Neutrino measurements relevant to g_A quenching

Saori Pastore

NuInt 17: 11th International Workshop on
Neutrino-Nucleus Scattering in the Few-GeV Region
Toronto, CA - June 2017

Los Alamos
NATIONAL LABORATORY
EST. 1943

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

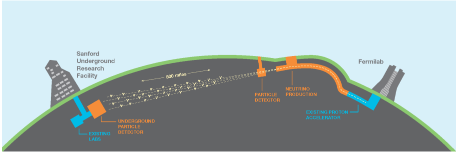
WITH

Carlson & Gandolfi (LANL) - Schiavilla & Baroni (ODU/JLAB) - Wiringa & Piarulli & Pieper (ANL)
Mereghetti & Dekens & Cirigliano (LANL)

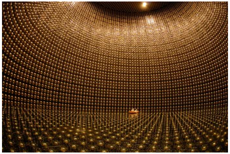
REFERENCES

PRC78(2008)064002 - PRC80(2009)034004 - PRL105(2010)232502 - PRC84(2011)024001 - PRC87(2013)014006
PRC87(2013)035503 - PRL111(2013)062502 - PRC90(2014)024321 - JPhysG41(2014)123002 - PRC(2016)015501

Fundamental Physics Quests: Accelerator Neutrinos



LBNF



T2K

neutrinos oscillate

$\rightarrow$

they have tiny masses

=

BSM physics

Beyond the Standard Model

Simplified 2 flavors picture:

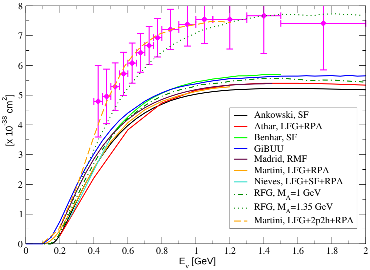
$$P(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta sin^2 \left(\frac{\Delta m^2 L}{2E_\nu} \right)$$

* Unknown *

ν-mass hierarchy, CP-violation, accurate mixing angles

Neutrino-Nucleus scattering

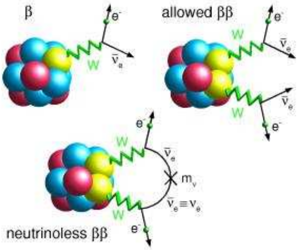
CCQE on ^{12}C



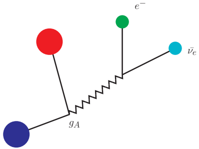
Alvarez-Ruso arXiv:1012.3871

DUNE, MiniBoone, T2K, Minerνa ... active material * ^{12}C, ^{40}Ar, ^{16}O, ^{56}Fe, ... *

The "g_A problem"

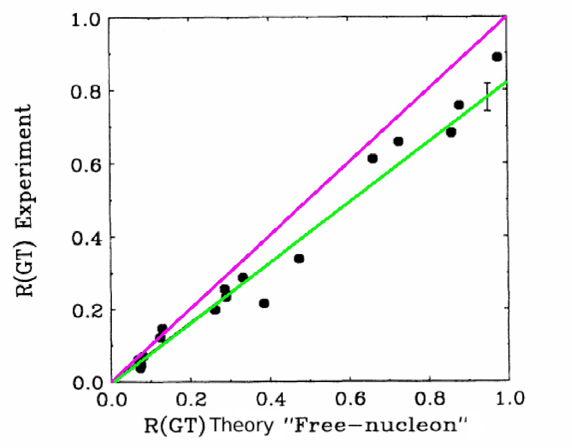


Berna U.



g_A nucleon axial coupling constant

Theory vs Experiment: The "g_A problem"

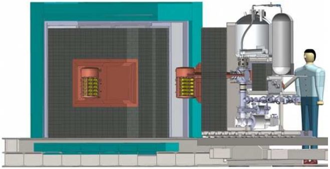


* $g_A^{\text{eff}} \simeq 0.70\, g_A$ * required to bring theory in agreement with expt

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

Fundamental Physics Quests: Double Beta Decay

observation of $0\nu\beta\beta$-decay
$\rightarrow$
lepton # $L = l - \bar{l}$ not conserved
$\rightarrow$
implications in
matter-antimatter imbalance



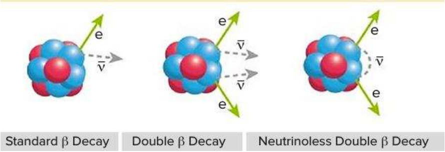
Majorana Demonstrator

* detectors' active material ^{76}Ge *

$0\nu\beta\beta$-decay $\tau_{1/2} \gtrsim 10^{25}$ years (age of the universe 1.4×10^{10} years)

1 ton of material to see (if any) ~ 5 decays per year

* also, if nuclear m.e.'s are known, absolute ν-masses can be extracted *



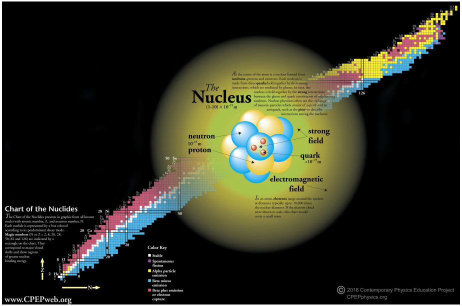
2015 Long Range Plane for Nuclear Physics

Fundamental Physics Quests rely on Nuclear Physics

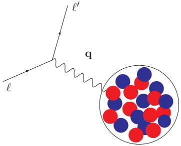
Nuclei used as laboratories for precision tests of the standard model and in searches for beyond the standard model physics

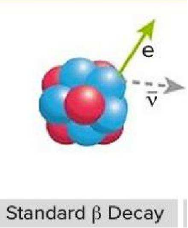
$\Longrightarrow$

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



http://www.cpepweb.org

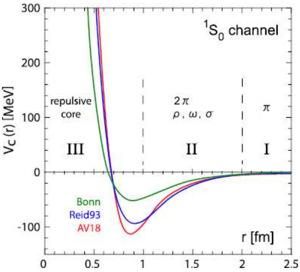




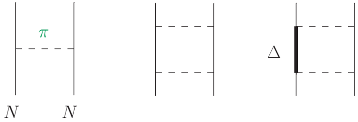
The nucleus is made of A non-relativistic interacting nucleons and its energy is

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

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



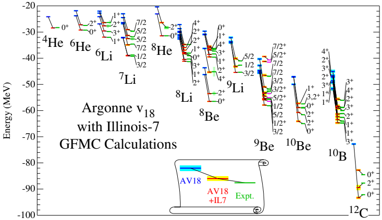
Aoki *et al.* Comput.Sci.Disc.1(2008)015009



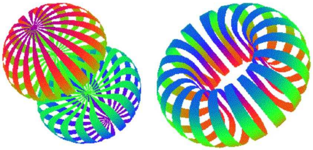
- One-pion-exchange: range$\sim \frac{1}{m_\pi}$
- Two-pion-exchange: range$\sim \frac{1}{2m_\pi}$

- AV18+UIX / AV18+IL7 - QMC
- NN(N3LO)+3N(N2LO) - QMC (π N Δ) by Maria Piarulli *et al.* PRC91(2015)024003

Energy Spectrum and Shape of Nuclei

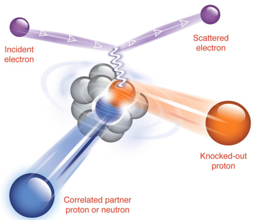


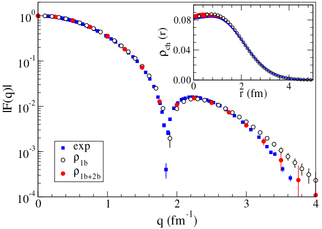
Carlson *et al.* Rev.Mod.Phys.87(2015)1067



Constant density surfaces for a polarized deuteron in the $M = \pm 1$ (left) and $M = 0$ (right) states

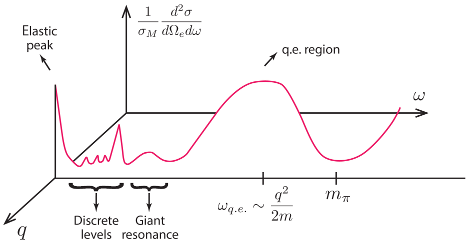
Carlson and Schiavilla Rev.Mod.Phys.70(1998)743



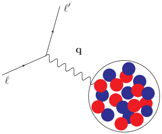


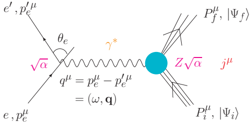
Lovato *et al.* PRL111(2013)092501

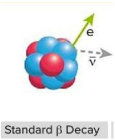
Electroweak Reactions



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

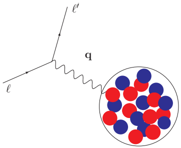




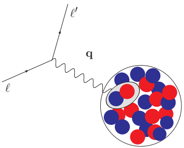


Nuclear Currents

1b



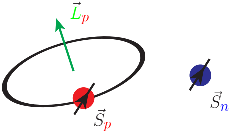
2b



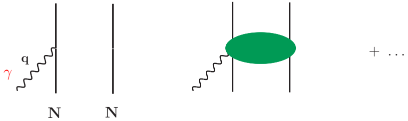
$$\rho = \sum_{i=1}^{A} \rho_i + \sum_{i<j} \rho_{ij} + \dots ,$$

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

* In Impulse Approximation IA nuclear currents are expressed in terms of those associated with individual protons and nucleons, *i.e.*, ρ_i and $\mathbf{j}_i$, 1b-operators



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

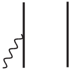


$$\mathbf{q} \cdot \mathbf{j} = [H, \rho] = [t_i + \upsilon_{ij} + V_{ijk}, \rho]$$

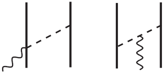
* Villars, Myiazawa, Chemtob, Riska, Schiavilla, Marcucci, . . .

Electromagnetic Currents from Chiral Effective Field Theory

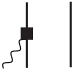
LO : $\mathbf{j}^{(-2)} \sim \mathbf{eQ^{-2}}$



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



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



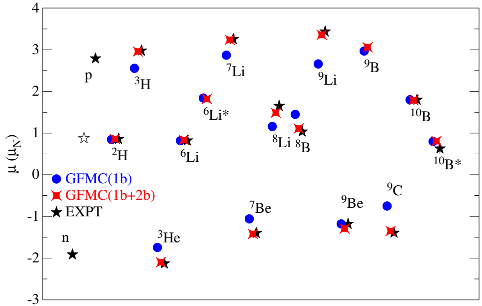
* 3 unknown Low Energy Constants:
fixed so as to reproduce d, ^3H, and ^{3}He magnetic moments

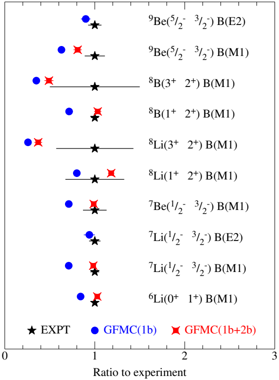
N^{3}LO: $\mathbf{j}^{(1)} \sim \mathbf{eQ}$

unknown LEC's →

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 *

Magnetic Moments and M1 Transitions

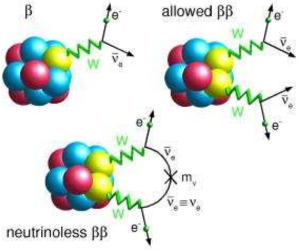




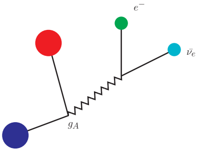
- 2b electromagnetic currents bring the THEORY in agreement with the EXPT
- $\sim 40\%$ 2b-current contribution found in ^{9}C m.m.
- $\sim 60-70\%$ of total 2b-current component is due to one-pion-exchange currents
- $\sim$ 20-30% 2b found in M1 transitions in ^{8}Be

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

The "g_A problem"
and
the role of two-nucleon correlations and two-body currents



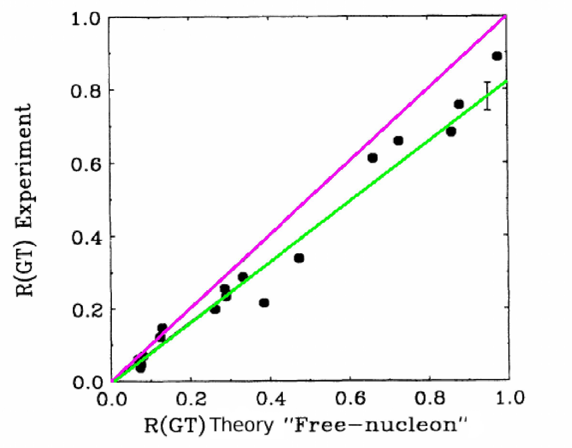
Berna U.



g_A nucleon axial coupling constant

Preliminary results

Theory vs Experiment: The "g_A problem"



* $g_A^{\text{eff}} \simeq 0.70\, g_A$ * required to bring theory in agreement with expt

We use ✓ $g_A = 1.2723$ from PDG ✓ without quenching factor

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

Correlations in our formalism

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

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

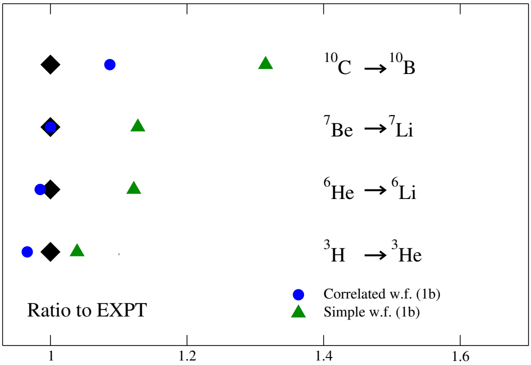
* single-particle $\Phi_A(JMTT_3)$ is fully antisymmetric and translationally invariant
* central pair correlations $f_c(r)$ keep nucleons at favorable pair separation
* pair correlation operators U_{ij} reflect influence of v_{ij} (AV18)
* triple correlation operators U_{ijk} reflect the influence of V_{ijk} (IL7)

In an uncorrelated wave function
1) U_{ij} and U_{ijk} are turned off, and
2) only the dominant spatial symmetry is kept

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

Wiringa, PRC43(1991)1585

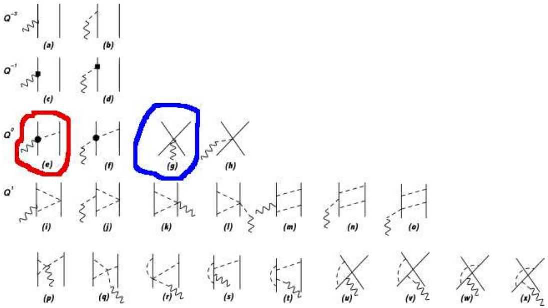
Role of correlations in beta-decay m.e.'s



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

* Preliminary *

Two-body Axial Currents from χEFT



* c_3 and c_4 are taken them from Entem and Machleidt fits of nuclear interactions
  PRC68(2003)041001 & Phys.Rep.503(2011)1
* c_D fitted to GT m.e. of tritium beta-decay

✓ $g_A = 1.2723$ from PDG ✓

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

Ab initio calculations with EW Currents from χEFT

- 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

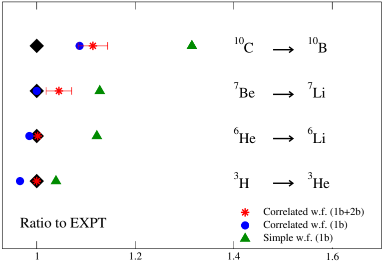
- Park, Min, and Rho *et al.* (90-ies)

  applications to A=2–4 systems including μ-capture, *pp*-fusion, *hep* ·

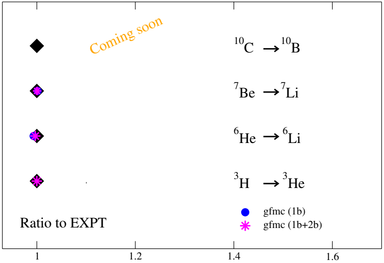
- Krebs and Epelbaum *et al.* (2016)
- Klos *et al.* (2015)

Role of two-body currents in beta-decay m.e.'s

SNPA currents VMC Calculations



χEFT currents GFMC calculations



✓ $g_A = 1.2723$ from PDG ✓

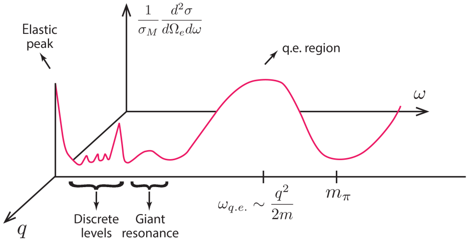
Preliminary

* SNPA and χEFT two-body currents are qualitatively in agreement (both are fitted to the tritium β-decay)

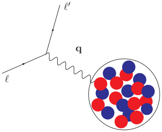
* Two-body currents are found to provide a small (negligible) contribution

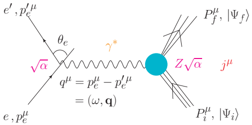
* no quenching required! (limited to the light systems we studied)

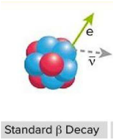
Neutrino measurements relevant to g_A quenching



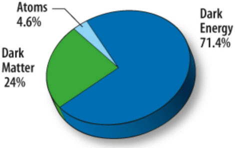
* Low-energy ν-scattering *

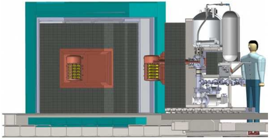


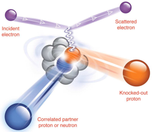


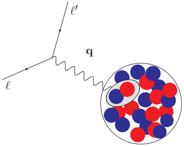


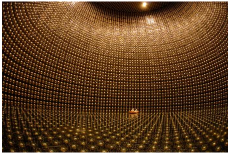
Outlook

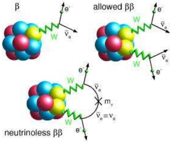


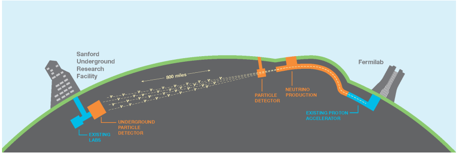


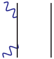




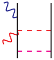








$\langle \mathbf{j}^{\dagger}_{1b}\ \mathbf{j}_{1b}\rangle > 0$



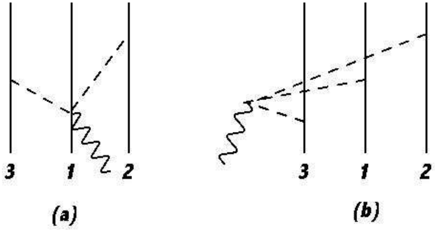
$\langle \mathbf{j}^{\dagger}_{1b}\ \mathbf{j}_{2b}\ v_{\pi}\rangle \propto \langle v_{\pi}^{2}\rangle > 0$

Fundamental Physics with Electroweak Probes of Light Nuclei
June 12 - July 13, 2018
S. Bacca, R. J. Hill, S. Pastore, D. Phillips

Contacts
http://www.int.washington.edu/
saori.pastore@gmail.com
saori@lanl.gov

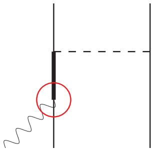
EXTRA SLIDES

Three-body Axial Currents from χEFT



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

SNPA Two-body Axial Currents

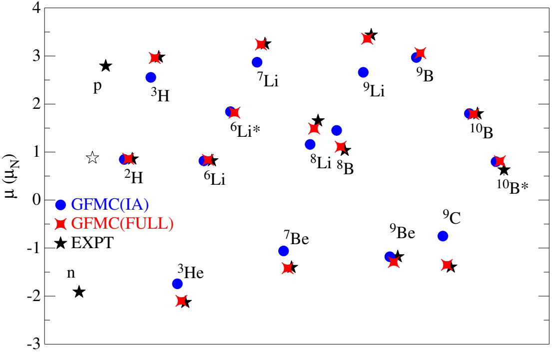


1) One body has GT, relativistic corrections, PS from pion-pole diagrams
2) Two-body currents
    2.a) Major contribution from Δ-excitation current
    2.b) Negligible contributions from $A\pi$, $A\rho$, $A\pi\rho$
3) $AN\Delta$ coupling fixed to tritium beta-decay
4) $\sim 3\%$ additive correction from Δ-current

Chemtob, Rho, Towner, Riska, Schiavilla, Marcucci …

see, e.g., Marcucci *et al.* PRC63(2001)015801 and references therein

Error Estimate



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

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

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

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’ *

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

Pastore *et al.* PRC87(2013)035503

$A = 7$ Captures

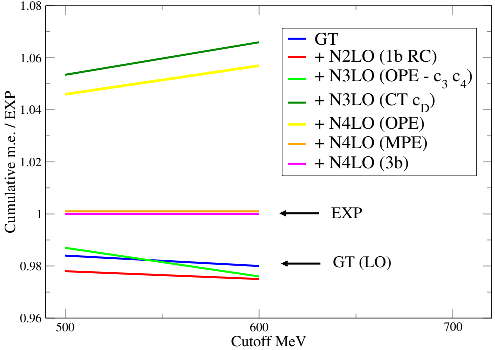
	gs	ex
LO	2.334	2.150
N2LO	-3.18×10^{-2}	-2.79×10^{-2}
N3LO(OPE)	-2.99×10^{-2}	-2.44×10^{-2}
N3LO(CT)	2.79×10^{-1}	2.36×10^{-1}
N4LO(2b)	-1.61×10^{-1}	-1.33×10^{-1}
N4LO(3b)	-6.59×10^{-3}	-4.86×10^{-3}
TOT(2b+3b)	0.050	0.046

* Large cancellations due to positive CT at N3LO with c_D fixed to GT m.e. of tritium

In preparation

Convergence and cutoff dependence

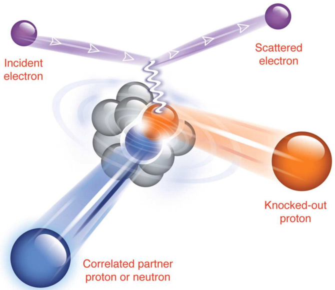
Tritium β-decay

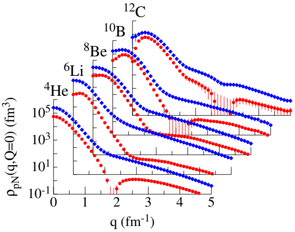


* $\sim$ 2% additive contribution from two-body currents

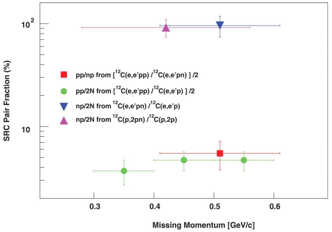
A. Baroni *et al.* PRC93(2016)015501 & PRC94(2016)024003

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





Wiringa *et al.* PRC89(2014)024305



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

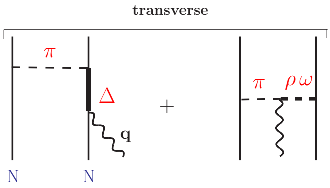
Nuclear properties are strongly affected by two-nucleon interactions!

Electromagnetic Currents from Nuclear Interactions (SNPA currents)

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

1) Longitudinal component fixed by current conservation
2) Plus transverse "phenomenological" terms

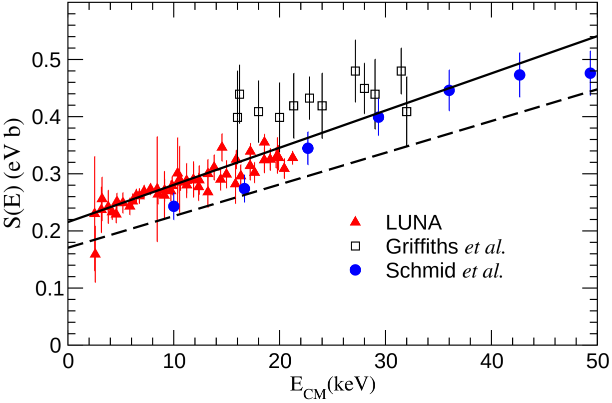
$$\mathbf{j} = \mathbf{j}^{(1)} + \mathbf{j}^{(2)}(v) + \mathbf{j}^{(3)}(V)$$



Villars, Myiazawa (40-ies), Chemtob, Riska, Schiavilla …
see, *e.g.*, Marcucci *et al.* PRC**72**(2005)014001 and references therein

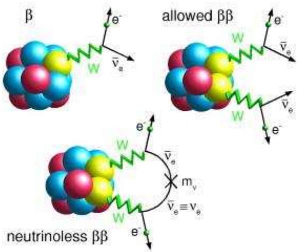
Satisfactory description of a variety of nuclear em properties in $A \leq 12$

^{2}H(p,γ)^{3}He capture

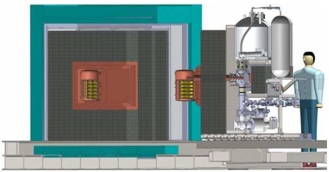


Marcucci *et al.* PRC**72**, 014001 (2005)

$0\nu\beta\beta$-decay matrix elements
and
the role of two-nucleon correlations



Berna U.

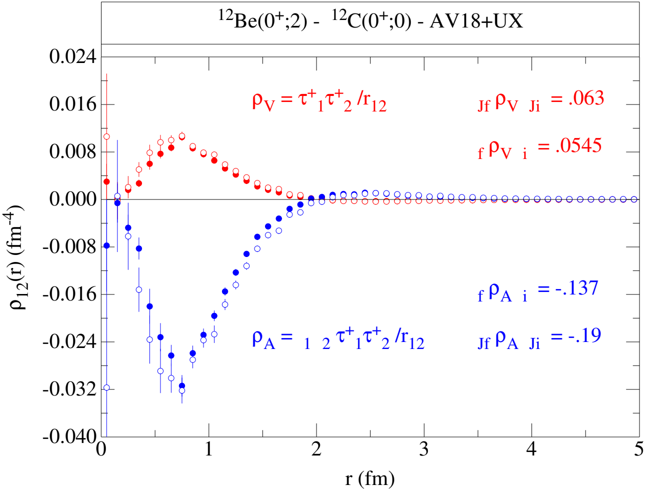


Majorana Demonstrator

Preliminary results

Double beta-decay m.e.'s in ^{12}Be$(0^+;2) \rightarrow {}^{12}C(0^+;0)$: A test case

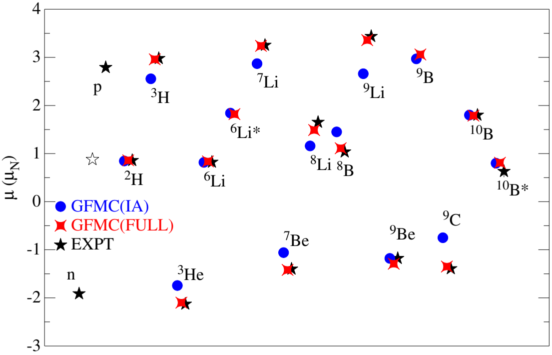
Preliminary

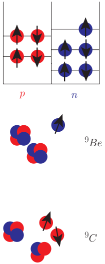


* $\frac{<\rho_V>_{\rm corr}}{<\rho_V>_{\rm uncorr}} \sim 0.86$ * $\frac{<\rho_A>_{\rm corr}}{<\rho_A>_{\rm uncorr}} \sim 0.72$

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] = $[\alpha, {}^3\mathrm{He}({}^3\mathrm{H}), pp(nn)] \rightarrow$ Large MEC
- ^{9}Be (^{9}B) dominant spatial symmetry [s.s.] = [441] = $[\alpha, \alpha, n(p)]$

PRC87(2013)035503

Outlook

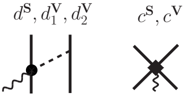
The microscopic description of nuclei successfully reproduces EXPT data provided that many-body effects in nuclear interactions and EM currents are accounted for.
J.Phys.G41(2014)123002 - S.Bacca&S.P.

* 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 ...
  - 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)
  - Zemach moments of light nuclei with 'MEC'

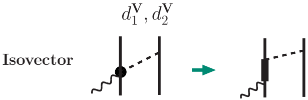
* Electroweak structure and dynamics of light nuclei
  - Test axial currents (chiral and conventional) in light nuclei (A. Baroni et al. PRC93(2016)015501)
  - Incorporate pion production mechanisms in STA

* Strong reactions in nuclei
  - QMC calculations of nuclear reactions

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:
  - model I = c^V from EXPT $npd\gamma$ xsec.

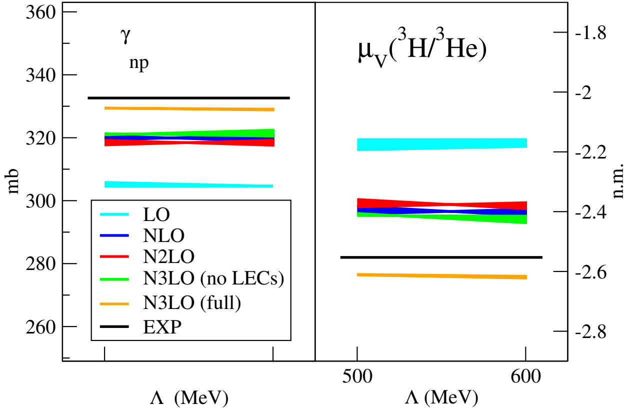
    or
  - model II = c^V from EXPT $\mu_V(^3\text{H}/^3\text{He})$ m.m. $\leftarrow$ our choice

Note that:
χEFT operators have a power law behavior $\rightarrow$ introduce a regulator to kill divergencies at large Q, *e.g.*, $C_\Lambda = e^{-(Q/\Lambda)^n}$, ...and also, pick n large enough so as to not generate spurious contributions

$$C_\Lambda \sim 1 - \left(\frac{Q}{\Lambda}\right)^n + \dots$$

Predictions with χEFT EM currents for $A = 2$–3 systems

np capture xsec. (using model II) / μ_V of $A = 3$ nuclei (using model I)
bands represent nuclear model dependence (N3LO/N2LO – AV18/UIX)



- $npd\gamma$ xsec. and $\mu_V(^3\text{H}/^3\text{He})$ m.m. are within 1% and 3% of EXPT
- Two-body currents important to reach agreement with exp data
- Negligible dependence on the cutoff entering the regulator $exp(-(k/\Lambda)^4)$

PRC87(2013)014006