Quantum MC Calculations of Beta Decays in Light Nuclei

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Beta Decay as a Probe of New Physics
ACFI UMass, Amherst MA - Nov 2018

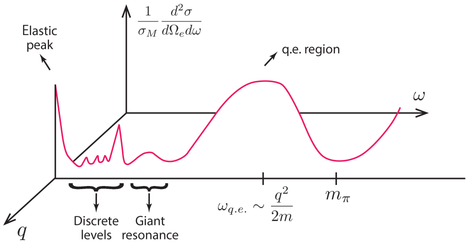
Washington University in St. Louis
Arts & Sciences

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

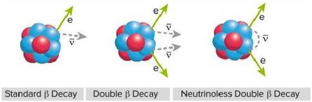
with
Carlson & Gandolfi (LANL) & Schiavilla (ODU+JLab)
Piarulli (WashU) & Baroni (USC) & Pieper & Wiringa (ANL)
Girlanda (Salento U.) & Marcucci & Viviani & Kievsky (Pisa U/INFN)
and with
Mereghetti & Dekens & Cirigliano & Graesser (LANL)
de Vries (Nikhef) & van Kolck (AU+CNRS/IN2P3)

Towards a coherent and unified picture of neutrino-nucleus interactions

* An accurate understanding of nuclear structure and dynamics is required to disentangle new physics from nuclear effects *



- $\omega \sim$ few MeV, $q \sim 0$: β-decay, $\beta\beta$-decays
- $\omega \sim$ few MeV, $q \sim 10^2$ MeV: Neutrinoless $\beta\beta$-decays
- $\omega \lesssim$ tens MeV: Nuclear Rates for Astrophysics
- $\omega \sim 10^2$ MeV: Accelerator neutrinos, ν-nucleus scattering

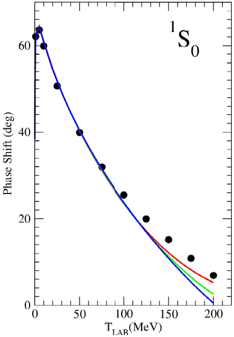


Nuclear Interactions

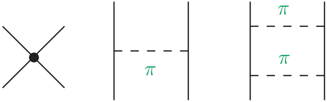
The nucleus is made of A non-relativistic interacting nucleons and its energy is

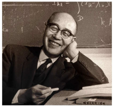
$$H = T + V = \sum_{i=1}^{A} t_i + \sum_{i<j} \upsilon_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

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

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

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

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

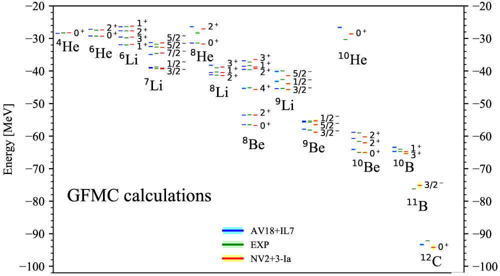
$$\Psi(\tau \to \infty) = a_0 \psi_0$$

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

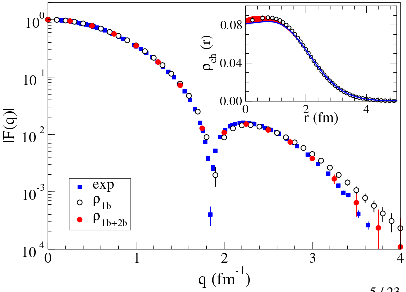
Energy Spectrum and Shape of Nuclei



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

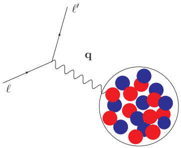
Lovato *et al.*

PRL111(2013)092501

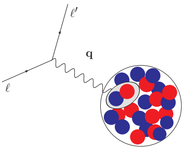


Nuclear Currents

1b



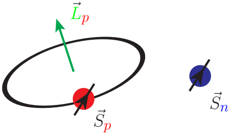
2b



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

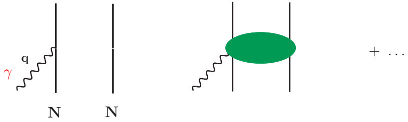
$$\mathbf{j} = \sum_{i=1}^{A} \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + \ldots$$

* 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

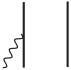
* We use Meson-Exchange Currents (MEC) or χEFT Currents



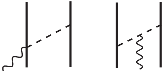
$$\mathbf{q} \cdot \mathbf{j} = [H, \rho] = \left[t_i + \upsilon_{ij} + V_{ijk}, \rho\right]$$

Electromagnetic Currents from Chiral Effective Field Theory

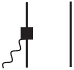
LO : $\mathbf{j}^{(-2)} \sim \mathbf{eQ^{-2}}$



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

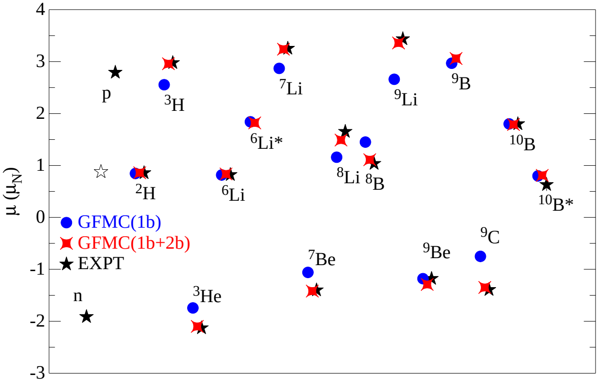
unknown LEC′s →

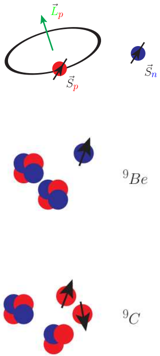
Pastore *et al.* PRC78(2008)064002 & PRC80(2009)034004 & PRC84(2011)024001

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



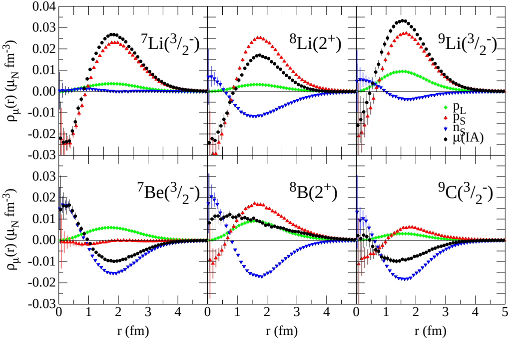


m.m.	THEO	EXP
^{9}C	-1.35(4)(7)	-1.3914(5)
^{9}Li	3.36(4)(8)	3.4391(6)

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

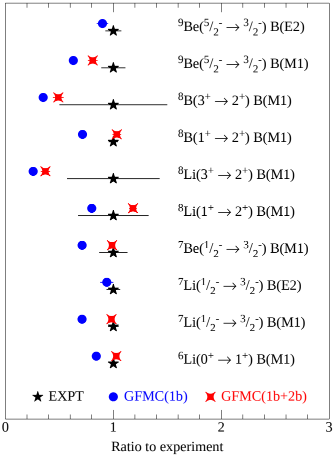


* one-body (IA) magnetic moment operator

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

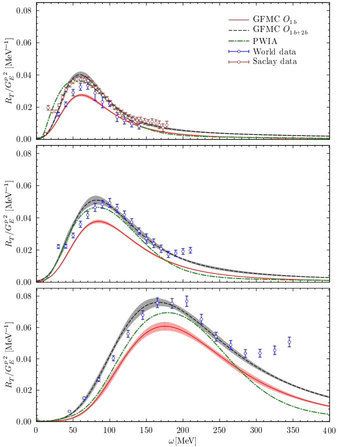
Electromagnetic Decays and *e*-scattering off nuclei

Electromagnetic Decay



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

Electromagnetic Transverse Responses

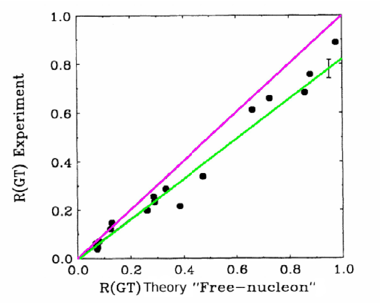


$q = [300 - 750]$ MeV

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

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

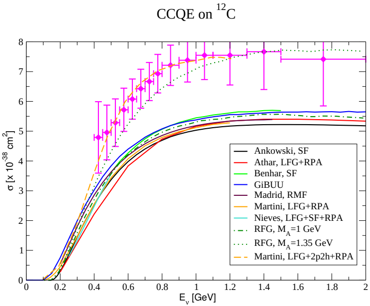
Beta Decay Rate



in 3≤ A≤ 18 $\longrightarrow g_A^{\text{eff}} \simeq 0.80\, g_A$

Chou *et al.* PRC47(1993)163

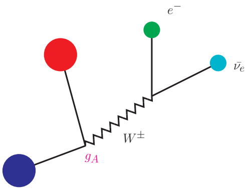
Neutrino-Nucleus Scattering



Alvarez-Ruso arXiv:1012.3871

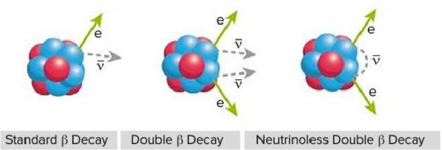
Standard Beta Decay

The "g_A problem"
and
the 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 $\propto g_A^2$ *

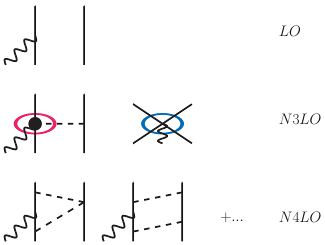
$$(Z,N) \to (Z+1, N-1) + e + \bar{\nu}_e$$



Nuclear Interactions and Axial Currents

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

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



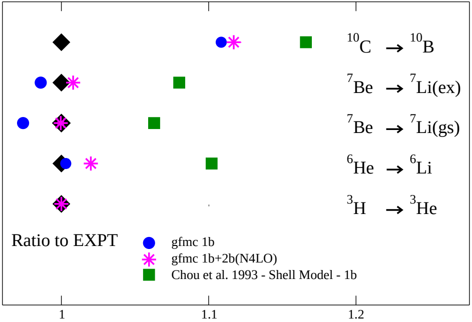
A. Baroni *et al.* PRC93(2016)015501

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

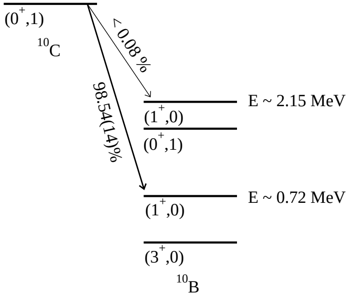
Based on $g_A \sim 1.27$ no quenching factor

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

* similar results were obtained with MEC currents

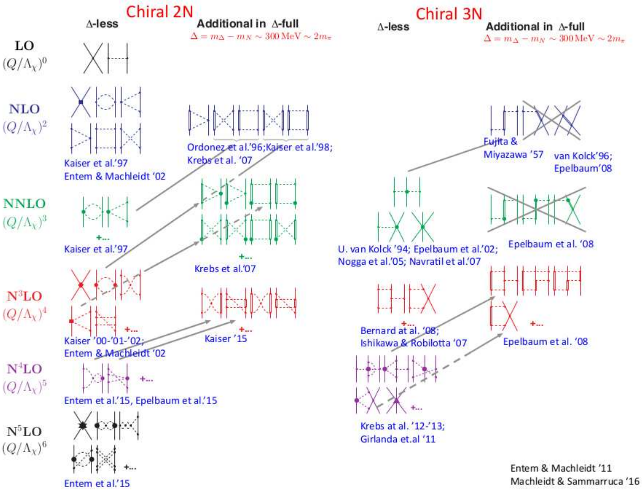
$*$ data from TUNL, Suzuki *et al.* PRC67(2003)044302, Chou *et al.* PRC47(1993)163

^{10}B



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

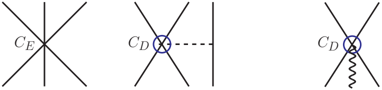
Chiral calculations of beta decay m.e.'s: Nuclear Interaction



courtesy of M. Piarulli

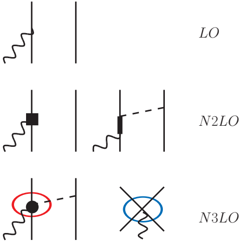
Chiral calculations of beta decay m.e.'s: Nuclear Currents

* 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

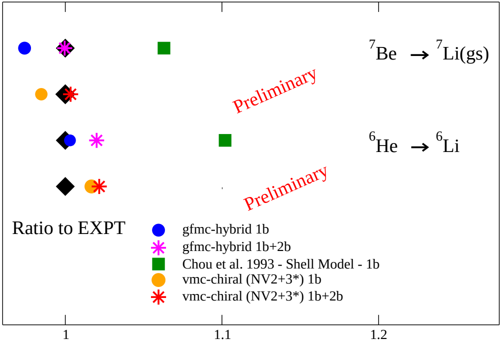
* c_D and c_E fitted to trinucleon B.E. and GT m.e. of tritium

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

* based on NV2+3* chiral interactions

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

Single Beta Decay Matrix Elements in $A = 6$–7 in chiEFT



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

vmc-chiral-NV2+3* (1b) and vmc-chiral-NV2+3* (1b+2b)

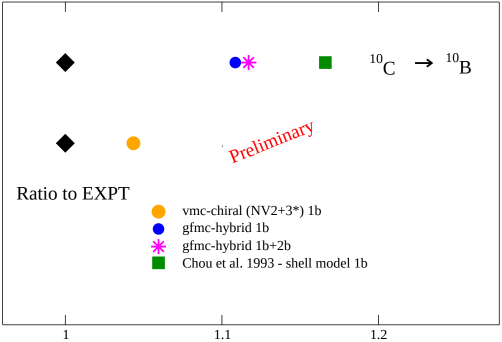
in collaboration with Piarulli *et al.*

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

* qualitative agreement with hybrid calculations

* many-body currents as manifestation of many-body correlations

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



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

vmc-chiral-NV2+3* (1b) and vmc-chiral-NV2+3* (1b+2b)

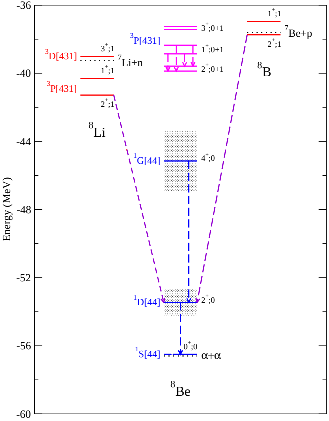
in collaboration with Piarulli *et al.*

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

* improvement w.r.t. hybrid calculations

* agreement at 3%

EM and GT transitions in $A = 8$ nuclei

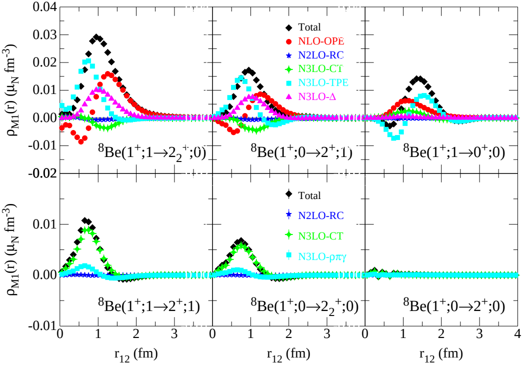


* B(M1) in ^{8}Be are calculated at the $\sim$ 10% level due to rich spectrum; presence of isospin-mixed states; transitions operators coupling "big" with "small components"

* 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

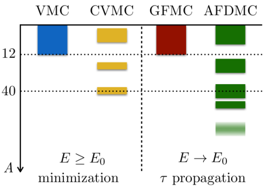
Two-body M1 transitions densities



$(J_i, T_i) \rightarrow (J_f, T_f)$	IA	NLO-OPE	N2LO-RC	N3LO-TPE	N3LO-CT	N3LO-Δ	MEC
$(1^+;1) \rightarrow (2_2^+;0)$	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

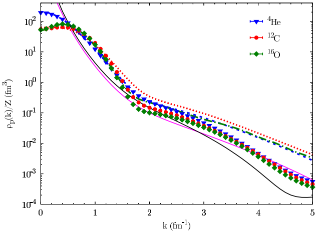


(C)VMC GFMC AFDMC	light systems	$A \leq 12$
CVMC AFDMC	light to medium-mass nuclei	$A \sim 50$
AFDMC	infinite matter	$A \to \infty$

figure by Lonardoni

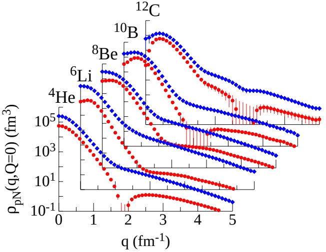
Use of Quantum Computers is being also explored - Roggero, Baroni, Carlson, Perdue *et al.*

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
- * ~ 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

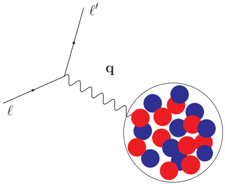
Bonus Material: Inclusive (e, ν) scattering

* inclusive xsecs *

$$\frac{d^2\sigma}{dE' d\Omega_{e'}} = \sigma_M \left[v_L R_L(q,\omega) + v_T R_T(q,\omega) \right]$$

$$R_\alpha(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) |\langle f | O_\alpha(\mathbf{q}) | 0 \rangle|^2$$

Longitudinal response induced by $O_L = \rho$
Transverse response induced by $O_T = \mathbf{j}$
... 5 nuclear responses in ν-scattering...



* Sum Rules *

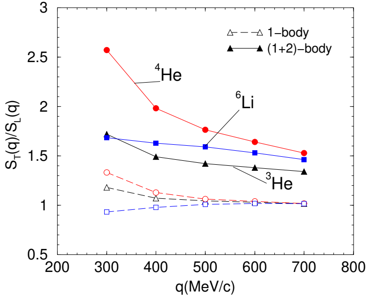
Exploit integral properties of the response functions + closure to avoid explicit calculation of the final states

$$S(q,\tau) = \int_0^\infty d\omega\, K(\tau,\omega) R_\alpha(q,\omega)$$

* Coulomb Sum Rules *

$$S_\alpha(q) = \int_0^\infty d\omega\, R_\alpha(q,\omega) \propto \langle 0 | O_\alpha^\dagger(\mathbf{q}) O_\alpha(\mathbf{q}) | 0 \rangle$$

Sum Rules and Two-Body Physics



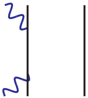
Carlson *et al.* PRC65(2002)024002

$$S_T(q) \propto \langle 0|\mathbf{j}^\dagger\, \mathbf{j}|0\rangle$$

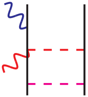
$$\propto \langle 0|\mathbf{j}_{1b}{}^\dagger\, \mathbf{j}_{1b}|0\rangle + \langle 0|\mathbf{j}_{1b}{}^\dagger\, \mathbf{j}_{2b}|0\rangle + \ldots$$

- $\mathbf{j} = \mathbf{j}_{1b} + \mathbf{j}_{2b}$

• enhancement of the transverse response is due to interference between 1b and 2b currents AND presence of two-nucleon correlations •



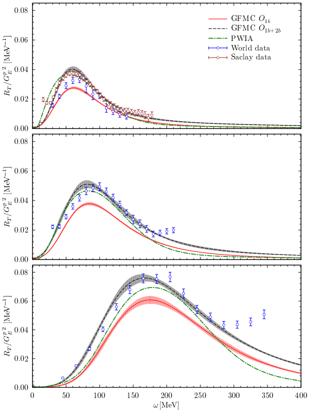
$\langle \mathbf{j}^\dagger_{1b}\ \ \mathbf{j}_{1b}\rangle\ > 0$



$\langle \mathbf{j}^\dagger_{1b}\ \mathbf{j}_{2b}\ v_\pi\rangle \propto \langle v_\pi^2\rangle\ \ > 0$

Recent Developments on Inclusive e and ν Scattering off ^{12}C

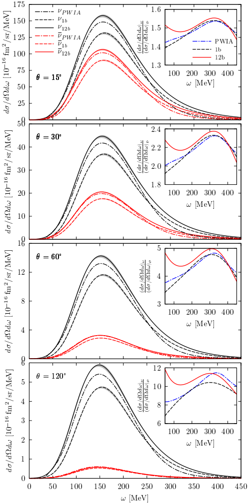
Electromagnetic Transverse Responses



$q = [300 - 750]$ MeV

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

NC Inclusive Xsec



$q = 750$ MeV

Lovato & Gandolfi *et al.* PRC97(2018)022502

$\sim$ 100 million core hours

Challenges and Opportunities

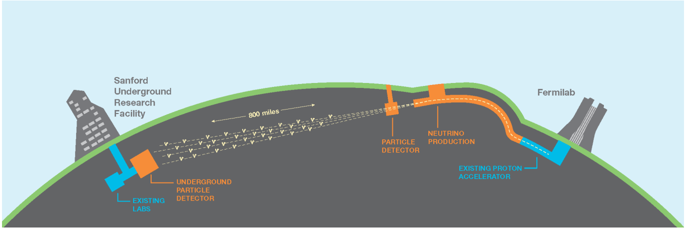
***

1. How to describe electroweak-scattering off $A > 12$ without losing two-body physics (*i.e.*, two-body correlations and currents)?

2. How to incorporate (more) exclusive processes?

3. How to incorporate relativistic effects?

***



Factorization: The Short-Time Approximation

$$R(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) \langle 0|O^\dagger(\mathbf{q})|f\rangle\langle f|O(\mathbf{q})|0\rangle$$

$$R(q,\omega) = \int dt \langle 0|O^\dagger(\mathbf{q})\, e^{i(H-\omega)t}\, O(\mathbf{q})|0\rangle$$

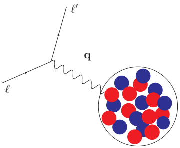
At short time, expand $P(t) = e^{i(H-\omega)t}$ and keep up to 2b-terms

$$H \sim \sum_i t_i + \sum_{i<j} v_{ij}$$

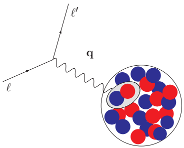
and

$$O_i^\dagger P(t) O_i + O_i^\dagger P(t) O_j + O_i^\dagger P(t) O_{ij} + O_{ij}^\dagger P(t) O_{ij}$$

1b



2b

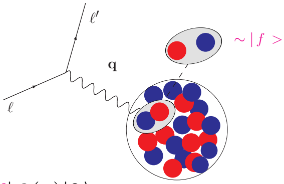


WITH

Carlson & Gandolfi (LANL) & Schiavilla (ODU+JLab) & Wiringa (ANL)

Factorization up to two-body operators: The Short-Time Approximation (STA)

Response functions are given by the scattering off pairs of fully interacting nucleons that propagate into a correlated pair of nucleons



$$R(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) \langle 0|O^\dagger(\mathbf{q})|f\rangle\langle f|O(\mathbf{q})|0\rangle$$

$$O(\mathbf{q}) = O^{(1)}(\mathbf{q}) + O^{(2)}(\mathbf{q}) = 1\mathrm{b} + 2\mathrm{b}$$

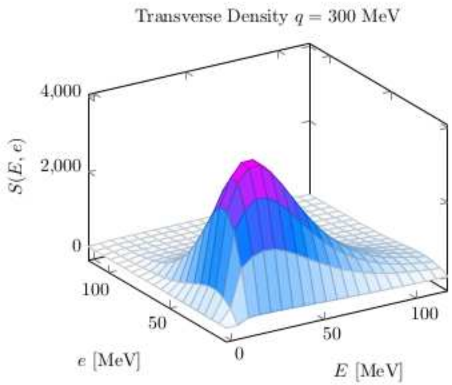
$$|f\rangle \sim |\psi_{p,P,J,M,L,S,T,M_T}(r,R)\rangle = \text{correlated two-nucleon w.f.}$$

* We retain two-body physics consistently in the nuclear interactions and electroweak currents

* STA can describe more two-body physics, *e.g.*, pion-production induced by e and ν

$$R(q,\omega) \sim \int \delta\left(\omega + E_0 - E_f\right) d\Omega_P\, d\Omega_p\, dP\, dp \left[p^2 P^2 \langle 0|O^\dagger(\mathbf{q})|\mathbf{p},\mathbf{P}\rangle\langle \mathbf{p},\mathbf{P}|O(\mathbf{q})|0\rangle\right]$$

The Short-Time Approximation



Transverse “response-density” 1b + 2b for ^4He

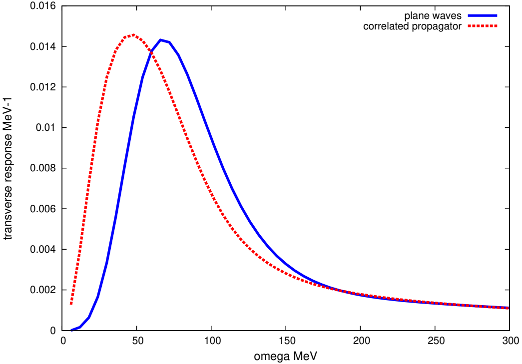
$$R(q,\omega) \qquad \sim \int \delta(\omega + E_0 - E_f)\, d\Omega_P\, d\Omega_p\, dP\, dp \left[p^2 P^2 \langle 0|O^\dagger(\mathbf{q})|\mathbf{p},\mathbf{P}\rangle\langle \mathbf{p},\mathbf{P}|O(\mathbf{q})|0\rangle \right]$$

* Preliminary results *

STA Transverse Response

$q = 300$ MeV

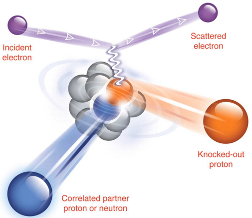
Plane Wave Propagator vs Correlated Propagator

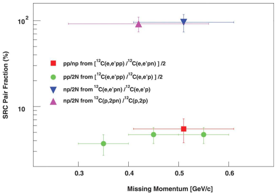


$$R_\alpha(q,\omega) \qquad \sim \int \delta\left(\omega + E_0 - E_f\right) d\Omega_P \, d\Omega_p \, dP \, dp \left[p^2 P^2 \langle 0 | O_\alpha^\dagger(\mathbf{q}) | \mathbf{p}, \mathbf{P} \rangle \langle \mathbf{p}, \mathbf{P} | O_\alpha(\mathbf{q}) | 0 \rangle\right]$$

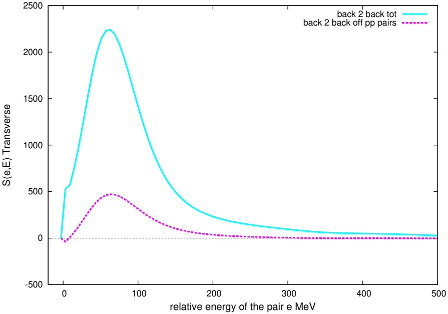
* Preliminary results *

STA back to back scattering





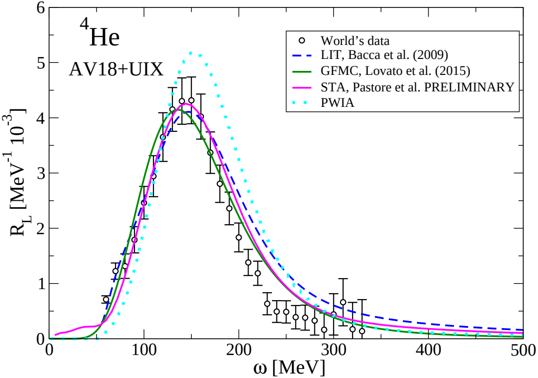
JLab, Subedi *et al.* Science320(2008)1475



$q = 500$ MeV, $E = 69$ MeV pp vs tot

* Preliminary results *

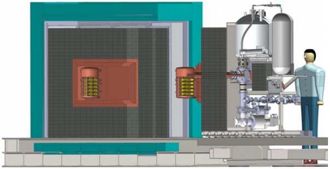
The Short-Time Approximation

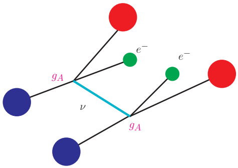


Longitudinal Response function at $q = 500$ MeV

* Preliminary results *

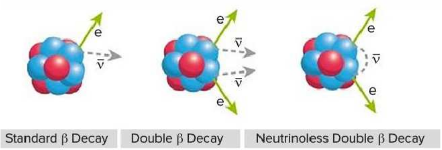
Neutrinoless Double Beta Decay



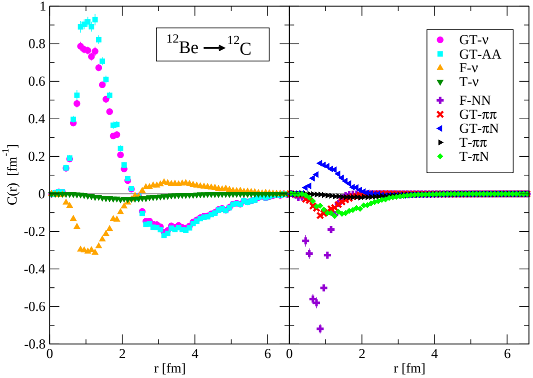


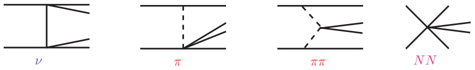
"The average momentum is about 100 MeV, a scale set by the average distance between the two decaying neutrons" cit. Engel&Menéndez

* Decay rate $\propto$ (nuclear matrix elements) $^2 \times \langle m_{\beta\beta} \rangle^2$ *



Double beta-decay Matrix Elements in $A = 12$

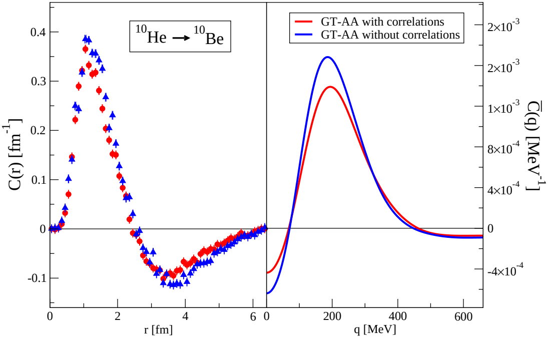




with Mereghetti & Dekens & Cirigliano & Carlson & Wiringa

PRC97(2018)014606

Sensitivity to ‘pion-exchange-like’ correlations

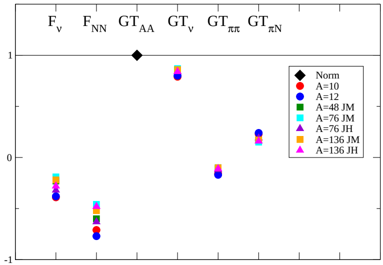


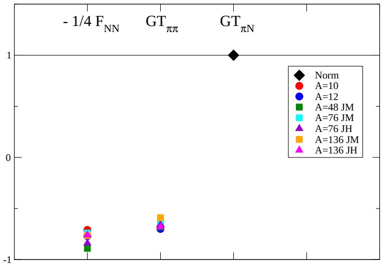
* no ‘pion-exchange-like’ correlations

* yes ‘pion-exchange-like’ correlations

Pastore, Dekens, Mereghetti *et al.* PRC97(2018)014606

Comparison with calculations of larger nuclei





JM = Javier Menendez private communication
JH = Hyvärien *et al.* PRC91(2015)024613

* Relative size of the matrix elements is approximately the same in all nuclei
* Short-range terms approximately the same in all nuclei

with Mereghetti & Dekens & Cirigliano & Carlson & Wiringa

PRC97(2018)014606

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

* Two-body currents can give $\sim 30-40\%$ contributions and improve on theory/EXPT agreement

* Calculations of $\beta-$ and $\beta\beta-$decay m.e.'s in $A \leq 12$ indicate two-body physics (currents and correlations) is required

* Short-Time-Approximation to evaluate ν-A scattering in $A > 12$ nuclei is in excellent agreement with exact calculations and data

- Extend STA to study electroweak scattering in $A > 4$ nuclei

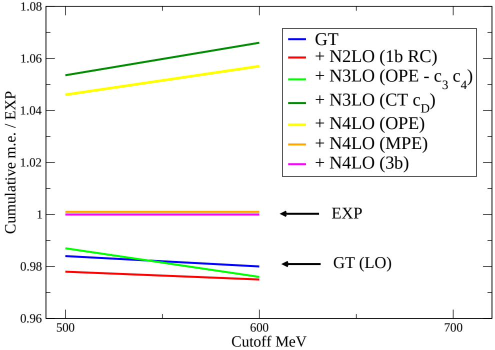
- Incorporate exclusive processes in the STA

- Study beta-decaay within a chiral framework

- Explore neutrino-nucleus intteraction at moderate value of momentum transfer

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

Tritium β-decay



* Results based on AV18+UIX and Chiral Currents are qualitatively in agreement
* All contributions "quench" but for the N3LO OPE (tiny due to a cancellation) and CT (fitted)
* They quench too much, and this is compensated by the fitting of c_D to EXP GT
* Use of N4LO 2b loop currents from H. Krebs *et al.* Ann.Phy.378(2017) leads to a reduced value of c_D

* $\sim$ 2% additive contribution from two-body currents *

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

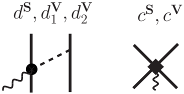
χEFT currents in $A > 3$ systems

$A = 7$ Captures

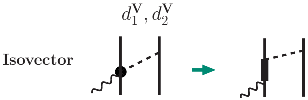
	gs	ex
LO	2.334	2.150
N2LO	-3.18×10^{-2}	-2.79×10^{-2}
N3LO(OPE)	-2.99×10^{-2}	-2.44×10^{-2}
N3LO(CT)	2.79×10^{-1}	2.36×10^{-1}
N4LO(2b)	-1.61×10^{-1}	-1.33×10^{-1}
N4LO(3b)	-6.59×10^{-3}	-4.86×10^{-3}
TOT(2b+3b)	0.050	0.046

* Large cancellations between CT at N3LO (with c_D fitted) and other 2b currents
* $\lesssim 3\%$ additive contribution from 2b currents in the $A \leq 10$ systems we considered
* this is in agreement with results obtained with "conventional" axial currents
* when using chiral axial currents $\lesssim 1\%$ error from chiral truncation (in the currents)

Electromagnetic LECs



d^S, d_1^V, and d_2^V could be determined by $\pi\gamma$-production data on the nucleon



$d_2^V = 4\mu^* h_A / 9 m_N (m_\Delta - m_N)$ and
$d_1^V = 0.25 \times d_2^V$
assuming Δ-resonance saturation

Left with 3 LECs: Fixed in the $A = 2-3$ nucleons' sector

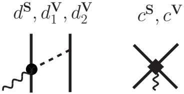
* Isoscalar sector:
  * d^S and c^S from EXPT μ_d and $\mu_S(^3\text{H}/^3\text{He})$
* Isovector sector:
  * c^V from EXPT $npd\gamma$ xsec.

    or
  * c^V from EXPT $\mu_V(^3\text{H}/^3\text{He})$ m.m.

* Regulator $C(\Lambda) = exp(-(p/\Lambda)^4)$ with $\Lambda = 500-600$ MeV

Λ	NN/NNN	$10 \times d^S$	c^S
500	AV18/UIX (N3LO/N2LO)	–1.731 (2.190)	2.522 (4.072)
600	AV18/UIX (N3LO/N2LO)	–2.033 (3.231)	5.238 (11.38)

Electromagnetic LECs



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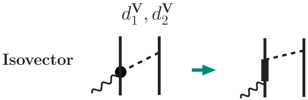

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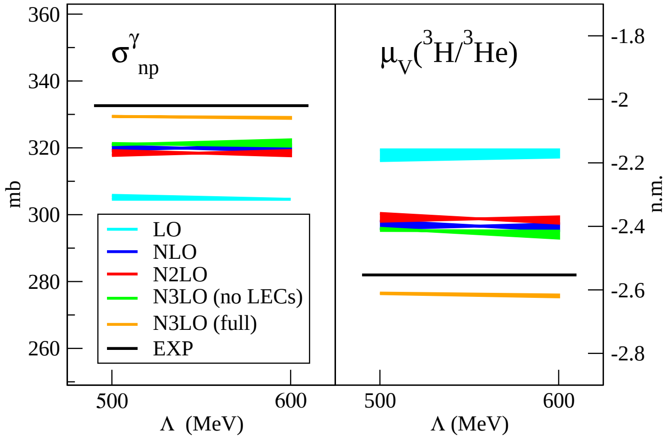
  * Regulator $C(\Lambda) = exp(-(p/\Lambda)^4)$ with $\Lambda = 500 - 600$ MeV

Λ	NN/NNN	Current	d_1^V	c^V
600	AV18/UIX	I	4.98	-11.57
		II	4.98	-1.025

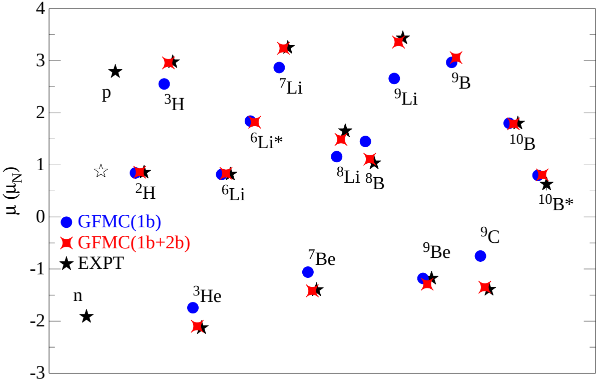
Convergence and cutoff dependence

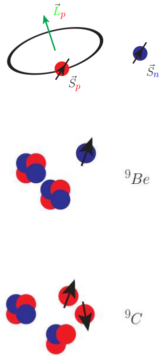
np capture x-section/ μ_V of $A = 3$ nuclei
bands represent nuclear model dependence [NN(N3LO)+3N(N2LO) – AV18+UIX]



Piarulli *et al.* PRC(2013)014006

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