Status of β-decay calculations and quenching in nuclei from ab-initio

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LDRD

Nuclear Computational Low-Energy Initiative

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Outline

- The "g_A quenching" "problem"
- Evidence of the importance of two-body currents
- The nuclear Hamiltonian and currents
- β-decay in nuclei
- Electro-magnetic currents and power counting
- Conclusions

Motivation

At "nuclear" energies, understanding neutrino-nucleus interactions very challenging and important!

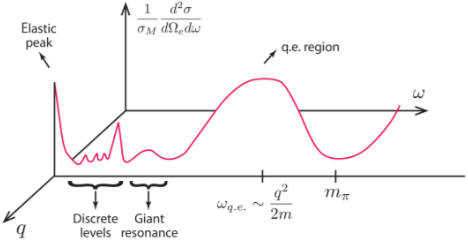
Understanding Nuclei:

- Nuclear interactions and structure
- Exotic nuclei - neutron rich
- Electro-weak processes

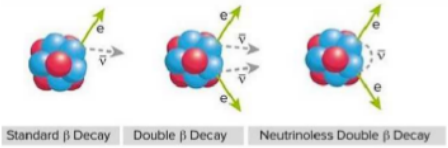
Relevance:

- Neutrino scattering in nuclei (neutrino oscillation experiments)
- Neutrinoless Double Beta Decay
- Neutrino interactions in supernovae and neutron stars, nucleosynthesis, etc.

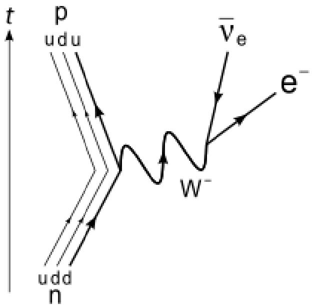
We need a coherent picture of ν-nucleus interactions

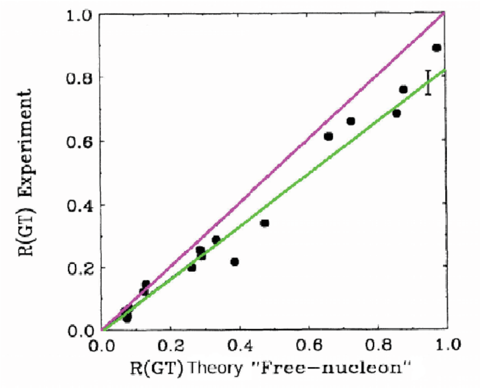


- $\omega \approx$ few MeV, $q \approx 0$: $\beta-$ and $\beta\beta-$decays
- $\omega \approx$ few MeV, $q \approx 10^2$ MeV: Neutrinoless $\beta\beta-$decays
- $\omega \leq$ tens MeV: Astrophysics
- $\omega \approx 10^2$ MeV: Accelerator neutrinos, ν-nucleus scattering



The "quenching"-g_A problem





$$g_A^{\rm eff} \simeq 0.70\, g_A$$

Chou et al., PRC 47, 163 (1993)

What's the origin (or is there a **need**) of g_A quenching?

Nuclear matrix elements. Basically we need to calculate things like:

$$O \propto \langle f | J | i \rangle$$

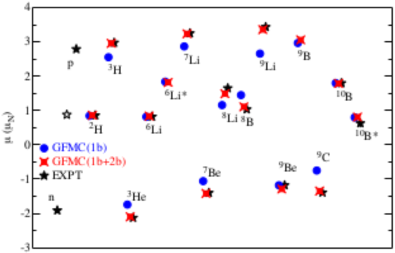
where

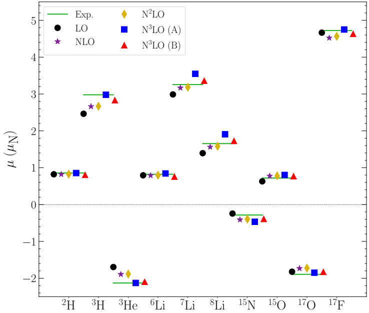
$$J = \sum_i J_i^{(1)} + \sum_{i<j} J_{ij}^{(2)} + \ldots$$

and $J^{(\cdot)}$ are one- two- and (in principle) many-body currents describing the interactions of nucleons with an external probe (electrons, neutrinos, ...).

The nuclear states $|i\rangle$ and $|f\rangle$ are obtained from a (many-body) nuclear Hamiltonian H.

Magnetic moments in light nuclei:

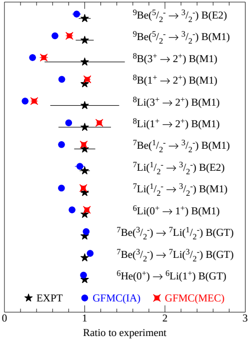




Pastore et al, PRC (2013); Martin et al., arXiv:2301.08349

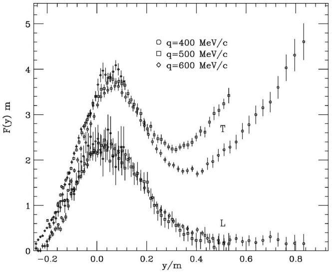
The role of two-body currents is essential.

Low-momentum, transitions:



Pastore et al, PRC (2014)

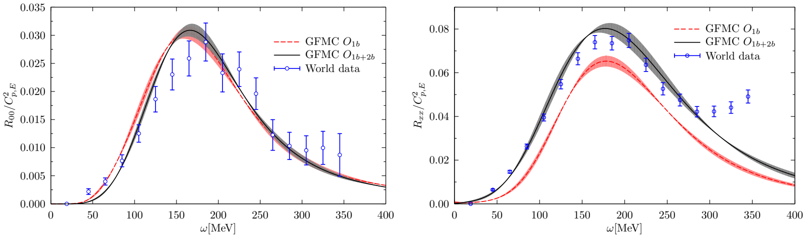
High-momentum, e^- scattering: rescaled longitudinal vs transverse electro-magnetic response in ^{12}C



Benhar, Day, Sick, RMP (2008)

Without two-body processes, the longitudinal and transverse response are about the same

Electro-magnetic longitudinal and transverse response functions of ^{12}C (q=570 MeV)

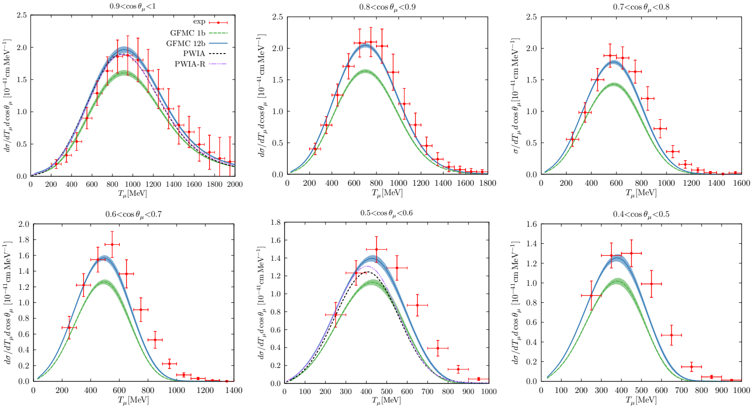


Lovato et al., PRL (2016).

Role of two-body currents very important.

ν_μ CCQE scattering on ^{12}C (MiniBooNE)

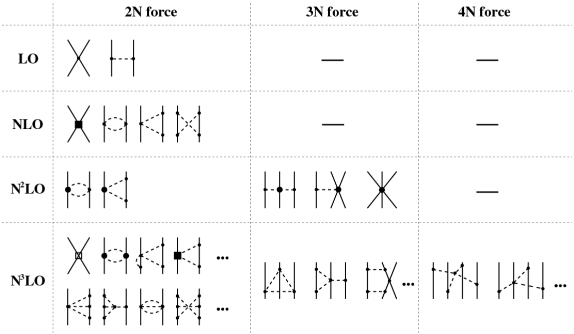
High-momentum, ν scattering:



Lovato et al., PRX 10, 031068 (2020)

Nuclear Hamiltonian (only pions)

Weinberg power counting:



Expansion in powers of Q/Λ, Q$\sim$100 MeV, Λ $\sim$1 GeV.

Long-range physics given by pion-exchanges (no free parameters).

Short-range physics: contact interactions (LECs) to fit.

Operators need to be regulated $\rightarrow$ cutoff dependency!

Order's expansion provides a way to quantify uncertainties!

Truncation error estimate

Error quantification (one possible scheme), friendly (easy) one. Define

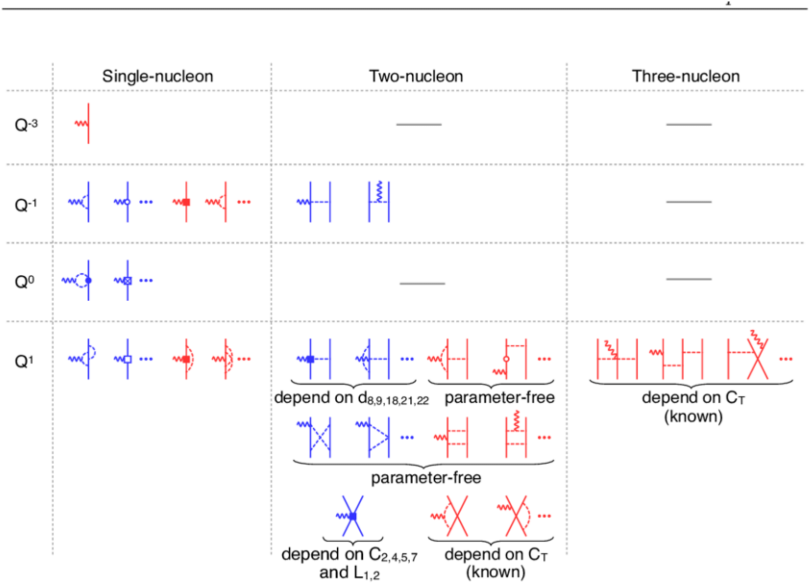
$$Q = \max\left(\frac{p}{\Lambda_b}, \frac{m_\pi}{\Lambda_b}\right) ,$$

where p is a typical nucleon's momentum or k_F for matter, Λ_b is the cutoff, and calculate:

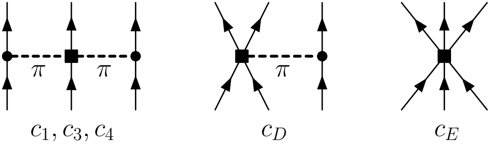
$$\Delta(N2LO) = \max\left(Q^4|\hat{O}_{LO}|,\ Q^2|\hat{O}_{LO} - \hat{O}_{NLO}|,\ Q|\hat{O}_{NLO} - \hat{O}_{N2LO}\right)$$

Epelbaum, Krebs, Meissner (2014).

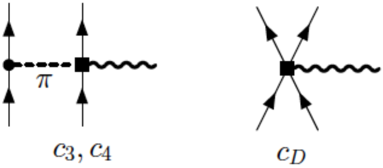
Electro-magnetic currents



Chiral three-body forces at N^{2}LO:



Chiral two-body currents:



NN and NNN often use different regulators and cutoffs (local vs non-local, or a mix).

Hamiltonian-currents consistency?

Solving the nuclear many-body problem

Various many-body methods (with various approximations):

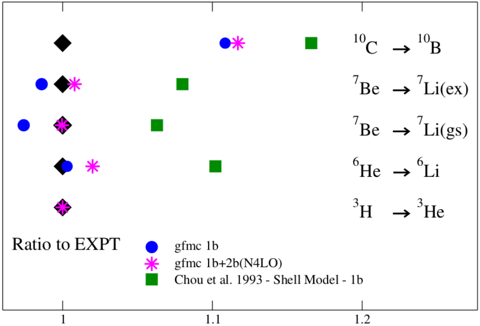
- Shell-model
- Quantum Monte Carlo (QMC)
- Coupled-cluster (CC)
- In-Medium SRG (IMSRG)
- No-core Shell model (NCSM)
- ...

Caveats:

- Regulators in Hamiltonian and currents
- Cutoff in Hamiltonian and currents
- SRG of Hamiltonian and currents
- Normal ordering (NNN to NN and 2BC to 1BC) in the Hamiltonian and currents
- Chiral order expansion consistency, i.e. NN vs NNN vs 2BC?

β-decays in light nuclei

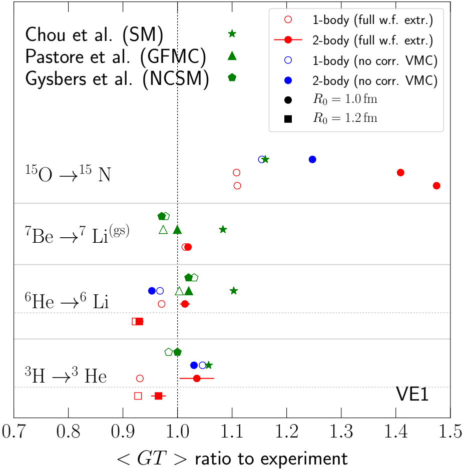
QMC calculations using a correlated wave function compared to shell-model calculations using the AV18+IL7 Hamiltonian and chiral currents.



Pastore, et al., PRC 97, 022501 (2018).

The effect of correlations in the nuclear wave function is critical!

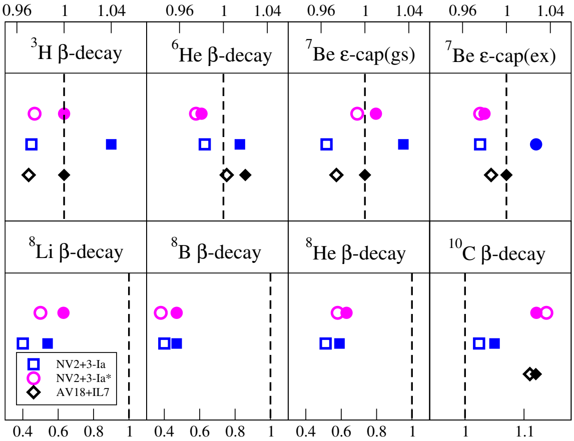
QMC calculations using chiral EFT Hamiltonians and currents:



Two-body currents always increase the matrix element. Huge contribution in A=15.

Unpublished.

QMC calculations using chiral EFT Hamiltonians and currents with Δ:

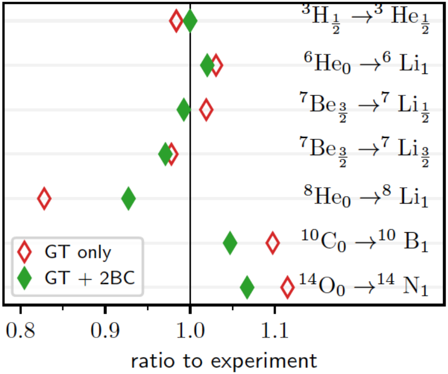


King et al., PRC 102, 025501 (2020)

Two-body currents (almost) always increase the matrix element.

β-decays in light nuclei

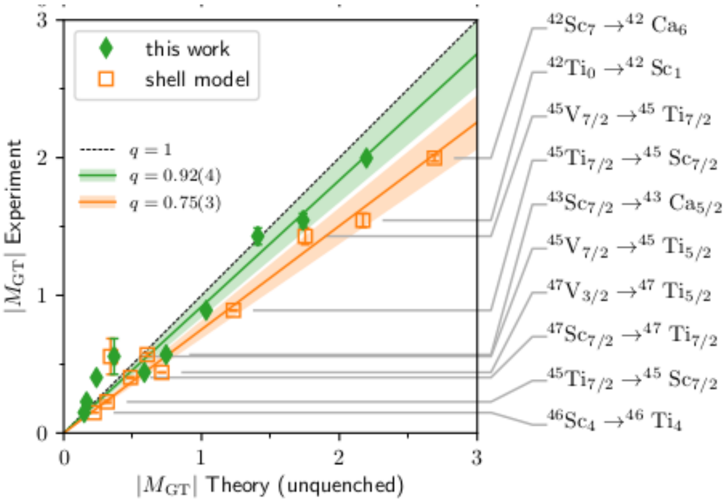
NCSM calculations using NN-N^{4}LO+3N$_{lnl}$



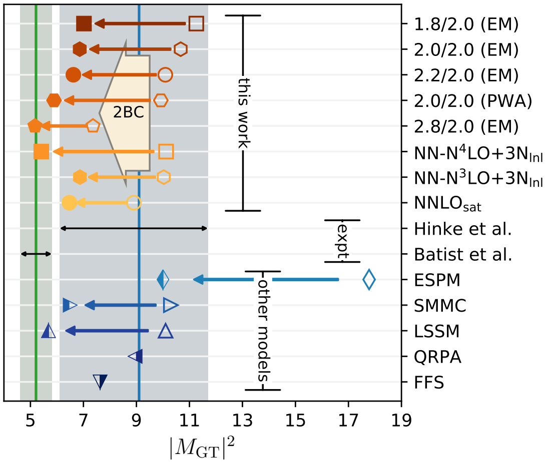
Gysbers et al., Nature Physics (2019).

Two-body currents can increase or reduce the matrix element.

VS-IMSRG calculations using NN-N^{4}LO+3N$_{lnl}$



Gysbers et al., Nature Physics (2019).



Gysbers et al., Nature Physics (2019).

ESPM: Extreme Single Particle Model

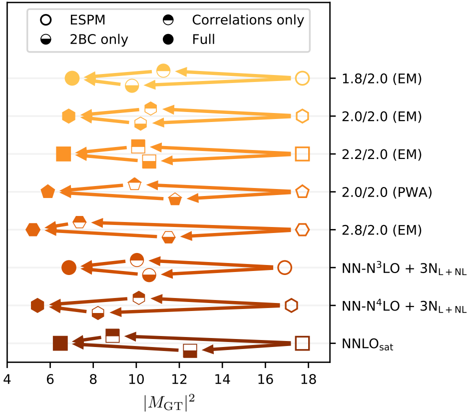
SMMC: Shell Model MC

LSSM: Large Space Shell Model

QRPA: quasiparticle random phase approximation

FFS: finite Fermi systems

Role of correlations vs 2BC



Gysbers et al., Nature Physics (2019).

Electro-magnetic currents

But, within chiral EFT, there are different ways to construct the currents, different expansions.

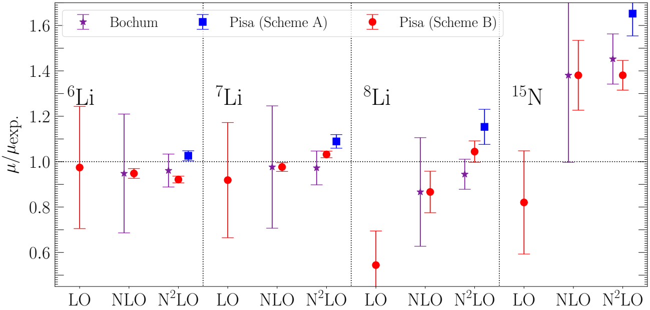
Hamiltonian	Pisa/Norfolk/WUSTL	Bochum
Q^0 LO	Q^{-2} LO	Q^{-3} LO
Q^1 –	Q^{-1} NLO	Q^{-2} –
Q^2 NLO	Q^0 N2LO	Q^{-1} NLO
Q^3 N2LO	Q^1 N3LO	Q^0 N2LO
		Q^1 N3LO
	2 LECS (contact)	2 LECS (contact)
	1 LEC (OPE)	

Understanding which currents to use, chiral order, regulators, continuity equation, etc., is still work in progress.

Same "issue" with axial (weak) currents?

Nuclear magnetic moments

Order by order calculation. Hamiltonian and currents consistent at each order.

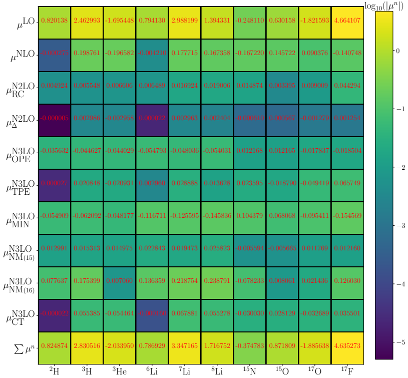


J. D. Martin, S. J. Novario, D. Lonardoni, J. Carlson, S. Gandolfi, I. Tews, arXiv:2301.08349.

Different power counting provide different results (and errors).

Nuclear magnetic moments

Magnetic moments, single contributions (Pisa).



In several cases, the contribution of N3LO terms is larger than N2LO and NLO. Worrisome?

Summary and future work

Conclusions:

- Role of two-body currents essential in electro-magnetic and electro-weak transitions.
- Role of strong correlations in the nuclear wave function critical.
- "Quenching" of g_A *qualitatively* understood.

Open questions:

- Role of regulators, cutoff, regulator&cutoff and power counting to be understood.
- Consistency of Hamiltonian and currents?
- Theoretical Uncertainties?

During a "precision frontier" era, all these questions should be addressed!

Acknowledgments:
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