Electroweak properties of light nuclei

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PRC78(2008)064002 - PRC80(2009)034004 - PRC84(2011)024001 - PRC87(2013)014006 - PRC87(2013)035503 - PRL111(2013)062502 - PRC90(2014)024321 - JPhysG41(2014)123002 - PRC(2016)015501

Key Questions

3. Nuclei continue to be used as laboratories for precision tests of the standard model of particle physics and in searches for physics that may exist beyond the standard model. . . .

• What are the present uncertainties in nuclear matrix elements relevant for dark matter searches and double beta decay, and how can they be improved?

•• How do nuclei interact with neutrinos in the GeV energy regime and how can calculations of these interaction cross sections be improved?

Question # 1.

- What are the present uncertainties in nuclear matrix elements relevant for dark matter searches and double beta decay, and how can they be improved?

  * EM transitions as test case
  * Single beta-decay in A$\leq$10 nuclei: g_A quenching and the role of correlations *Preliminary results*
  * Ab-initio calculations of 2β-decay m.e.'s in light nuclei and the role of correlations *Preliminary results*

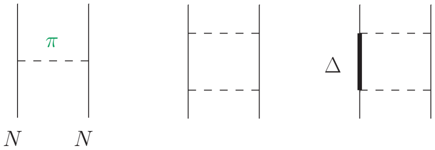
The Basic Model: Nuclear Potentials

- The nucleus is a system made of A non-relativistic interacting nucleons, its energy is given by

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

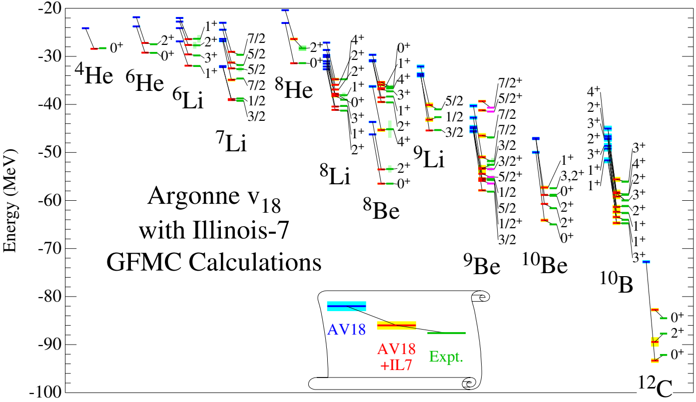
where υ_{ij} and V_{ijk} are 2- and 3-nucleon interaction operators

- Realistic υ_{ij} and V_{ijk} interactions are based on EXPT data fitting and fitted parameters subsume underlying QCD
- Realistic potentials at large inter-particle distances are described in terms of one-pion-exchange, range $\sim 1/m_\pi$. Other mechanisms are, *e.g.*, two-pion exchange, range $\sim 1/2m_\pi$; Δ-excitations …



- Potentials utilized in these sets of calculations to generate nuclear wave functions $|\Psi_i\rangle$ solving $H|\Psi_i\rangle = E_i|\Psi_i\rangle$ are:
[AV18+UIX], [AV18+IL7], [NN(N3LO)+3N(N2LO)]

AV18+IL7

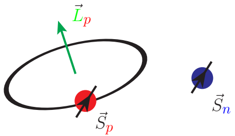


Carlson *et al.* - Rev.Mod.Phys.87(2015)1067

- Current and charge operators describe the interaction of nuclei with external fields. They are expanded as a sum of $1-$, $2-$, ... nucleon operators:

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

- In Impulse Approximation IA nuclear EM currents are expressed in terms of those associated with individual protons and nucleons, *i.e.*, ρ_i and $\mathbf{j}_i$

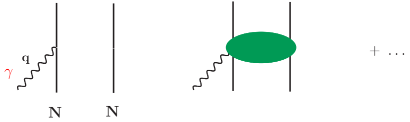


- IA picture is however incomplete; Historical evidence is the 10% underestimate of the *np* radiative capture 'fixed' by incorporating corrections from two-body meson-exchange EM currents - Riska&Brown 1972

The Basic Model: Nuclear Electromagnetic Currents

- Current and charge operators describe the interaction of nuclei with external fields. They are expanded as a sum of 1−, 2−, ... nucleon operators:

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



- Longitudinal EM current operator **j** linked to the nuclear Hamiltonian via continuity eq. (**q** momentum carried by the external EM probe γ)

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

* Meson-exchange currents MEC follow once meson-exchange mechanisms are implemented to describe nuclear forces - Villars&Miyazawa 40ies

These days we have:

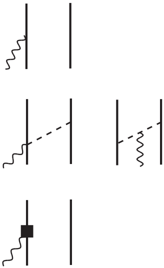
- Highly sophisticated MEC projected out realistic potentials
- EM currents derived from χEFTs

EM current up to $n = 1$ (or up to N3LO)

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

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

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



* Two-body charge operators enter at N3LO and vanish in the static limit *

- LO = IA
  N2LO = IA(relativistic- correction)
- NLO is purely isovector
- Strong contact LECs fixed from fits to *np* phases shifts—PRC**68**, 041001 (2003)
- No three-body EM currents at this order !

- 5 unknown EM LECs enter the N3LO contact and tree-level currents:
  - 2 isovector LECs entering the tree-level current are fixed by Δ-saturation
  - remaining 3 LECs fixed to reproduce, *e.g.*, $A = 2$ and 3 magnetic moments

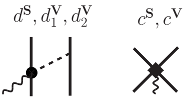
N^{3}LO: $\mathbf{j}^{(1)} \sim \mathbf{eQ}$

unknown LEC's →

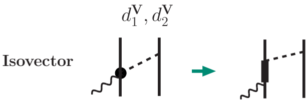
PRC78(2008)064002, PRC80(2009)034004, PRC84(2011)024001

* analogue expansion exists for the Axial nuclear current - Baroni et at. PRC93 (2016)015501 *

χEFT EM currents at N3LO: fixing the EM LECs



Five LECs: d^S, d_1^V, and d_2^V could be determined by pion photo-production data on the nucleon

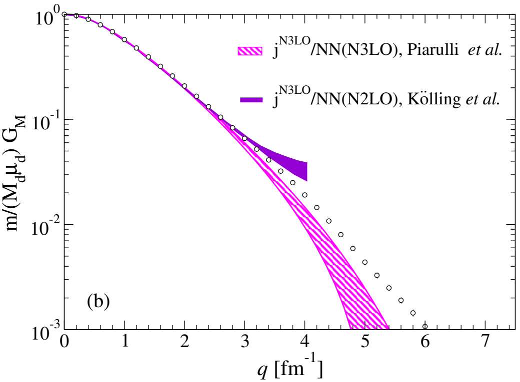


d_2^V and d_1^V are known assuming Δ-resonance saturation

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

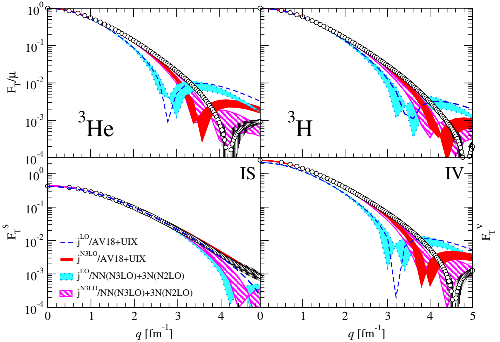
- Isoscalar sector:
  - d^S and c^S from EXPT μ_d and $\mu_S(^3\text{H}/^3\text{He})$
- Isovector sector:
  - c^V from EXPT $\mu_V(^3\text{H}/^3\text{He})$ m.m. $\leftarrow$ our choice

Predictions with χEFT EM Currents for the Deuteron Magnetic f.f.



PRC86(2012)047001 & PRC87(2013)014006

Predictions with χEFT EM Currents for ^{3}He and ^{3}H Magnetic f.f.'s



LO/N3LO with AV18+UIX – LO/N3LO with χ-potentials NN(N3LO)+3N(N2LO)

- ^{3}He/^{3}H m.m.'s used to fix EM LECs; $\sim$ 15% correction from two-body currents
- Two-body corrections crucial to improve agreement with EXPT data

	^{3}He $< r >_{EXP} = 1.976 \pm 0.047$ fm		^{3}H $< r >_{EXP} = 1.840 \pm 0.181$ fm	
Λ	500	600	500	600
LO	2.098 (2.092)	2.090 (2.092)	1.924 (1.918)	1.914 (1.918)
N3LO	1.927 (1.915)	1.913 (1.924)	1.808 (1.792)	1.794 (1.797)

PRC87(2013)014006

Calculations with EM Currents from χEFT with π's and N's

- Park, Min, and Rho *et al.* (1996)

  applications to A=2–4 systems by Song, Lazauskas, Park *at al.* (2009-2011) within the hybrid approach

  ......

  * Based on EM χEFT currents from NPA596(1996)515

- Meissner and Walzl (2001);
  Kölling, Epelbaum, Krebs, and Meissner (2009–2011)

  applications to:
  d and ^{3}He photodisintegration by Rozpedzik *et al.* (2011); e-scattering (2014);
  d magnetic f.f. by Kölling, Epelbaum, Phillips (2012);
  radiative $N-d$ capture by Skibinski *et al.* (2014)

  ......

  * Based on EM χEFT currents from PRC80(2009)045502 & PRC84(2011)054008 and consistent χEFT potentials from UT method

- Phillips (2003-2007)

  applications to deuteron static properties and f.f.'s

  ......

* Axial currents by *

Park *et al.* (1996), Baroni *et al.* (2016), Krebs *et al.* (2016) , Klos *et al.* (2015) ...

Predictions with χEFT EM currents for $A = 6$–10 systems: Variational Monte Carlo (VMC)

Minimize expectation value of H = T + AV18 + IL7

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

using trial function

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

- single-particle $\Phi_A(JMTT_3)$ is fully antisymmetric and translationally invariant
- central pair correlations $f_c(r)$ keep nucleons at favorable pair separation
- pair correlation operators U_{ij} reflect influence of v_{ij} (AV18)
- triple correlation operator U_{ijk} added when V_{ijk} (IL7) is present
- Ψ_V are spin-isospin vectors in $3A$ dimensions with $\sim 2^A \binom{A}{Z}$ components

Lomnitz-Adler, Pandharipande, and Smith NPA361(1981)399

Wiringa, PRC43(1991)1585

Green's function Monte Carlo

A trial w.f. Ψ_V is obtained by minimizing the H = T + AV18 + IL7 expectation value

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

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

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

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

Evaluation of $\Psi(\tau)$ is done stochastically (Monte Carlo method) in small time steps $\Delta\tau$ using a Green's function formulation.
In practice, we evaluate a "mixed" estimates

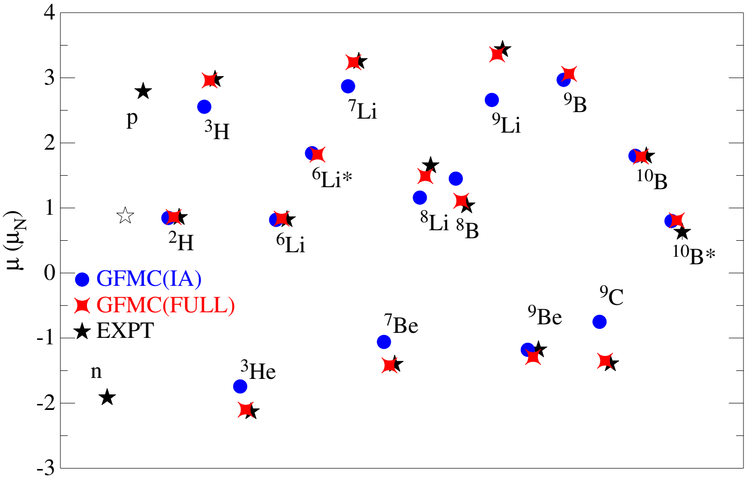
$$\langle O(\tau) \rangle = \frac{{}_f\langle \Psi(\tau) | O | \Psi(\tau) \rangle_i}{\langle \Psi(\tau) | \Psi(\tau) \rangle} \approx \langle O(\tau) \rangle^i_{\text{Mixed}} + \langle O(\tau) \rangle^f_{\text{Mixed}} - \langle O \rangle_V$$

$$\langle O(\tau) \rangle^i_{\text{Mixed}} = \frac{{}_f\langle \Psi_V | O | \Psi(\tau) \rangle_i}{{}_f\langle \Psi_V | \Psi(\tau) \rangle_i} \; ; \; \langle O(\tau) \rangle^f_{\text{Mixed}} = \frac{{}_f\langle \Psi(\tau) | O | \Psi_V \rangle_i}{{}_f\langle \Psi(\tau) | \Psi_V \rangle_i}$$

[Wiringa *et al.* PRC51(1995)38 + Piper *et al.* PRC64(2001)014001]

Magnetic Moments in $A \leq 10$ Nuclei

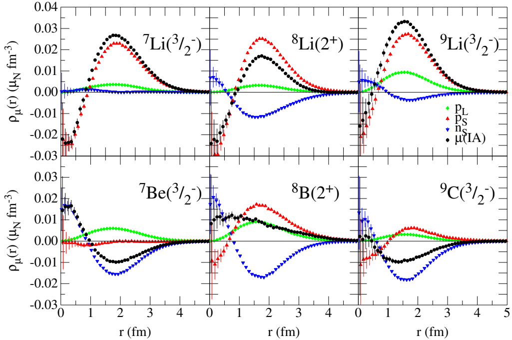
Predictions for $A > 3$ nuclei



- $\mu(\text{IA}) = \mu_N \sum_i [(L_i + g_p S_i)(1+\tau_{i,z})/2 + g_n S_i (1-\tau_{i,z})/2]$
- GFMC calculations based on H = T + AV18 + IL7

PRC87(2013)035503

One-body magnetic densities

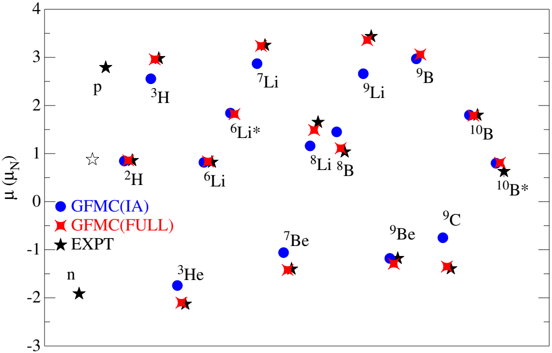


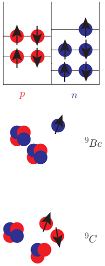
- IA magnetic moment operator

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

Magnetic Moments in $A \leq 10$ Nuclei - bis

Predictions for $A > 3$ nuclei



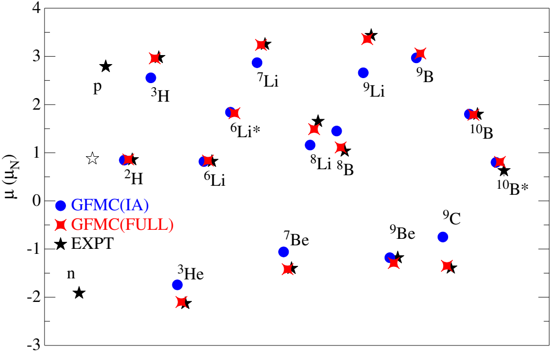


- $\mu_N(\mathrm{IA}) = \sum_i [(L_i + g_p S_i)(1+\tau_{i,z})/2 + g_n S_i (1-\tau_{i,z})/2]$
- ^{9}C (^{9}Li) dominant spatial symmetry [s.s.] = [432] = [α,^{3}He(^{3}H),$pp(nn)$] $\rightarrow$ Large MEC
- ^{9}Be (^{9}B) dominant spatial symmetry [s.s.] = [441] = [$\alpha, \alpha, n(p)$]

PRC87(2013)035503

Magnetic Moments in $A \leq 10$ Nuclei - ter

Predictions for $A > 3$ nuclei



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

$$\delta^{\rm N3LO} = \max\left[Q^4 \mu^{\rm LO}, Q^3 |\mu^{\rm LO} - \mu^{\rm NLO}|, Q^2 |\mu^{\rm NLO} - \mu^{\rm N2LO}|, Q^1 |\mu^{\rm N2LO} - \mu^{\rm N3LO}| \right]$$

$$Q = \max\left[\frac{m_\pi}{\Lambda}, \frac{p}{\Lambda}\right]$$

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

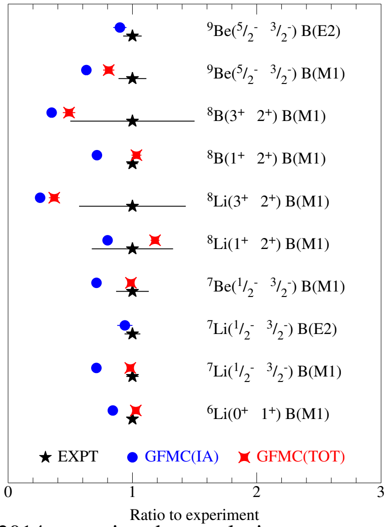
* ‘N3LO-Δ’ corrections can be ’large’ *

* SNPA and χEFT currents qualitatively in agreement, χEFT isoscalar currents provide better description exp data *

PRC87(2013)035503

EM Transitions in $A \leq 9$ Nuclei

- Two-body EM currents bring the theory in a better agreement with the EXP
- Significant correction in $A = 9$, $T = 3/2$ systems. Up to $\sim 40\%$ correction found in ^{9}C m.m.
- Major correction ($\sim 60 - 70\%$ of total MEC) is due to the one-pion-exchange currents at NLO – purely isovector



One M1 prediction: ^{9}Li$(1/2 \to 3/2)$*

$\Gamma(\text{IA}) = 0.59(2)$ eV
$\Gamma(\text{TOT}) = 0.79(3)$ eV

+ a number of B(E2)s in IA

*Ricard-McCutchan *et al.* TRIUMF proposal 2014 - ongoing data analysis

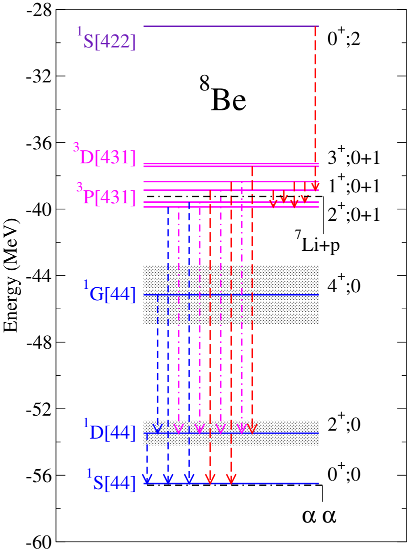
PRC87(2013)035503

* M1 transtions in ^{8}Be reported in PRL111(2013)062502 & PRC90(2014)024321 MEC $\sim$ 20-30% *

^{8}Be Energy Spectrum

- 2^+ and 4^+ broad states at ~ 3 MeV and ~ 11 MeV
- isospin-mixed states at ~ 16 MeV, ~ 17 MeV, ~ 19 MeV
- M1 transitions
- E2 transitions
- E2 + M1 transitions

$J^\pi;T$	GFMC	Iso-mixed	Experiment
0^+	-56.3(1)		-56.50
2^+	+ 3.2(2)		+ 3.03(1)
4^+	+11.2(3)		+11.35(15)
$2^+;0$	+16.8(2)	+16.746(3)	+16.626(3)
$2^+;1$	+16.8(2)	+16.802(3)	+16.922(3)
$1^+;1$	+17.5(2)	+17.67	+17.640(1)
$1^+;0$	+18.0(2)	+18.12	+18.150(4)
$3^+;1$	+19.4(2)	+19.10	+19.07(3)
$3^+;0$	+19.9(2)	+19.21	+19.235(10)



PRL111(2013)062502 & PRC90(2014)024321

M1 transitions in ^{8}Be isospin-mixed states

- 2^+, 1^+, and 3^+ states are isospin mixed, with mixing coefficients $\alpha_J^2 + \beta_J^2 = 1$

$$\psi^a = \alpha_J\, \psi_{\mathrm{T}=0} + \beta_J\, \psi_{\mathrm{T}=1}$$
$$\psi^b = \beta_J\, \psi_{\mathrm{T}=0} - \alpha_J\, \psi_{\mathrm{T}=1}$$

- ($\alpha_2 \sim 0.77$, β_2) well known; while ($\alpha_1 \sim 0.21$, β_1) and ($\alpha_3 \sim 0.41$, β_3) involve multiple decay channels $\rightarrow$ hard to extract them (Barker NP83(1966)418)

Using empirical mixings, we find:

* MEC contribute $\sim$ 20–30% of the total m.e.'s
* m.e.'s are not stable against variations in the mixing angles

Questions on the '5th force' exp paper Krasznahorkay *et al.* PRL111(2016)042501:

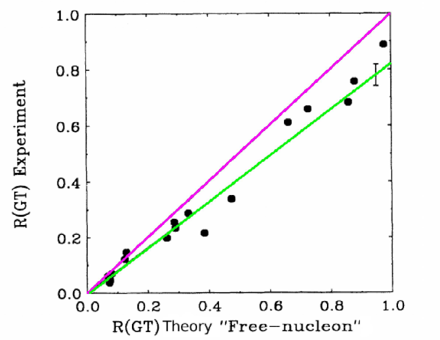
* In the Ref. the $\sim$ 17 ($\sim$ 18) MeV state is taken as purely isovector (isoscalar). Mixing angles do not affect M1 m.e.'s entering resonant capture $^7Li + p \rightarrow ^8Be^* \rightarrow ^8Be + e^+ + e^-$?
* Data are corrected by accounting for direct capture contaminations occurring via E1. Are higher multipoles negligible?

Beta-decay rates for $A \leq 10$ nuclei: M1 vs GT operators in IA

$$\mathrm{M1}^{\mathrm{IA}} = \sum_i \left(e_i \mathbf{L}_i + \mu_i \, \sigma_i \right)$$

$$\mathrm{GT}^{\mathrm{IA}} = \sum_i \tau_{i,\pm} \, \sigma_i$$

Theory vs Experiment: Quenching



$3 \leq A \leq 18$

Fig. from Chou *et al.* PRC47(1993)163

perfect agreement

theory > experiment

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

Quenching origin: *i*) better w.f.'s and/or *ii*) many body currents are required

$\beta\pm$ - $(J_i^\pi, T_i) \rightarrow (J_f^\pi, T_f)$	simple w.f.'s	IA	IA+MEC	Experiment
^{3}H($1/2^+$,1/2) $\rightarrow$ ^{3}He($1/2^+$,1/2)	2.449	2.2765(1)		2.357(10)*
^{6}He(0^+,1) $\rightarrow$ ^{6}Li(1+,0)	2.449	2.150	2.187	2.182*
^{7}Be($3/2^-$,1/2) $\rightarrow$ ^{7}Li(3/2−,1/2)	2.582	2.292	2.395	2.290*
^{10}C(0^+,1) $\rightarrow$ ^{10}B(1+,0)	2.449	2.024	2.076	1.862* − 2.344* (?)

Preliminary

- in collaboration with Bob Wiringa, Stefano Gandolfi, Rocco Schiavilla, Joe Carlson

∗ data from TUNL compilations

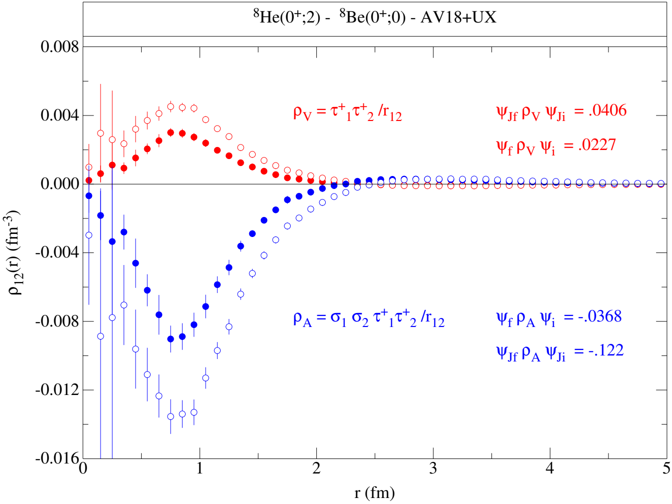
∗ data from Suzuki *et al.* PRC67(2003)044302

∗ data from Chou *et al.* PRC47(1993)163

Double beta-decay m.e.'s: a test case

^{8}He(0^{+};2) - 1S[422] $\rightarrow$ ^{8}Be(0^{+};0) - 1S[44]

Double beta-decay m.e.'s in $^{8}He(0^{+};2) \rightarrow {}^{8}Be(0^{+};0)$



Bob Wiringa et al. *Preliminary*

Summary # 1.

The microscopic description of nuclei successfully reproduces EXPT data provided that many-body effects in nuclear interactions and EM currents are accounted for.
J.Phys.G41(2014)123002 - S.Bacca&S.P.

- Two-body EM currents from χEFT tested in $A \leq 10$ nuclei
- Two-body corrections can be sizable and improve on theory/EXPT agreement
- EM structure of $A = 2$–3 nuclei well reproduced with chiral charge and current operators for $q \lesssim 3m_\pi$
- $\sim 40\%$ two-body correction found in ^{9}C's m.m.
- $\sim$ 20-30% corrections found in M1 transitions in low-lying states of ^{8}Be
- Preliminary studies on beta decay m.e.'s in light nuclei indicate that correlations and MEC play an important role in explaining the orgin of the g_A quenching
- Light nuclei are used in preliminary calculations on double-beta decay m.e.'s as test case to study the role of correlations and MEC

Outlook # 1.

The microscopic description of nuclei successfully reproduces EXPT data provided that many-body effects in nuclear interactions and EM currents are accounted for.
J.Phys.G41(2014)123002 - S.Bacca&S.P.

- EM structure and dynamics of light nuclei
  - Charge and magnetic form factors of $A \leq 10$ systems
  - M1/E2 transitions in light nuclei
  - Radiative captures, photonuclear reactions ...
  - Role of Δ-resonances in 'MEC' (EM current consistent with the chiral 'Δ-full' NN potential developed by M. Piarulli et al. PRC91(2015)024003)
  - Fully consistent χEFT calculations with 'MEC' for $A > 4$ (based on, *e.g.*, PRC91(2015)024003)

- Electroweak structure and dynamics of light nuclei
  - Test axial currents (chiral and conventional) in light nuclei (A. Baroni et al.PRC93(2016)015501)

Question # 2.

•• How do nuclei interact with neutrinos in the GeV energy regime and how can calculations of these interaction cross sections be improved?

i.e.

Towards a microscopic description of the ν-A inclusive cross section:
The Short-Time-Approximation

Inclusive (e, e') scattering in light nuclei

- ν/e inclusive xsecs are completely specified by the response functions
- 2 response functions for (e, e') inclusive xsec

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

Longitudinal response induced by $O_L = \rho$
Transverse response induced by $O_T = \mathbf{j}$

- Requires accurate knowledge of:
i) nuclear Hamiltonians and ii) associated EW currents, and
iii) final states $|f\rangle$ (which are hard to calculate)

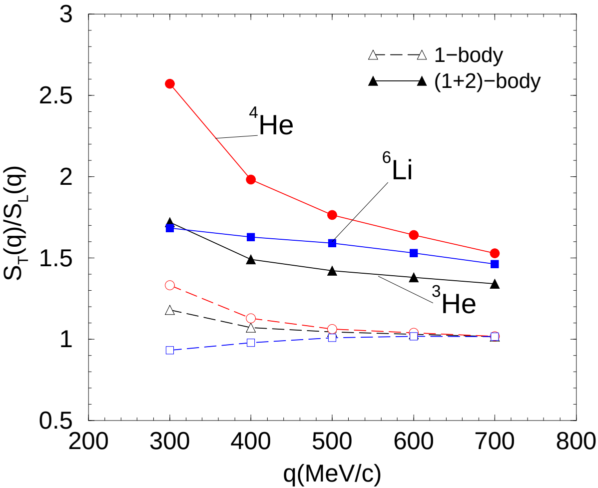
* Sum Rules *

Exploit integral properties of the response functions + closure over the final states to avoid explicit calculation of the final states → Sum Rules = ground state observables

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

kernel $K(\tau,\omega)$, e.g., Laplace, Lorentz.
Coulomb Sum Rules= $S_\alpha(q) = \int_0^\infty d\omega\, R_\alpha(q,\omega) \propto \langle 0|O_\alpha^\dagger(\mathbf{q})O_\alpha(\mathbf{q})|0\rangle$

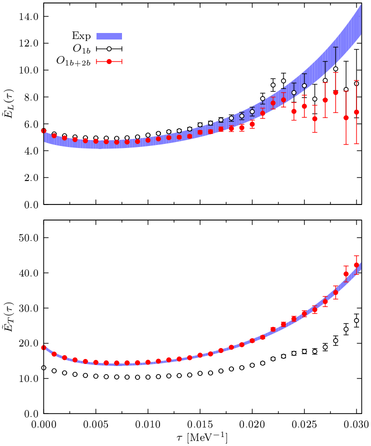
Sum Rules and MEC: Excess Transverse Strength

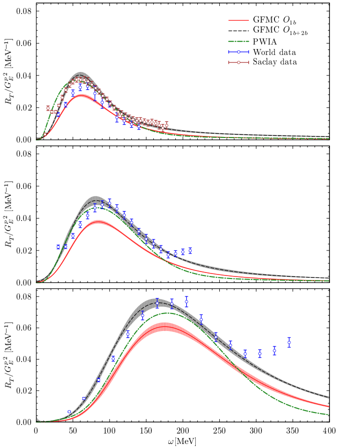


Carlson, Jourdan, Schiavilla, and Sick - PRC65(2002)024002

Euclidean Response Functions: Recent Developments on ^{12}C

$$\tilde{E}(q,\tau) = \int_{\omega_{th}}^{\infty} d\omega\, e^{-\tau(\omega - E_0)} R_\alpha(q,\omega) \propto \langle 0|O_\alpha^\dagger(\mathbf{q}) e^{-\tau(H-E_0)} O_\alpha(\mathbf{q})|0\rangle$$





$q = [300 - 750]$ MeV

$\sim$ 45 million core hours

$\sim$ 100 million core hours

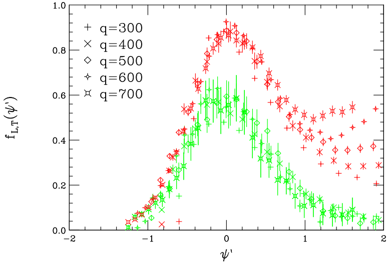
At present, an implementation for $A = 40$ is not feasible

Lovato, Gandolfi *et al.* - PRC91(2015)062501 + arXiv:1605.00248

Scaling properties of the Response Functions

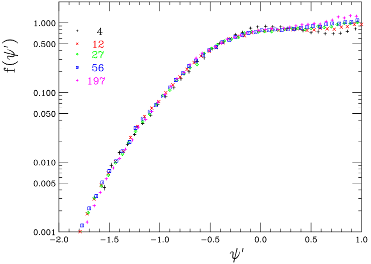
Inclusive xsec depends on a single (scaling) function of ω and q

Scaling of the 1st kind - ^{4}He



Carlson *et al.* - PRC65(2002)024002

Scaling of the 2st kind - fixed kinematics



Donnelly and Sick - PRC60(1999)065502

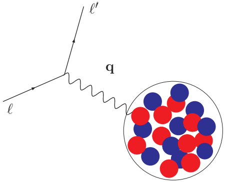
- Scaling 1st kind: independence from the momentum transfer
- Scaling 2nd kind: independence form A

* Rely on observed scaling properties of inclusive xsecs, universal behavior of nucleon/A momentum distributions, and exhibited locality of nuclear properties to build approximate response functions for $A > 12$ nuclei *

Factorization I: PWIA

Plane Wave Impulse Approximation:

Response functions given by incoherent scattering off single nucleons that propagate freely in the final state (plane waves)



$$R_L^{\mathrm{PWIA}}(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) \langle 0|O_L^{(1)\dagger}(\mathbf{q})|f\rangle\langle f|O_L^{(1)}(\mathbf{q})|0\rangle$$

$$= \int dt \langle 0|O_L^{(1)\dagger}(\mathbf{q}) e^{i(H-E_0)t} O_L^{(1)}(\mathbf{q})|0\rangle e^{-i\omega t}$$

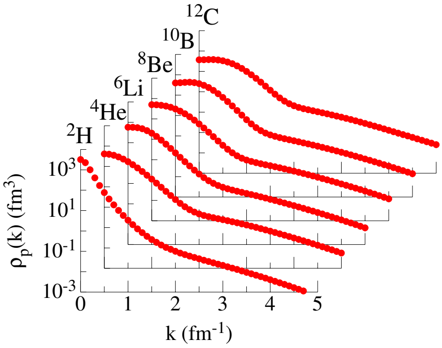
$$O_L^{(1)}(\mathbf{q}) = \sum_i e \frac{1+\tau_{z,i}}{2} e^{i\mathbf{q}\cdot\mathbf{r}_i}$$

$$E_f - E_0 = \frac{(\mathbf{k}+\mathbf{q})^2}{2m_N} - \frac{\mathbf{k}^2}{2m_N}, \qquad |f\rangle \sim e^{i(\mathbf{k}+\mathbf{q})\cdot\mathbf{r}}$$

- PWIA L-Response in terms of the proton momentum distribution $n_p(\mathbf{k})$ as

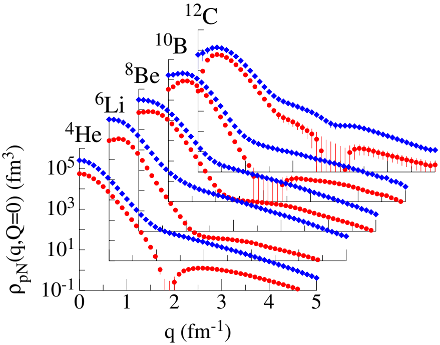
$$R_L^{\mathrm{PWIA}}(q,\omega) = \int d\mathbf{k}\, n_p(\mathbf{k}) \delta\left(\omega - \frac{(\mathbf{k}+\mathbf{q})^2}{2m_N} + \frac{\mathbf{k}^2}{2m_N}\right)$$

Proton Momentum Distributions



Wiringa *et al.* - PRC89(2014)024305

Back-to-back *np* and *pp* Momentum Distributions



Wiringa *et al.* - PRC89(2014)024305

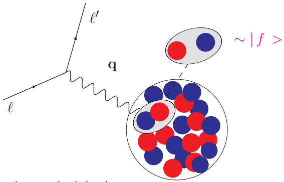
Nuclear properties are strongly affected by correlations!

Triple coincidence reactions $A(e,e'\ np\ \text{or}\ pp)A-2$ measurements @ JLab on ^{12}C indicate that 20% of the nucleons act in correlated pairs, and that at high values of relative momenta $(400-500$ MeV$)$, $\sim 90\%$ of the pairs are in the form of *np* pairs and $\sim 5\%$ in *pp* pairs

Factorization II: Short-Time Approximation - STA

In STA:

Response functions are given by the scattering off pairs of fully interacting nucleons that propagate (for a short time) into a correlated pair of nucleons in the final state



$$
\begin{aligned}
R_\alpha^{40}(q,\omega) &= \sum_f \delta\left(\omega + E_0 - E_f\right)\langle 0|O_\alpha^\dagger(\mathbf{q})|f\rangle\langle f|O_\alpha(\mathbf{q})|0\rangle \\
&= \int dt \langle 0|O_\alpha^\dagger(\mathbf{q}) e^{i(H-E_0)t} O_\alpha(\mathbf{q})|0\rangle e^{-i\omega t} \\
O_\alpha(\mathbf{q}) &= O_\alpha^{(1)}(\mathbf{q}) + O_\alpha^{(2)}(\mathbf{q}) \\
|f\rangle &\sim |\psi_{p,P,J,M,L,S,T,M_T}(r,R)\rangle
\end{aligned}
$$

- We keep $A-2$ nucleons still, while the final states of the interacting two-nucleon system are generated by the AV18 two-nucleon potential

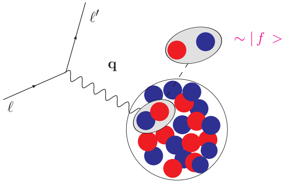
* Interaction occurs via 1- and 2-body operators *

* Fully interacting nucleon-pairs in the final states *

* $R_\alpha^{40}(q,\omega)$ is a ground-state observable *

Benchmarking STA in ^{4}He: two tests

$$R^{40}_{\alpha}(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) |\langle f|O_\alpha(\mathbf{q})|0\rangle|^2$$



- $R^{40}_{L}(q,\omega)$ with

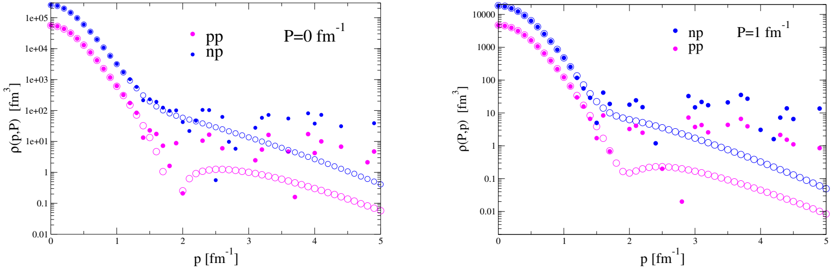
$$O^{(1)}_L(\mathbf{q}) = \sum_i e\frac{1+\tau_{z,i}}{2}e^{i\mathbf{q}\cdot\mathbf{r}_i}\,, \qquad |f\rangle \sim e^{i\mathbf{p}\cdot\mathbf{r}}e^{i\mathbf{P}\cdot\mathbf{R}}$$

- reduces to

$$R^{40}_{L}(q,\omega) = \int d\mathbf{p}\int d\mathbf{P}\,\rho_{NN}(\mathbf{p},\mathbf{P})\delta\left(\omega + E_0 - E_f\right) \equiv R^{\text{PWIA}}_{L}(q,\omega)$$

- We can benchmark ^{4}He *i*) nucleon-pair momentum distributions and *ii*) PWIA longitudinal response function

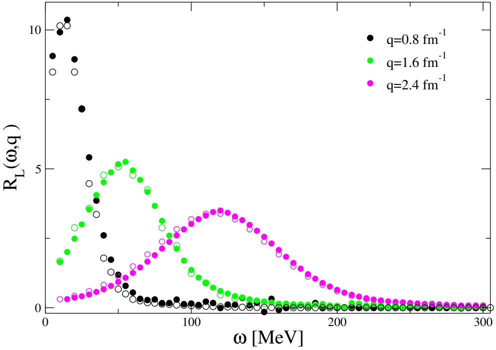
Benchmark on ^{4}He: 2-body momentum distributions



Open circles from Wiringa *et al.* - PRC89(2014)024305

- $\sim$ 3k core hours
- Noise for $p > 1.5$ fm^{-1} can be reduced with more statistics

Benchmark on ^{4}He: PWIA Longitudinal Response



Summary and Outlook # 2.

The microscopic description of nuclei successfully reproduces EXPT data provided that many-body effects in nuclear interactions and EM currents are accounted for.
J.Phys.G41(2014)123002 - S.Bacca&S.P.

- In STA the response functions are given by the scattering off pairs of fully interacting nucleons that propagate into a correlated pair of nucleons in the final state
- The interactions with the external probe occurs via one- and two-body current operators
- The responses in STA are ground-state observables

To do list:

- Implement two-body current operators
- Implement fully interacting two-nucleon propagators