M_i}(\hat{\mathbf{r}}_s)\delta_{wu}$
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$\mathcal{M}[0\,w\,u\,p]$	$i j_w(qr_s)G_{-1}(r_s)\mathcal{Y}_{0wu}^{M_f-M_i}(\hat{\mathbf{r}}_s)\boldsymbol{\sigma}_s \cdot \mathbf{p}_s\delta_{wu}$
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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 $\mathbf{q} = -\mathbf{k}_1 - \mathbf{k}_2$

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)

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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

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

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

Discovery, accelerated

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$$\Psi^A = \sum_{N=0}^{N_{\max}} \sum_i c_{Ni} \Phi^{\mathrm{HO}}_{Ni}(\boldsymbol{\xi}_1, \boldsymbol{\xi}_2, ..., \boldsymbol{\xi}_{A-1})$$

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

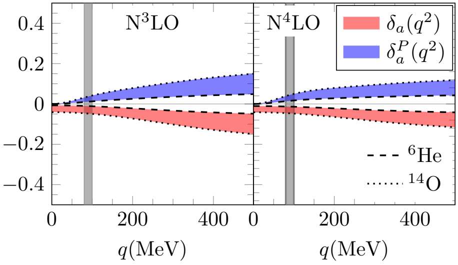
$$\Psi^A_{\mathrm{SD}} = \sum_{N=0}^{N_{\max}} \sum_i c^{\mathrm{SD}}_{Nj} \Phi^{\mathrm{HO}}_{\mathrm{SD}\ Nj}(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_A) = \Psi^A \Psi_{\mathrm{CM}}(\mathbf{R}_{\mathrm{CM}})$$

Discovery, accelerated

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, in preparation

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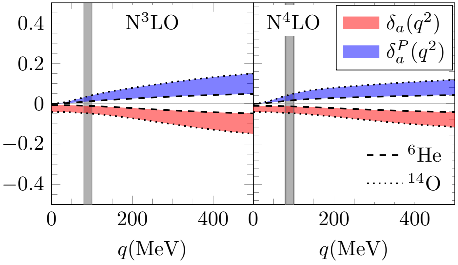
- Two-body currents typically **reduce** the OMC rates by $\sim 1 - 2\%$ **in** ^{6}**Li** and by $\lesssim 10\%$ **in** ^{12}**C and** ^{16}**O**



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