TRIUMF

Theory estimates for muon capture in light and heavy nuclei

Lotta Jokiniemi

MONUMENT Collaboration meeting

24/05/2023

Arthur B. McDonald Canadian Astroparticle Physics Research Institute

Universitat de Barcelona

ICCUB

Suomen Kulttuurirahasto

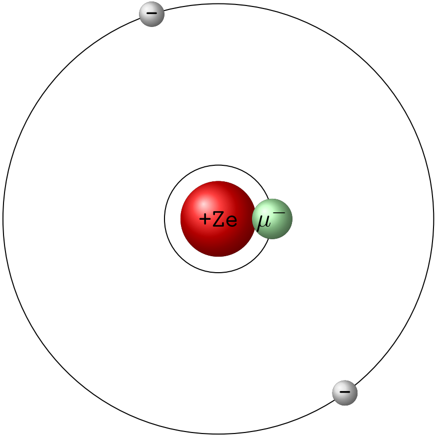
Discovery, accelerated

Outline

Ordinary Muon Capture (OMC)

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

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



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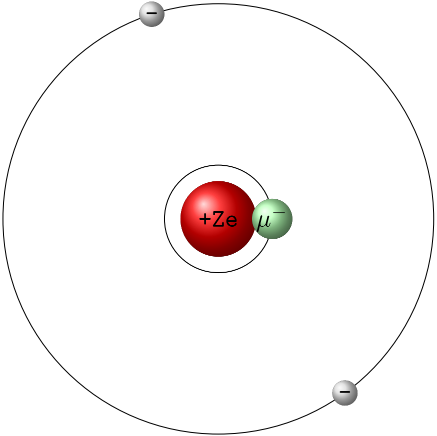

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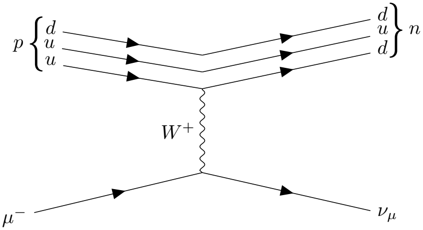

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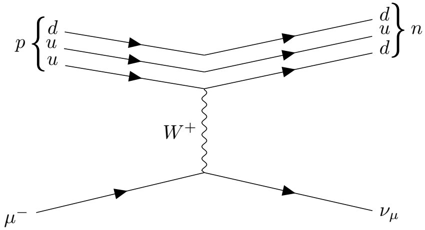
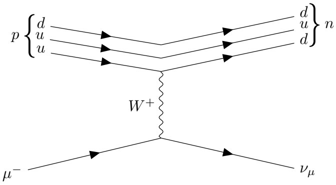
Ordinary = non-radiative

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



Discovery, accelerated

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



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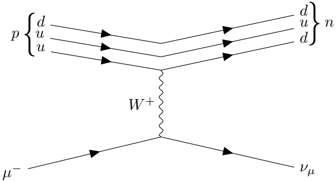

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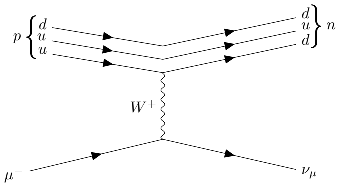

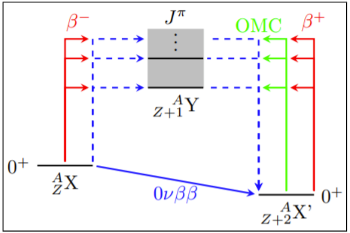

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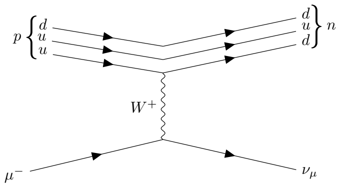

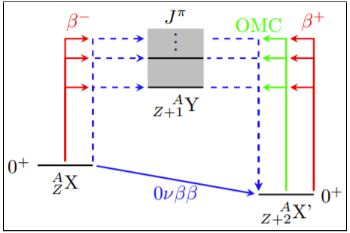

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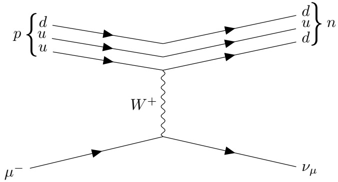

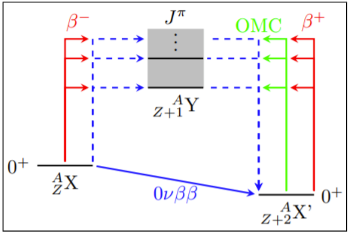

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- Large m_μ allows **transitions to all J^π states** up to high energies
- **Same currents involved** (vector, magnetic, axial-vector and psedoscalar)
  - $\rightarrow$ Similar to $0\nu\beta\beta$ decay!

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Muon-Capture Theory

- Interaction Hamiltonian $\rightarrow$ capture rate:

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

PHYSICAL REVIEW VOLUME 118, NUMBER 2 APRIL 15, 1960

Theory of Allowed and Forbidden Transitions in Muon Capture Reactions*

MASATO MORITA
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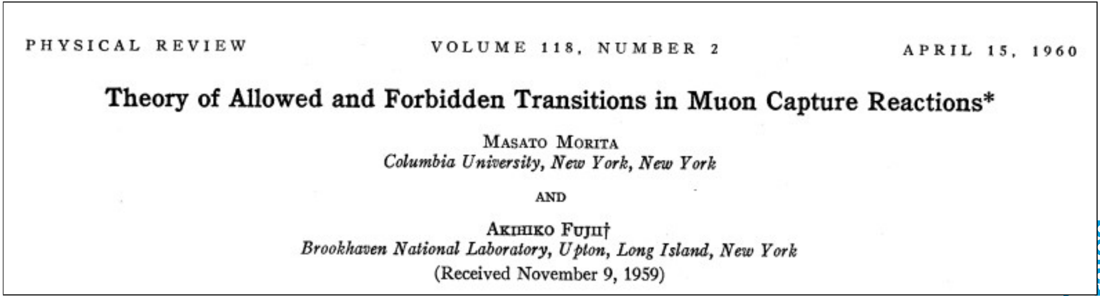

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- Use **realistic bound-muon wave functions**
- Add the effect of **two-body currents**

Nuclear matrix elements

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Discovery, accelerated

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- **Operator** (muon capture)

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Axial-Vector Quenching

- From β decay of neutrons, we know that $g_{\mathrm{A}} = 1.27641(45)_{\mathrm{stat}}(33)_{\mathrm{syst}}$

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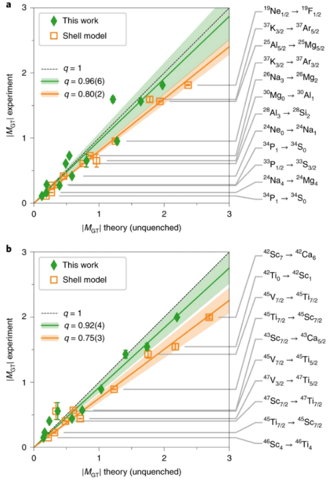

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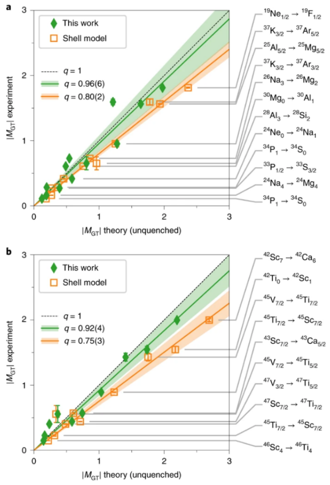

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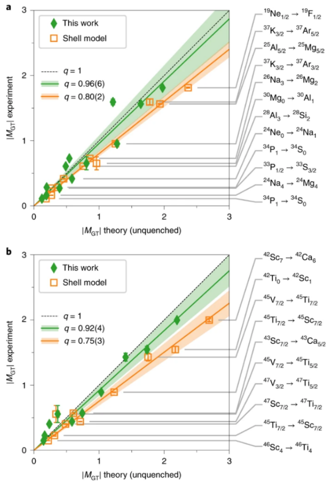

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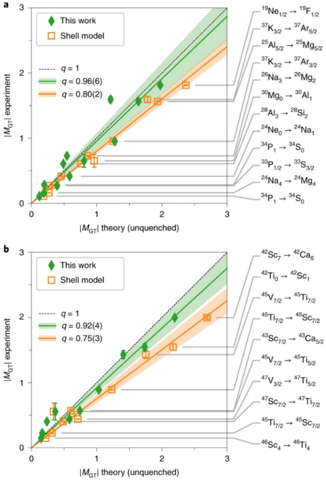

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Discovery, accelerated

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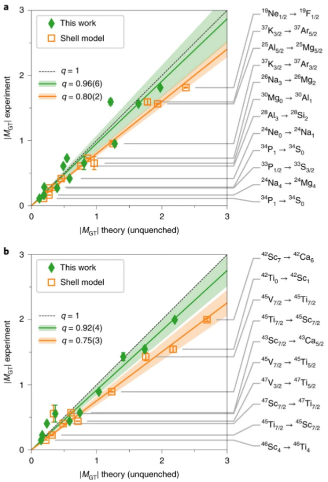
- In principle, one could also access the pseudoscalar coupling g_P



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

Discovery, accelerated

Outline

Introduction

***Ab initio* studies on muon capture in light nuclei**

Phenomenological study on ^{136}Ba

Summary and Outlook

Discovery, accelerated

First principles or *ab initio* nuclear theory

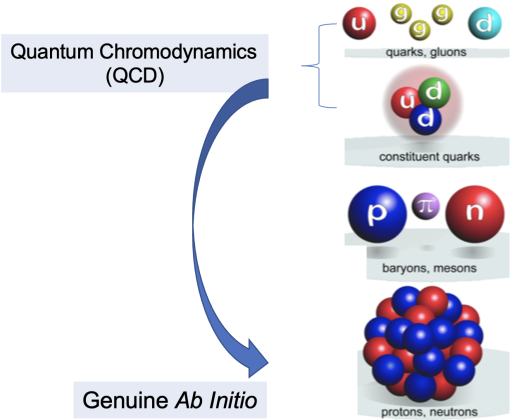


Figure courtesy of P. Navrátil

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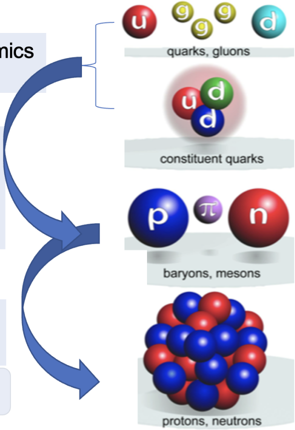
First principles or *ab initio* nuclear theory – what is done at present

Quantum Chromodynamics (QCD)

Chiral Effective Field Theory (parameters fitted to NN data)

Current *ab initio* nuclear theory

$$H\,\Psi^{(A)} = E\,\Psi^{(A)}$$



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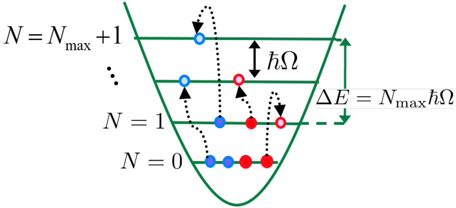
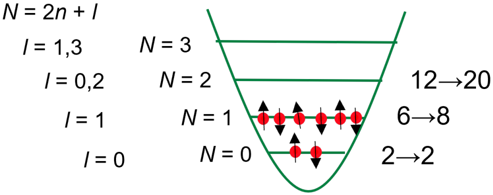
Discovery, accelerated

No-Core Shell Model (NCSM)

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





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

Figure courtesy of P. Navrátil

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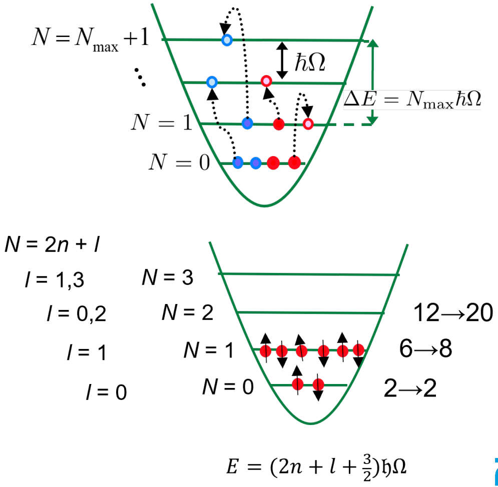

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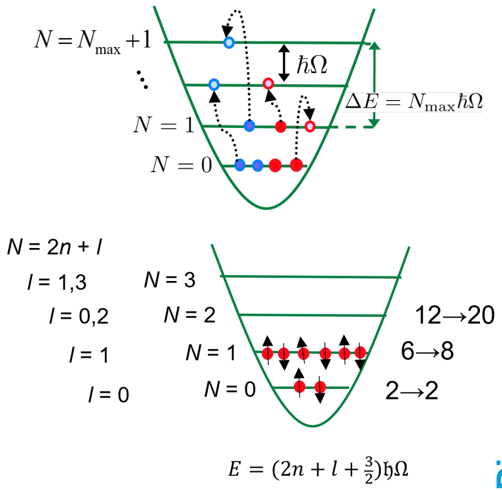

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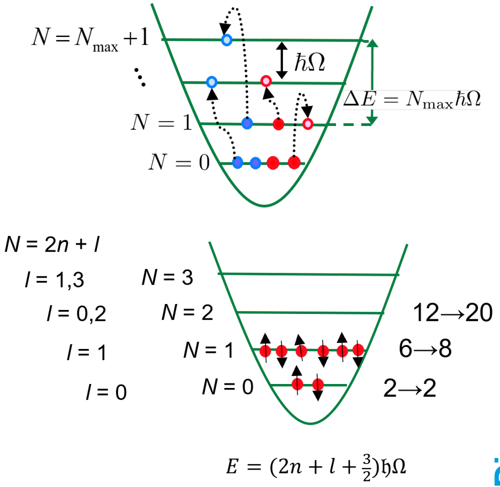

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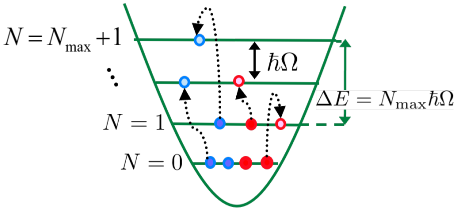
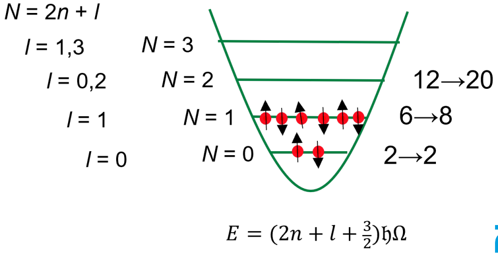
$\rightarrow$ **OMC on ^{6}Li, ^{12}C and ^{16}O**





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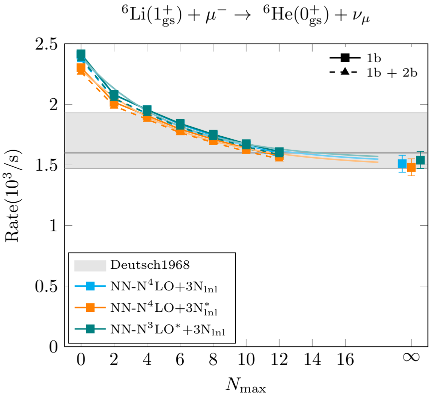
Capture Rates to the Ground State of ^{6}He

- NCSM in keeping with experiment



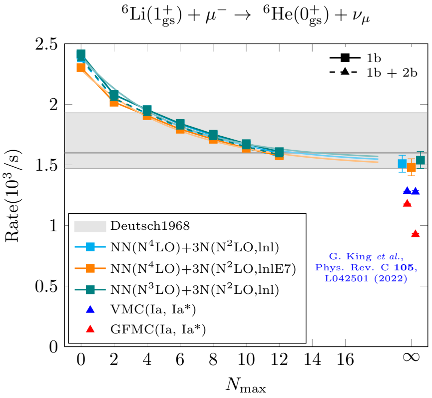
LJ, Navrátil, Kotila, Kravvaris,

work in progress

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

- NCSM in keeping with experiment
- The rates can be compared with other *ab initio* calculations

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



LJ, Navrátil, Kotila, Kravvaris, work in progress

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

- Interaction dependence

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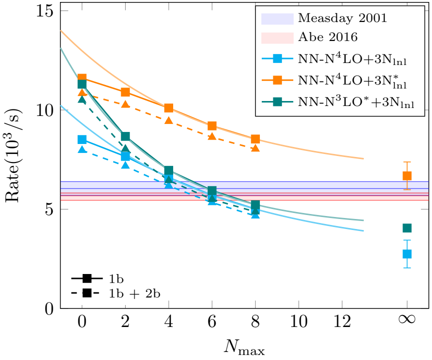

LJ, Navrátil, Kotila, Kravvaris,

work in progress

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

- Interaction dependence
- Converge slow (clustering effects?)

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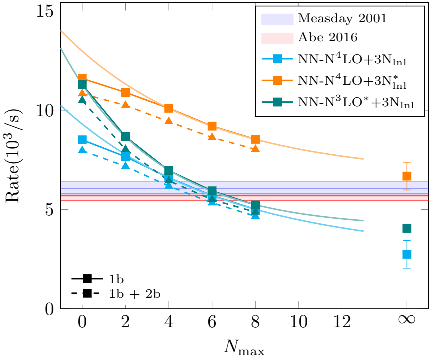

LJ, Navrátil, Kotila, Kravvaris,

work in progress

Discovery, accelerated

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

- Interaction dependence
- Converge slow (clustering effects?)
- The results can be compared against earlier NCSM ones

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

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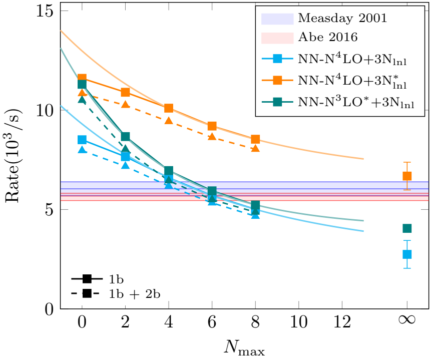

LJ, Navrátil, Kotila, Kravvaris,

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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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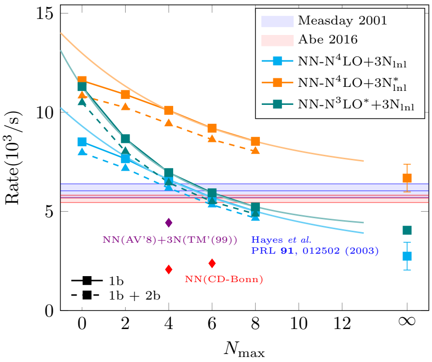
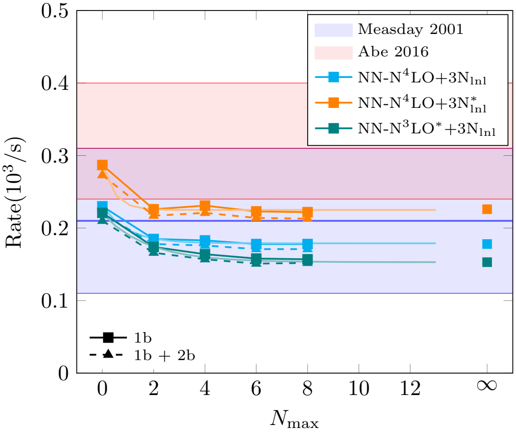


LJ, Navrátil, Kotila, Kravvaris, work in progress

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

$$^{12}\mathrm{C}(0^+_{\mathrm{gs}}) + \mu^- \to \; ^{12}\mathrm{B}(2^+_1) + \nu_\mu$$



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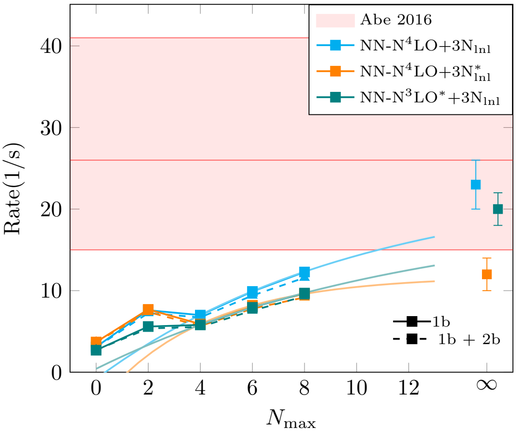

LJ, Navrátil, Kotila, Kravvaris, work in progress

Discovery, accelerated

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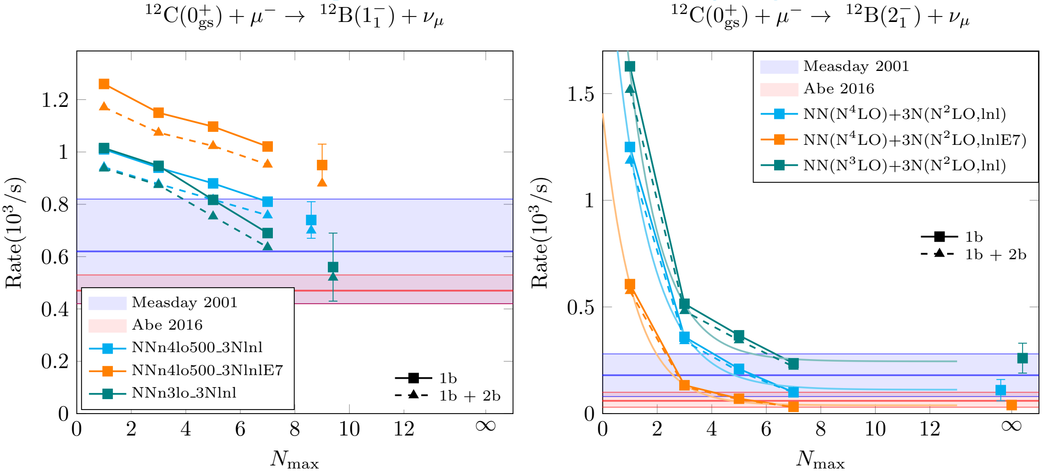

LJ, Navrátil, Kotila, Kravvaris, work in progress

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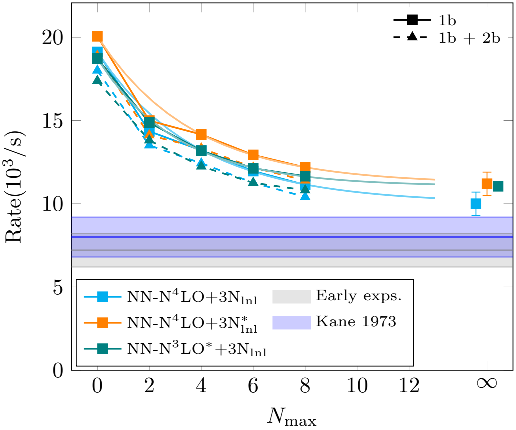
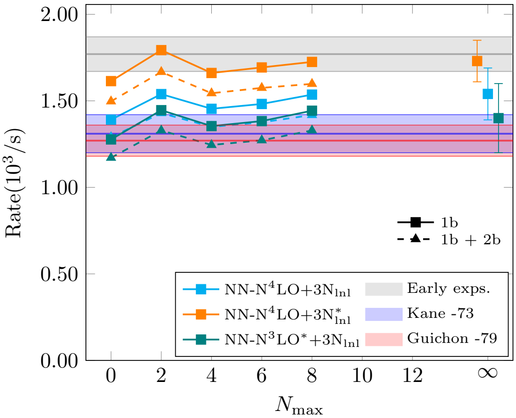
Capture Rates to Low-Lying States in ^{16}N

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



$^{16}O(0^+_{gs}) + \mu^- \rightarrow {}^{16}N(1^-_1) + \nu_\mu$



LJ, Navrátil, Kotila, Kravvaris, work in progress

TRIUMF

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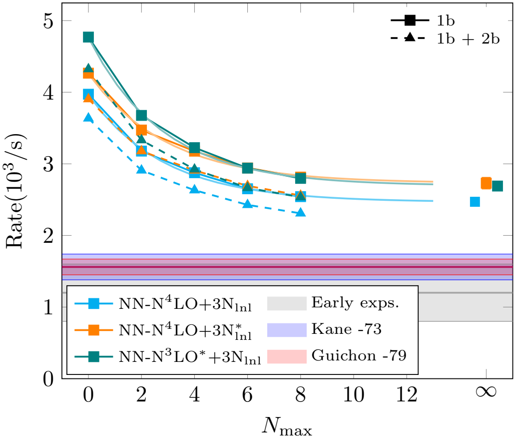
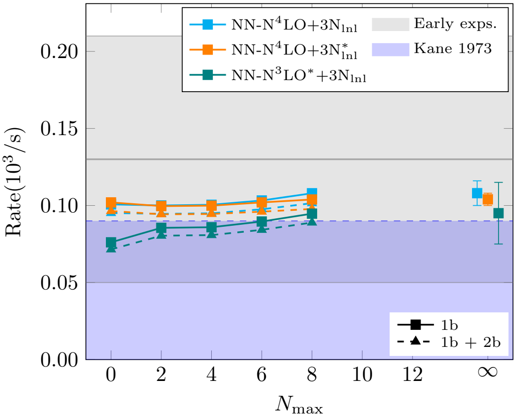


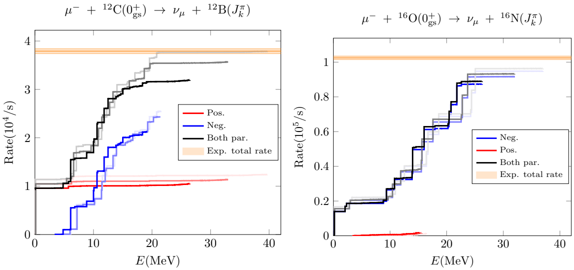
$$^{16}\mathrm{O}(0^+_{\mathrm{gs}}) + \mu^- \rightarrow \ ^{16}\mathrm{N}(3^-_1) + \nu_\mu$$



LJ, Navrátil, Kotila, Kravvaris, work in progress

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

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



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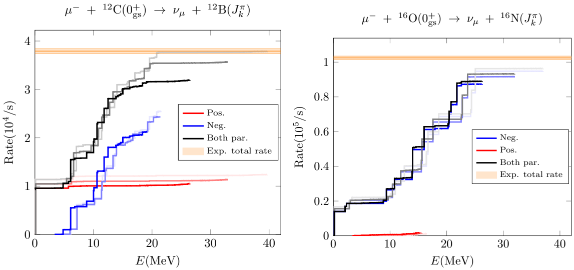

LJ, Navrátil, Kotila, Kravvaris, work in progress

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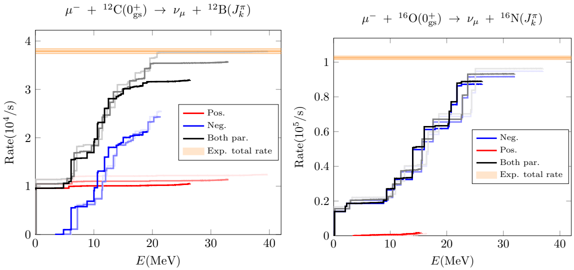

LJ, Navrátil, Kotila, Kravvaris, work in progress

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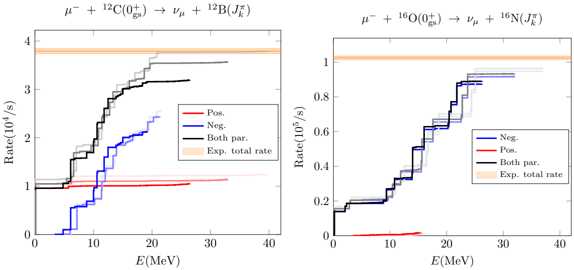
  - Can be improved
- Summing up **the rates up to ~ 20 MeV**, we capture **$\sim 85\%$ of the total rate** in both ^{12}B and ^{16}N

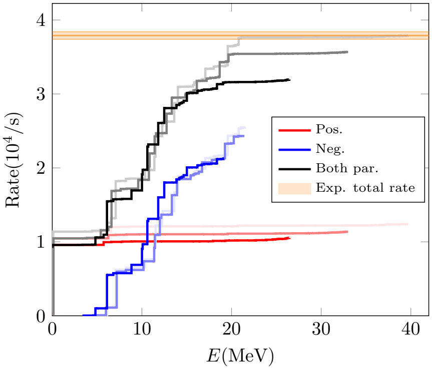


LJ, Navrátil, Kotila, Kravvaris, work in progress

Total Muon-Capture Rates

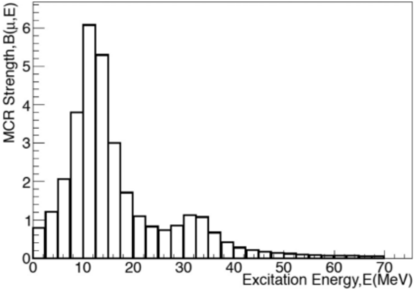
Calculation:

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



Experiment:

$$\boxed{\mu^- + {}^{100}\mathrm{Mo} \rightarrow \nu_\mu + {}^{100}\mathrm{Nb}}$$



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

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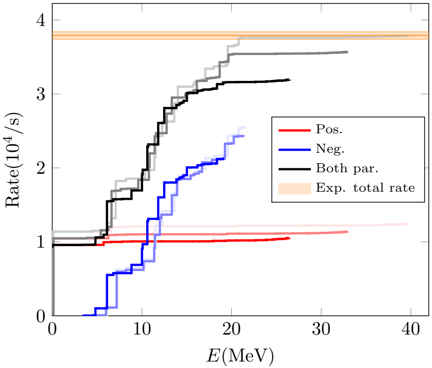

Missing potentially important contribution from high energies

Experiment:

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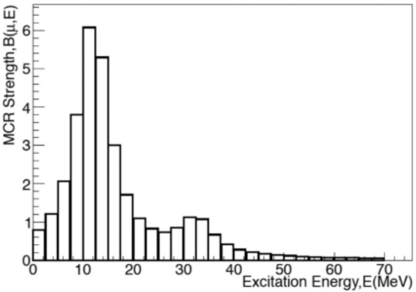


*Hashim et al., Phys. Rev. C **97**, 014617 (2018)*

Discovery, accelerated

Outline

Introduction

Ab initio studies on muon capture in light nuclei

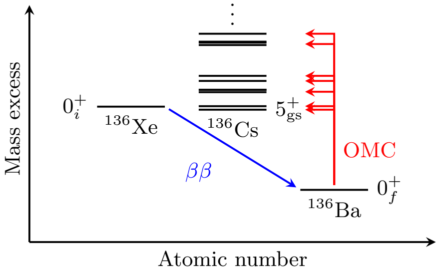
Phenomenological study on ^{136}Ba

Summary and Outlook

Discovery, accelerated

Muon capture on ^{136}Ba

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



Muon capture on ^{136}Ba

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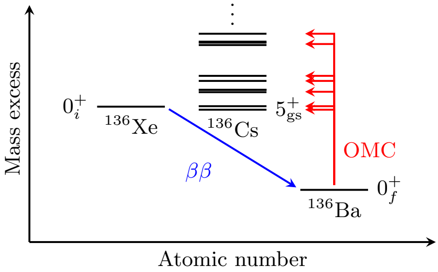
- Calls for phenomenology:



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Muon capture on ^{136}Ba

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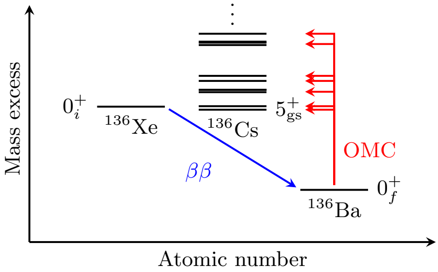

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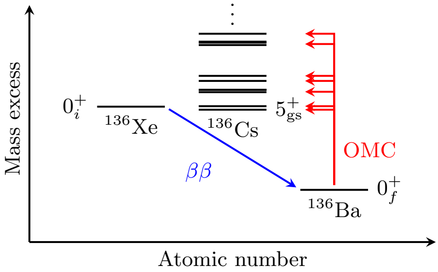

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- Calls for phenomenology:
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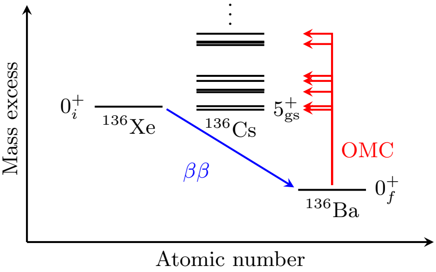
- Solution: (phenomenological) nuclear shell model and proton-neutron QRPA



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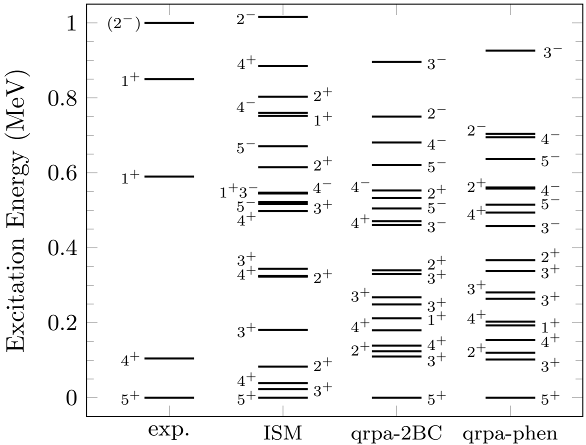
Excitation energies in ^{136}Cs ($J \leq 5$)

- The shell-model and pnQRPA energies are surprisingly similar

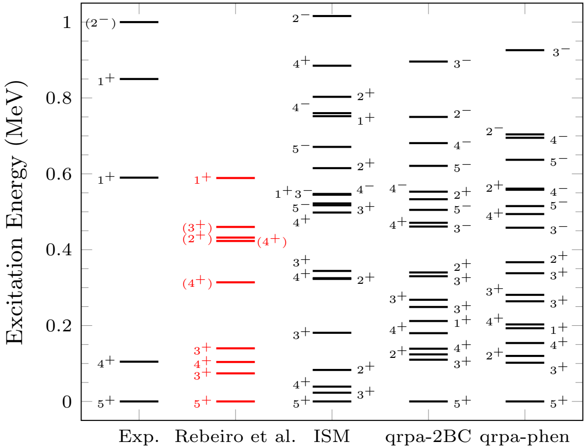


P. Gimeno, LJ, J. Kotila, M. Ramalho, J. Suhonen, 10.20944/preprints202304.0899.v1 (submitted to Universe)

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

- The shell-model and pnQRPA energies are surprisingly similar
- Agreement with experiment gets much better with the new measurement

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



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

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

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

- Summing up the rates to states with $E_X < 1$ MeV:

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

	Rate (1b)$(10^3 1/s)$	Rate (1b+2b)$(10^3 1/s)$	Rate (1b+2b) / Total rate
NSM	248	$150 - 174$	$1.4 - 1.5\%$
pnQRPA	1103	$592 - 807$	$5 - 7\%$

- pnQRPA gives ≈4 times larger rates than NSM
  - With experimental data, we will know which one is (more) correct
  - May hint which model is more reliable for the $0\nu\beta\beta$ decay of ^{136}Xe!
- Similar study ongoing for OMC on ^{128,130}Xe
- In pnQRPA, can be extended to strength functions!

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Discovery, accelerated

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Summary

- Ab initio muon-capture studies could shed light on g_{A} quenching at finite momentum exchange regime relevant for $0\nu\beta\beta$ decay
- No-core shell-model describes well partial muon-capture rates in light nuclei ^{6}He, ^{12}B and ^{16}N
- Phenomenological methods still needed for heavy/difficult systems

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Outlook

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

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Outlook

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TRIUMF

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- The “brute force” method cannot reach the total muon-capture rates
  $\rightarrow$ use the **Lanczos strength-function** method, instead

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- Study the effect of **vector two-body currents** (one-pion-exchange & pion-in-flight) on OMC rates
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- The "brute force" method cannot reach the total muon-capture rates
  $\rightarrow$ use the **Lanczos strength-function** method, instead
- Study the effect of **exact two-body currents and/or continuum** on the OMC rates

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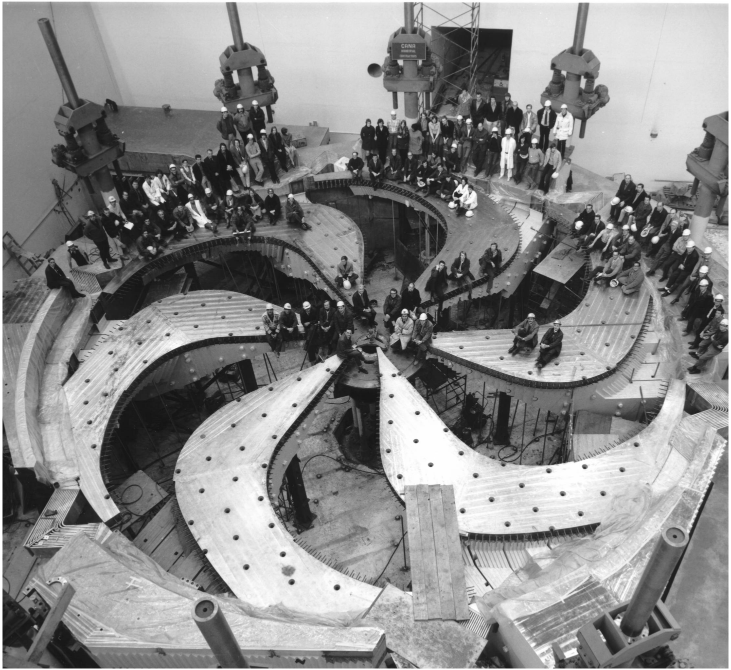
Thank you
Merci



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Excitation Energies of ^{12}B

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

Excitation Energies of ^{16}N

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