Strong and electroweak interactions in nuclei

Saori Pastore

NuSTEC

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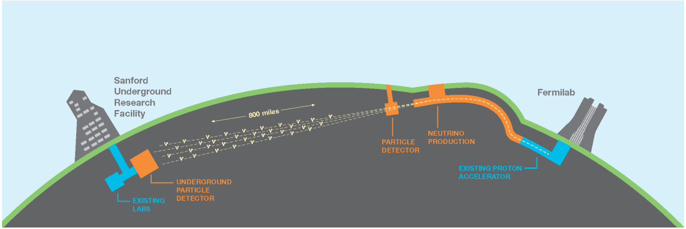
Thanks to Jorge and Luis

Motivations (Why Nuclear Physics?)

* Nuclei active material in experiments that test the SM and search for BSM physics (neutrino experiments, DM, neutrinoless double beta decay ...)

* Nuclear Physics required to *

1. Have meaningful interpretations of the data
2. Disentangle new physics from nuclear effects



LBNF

Creating a Common Language

* Interface Theory with Experiments and with Neutrino Generators and likewise *

Topics (3 hours)

* Two- and Three-nucleon Pion Exchange Interactions ✓
* Realistic Models of Two- and Three-Nucleon Interactions ✓
* Realistic Models of Many-Body Nuclear Electroweak Currents
* Short-range Structure of Nuclei, Nuclear Correlations, and Quasi-Elastic Scattering

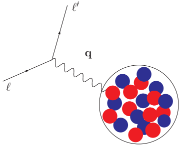
The *ab initio* Approach

The nucleus is made of A interacting nucleons and its energy is

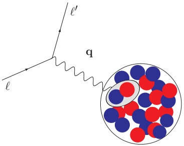
$$H = T + V = \sum_{i=1}^{A} t_i + \sum_{i<j} \upsilon_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

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

1b



2b



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

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

Two-body 2b currents essential to satisfy current conservation

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

* "Longitudinal" component fixed by current conservation

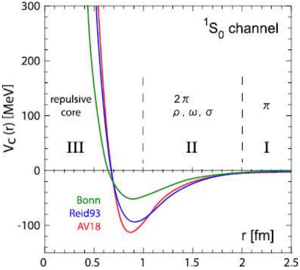
* "Transverse" component "model dependent"

The Basic Model
Requirement 1: Nuclear Interactions
DAY 1

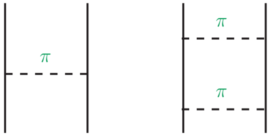
$$H = T + V = \sum_{i=1}^{A} t_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

Step 1. Construct two- and three-body interactions

* Chiral Effective Field Theory Interactions
* "Conventional" or "Phenomenological" Interactions



Aoki *et al.* Comput.Sci.Disc.1(2008)015009



* One-pion-exchange: range$\sim \frac{1}{m_\pi} \sim 1.4$ fm
* Two-pion-exchange: range$\sim \frac{1}{2m_\pi} \sim 0.7$ fm

DAY 1: Summary

- * Two-nucleon Interactions have ~ 40 parameters fitted to ~ 4000 data up to ~ 350 MeV
- * Three-nucleon force have $2-4$ parameters fitted to $A=3$ observables or ~ 20 nuclear energy levels
- * One-pion-exchange physics dominates and it is present in both Conventional and Chiral Formulations
- * Due to a cancellation between kinetic and two-body terms in $\langle H \rangle$ three-body is necessary to reproduce the data (but it is $\lesssim 10\%$ of two-body force)

pros Shapes of nuclei and spectra and electromagnetic properties successfully explained

pros Two-body physics (correlations, and two-body currents) essential to explain the data

pros Two-body tensor force essential to explain the data

cons Non-relativistic

cons Pion, Δ, ... are only virtual (no pion production)

cons Applicability to low-energy ($\lesssim 1$ GeV)

RECITATIONS DAY 1: Summary

Q1 To include relativity, why don't you use covariant perturbation theory?

TA1 You will then need to solve the Bethe-Slapeter equation or similar (analogue to Schrödinger equation but with relativity) presently limited to $A = 3$ (involves 4-momenta integrations ... ask Prof Wally Van Orden)

Q2 What is the regime of applicability of Chiral formulation vs Conventional?

TA2 They are both non-relativistic models, the Conventional approach has been pushed up to ~ 1 GeV. Conceptually, the chiral formulation is meant for low-momenta regimes. Practically, it has been applied in the same regime (and in the same spirit) as the Conventional formulation, in the sense that there are chiral potential (see review by Entem and Machleidt) fitted up to ~ 350 MeV (just like the "conventional" AV18).

Q3 What can we do while you guys try to figure out how to put pion-production, K-production, ... ?

TA3 I don't know. But here are a couple of links with one-body and two-body momentum distributions evaluated from correlated variational Monte Carlo nuclear wave-functions by Bob Wiringa. It is really informative

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

Q4 Lots of questions about kinematics

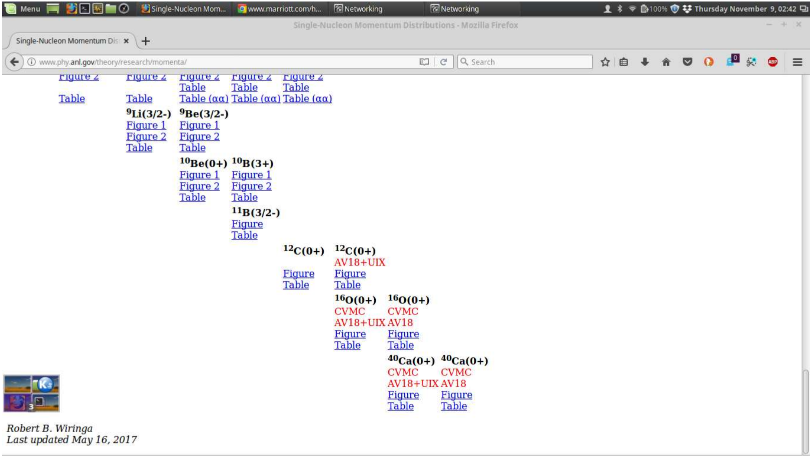
TA4 ...

Q5 Argon?

TA5 There is hope:
* Computational Methods to solve the many-body problem:
Auxiliary Field Diffusion Monte Carlo (sampling also spins, ...), Cluster Variational Monte Carlo, Quantum Computing new!
* Approximated methods to solve for the nuclear responses with two-body currents:
Short-Time Approximation, ... (more by Prof. Natalie Jachowicz, Dr Alessandro Lovato, Dr. Artur Ankowski, ...)

TA=Tentative Answer

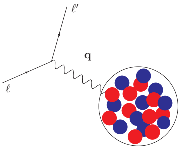
One- and Two-Body Momentum Distributions from Variational Monte Carlo nuclear wave functions (include two- and three-body correlations)



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

The Basic Model
Requirement 2: Nuclear Many-Body Currents
DAY 2 and 3

1b



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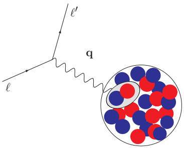


$$\rho = \sum_{i=1}^{A} \rho_i + \sum_{i<j} \rho_{ij} + \ldots\,,$$

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

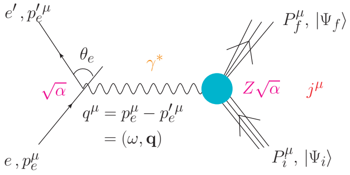
Step 2. Understand how external probes (electrons, neutrinos, DM ...) interact with nucleons, nucleon pairs, nucleon triplets...

* Chiral Effective Field Theory Electroweak Many-Body Currents
* "Conventional" or "Phenomenological" Electroweak Many-Body Currents

Step 2.a Validate and then Use the model

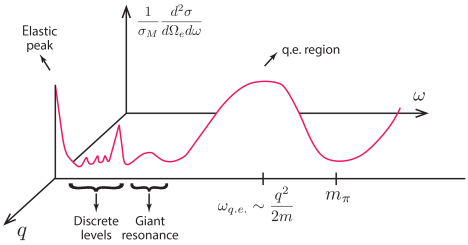
* Validation of the theory against Electromagnetic observables in a wide range of energies
* Neutrino-Nucleus Observables from low to high energies and momenta

Electromagnetic Probes as tool to test theoretical models



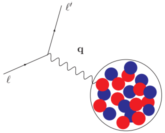
* coupling constant $\alpha \sim 1/137$ allows for a perturbative treatment of the EM interaction $\rightarrow$ single photon γ exchange suffices
* calculated x-sections $\propto |\langle \Psi_f | j^{\mu} | \Psi_i \rangle|^2$ with j^{μ} nuclear EM currents $\rightarrow$ clear connection between measured x-sections and calculated properties of nuclear targets
* EXPT data (in most cases) known with great accuracy $\rightarrow$ viable EXPT constraints on theories
* For few-nucleon systems, the many-body problem can be solved exactly or within controlled approximations

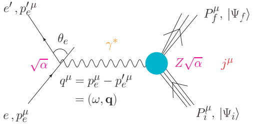
Electroweak Reactions

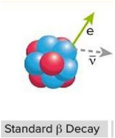


- $\omega \sim 10^2$ MeV: Accelerator neutrinos
- $\omega \sim 10^1$ MeV: EM decay, β-decay
- $\omega \lesssim 10^1$ MeV: Nuclear Rates for Astrophysics

- by varying ω we can explore ground and excited nuclear states
- by varying $\mathbf{q}$ we access the EM current spatial distributions with spatial resolution $\propto 1/|\mathbf{q}|$ (these are the form factors, analogue to nucleonic form factors but for nuclei)





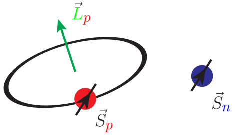


The Basic Model: Nuclear Electromagnetic Currents - One-body component

* 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 $\mathbf{j}_i$
* The nucleons' size given by EM nucleonic form factors (take them from experimental data, *e.g.*, Kelly, Hölster, even dipole parameterizations) or calculate them from LQCD

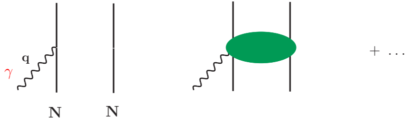


* IA picture is however incomplete; Historical evidence is the 10% underestimate of the *np* radiative capture 'fixed' by incorporating corrections from two-body meson-exchange EM currents - Riska&Brown 1972

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

Time-Ordered-Perturbation Theory

The relevant degrees of freedom of nuclear physics are bound states of QCD

* non relativistic nucleons N
* pions π as mediators of the nucleon-nucleon interaction
* non relativistic Delta's Δ with $m_\Delta \sim m_N + 2m_\pi$

Transition amplitude in time-ordered perturbation theory

$$T_{fi} = \langle N'N' \mid H_1 \sum_{n=1}^{\infty} \left(\frac{1}{E_i - H_0 + i\eta} H_1 \right)^{n-1} \mid NN \rangle^*$$

H_0 = free π, N, Δ Hamiltonians
H_1 = interacting π, N, Δ, and external electroweak fields Hamiltonians

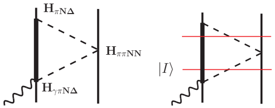
$$T_{fi} = \langle N'N' \mid T \mid NN \rangle \propto \upsilon_{ij} \,, \qquad T_{fi} = \langle N'N' \mid T \mid NN;\gamma \rangle \propto (A^0 \rho_{ij}, \mathbf{A} \cdot \mathbf{j}_{ij})$$

* $A^\mu = (A^0, \mathbf{A})$ photon field

(Naïve) Power Counting

Each contribution to the $T_{f\,i}$ scales as

$$\underbrace{\left(\prod_{i=1}^{N} Q^{\alpha_i-\beta_i}\right)}_{H_1\,\text{scaling}} \times \underbrace{Q^{-(N-1)}}_{\text{denominators}} \times \underbrace{Q^{3L}}_{\text{loop integration}}$$



$\alpha_i =$ # of derivatives (momenta) in H_1;
$\beta_i =$ # of π's;
$N =$ # of vertices; $N-1 =$ # of intermediate states;
$L =$ # of loops

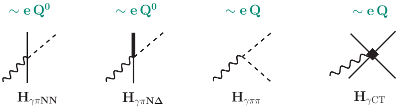
$$H_1 \text{ scaling} \sim \underbrace{Q^1}_{H_{\pi N\Delta}} \times \underbrace{Q^1}_{H_{\pi\pi NN}} \times \underbrace{Q^0}_{H_{\pi\gamma N\Delta}} \times Q^{-2} \sim Q^0$$

$$\text{denominators} \sim \frac{1}{E_i - H_0}|I\rangle \sim \frac{1}{2m_N - (m_\Delta + m_N + \omega_\pi)}|I\rangle = -\frac{1}{m_\Delta - m_N + \omega_\pi}|I\rangle \sim \frac{1}{Q}|I\rangle$$

$$Q^1 = Q^0 \times Q^{-2} \times Q^3$$

* This power counting also follows from considering Feynman diagrams, where loop integrations are in 4D

External Electromagnetic Field



"Minimal" Electromagnetic Vertices

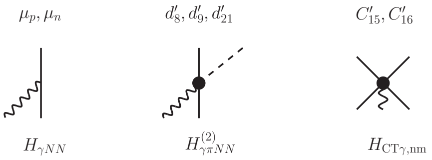
* EM H_1 obtained by minimal substitution in the π- and N-derivative couplings (same as doing $\mathbf{p} \to \mathbf{p} + e\,\mathbf{A}$, minimal coupling)

$$\begin{aligned} \nabla\pi_{\mp}(\mathbf{x}) &\to [\nabla \mp i e \mathbf{A}(\mathbf{x})]\,\pi_{\mp}(\mathbf{x}) \\ \nabla N(\mathbf{x}) &\to [\nabla - i e\, e_N \mathbf{A}(\mathbf{x})]\,N(\mathbf{x})\ , \qquad e_N = (1+\tau_z)/2 \end{aligned}$$

* same LECs as the Strong Vertices *

* This is equivalent to say that the currents are conserved, *i.e.*, the continuity equation is satisfied

External Electromagnetic Field



"Non-Minimal" Electromagnetic Vertices

* EM H_1 involving the tensor field $F_{\mu\nu} = (\partial_\mu A_\nu - \partial_\nu A_\mu)$

LECs are not constrained by the strong interaction
there are additional LECs fixed to EM observables

- * $H_{\gamma NN}$ obtained by non-relativistic reduction of the covariant single nucleon currents constrained to $\mu_p = 2.793$ n.m. and $\mu_n = -1.913$ n.m.
- * $H_{\gamma\pi NN}$ involves $\nabla\pi$ and ∇N and 3 new LECs (2 of them are "saturated" by the Δ)
- * $H_{CT2\gamma}$ involves 2 new LECs

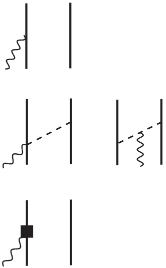
* These are the so called the "transverse" currents

Vector Electromagnetic Current $\mathbf{j}$ from Chiral Effective Field Theory up to N2LO

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

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

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



* Note that $\mathbf{j}_\pi$ satisfies the continuity equation with υ_π (can be done analytically)

$$\upsilon_\pi(\mathbf{k}) = -\frac{g_A^2}{F_\pi^2}\frac{\boldsymbol{\sigma}_1\cdot\mathbf{k}\,\boldsymbol{\sigma}_2\cdot\mathbf{k}}{\omega_k^2}\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2$$

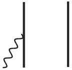
$$\mathbf{j}_\pi(\mathbf{k}_1,\mathbf{k}_2) = -ie\frac{g_A^2}{F_\pi^2}(\boldsymbol{\tau}_1\times\boldsymbol{\tau}_2)_z\boldsymbol{\sigma}_1\,\frac{\boldsymbol{\sigma}_2\cdot\mathbf{k}_2}{\omega_{k_2}^2}+1\rightleftharpoons 2$$

$$+\quad ie\frac{g_A^2}{F_\pi^2}(\boldsymbol{\tau}_1\times\boldsymbol{\tau}_2)_z\frac{\mathbf{k}_1-\mathbf{k}_2}{\omega_{k_1}^2\,\omega_{k_2}^2}\boldsymbol{\sigma}_1\cdot\mathbf{k}_1\,\boldsymbol{\sigma}_2\cdot\mathbf{k}_2$$

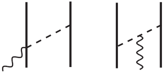
* LO = one-body current *

Vector Electromagnetic Current **j** from Chiral Effective Field Theory

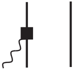
LO : $\mathbf{j}^{(-2)} \sim \mathbf{eQ^{-2}}$



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



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



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

unknown LEC′s →

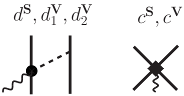
No three-body currents at this order!!

* Analogue expansion exists for the Time Component (Charge Operator) ρ
* Two-body corrections to the one-body Charge Operator appear at N3LO!!

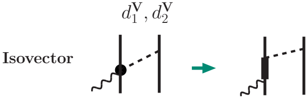
* LO = one-body current *

Pastore *et al.* PRC78(2008)064002 & PRC80(2009)034004 & PRC84(2011)024001
* analogue expansion exists for the Axial nuclear current - Baroni et al. PRC93 (2016)015501 *

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

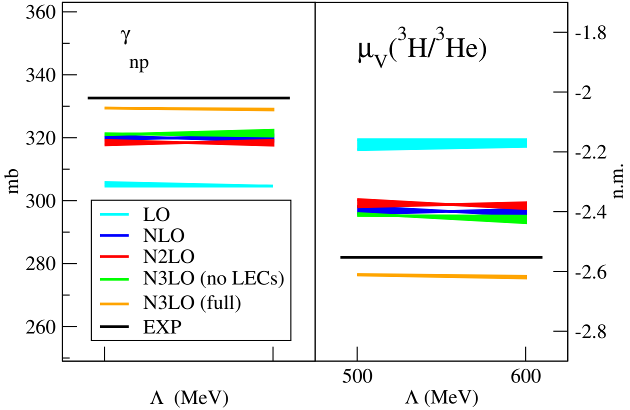
* Isoscalar sector:
  * d^S and c^S from EXPT μ_d and $\mu_S(^3\text{H}/^3\text{He})$
* Isovector sector:
  * c^V from EXPT $npd\gamma$ xsec.

    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

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]



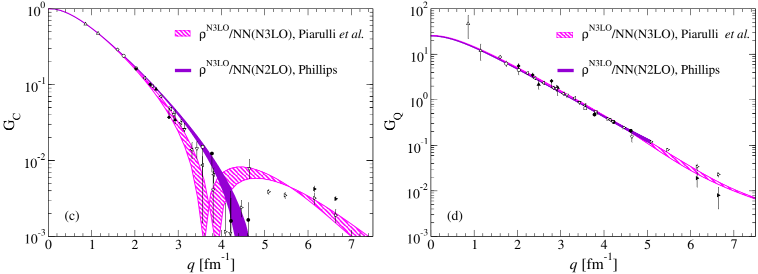
- $npd\gamma$ x-section and $\mu_V(^3\mathrm{H}/^3\mathrm{He})$ m.m. are within 1% and 3% of EXPT
- negligible dependence on the cutoff

$$\text{Observables} \propto \langle \Psi_f | \mathbf{j} | \Psi_i \rangle$$

Piarulli *et al.* PRC87(2013)014006

Predictions with χEFT EM currents for the deuteron Charge and Quadrupole f.f.'s

Bands represent cutoff Λ dependence



$*$ Calculations include nucleonic form factors taken from EXPT data $*$

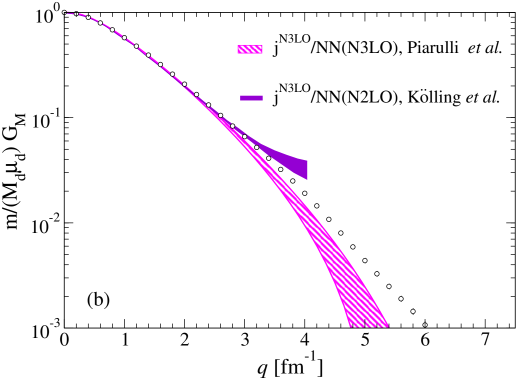
$*$ Effect of two-body contributions to the charge operator (not shown) is negligible–small (lower–higher momenta) $*$

Observables $\propto \langle \Psi_f | \rho | \Psi_i \rangle$

J.Phys.G34(2007)365 & PRC87(2013)014006

Predictions with χEFT EM currents for the deuteron magnetic f.f.

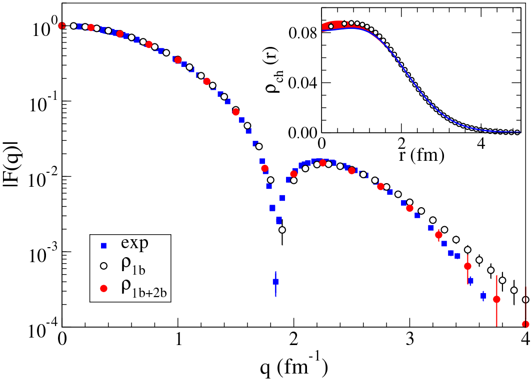
Bands represent cutoff Λ dependence



Observables $\propto \langle \Psi_f | \mathbf{j} | \Psi_i \rangle$

PRC86(2012)047001 & PRC87(2013)014006

Charge form factor of $12C$: Effects of two-body charge components

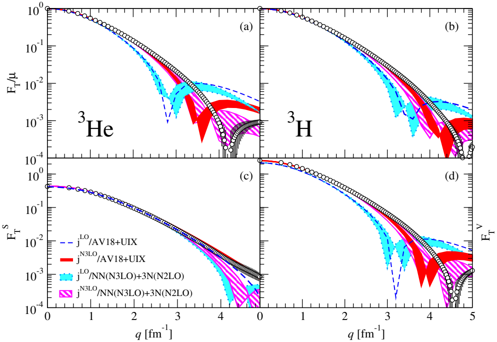


Observables $\propto \langle \Psi_f | \rho | \Psi_i \rangle$

Lovato *et al.*

PRL111(2013)092501

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; ∼ 10% correction from two-body currents
- Two-body corrections crucial to improve agreement with EXPT data

$$\text{Observables} \propto \langle \Psi_f | \mathbf{j} | \Psi_i \rangle$$

Piarulli *et al.* PRC87(2013)014006

Electromagnetic Currents from Chiral Effective Field Theory: Summary

* (Space) Vector Part of the electromagnetic current $\mathbf{j}$ derived up to N3LO in the chiral expansion
* It has two-body currents given by one- and two-pion exchanges plus contact currents
* Two-body one-pion-exchange currents appears at NLO in the chiral expansion (big correction to the LO term)
* They involve 5 unknown parameters (Low Energy Constants) 2 are saturated by the Δ
* Three-body currents absent at N3LO they appear at N4LO (they are neglected in almost all calculations)
* One-pion exchange $\mathbf{j}_\pi$ currents provide $\sim 0.8\, \mathbf{j}_{ij}$

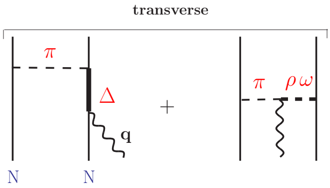
* Time Component of the electromagnetic current ρ derived up to N4LO in the chiral expansion
* It has two-body currents given by one- and two-pion exchanges (no contact operators)
* Two-body one-pion-exchange contribution appears at N3LO in the chiral expansion (small correction to the LO term)

Electromagnetic Currents from Nuclear Interactions
aka Standard Nuclear Physics Approach (SNPA) Currents
aka Meson Exchange Currents (MEC)

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

1) "Longitudinal" component fixed by current conservation
2) "Plus transverse" component "model dependent"

$$\mathbf{j} = \mathbf{j}^{(1)} + \mathbf{j}^{(2)}(\upsilon) + \ldots + \mathbf{j}^{(3)}(V)$$

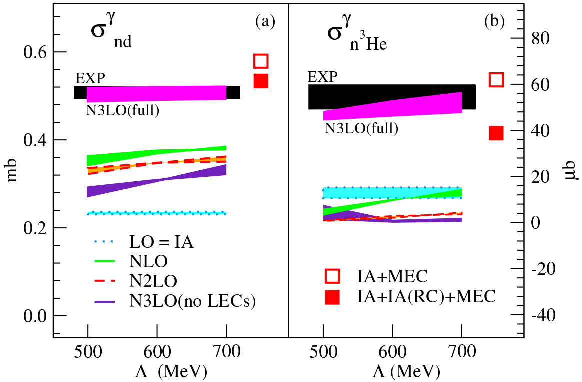


* $\mathbf{j}^{(2)}(\upsilon)$ has the same range of applicability as υ=AV18
* Because AV18 contains one-pion-exchange potential υ_π then one-pion-exchange currents $\mathbf{j}_\pi$ are included in $\mathbf{j}^{(2)}(\upsilon)$!!!
  same two-body physics as Chiral Formulation

Villars, Myiazawa (40-ies), Chemtob, Riska, Schiavilla . . .

see, *e.g.*, Marcucci *et al.* PRC**72**(2005)014001 and references therein

Chiral vs Conventional Approach



Girlanda *et al.* PRL105(2010)232502

Observables $\propto \langle \Psi_f | \mathbf{j} | \Psi_i \rangle$

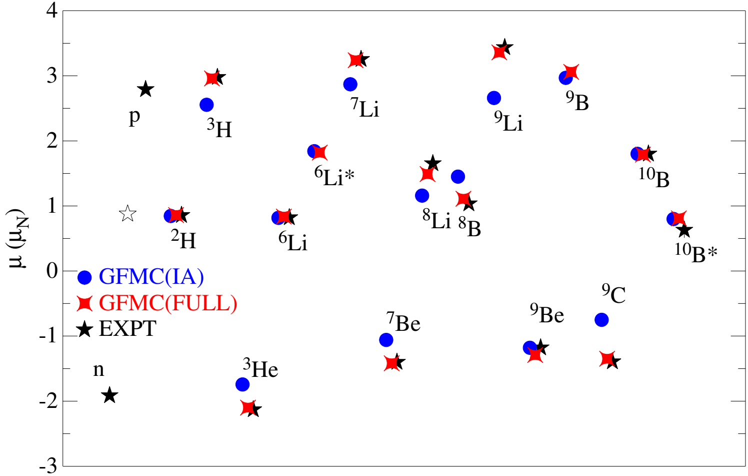
Power Counting doesn't know about suppressions/cancellations at LO

Suppression at LO is a nuclear feature due to "pseudo-orthogonality" of initial and final wave functions

Observable sensitive to many-body components

Magnetic Moments in $A \leq 10$ Nuclei

Predictions for $A > 3$ nuclei

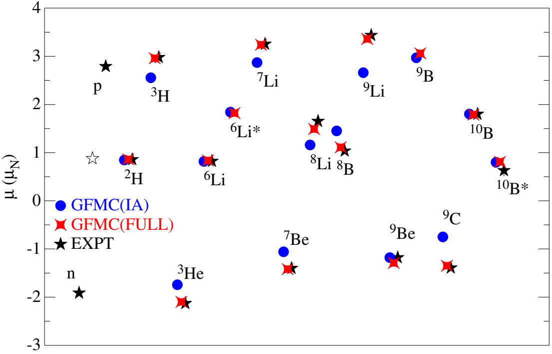


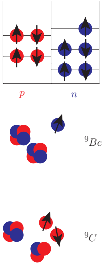
- $\mu(\text{IA}) = \mu_N \sum_i [(L_i + g_p S_i)(1 + \tau_{i,z})/2 + g_n S_i (1 - \tau_{i,z})/2]$

Observables $\propto \langle \Psi_f | \mathbf{j} | \Psi_i \rangle$

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

Predictions for $A > 3$ nuclei



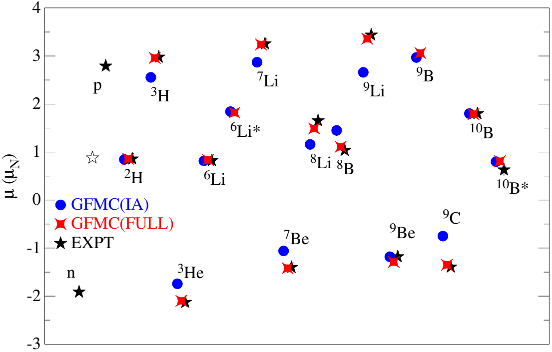


- $\mu_N(\text{IA}) = \sum_i [(L_i + g_p S_i)(1+\tau_{i,z})/2 + g_n S_i (1-\tau_{i,z})/2]$

Observables $\propto \langle \Psi_f | \mathbf{j} | \Psi_i \rangle$

PRC87(2013)035503

Error Estimate



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

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

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

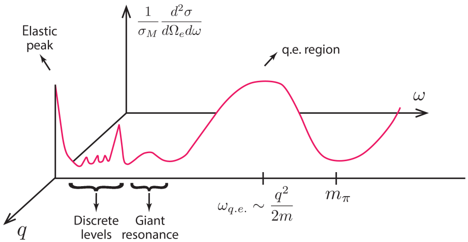
m.m.	THEO	EXP
^{9}C	-1.35(4)(7)	-1.3914(5)
^{9}Li	3.36(4)(8)	3.4391(6)

* 'N3LO-Δ' corrections can be 'large' *

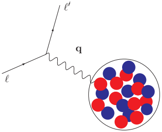
* "Conventional" and χEFT currents qualitatively in agreement, χEFT isoscalar currents provide better description exp data *

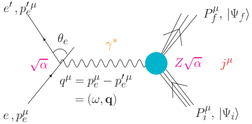
Pastore *et al.* PRC87(2013)035503

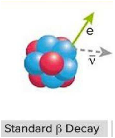
Electroweak Reactions



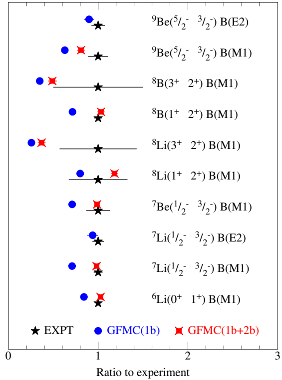
- * $\omega \sim 10^2$ MeV: Accelerator neutrinos
- * $\omega \sim 10^1$ MeV: EM decay, β-decay
- * $\omega \lesssim 10^1$ MeV: Nuclear Rates for Astrophysics







Electromagnetic Transitions



* 2b electromagnetic currents bring the THEORY in agreement with the EXPT
* $\sim 60 - 70\%$ of total 2b-current component is due to one-pion-exchange currents
* $\sim$ 20-30% 2b found in M1 transitions in ^{8}Be

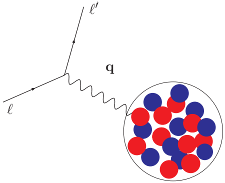
Pastore *et al.* PRC87(2013)035503 & PRC90(2014)024321, Datar *et al.* PRL111(2013)062502

Inclusive (e,e') scattering: Intro to Short-Time-Approximation

* ν/e inclusive xsecs are completely specified by the response functions
* Two 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 $O_T = \mathbf{j}$



* Sum Rules *

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

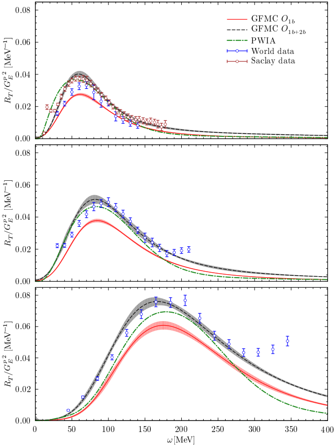
$$S(q,\tau) = \int_0^\infty d\omega\, K(\tau,\omega) R_\alpha(q,\omega)$$

* Coulomb Sum Rules *

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

Recent Developments on ^{12}C
Quantum Monte Carlo Calculations of Nuclear Responses and Sum Rules

Electromagnetic Transverse Responses



$q = [300 - 750]$ MeV

More by Alessandro Lovato

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

Chiral Electroweak Currents (Incomplete List of Credits)

* Electromagnetic Currents *

* Park, Min, and Rho *et al.* - NPA596(1996)515
  applications to A=2–4 systems including magnetic moments and M1 properties and radiative captures by Song, Lazauskas, Park *at al.*
* Meissner, Kölling, Epelbaum, Krebs *et al.* - PRC80(2009)045502 & PRC84(2011)054008
  applications to A=2–4 systems including d and ^{3}He photodisintegration by Rozpedzik *et al.*; d magnetic f.f. by Kölling, Epelbaum, Phillips; radiative $N-d$ capture by Skibinski *et al.* (2014)
* Phillips

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

* Axial Currents *

* Park, Min, and Rho *et al.* - PhysRept233(1993)341
  applications to A=2–4 systems including μ-capture, pp-fusion, *hep* ·
* Krebs and Epelbaum *et al.* - AnnalsPhys378(2017)317
* Baroni *et al.* - PRC93(2016)015501
  applications to low-energy neutrino scattering off d and Quantum Monte Carlo calculations of β-decay matrix elements in A=3-10 nuclei

Observations

* Electromagnetic currents both Charge and Vector components have been derived in Chiral Effective Field Theory
* They consists of one- and two-pion exchange operators plus contact vector currents
* Two-body components in the vector current operator **j** appear at NLO in the chiral expansion
* They involve 5 Low Energy Constants fitted to data

* Conventional Longitudinal two-body currents are constructed so as to satisfy the continuity equation with the AV18
* Because the AV18 has the one-pion-exchange potential the conventional currents include the one-pion-exchange currents
* Conventional “model dependent” transverse components include excitations of the Δ and transitions currents with heavier mesons (these, in the Chiral Effective Field Theory currents, are parametrized by the Low Energy Constants)

Observations Continuation

* In general *

* Two-body components are essential to explain the data
* They provide up to $\sim 40\%$ contributions to magnetic moments of nuclei (static observables)
* They enhance the transverse response up $\sim 50\%$ (dynamical observables)
* One-pion-exchange currents $\mathbf{j}_\pi$, present in both formulations, provide $\sim 0.8\,\mathbf{j}_{ij}$

$\mathbf{j}_\pi$

Conclusion and Outlook II

* The Microscopic picture of the nucleus based on many-body interactions and electroweak currents successfully explains the data both qualitatively and quantitatively

* It explains the spectra and shapes of nuclei

* It has been validated against electromagnetic observables in a wide range of energies from *keV* (relevant to astrophysics) to *GeV* (relevant to accelerator neutrino experiments)

* Two-body physics, correlations and two-body currents, is essential to understand the data both for static nuclear properties (spectra, electromagnetic moments, nuclear form factors) and dynamical properties (transitions in low-lying nuclear states, nuclear responses)

* We want the same coherent picture for interactions with neutrinos *