Electroweak structure of light nuclei

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"Interfacing theory and experiment for reliable double-beta decay matrix element calculations"

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EST. 1943

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PRC78(2008)064002 - PRC80(2009)034004 - PRC84(2011)024001 - PRC87(2013)014006 - PRC87(2013)035503 - PRL111(2013)062502 -

Key Workshop Questions

- What is the status of electroweak current calculations and the prospect for matrix element inputs for available many-body methods?
- Other than currents, how can we quantify other uncertainties in the bare operator (short-range correlations, closure)? Is everything else under control?

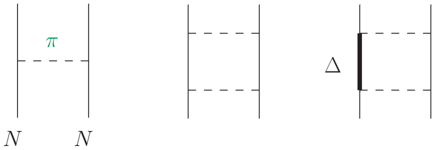
* EM transitions as test case
* Single beta-decay in A$\leq$10 nuclei: g_A quenching and the role of correlations *Preliminary results*
* Ab-initio calculations of 2β-decay m.e.'s in light nuclei and the role of correlations *Preliminary results*

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 ...



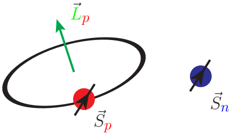
- Potentials utilized in these sets of calculations to generate nuclear wave functions $|\Psi_i\rangle$ solving $H|\Psi_i\rangle = E_i|\Psi_i\rangle$ are: [AV18+UIX], [AV18+IL7], [NN(N3LO)+3N(N2LO)]

The Basic Model: Nuclear Electromagnetic Currents - One-body component

- 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 $\mathbf{j}_i$

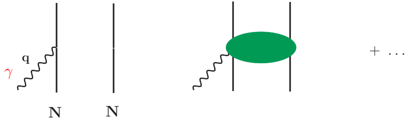


- IA picture is however incomplete; Historical evidence is the 10% underestimate of the *np* radiative capture 'fixed' by incorporating corrections from two-body meson-exchange EM currents - Riska&Brown 1972

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:

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



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

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

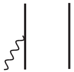
* Meson-exchange currents MEC follow once meson-exchange mechanisms are implemented to describe nuclear forces - Villars&Miyazawa 40ies

These days we have:

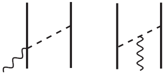
- Highly sophisticated MEC projected out realistic potentials
- EM currents derived from χEFTs

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

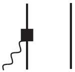
LO : $\mathbf{j}^{(-2)} \sim e\mathbf{Q}^{-2}$



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



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



* 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

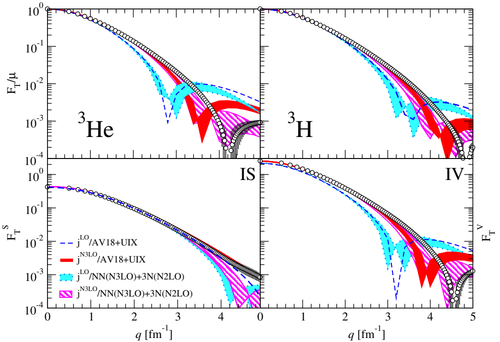
$\mathbf{N^3LO}$: $\mathbf{j}^{(1)} \sim e\mathbf{Q}$

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 *

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

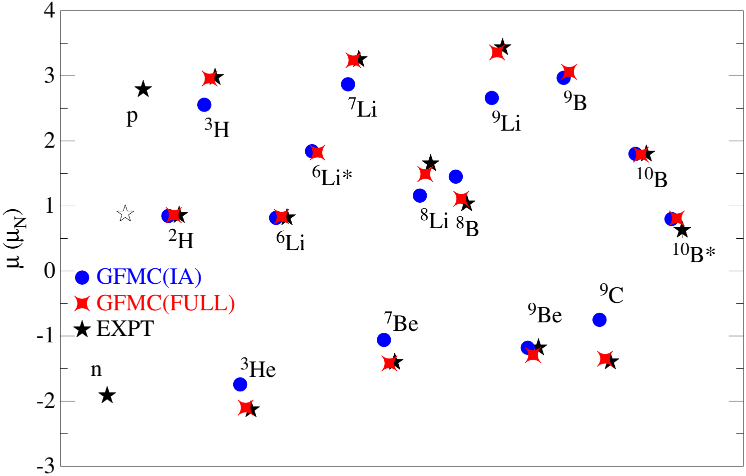
M1 vs GT operators in IA

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

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

Magnetic Moments in $A \leq 10$ Nuclei

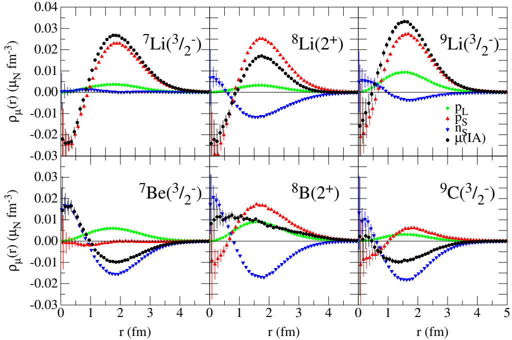
Predictions for $A > 3$ nuclei



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

PRC87(2013)035503

One-body magnetic densities

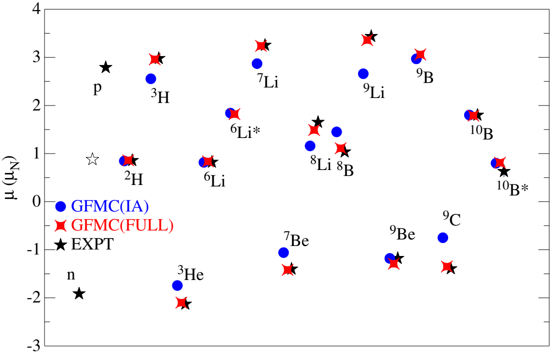


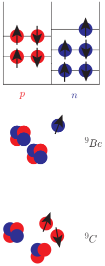
- IA magnetic moment operator

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

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

Predictions for $A > 3$ nuclei

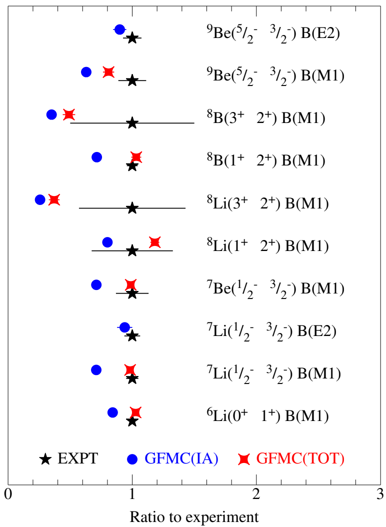




- $\mu_N(\text{IA}) = \sum_i [(L_i + g_p S_i)(1+\tau_{i,z})/2 + g_n S_i (1-\tau_{i,z})/2]$
- ^{9}C (^{9}Li) dominant spatial symmetry [s.s.] = [432] = [α,^{3}He(^{3}H),$pp(nn)$] $\rightarrow$ Large MEC
- ^{9}Be (^{9}B) dominant spatial symmetry [s.s.] = [441] = [$\alpha, \alpha, n(p)$]

PRC87(2013)035503

- 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$(1/2 \rightarrow 3/2)$*

$\Gamma(\text{IA}) = 0.59(2)$ 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

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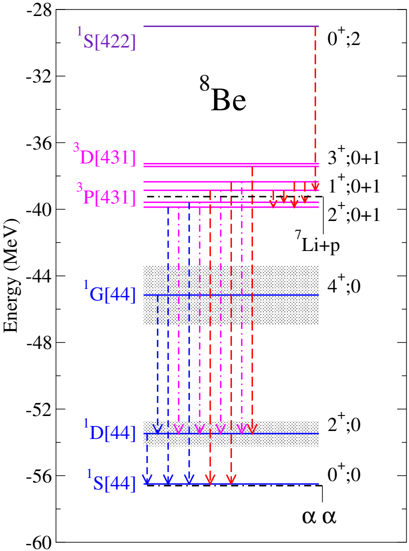
^{8}Be Energy Spectrum

- 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)

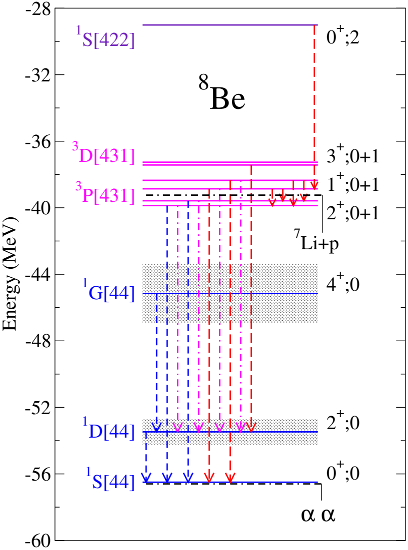


PRL111(2013)062502 & PRC90(2014)024321

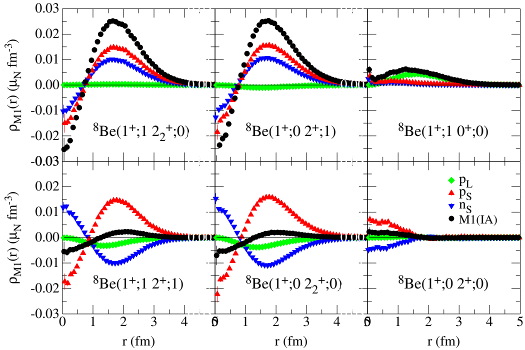
^{8}Be energy spectrum - bis

- isospin-mixed states at ~ 16 MeV, ~ 17 MeV, ~ 19 MeV
- M1 transitions: 4 classes from largest to smallest
  - conserve w.f. [s.s.]* and $\Delta T = 1$
  - conserve w.f. [s.s.] and $\Delta T = 0$
  - change w.f. [s.s.] and $\Delta T = 1$
  - change w.f. [s.s.] and $\Delta T = 0$
- E2 transitions
- E2 + M1 transitions

*[s.s.] = dominant spatial symmetry



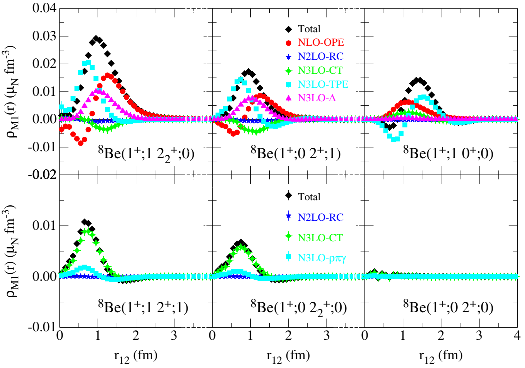
One-body M1 transitions densities



- [s.s.]-conserving transitions are enhanced due to overlap between large components of the initial and final w.f.'s
- Isospin-conserving transitions are suppressed w.r.t. isospin-changing transitions due to a cancellation between proton and neutron spin magnetization terms

$$\mathrm{M1(IA)} = \mu_N \sum_i [(L_i + g_p S_i)(1+\tau_{i,z})/2 + g_n S_i (1-\tau_{i,z})/2]$$

Two-body M1 transitions densities



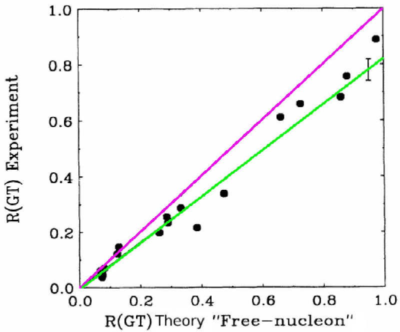
$(J_i,T_i) \rightarrow (J_f,T_f)$	IA	NLO-OPE	N2LO-RC	N3LO-TPE	N3LO-CT	N3LO-Δ	MEC
$(1^+;1) \rightarrow (2_2^+;0)$	2.461 (13)	0.457 (3)	-0.058 (1)	0.095 (2)	-0.035 (3)	0.161 (21)	0.620 (5)

PRC90(2014)024321

Beta-decay rates for $A \leq 10$ nuclei

The simple case *i.e.* transitions with same dominant spatial symmetry in the initial and final states

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

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

Preliminary

- in collaboration with Bob Wiringa, Stefano Gandolfi and Rocco Schiavilla

∗ data from TUNL compilations

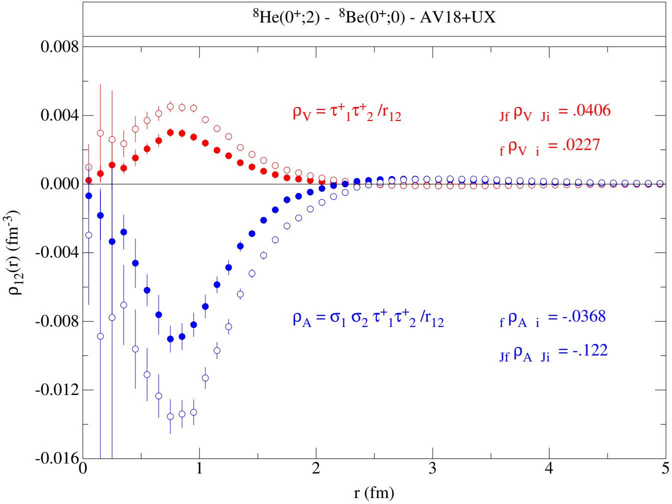
∗ data from Suzuki *et al.* PRC67(2003)044302

∗ 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 $^8He(0^+;2) \rightarrow {}^8Be(0^+;0)$



Bob Wiringa et al. *Preliminary*

Summary

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
- Double-beta and beta decay m.e.'s in light nuclei as test case to study the role of correlations and MEC

Outlook

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 ...
  - Fully consistent χEFT calculations with 'MEC' for $A > 4$
  - 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)

* Electroweak structure and dynamics of light nuclei
  - ν-nucleus scattering J. Carlson, S. Gandolfi, B. Wiringa, R. Schaivilla
  - Test axial currents (chiral and conventional) in light nuclei (A. Baroni et al.PRC93(2016)015501)
  - Many-body effects in ν-d pion-production at threshold (in preparation)