Many-body currents in the analysis of precision experiments

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Precise beta decay calculations for searches for new physics
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Washington University in St.Louis
Arts & Sciences

Open Questions in Fundamental Symmetries and Neutrino Physics
Majorana Neutrinos, Neutrinos Mass Hierarchy,
CP-Violation in Neutrino Sector, Dark Matter

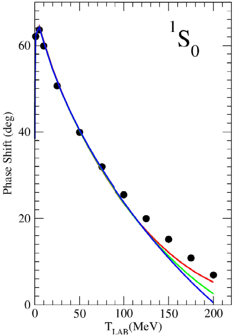
with
Carlson & Gandolfi (LANL) & Schiavilla (ODU+JLab)
Piarulli (WashU) & Baroni (USC) & Pieper & Wiringa (ANL)
Girlanda (Salento U.) & Marcucci & Viviani & Kievsky (Pisa U/INFN)
and with
Mereghetti & Dekens & Cirigliano & Graesser (LANL)
de Vries (Nikhef) & van Kolck (AU+CNRS/IN2P3)

Nuclear Interactions

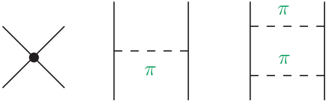
The nucleus is made of A non-relativistic interacting nucleons and its energy is

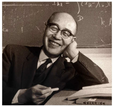
$$H = T + V = \sum_{i=1}^{A} t_i + \sum_{i<j} \upsilon_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

where υ_{ij} and V_{ijk} are two- and three-nucleon operators based on EXPT data fitting and fitted parameters subsume underlying QCD



Pastore *et al.* PRC80(2009)034004





Hideki Yukawa

- Contact terms: short-range
- One-pion-exchange: range$\sim \frac{1}{m_\pi}$
- Two-pion-exchange: range$\sim \frac{1}{2m_\pi}$

Quantum Monte Carlo Methods

Minimize expectation value of H = T + V_{ij} + V_{ijk}

$$E_V = \frac{\langle \Psi_V | H | \Psi_V \rangle}{\langle \Psi_V | \Psi_V \rangle} \geq E_0$$

using trial function

$$|\Psi_V\rangle = \left[\mathscr{S} \prod_{i<j} \left(1 + U_{ij} + \sum_{k \neq i,j} U_{ijk}\right) \right] \left[\prod_{i<j} f_c(r_{ij}) \right] |\Phi_A(JMTT_3)\rangle$$

Ψ_V is further improved it by "filtering" out the remaining excited state contamination

$$\Psi(\tau) = \exp[-(H - E_0)\tau]\Psi_V = \sum_n \exp[-(E_n - E_0)\tau] a_n \psi_n$$

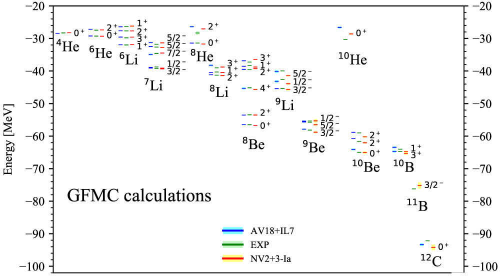
$$\Psi(\tau \to \infty) = a_0 \psi_0$$

* QMC: AV18+UIX / AV18+IL7; Wiringa+Schiavilla+Pieper *et al.*
* QMC: NN(N2LO)+3N(N2LO) ($\pi \& N$); Gerzelis+Tews+Epelbaum+Gandolfi+Lynn *et al.*
* QMC: NN(N3LO)+3N(N2LO) ($\pi \& N \& \Delta$); Piarulli *et al.*

Lomnitz-Adler *et al.* NPA361(1981)399 - Wiringa PRC43(1991)1585 - Pudliner *et al.* PRC56(1997)1720 - Wiringa *et al.* PRC62(2000)014001

Pieper *et al.* PRC70(2004)054325 - Carlson *et al.* RevModPhys87(2014)1067

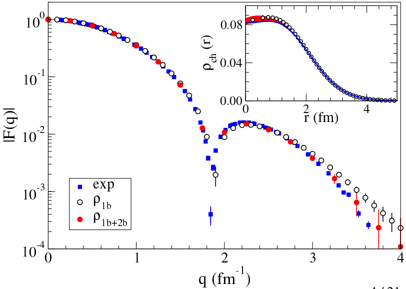
Energy Spectrum and Shape of Nuclei



Piarulli *et al.* - PRL120(2018)052503

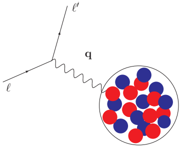
Lovato *et al.*

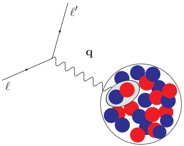
PRL111(2013)092501



Nuclear Currents

1b 2b

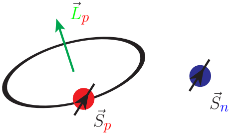




$$\rho = \sum_{i=1}^{A} \rho_i + \sum_{i<j} \rho_{ij} + \dots ,$$

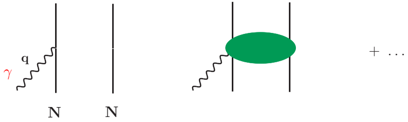
$$\mathbf{j} = \sum_{i=1}^{A} \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + \dots$$

* Nuclear currents given by the sum of p's and n's currents, one-body currents (1b)



* Two-body currents (2b) essential to satisfy current conservation

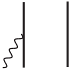
* We use Meson-Exchange Currents (MEC) or χEFT Currents



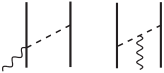
$$\mathbf{q} \cdot \mathbf{j} = [H, \rho] = [t_i + v_{ij} + V_{ijk}, \rho]$$

Electromagnetic Currents from Chiral Effective Field Theory

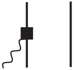
LO : $\mathbf{j}^{(-2)} \sim \mathbf{eQ^{-2}}$



NLO : $\mathbf{j}^{(-1)} \sim \mathbf{eQ^{-1}}$



N^{2}LO : $\mathbf{j}^{(-0)} \sim \mathbf{eQ^{0}}$



* 3 unknown Low Energy Constants:
fixed so as to reproduce d, ^3H, and ^{3}He magnetic moments

** also obtainable from LQCD calculations **

N^{3}LO: $\mathbf{j}^{(1)} \sim \mathbf{eQ}$

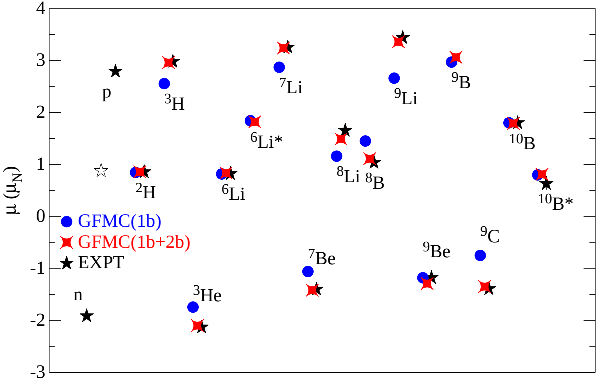
unknown LEC′s →

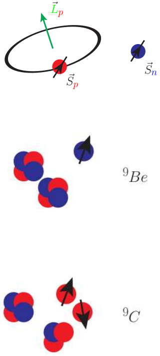
Pastore *et al.* PRC78(2008)064002 & PRC80(2009)034004 & PRC84(2011)024001

Piarulli *et al.* PRCC87(2013)014006

derived by Park+Min+Rho NPA596(1996)515 in CPT
and by Kölling+Epelbaum+Krebs+Meissner PRC80(2009)045502 & PRC84(2011)054008 with UT

Magnetic Moments of Nuclei



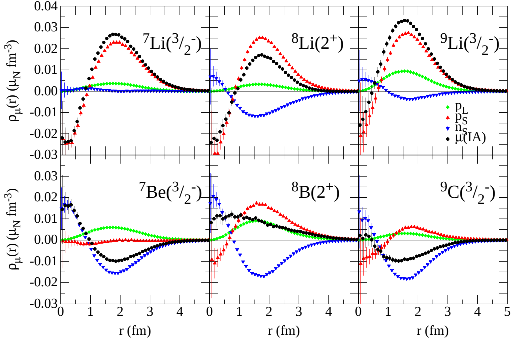


m.m.	THEO	EXP
^{9}C	-1.35(4)(7)	-1.3914(5)
^{9}Li	3.36(4)(8)	3.4391(6)

chiral truncation error based on EE *et al.* error algorithm, Epelbaum, Krebs, and Meissner EPJA51(2015)53

Pastore *et al.* PRC87(2013)035503

One-body magnetic densities

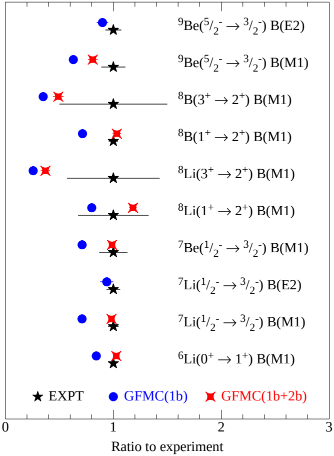


* one-body (IA) magnetic moment operator

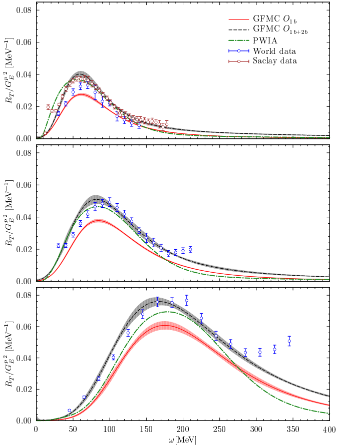
$$\mu(\mathrm{IA}) = \mu_N \sum_i [(L_i + g_p S_i)(1+\tau_{i,z})/2 + g_n S_i (1-\tau_{i,z})/2]$$

Electromagnetic Decays and e-scattering off nuclei

Electromagnetic Decay



Electromagnetic Transverse Responses



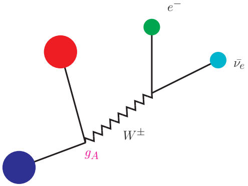
$q = [300 - 750]$ MeV

Pastore *et al.* PRC87(2013)035503 & PRC90(2014)024321

Lovato & Gandolfi *et al.* PRC91(2015)062501 & arXiv:1605.00248

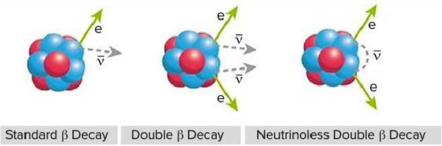
Electromagnetic data are explained when
two-body correlations and currents are accounted for!

Role of two-body correlations and two-body currents



* Matrix Element $\langle\Psi_f|\mathrm{GT}|\Psi_i\rangle \propto g_A$ and Decay Rates $\propto g_A^2$ *

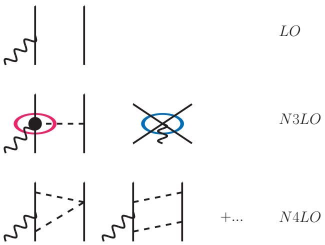
$$(Z,N) \to (Z+1,N-1)+e+\bar{\nu}_e$$



Nuclear Interactions and Axial Currents

$$H = T + V = \sum_{i=1}^{A} t_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

so far results are available with AV18+IL7 ($A \leq 10$)
and SNPA or chiral currents (*a.k.a.* hybrid calculations)



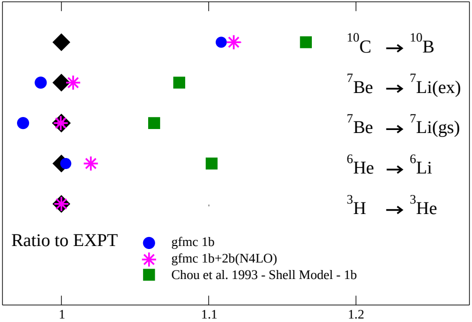
A. Baroni *et al.* PRC93(2016)015501

H. Krebs *et al.* Ann.Phy.378(2017)

- c_3 and c_4 are taken them from Entem and Machleidt PRC68(2003)041001 & Phys.Rep.503(2011)1
- c_D fitted to GT m.e. of tritium Baroni *et al.* PRC94(2016)024003
- cutoffs $\Lambda = 500$ and 600 MeV
- include also N4LO 3b currents (tiny)

* derived by Park *et al.* in the ′90
used at tree-level in many calculations (Song-Ho, Kubodera, Gazit,Marcucci, Lazauskas, Navratil ...)
* pion-pole at tree-level derived
by Klos, Hoferichter *et al.* PLB(2015)B746

Single Beta Decay Matrix Elements in $A = 6$–10



gfmc (1b) and gfmc (1b+2b); shell model (1b)

Pastore *et al.* PRC97(2018)022501

A. Baroni *et al.* PRC93(2016)015501 & PRC94(2016)024003

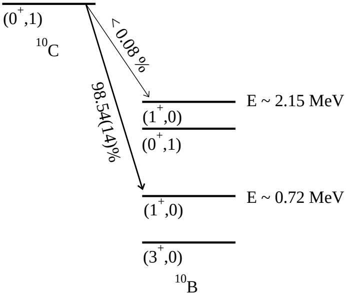
Based on $g_A \sim 1.27$ no quenching factor

GT in ^{3}H is fitted to expt - 2b give a 2% additive contribution to 1b prediction

* similar results were obtained with MEC currents

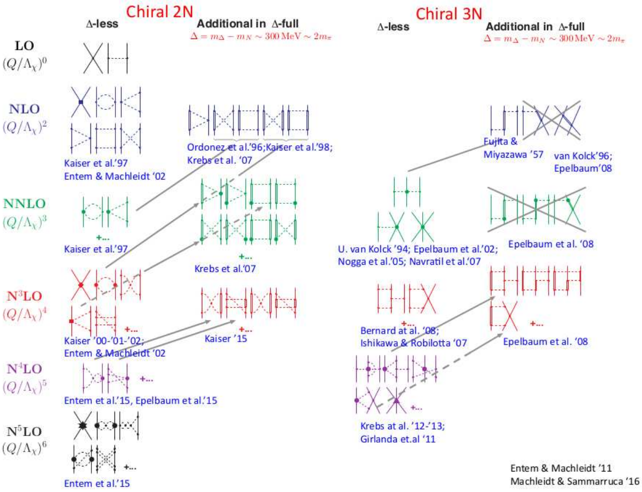
$*$ data from TUNL, Suzuki *et al.* PRC67(2003)044302, Chou *et al.* PRC47(1993)163

^{10}B



* In ^{10}B, ΔE with same quantum numbers ~ 1.5 MeV
* In $A = 7$, ΔE with same quantum numbers $\gtrsim 10$ MeV

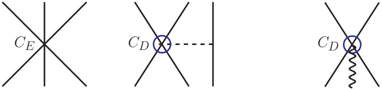
Chiral calculations of beta decay m.e.'s: Nuclear Interaction



courtesy of M. Piarulli

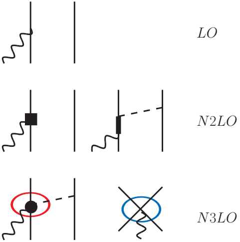
Chiral calculations of beta decay m.e.'s: Nuclear Currents

* Chiral interactions and axial currents



we now use

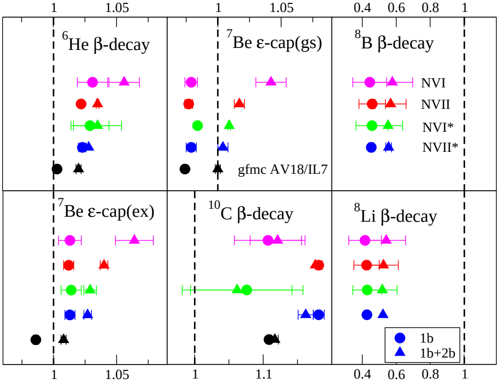
1. chiral 2– and 3–body interactions with πN and Δ's developed by Piarulli *et al.* and
2. axial currents with Δ's up to N3LO (tree-level) A. Baroni *et al.* arXiv:1806.10245 (2018)



* c_3 and c_4 are taken them from Krebs *et al.* Eur.Phys.J.(2007)A32
* (c_D,c_E) fitted to
  a. trinucleon B.E. and *nd* doublet scattering length **NV models**
  or
  b. trinucleon B.E. and GT m.e. of tritium **NV* models**

A. Baroni *et al.* arXiv:1806.10245 (2018)

Single Beta Decay Matrix Elements in $A = 6$–10 in chiEFT



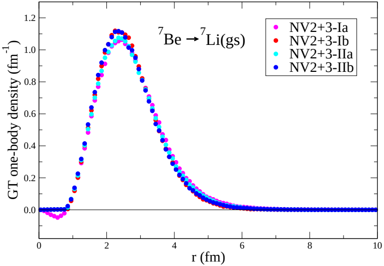
NVI - database fitted up to 125 MeV - c_D, c_E fitted to B.E. and *nd*-scattering length (VMC calculations)
NVII - database fitted up to 200 MeV - c_D, c_E fitted to B.E. and *nd*-scattering length (VMC calculations)
NVI* - database fitted up to 125 MeV - c_D, c_E fitted to B.E. and GT triton (VMC calculations)
NVII* - database fitted up to 200 MeV - c_D, c_E fitted to B.E. and GT triton (VMC calculations)

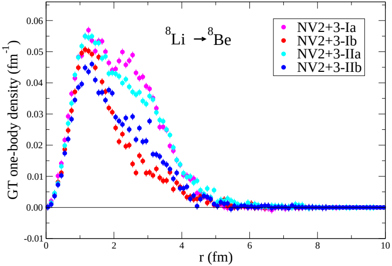
PRELIMINARY

AV18+IL7 - database fitted up to 350 MeV - c_D fitted to GT triton (GFMC calculations)

in collaboration with Piarulli *et al.*

Single Beta Decay Matrix Element Densities in chiEFT



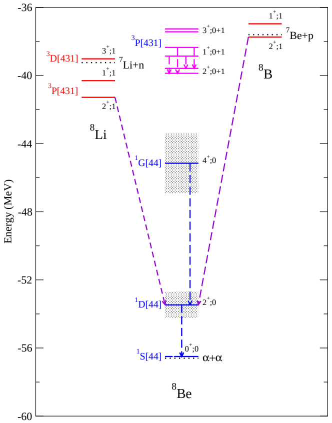


in collaboration with Piarulli *et al.*

based on chiral axial currents from A. Baroni *et al.* PRC93(2016)015501 & arXiv:1806.10245 (2018)

PRELIMINARY

EM and GT transitions in $A = 8$ nuclei

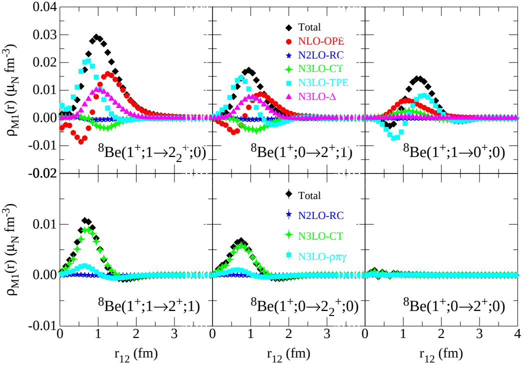


* B(M1) in ^{8}Be are calculated at the $\sim$ 10% level due to rich spectrum; presence of isospin-mixed states; transitions operators coupling “big” with “small components”

* 10% – 30% correction from two-body currents in M1 transitions

* ^{8}Li and ^{8}B GT rme with one-body currents alone are $\sim$ 30% smaller than expt; we expect large effect from two-body currents

Two-body M1 transitions densities



$(J_i, T_i) \to (J_f, T_f)$	IA	NLO-OPE	N2LO-RC	N3LO-TPE	N3LO-CT	N3LO-Δ	MEC
$(1^+; 1) \to (2_2^+; 0)$	2.461 (13)	0.457 (3)	-0.058 (1)	0.095 (2)	-0.035 (3)	0.161 (21)	0.620 (5)

Pastore *et al.* PRC90(2014)024321

The Present and Future of Quantum Monte Carlo Calculations

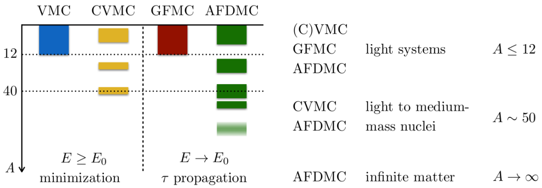
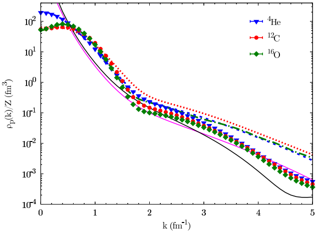


figure by Lonardoni

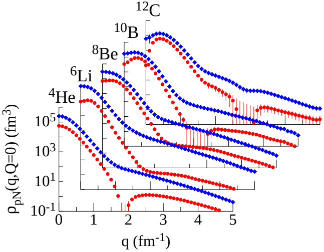
Use of Quantum Computers is being also explored - Roggero, Baroni, Carlson, Perdue *et al.*

One-body momentum distributions



Lonardoni *et al.* to appear on PRC arXiv:1804.08027

Two-body momentum distributions



Wiringa *et al.* PRC89(2014)024305

One-body momentum distributions http://www.phy.anl.gov/theory/research/momenta/
Two-body momentum distributions http://www.phy.anl.gov/theory/research/momenta2/

Summary and Outlook

Two-nucleon correlations and two-body electroweak currents
are crucial to explain available experimental data of both static (ground state properties) and dynamical (cross sections and rates) nuclear observables

- * We validate the computational framework vs electromagnetic data
- * Two-body electromagnetic currents successfully tested in $A \leq 12$ nuclei
- * $\sim 40\%$ two-body contribution found in ^{9}C's magnetic moments
- * $\sim$ 10-30% two-body contributions found in M1 transitions in low-lying states of $A \leq 8$ nuclei
- * Calculations of $\beta-$decay matrix elements in $A \leq 10$ nuclei in agreement with the data at $2\% - 3\%$ level
- * in $A \leq 10$ two-body currents ($q \sim 0$) are small ($\sim 2-3\%$) while correlations are crucial to improve agreement with expt
- Study beta-decay within chiral framework (in progress)
- Study beta-decay densities (in progress)
- Extend calculations to $A \sim 40$ in AFDMC (in progress by LANL group)
- Explore different kinematics for neutrino-nucleus interactions (including evaluation of the spectrum)

* We are developing a coherent picture for neutrino-nucleus interactions