Muon Capture Helping New Physics Studies

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Collaborators

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K. Kravvaris

J. Kotila

R. Plestid

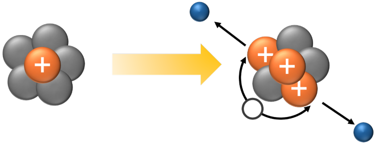
M. Drissi

Outline

TECHNISCHE UNIVERSITÄT DARMSTADT

Muon Capture and Beyond Standard Model (BSM) Physics

Neutrinoless double-beta ($0\nu\beta\beta$) decay



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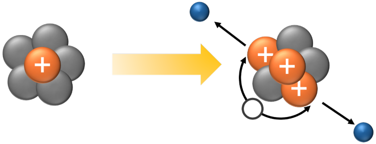

- **Lepton-number violation**

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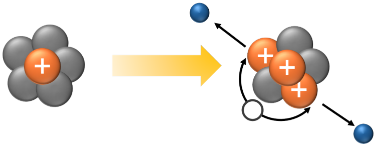
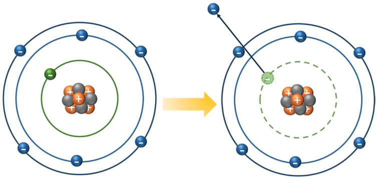


Muon-to-Electron Conversion in Nuclei



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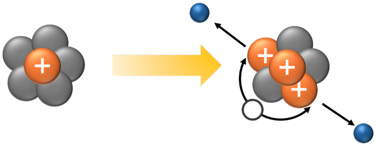

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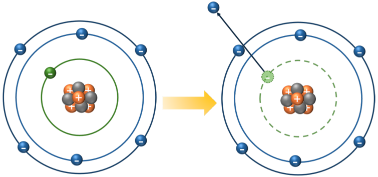

- **Lepton-flavor violation**

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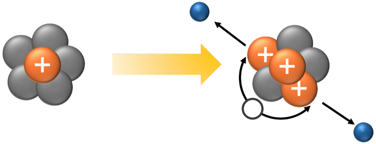
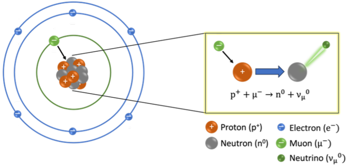


- Lepton-number violation

Muon Capture on Nuclei



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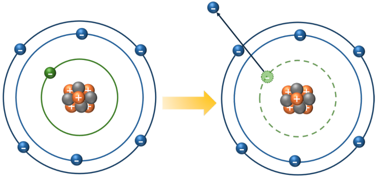

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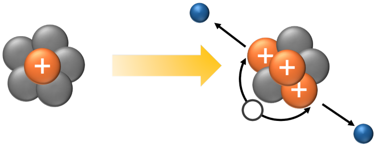

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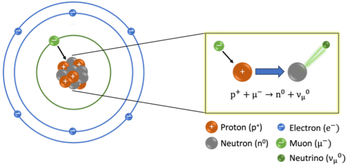
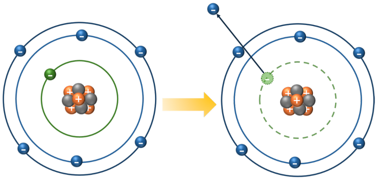
Muon Capture on Nuclei



- **Probe for $0\nu\beta\beta$ decay**

Muon-to-Electron Conversion in Nuclei



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Muon Capture and Beyond Standard Model (BSM) Physics

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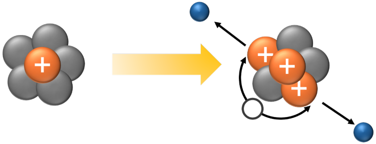

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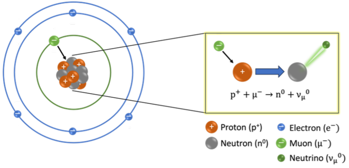
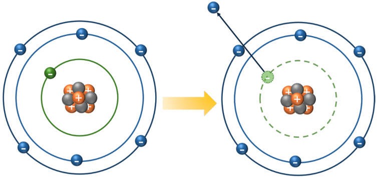
Muon Capture on Nuclei



- **Probe for $0\nu\beta\beta$ decay**
- **Background for muon-to-electron conversion**

Muon-to-Electron Conversion in Nuclei



- **Lepton-flavor violation**

Muon Capture on Nuclei

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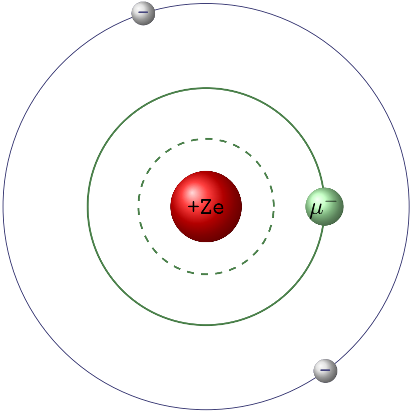
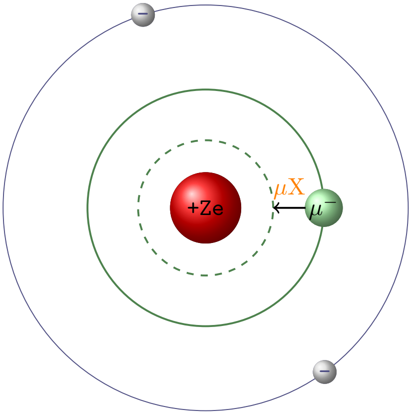
- Starting point: a **muonic atom**



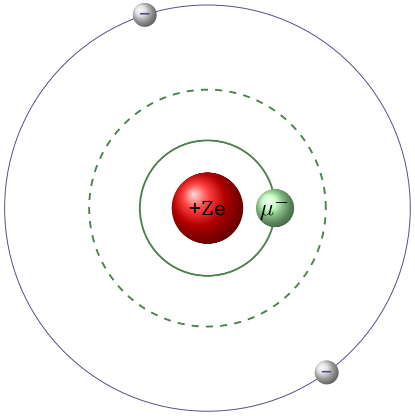
Muon Capture on Nuclei

- Starting point: a **muonic atom**
- The muon quickly transitions to the lowest, **$1s_{1/2}$ orbit**



Muon Capture on Nuclei

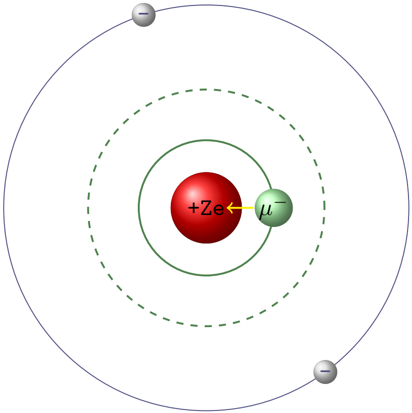
- Starting point: a **muonic atom**
- The muon quickly transitions to the lowest, **$1s_{1/2}$ orbit**
- From there, the muon can be **captured by the nucleus**



Muon Capture on Nuclei

- Starting point: a **muonic atom**
- The muon quickly transitions to the lowest, **$1s_{1/2}$ orbit**
- From there, the muon can be **captured by the nucleus**
  - **Ordinary muon capture (OMC)**:

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



Muon Capture on Nuclei

- Starting point: a **muonic atom**
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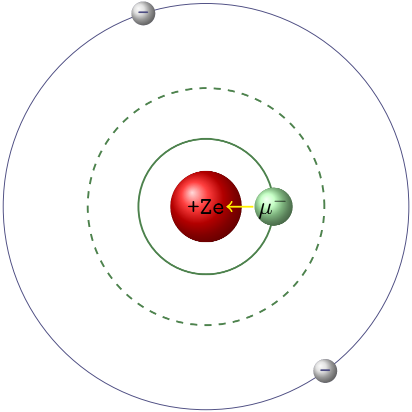
- From there, the muon can be **captured by the nucleus**
  - **Ordinary muon capture (OMC)**:

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

  - **Radiative muon capture (RMC)**:

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



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

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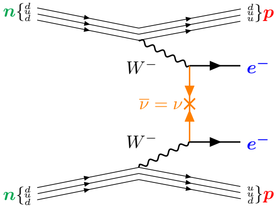
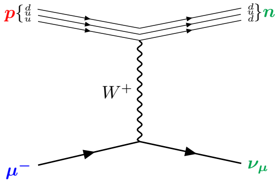
$0\nu\beta\beta$ Decay



Ordinary Muon Capture



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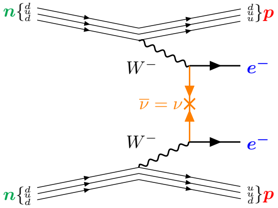
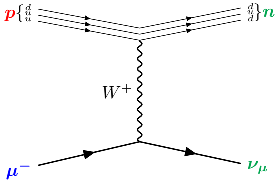
$0\nu\beta\beta$ Decay



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

Ordinary Muon Capture



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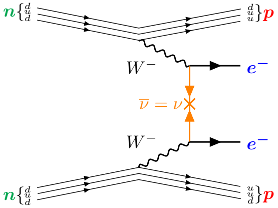

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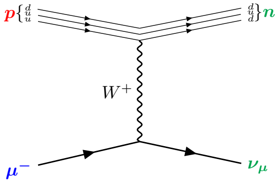
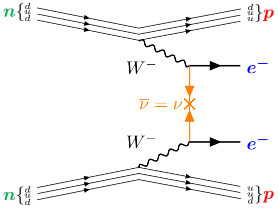


- $q \approx m_\mu + E_i - E_f \approx 100$ MeV

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

$0\nu\beta\beta$ Decay



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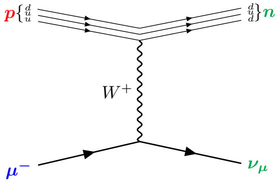
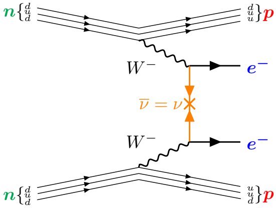


- $q \approx m_\mu + E_i - E_f \approx 100$ MeV

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

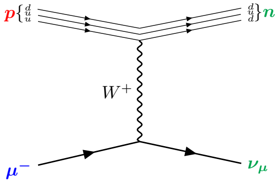
$0\nu\beta\beta$ Decay vs Ordinary Muon Capture

$0\nu\beta\beta$ Decay



- $q \approx 1/|r_1 - r_2| \approx 100 - 200$ MeV
- No experimental signal so far

Ordinary Muon Capture



- $q \approx m_\mu + E_i - E_f \approx 100$ MeV
- Has been measured

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

MONUMENT (a.k.a OMC4DBD) Experiment at PSI

TECHNISCHE UNIVERSITÄT DARMSTADT

Eur. Phys. J. C (2024) 84:1188
https://doi.org/10.1140/epjc/s10052-024-13470-6

THE EUROPEAN PHYSICAL JOURNAL C

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Regular Article

Experimental Physics

The MONUMENT experiment: ordinary muon capture studies for $0\nu\beta\beta$ decay

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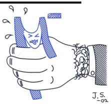

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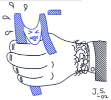

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- **Aim 1:** Measure OMC in $\beta\beta$-decay nuclei

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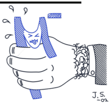

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- **Aim 1:** Measure OMC in $\beta\beta$-decay nuclei
- **Aim 2:** Measure OMC in light nuclei accessible by *ab initio* nuclear theory

Outline

TECHNISCHE UNIVERSITÄT DARMSTADT

Ordinary muon capture rate

$$W(J_i \rightarrow J_f) = \frac{1}{2J_i + 1}\left(1 - \frac{q}{m_\mu + AM}\right) q^2 \sum_{\kappa, u} \left| g_{\rm V} M_{\rm V}(\kappa, u) + g_{\rm A} M_{\rm A}(\kappa, u) + g_{\rm M} M_{\rm M}(\kappa, u) + g_{\rm P} M_{\rm P}(\kappa, u) \right|^2$$

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)

Muon Capture Operators

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

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

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

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

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

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TECHNISCHE UNIVERSITÄT DARMSTADT

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TECHNISCHE UNIVERSITÄT DARMSTADT

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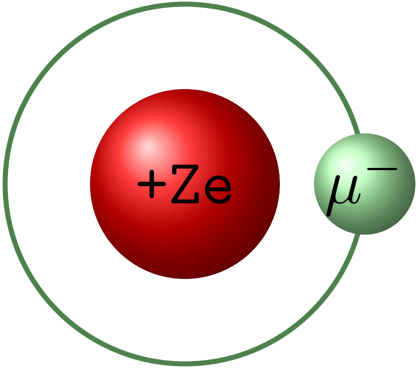
Morita, Fujii, *Phys. Rev.* **118**, 606 (1960)

Bound-Muon Wave Function

- Muon wave function

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



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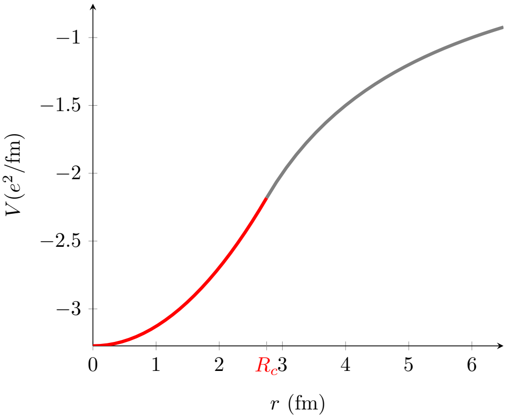
- from Dirac equations with potential

$$V(r) = \begin{cases} -\frac{Ze^2}{2R_c}\left[3 - \left(\frac{r}{R_c}\right)^2\right] , & \text{if } r \leq R_c \\ -\frac{Ze^2}{r} , & \text{if } r > R_c \end{cases}$$



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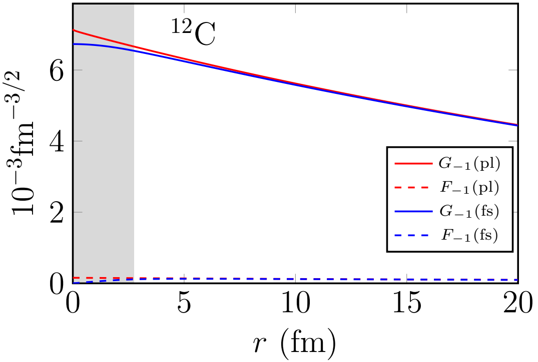
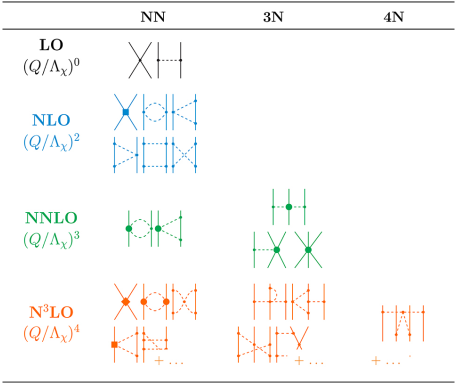


LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C 109, 065501 (2024)

Nuclear Forces from Chiral Effective Field Theory

- We use Nucleon-Nucleon (NN) and 3-Nucleon (3N) forces based on Chiral Effective Field Theory:



H. Hergert, Front. Phys. 8 (2020)

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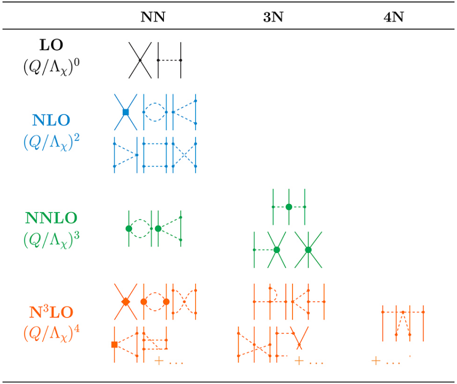

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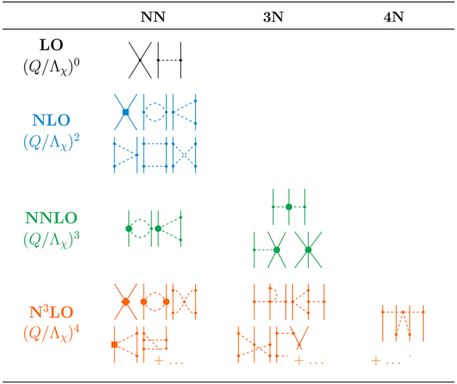

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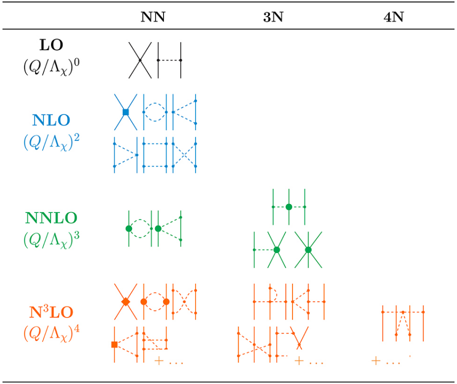
    Girlanda, Kievsky, Viviani, Phys. Rev. C 84, 014001 (2011) (E_7)

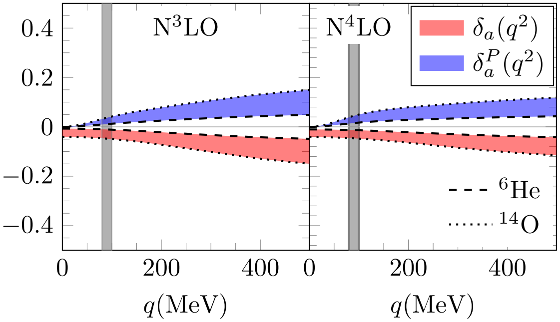


H. Hergert, Front. Phys. 8 (2020)

Momentum-Dependent Two-Body Currents

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

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



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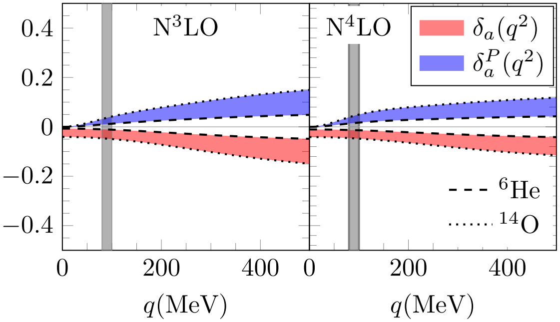
- Approximate 2BCs by normal-ordering w.r.t. spin-isospin–symmetric reference state:

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

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

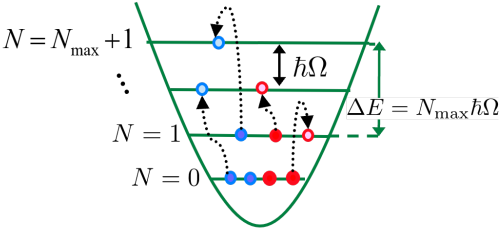
$$\rightarrow \boxed{\mathbf{J}^\text{eff}_{i,2\text{b}} = g_\text{A}\frac{\tau_i^3}{2}\left[\delta a(\mathbf{q}^2)\boldsymbol{\sigma}_i + \frac{\delta a^P(\mathbf{q}^2)}{\mathbf{q}^2}(\mathbf{q}\cdot\boldsymbol{\sigma}_i)\mathbf{q}\right]}$$



No-core Shell Model

- Solve the nuclear many-body problem

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



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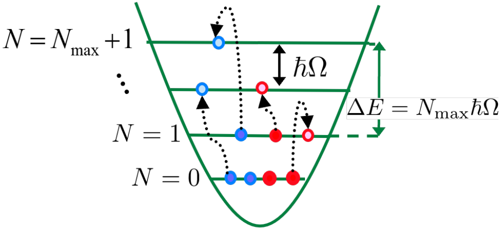
$$H^{(A)} = \sum_{i=1}^{A}\frac{p_i^2}{2m} + \sum_{i<j=1}^{A} V_{ij}^{\mathrm{NN}}(\mathbf{r}_i - \mathbf{r}_j) + \sum_{i<j<k=1}^{A} V_{ijk}^{\mathrm{3N}}$$



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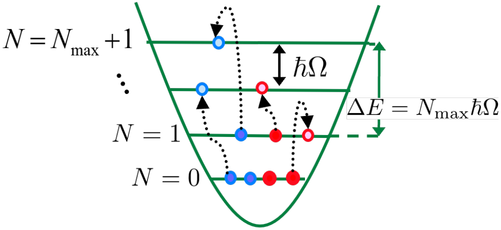
- Expansion in **Harmonic Oscillator (HO) basis**:

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



Dependency on Harmonic-Oscillator Frequency

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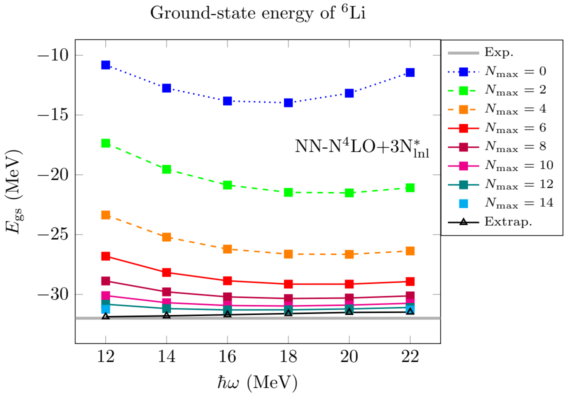
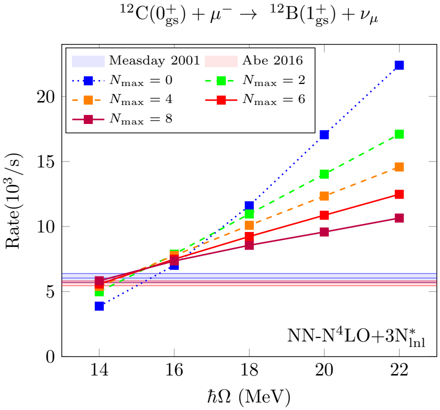
$$\Psi^{(A)} = \sum_{N=0}^{N_{\max}} \sum_{j} = c_{Nj}\Phi^{\mathrm{HO}}_{Nj}(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_A)$$

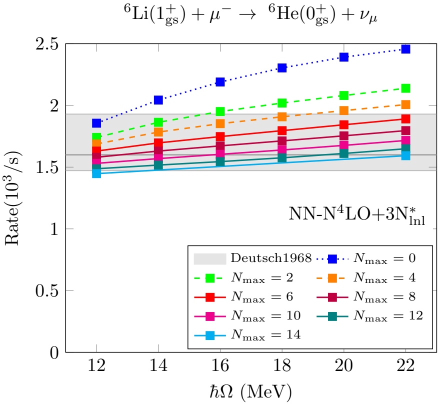
- The expansion depends on the HO frequency ($\hbar\omega$) because of the $N_{\max}$ truncation
  - **Increasing $N_{\max}$ leads towards converged results**



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

Frequency-Dependence of Muon-Capture Rates





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

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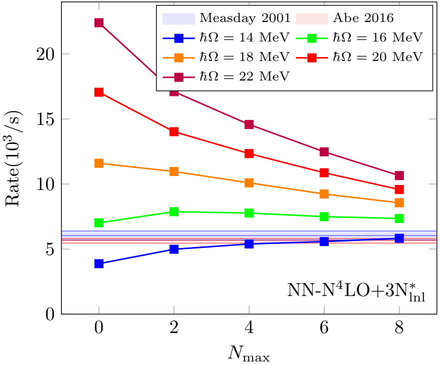
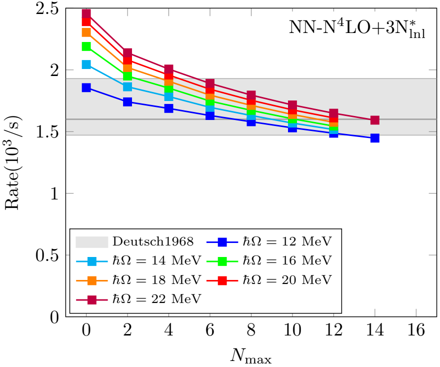
$^{12}\mathrm{C}(0^+_{\mathrm{gs}}) + \mu^- \rightarrow {}^{12}\mathrm{B}(1^+_{\mathrm{gs}}) + \nu_\mu$

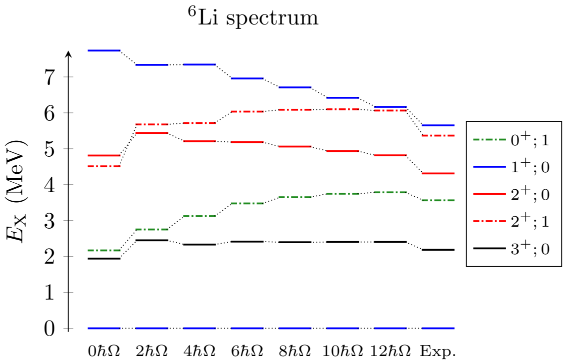


$^{6}\mathrm{Li}(1^+_{\mathrm{gs}}) + \mu^- \rightarrow {}^{6}\mathrm{He}(0^+_{\mathrm{gs}}) + \nu_\mu$



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

Energy Spectrum of ^{6}Li



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

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

- NCSM slightly underestimating the experiment

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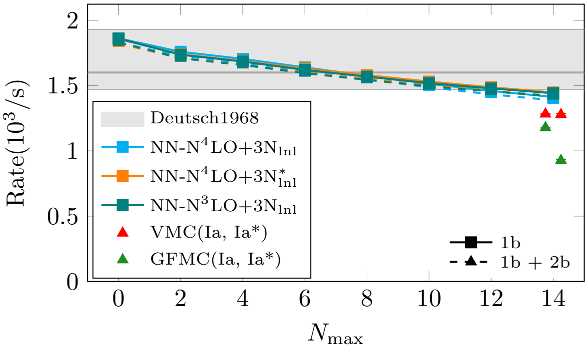

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G.B. King et al., Phys. Rev. C. 105, L042501 (2022)

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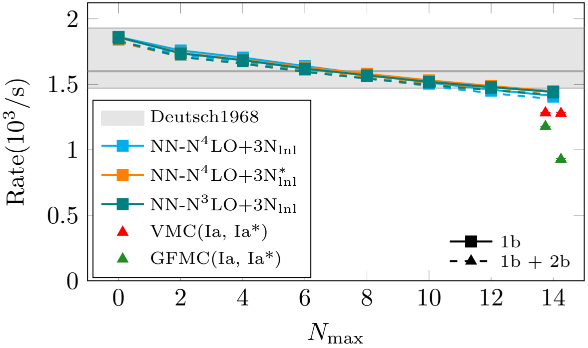

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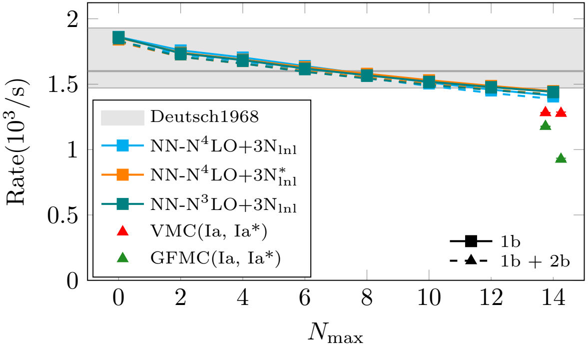

LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C 109, 065501 (2024)

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

- Slow convergence due to clustering not captured by the NCSM?
  - NCSM with continuum (NCSMC) might give better results?

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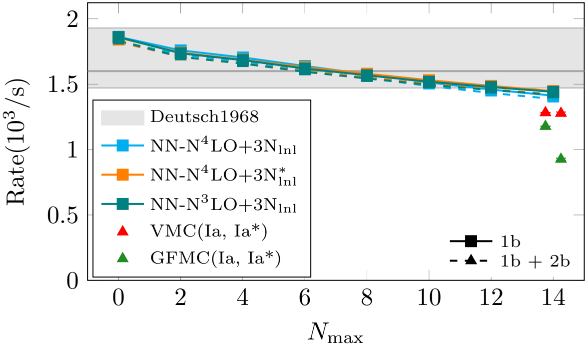
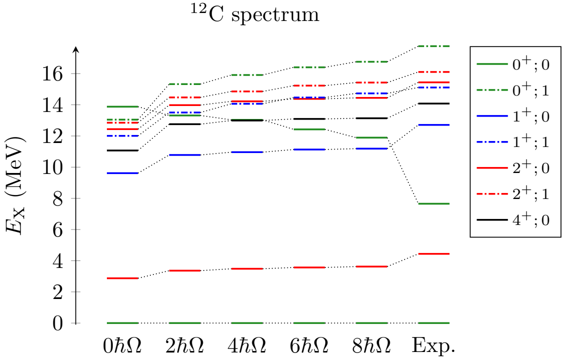
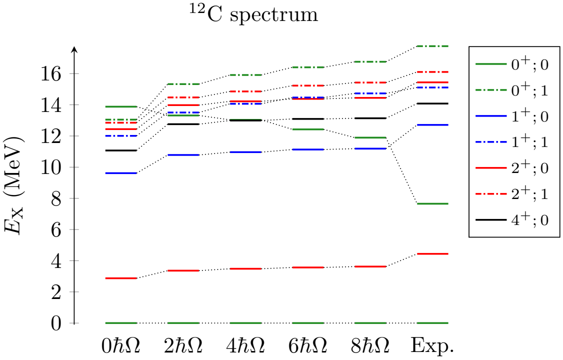


LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C 109, 065501 (2024)

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





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

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

- Significant interaction dependence

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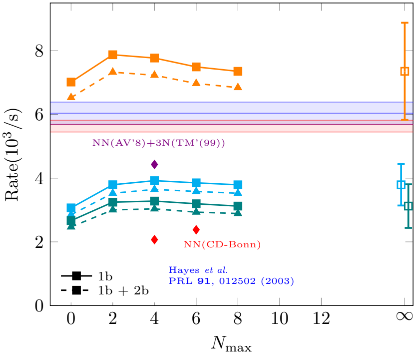

LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C 109, 065501 (2024)

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

- Significant interaction dependence
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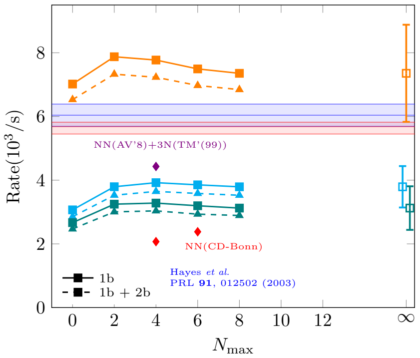

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Hayes et al., Phys. Rev. Lett. 91, 012501 (2003)

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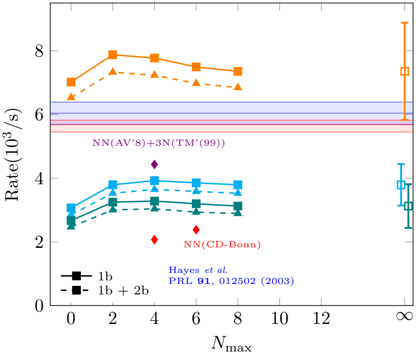

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Hayes et al., Phys. Rev. Lett. 91, 012501 (2003)

- **3-body forces** essential to reproduce the measured rate

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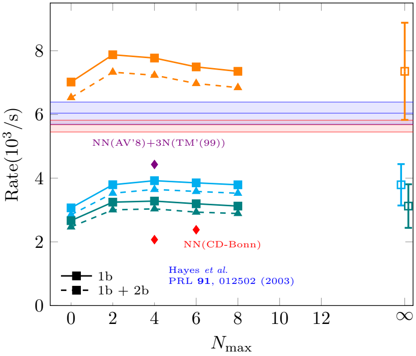

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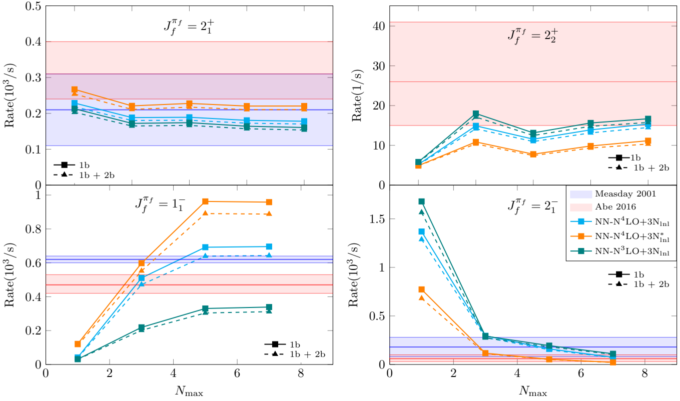
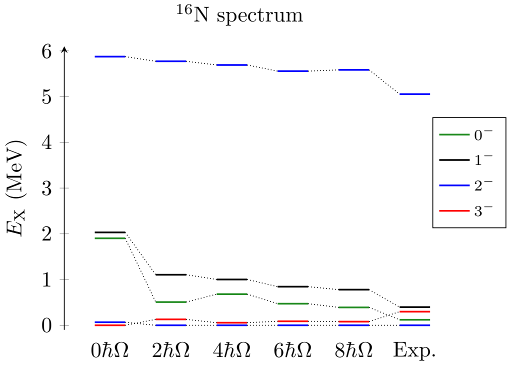
Muon Capture to Excited States of ^{12}B



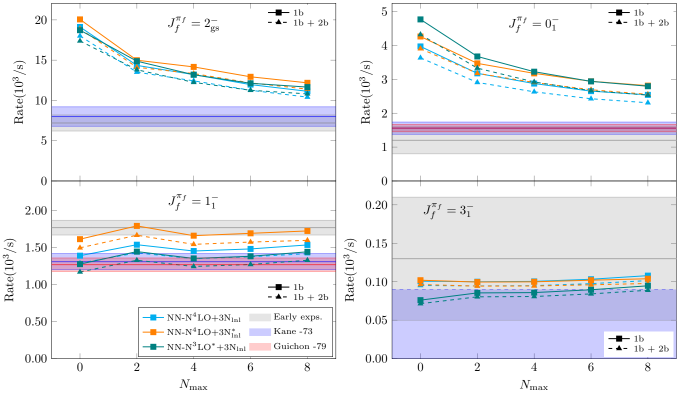
LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C 109, 065501 (2024)

Energy Spectrum of ^{16}N



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

Muon Capture on ^{16}N

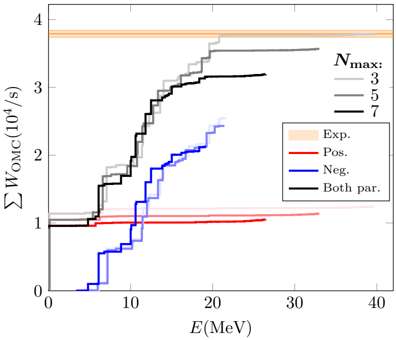


LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C 109, 065501 (2024)

Total Muon-Capture Rates

- Rates obtained by summing over $\sim$ **50 final states of each parity**

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



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

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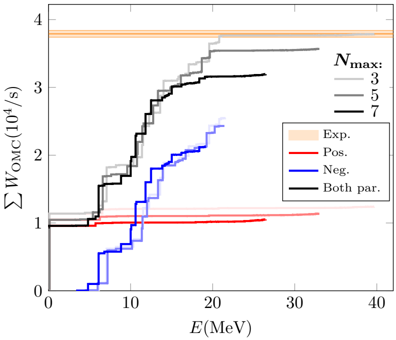

LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C 109, 065501 (2024)

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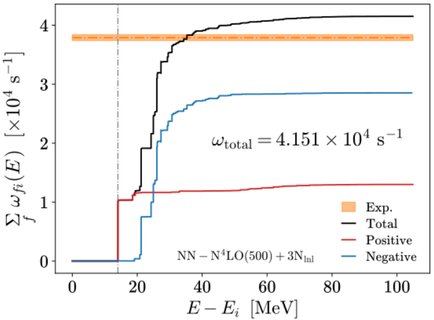
- Rates obtained by summing over $\sim$ **50 final states of each parity**
- Summing up the rates up to $\sim$ 20 MeV, we capture $\sim$ **85% of the total rate** in both ^{12}B and ^{16}N
- Better estimation with the **Lanczos strength function method** ongoing

D. Araujo Najera, M. Gennari, LJ, M. Drissi, P. Navrátil, work in progress



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Radiative Muon Capture as Background of $\mu \to e$ Conversion

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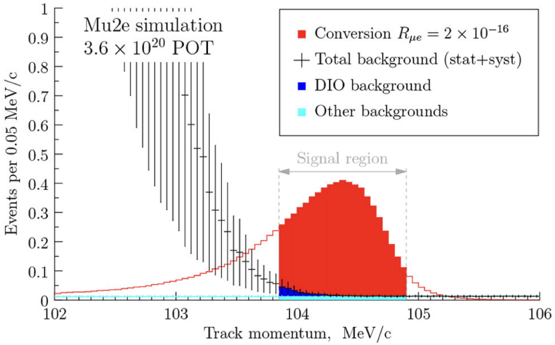
Radiative Muon Capture as Background of $\mu \to e$ Conversion

- RMC the main background for $\mu^- \to e^+$ searches:

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



R. H. Bernstein, Front. Phys. 7 (2019)

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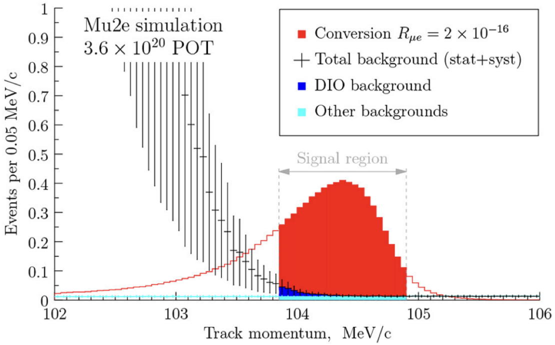
D. S. Armstrong et al., Phys. Rev. C 46, 1094 (1993)



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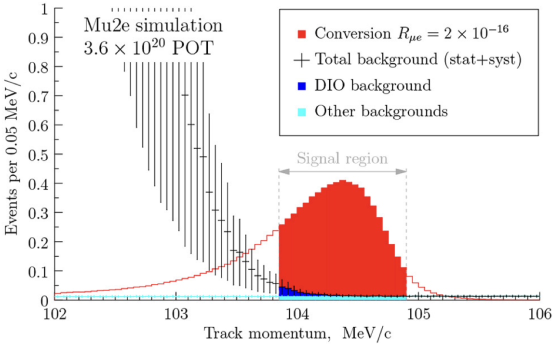
- 0.1 – 1% probability for $\gamma \to e^+e^-$



R. H. Bernstein, Front. Phys. 7 (2019)

RMC Spectra and Closure Approximation

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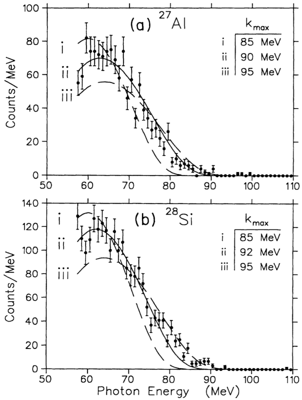

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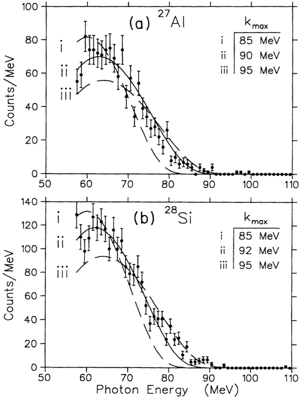
$$\frac{dW_{\mathrm{RMC}}}{dk} \propto x(1-x^2)[1-2x(1-x)], \text{ where } x = k/k_{\mathrm{max}}$$



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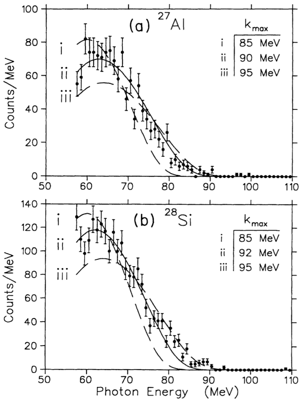

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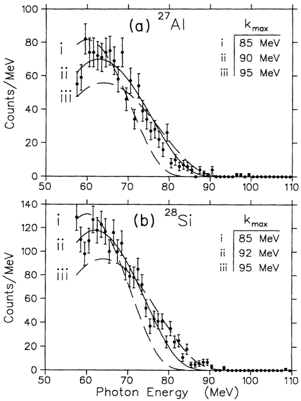
- Fitted k_{max} values below the kinematic endpoint $E_\gamma^{\mathrm{max}} = \mathbf{101.36}$ **MeV** (^{27}Al)



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RMC Estimates from Chiral Perturbation Theory + Nuclear Shell Model

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

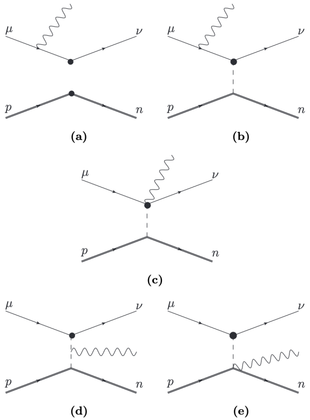
- Differential decay rate:

$$\frac{\mathrm{d}\Gamma_B}{\mathrm{d}\omega} = \frac{1}{2M}\int_{-1}^{1} \mathrm{d}\cos\theta\, \Pi(\cos\theta,\omega)\, \langle\, |\mathcal{M}_{B\gamma}|^2 \rangle$$

with

$$\Pi(\cos\theta,\omega) = \frac{1}{8}\frac{1}{(2\pi)^3}\frac{|\mathbf{k}_\nu|\,\omega}{M-\omega(1-\cos\theta)}$$

- **Aim: Differential decay rate with 10% uncertainty near the endpoint**



R. Plestid, LJ, work in progress

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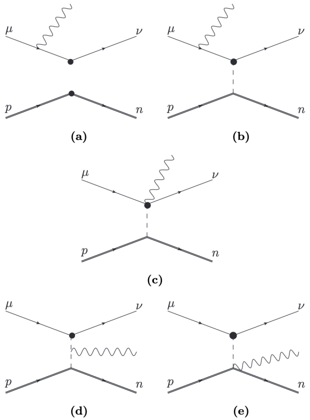

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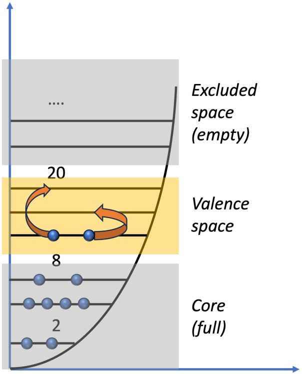
Nuclear Wave Functions from Nuclear Shell Model



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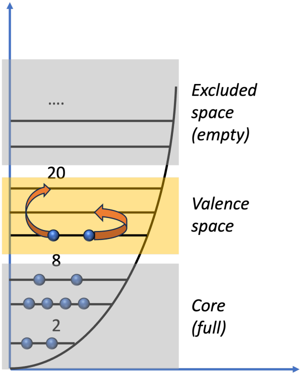
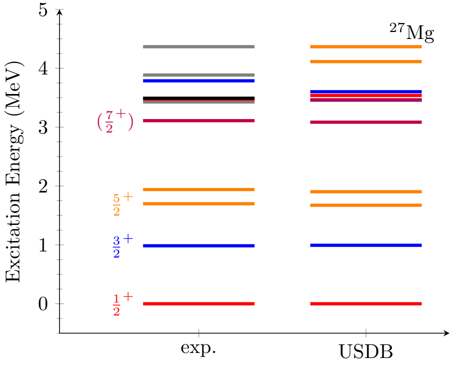


✓ Solve nuclear many-body problem in valence space

$$\boxed{H^{\text{eff}}\Psi^{(A)} = E^{(A)}\Psi^{(A)}}$$



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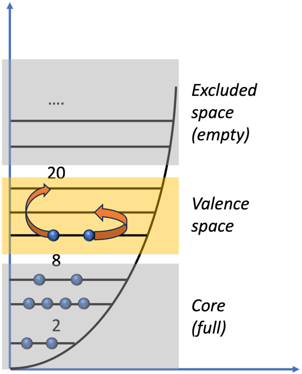

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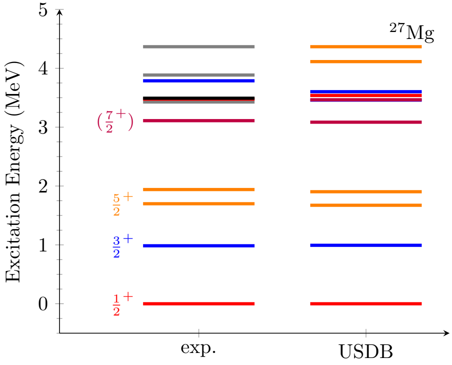

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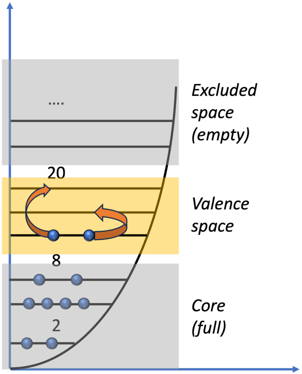

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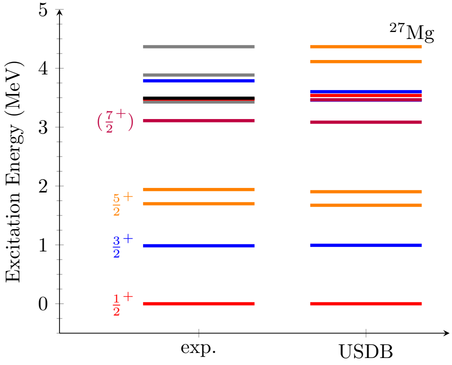
- TODO: Compute the differential RMC rate



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- Ordinary muon capture on nuclei can probe $0\nu\beta\beta$ decay
- *Ab initio* predictions for partial OMC rates in good agreement with data
- *Ab initio* total OMC rates look promising
- Radiative muon capture important background for $\mu \to$ e
- Work in progress to estimate differential RMC rate with χPT and nuclear shell model