EM response and weak decays in light nuclei

Saori Pastore

ECT*-18: Exploring the role of electro-weak currents in Atomic Nuclei
Trento, IT - April 2018

Open Questions in Fundamental Symmetries and Neutrino Physics

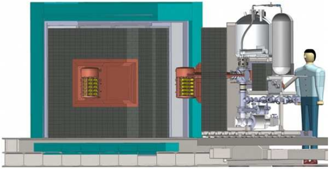
Majorana Neutrinos, Neutrinos Mass Hierarchy,
CP-Violation in Neutrino Sector, Dark Matter

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

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 - PRC93(2016)01550
*** PRC97(2018)014606 - PRC97(2018)022501 - arXiv:1802.10097 ***

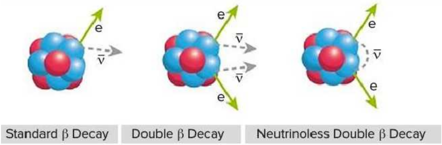
Fundamental Physics Quests: Double Beta Decay

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



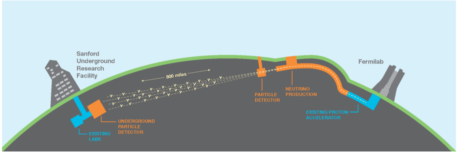
Majorana Demonstrator

$0\nu\beta\beta$-decay $\tau_{1/2} \gtrsim 10^{25}$ years (age of the universe 1.4×10^{10} years)
need 1 ton of material to see (if any) ~ 5 decays per year
* Decay Rate $\propto$ (nuclear matrix elements)$^2 \times \langle m_{\beta\beta} \rangle^2$ *

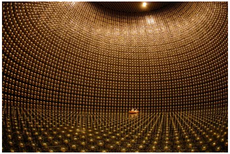


2015 Long Range Plane for Nuclear Physics

Fundamental Physics Quests: Accelerator Neutrinos



LBNF



T2K

neutrinos oscillate

$\rightarrow$

they have tiny masses

=

BSM physics

Beyond the Standard Model

Simplified 2 flavors picture:

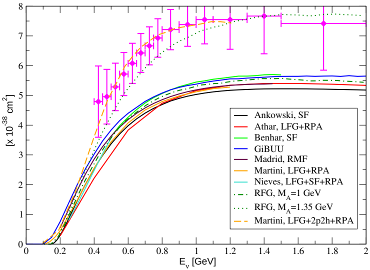
$$P(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta sin^2\left(\frac{\Delta m^2 L}{2E_\nu}\right)$$

* Unknown *

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

Neutrino-Nucleus scattering

CCQE on ^{12}C

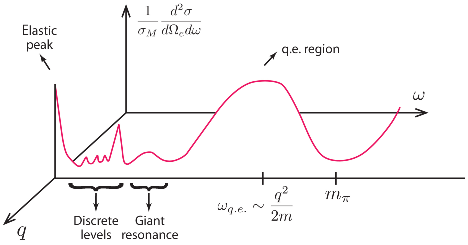


Alvarez-Ruso arXiv:1012.3871

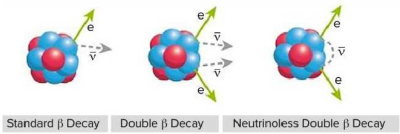
DUNE, MiniBoone, T2K, Minerνa ... active material * ^{12}C, ^{40}Ar, ^{16}O, ^{56}Fe, ... *

Nuclear Structure and Dynamics

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



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

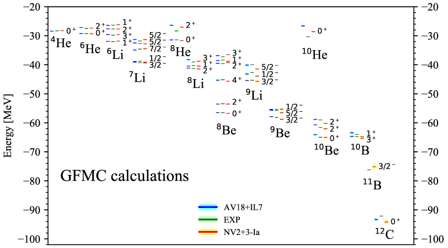


Nuclear Interactions

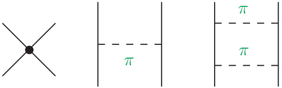
The nucleus is made of A non-relativistic interacting nucleons and its energy is

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

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



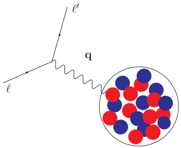
Piarulli *et al.* - PRL120(2018)052503



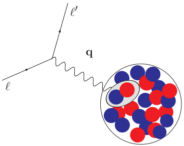
* QMC: AV18+UIX / AV18+IL7
  Wiringa+Schiavilla+Pieper *et al.*
* QMC: NN(N2LO)+3N(N2LO) (π&N)
  Gerzelis+Tews+Epelbaum+Gandolfi+Lynn *et al.*
* QMC: NN(N3LO)+3N(N2LO) (π&N&Δ)
  Piarulli *et al.*

Nuclear Currents

1b



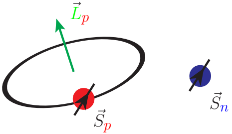
2b



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

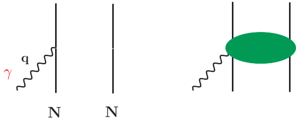
$$\mathbf{j} = \sum_{i=1}^{A} \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + \ldots$$

* Nuclear currents given by the sum of p's and n's currents, one-body currents (1b)



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

* We use MEC (SNPA) or χEFT currents

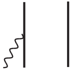


$+ \ldots$

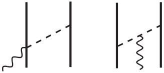
$$\mathbf{q} \cdot \mathbf{j} = [H, \rho] = \left[t_i + \upsilon_{ij} + V_{ijk}, \rho\right]$$

Electromagnetic Currents from Chiral Effective Field Theory

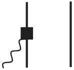
LO : $\mathbf{j}^{(-2)} \sim \mathbf{eQ^{-2}}$



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



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



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

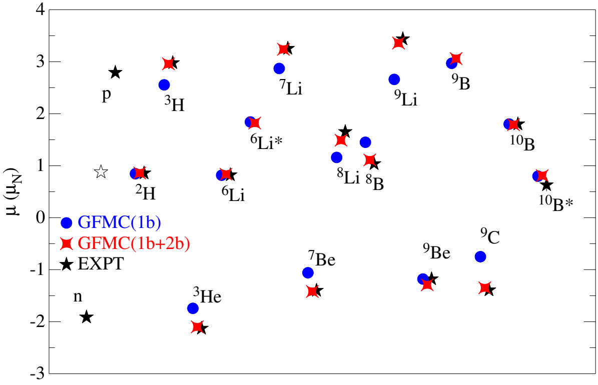
N^{3}LO: $\mathbf{j}^{(1)} \sim \mathbf{eQ}$

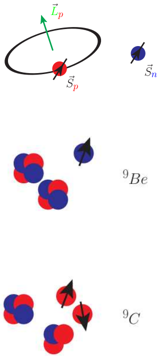
unknown LEC′s →

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 *

also derived by Park+Min+Rho NPA596(1996)515, Kölling+Epelbaum+Krebs+Meissner PRC80(2009)045502 & PRC84(2011)054008

Magnetic Moments of Nuclei





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

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

Pastore *et al.* PRC87(2013)035503

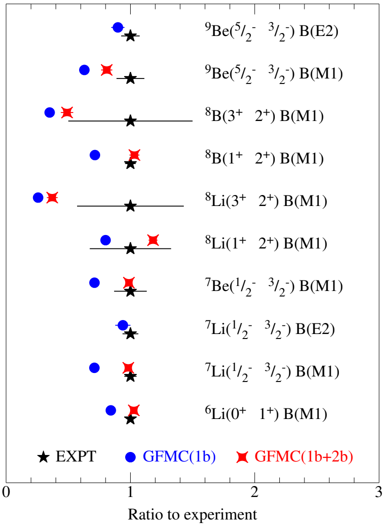
Electromagnetic Transitions in Light Nuclei

- 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

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

+ a number of B(E2)s

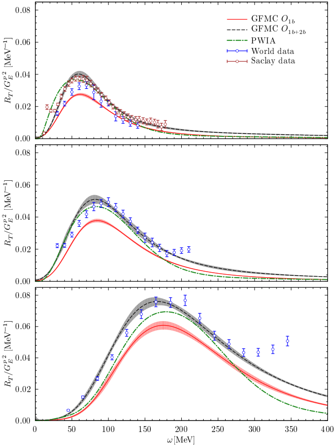
*2014 TRIUMF proposal Ricard-McCutchan *et al.*



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

Electron Scattering off ^{12}C

Electromagnetic Transverse Responses

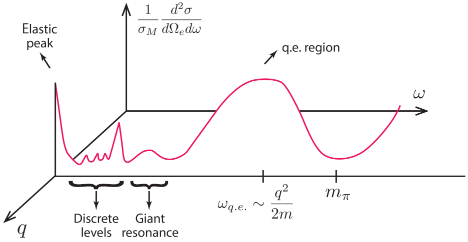


$q = [300 - 750]$ MeV

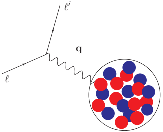
Lovato *et al.* - PRC91(2015)062501 + arXiv:1605.00248

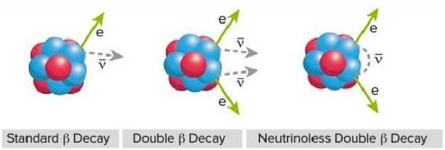
Electron-scattering data are explained when two-body correlations and currents are accounted for!

Nuclei and Neutrinos



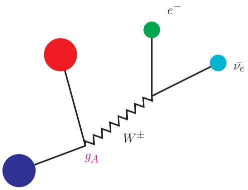
* $\omega \sim$ few MeVs, $q \sim 0$: "g_A-problem" in single beta decays
* Scarce data at moderate values of momentum transfer
* $\omega \sim 10^2$ MeV: ν-A scattering "Anomalies" the QE region





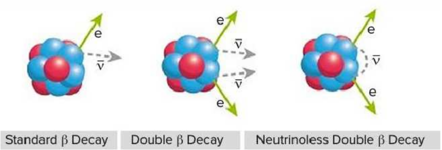
Standard Beta Decay

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



* Matrix Element $\langle \Psi_f | \mathrm{GT} | \Psi_i \rangle \propto g_A$ and Decay Rates $\propto g_A^2$ *

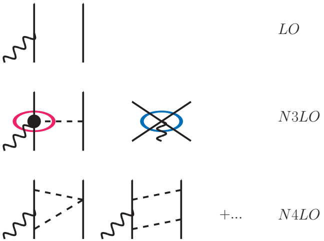
$$(Z, N) \rightarrow (Z+1, N-1) + e + \bar{\nu}_e$$



Nuclear Interactions and Axial Currents

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

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



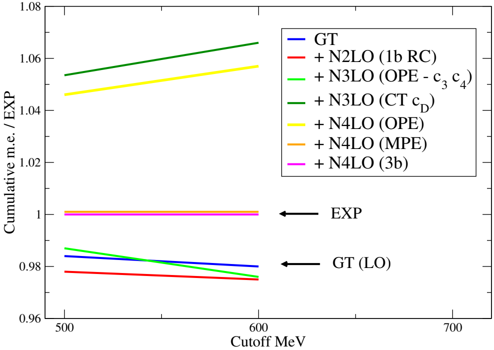
A. Baroni *et al.* PRC93(2016)015501

H. Krebs *et al.* Ann.Phy.378(2017)

- c_3 and c_4 are taken them from Entem and Machleidt PRC68(2003)041001 & Phys.Rep.503(2011)1
- c_D fitted to GT m.e. of tritium
  Baroni *et al.* PRC94(2016)024003
- cutoffs $\Lambda = 500$ and 600 MeV
- include also N4LO 3b currents (tiny)

* derived by Park *et al.* in the ′90
used (mainly at tree-level) in many calculations
* pion-pole at tree-level derived
by Klos, Hoferichter *et al.* PLB(2015)B746

Tritium β-decay



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

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

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

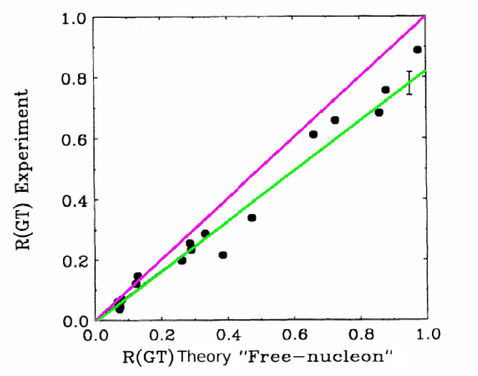
χEFT currents in $A > 3$ systems

$A = 7$ Captures

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

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

Single β-decay: The "g_A problem"

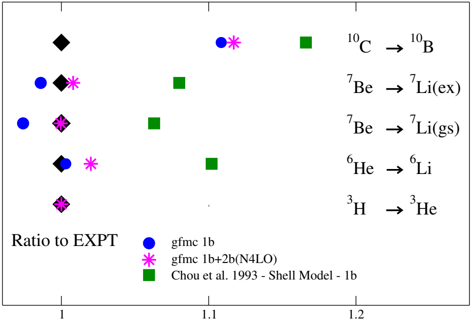


in $3 \leq$ A$\leq 18 \longrightarrow g_A^{\text{eff}} \simeq 0.80\, g_A$

Chou *et al.* PRC47(1993)163

Missing Physics: 1. Correlations and/or 2. Two-body currents

Single Beta Decay Matrix Elements in $A = 6–10$



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

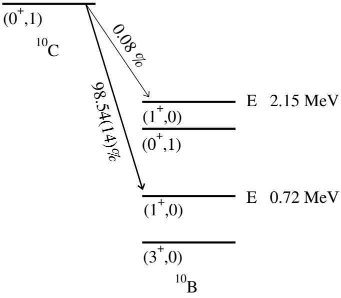
Pastore *et al.* PRC97(2018)022501

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

Based on $g_A \sim 1.27$ no quenching factor

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

^{10}B

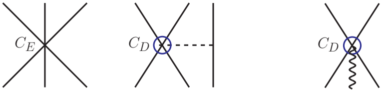


* In ^{10}B, ΔE with same quantum numbers ~ 1.5 MeV
* In $A = 7$, ΔE with same quantum numbers $\gtrsim 10$ MeV

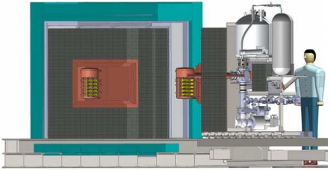
Beta-decay

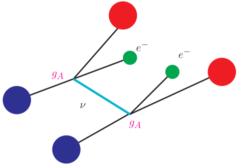
To do list:

* QMC calculations based on both chiral interactions and chiral currents
* In this case c_D enters both the 3b interaction and 2b axial current
    * c_D (and c_E) depend on the fitting strategy, *e.g.*, EXP GT in tritium, EXP B.E. A=3, EXP B.E. A=4, scattering length, ...
    * c_D (and c_E) depend on the regulator utilized in the fitting procedure
* Pions and nucleons d.o.f.'s:
  axial currents fully developed
* Pions, nucleons, and deltas d.o.f.'s (interaction by Piarulli *et al.* PRC91(2015)024003-PRC94(2016)054007-PRL120(2018)052503):
  axial currents at tree-level fully developed (on going)
* Benchmark with calculations by Gaute, Quaglioni *et al.*
* yesterday resolution: quote c_D and c_E and if 3NF is attractive or repulsive



Neutrinoless Double Beta Decay

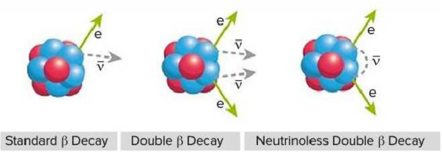




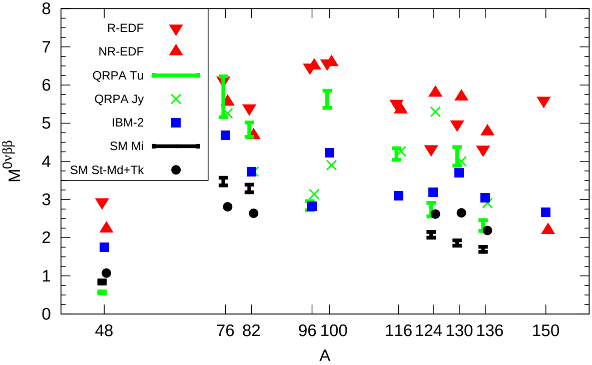
"The average momentum is about 100 MeV, a scale set by the average distance between the two decaying neutrons" cit. Engel&Menéndez

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

* Nuclear matrix elements $\propto g_A^2$ and Decay Rates $\propto g_A^4$ *

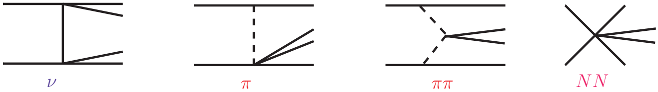


Neutrinoless double beta decay: STATUS



Javier Menendez arXiv:1703.08921 (2017)

Double beta-decay Potentials



$$\upsilon_{\nu} \sim L_{\nu}\, \tau_{1,+}\, \tau_{2,+}\, \frac{\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2}{m_\pi\, \mathbf{q}^2} + \cdots + \upsilon_{\nu}{}^{\text{N2LO}-\text{loop}*}$$

$$\upsilon_{\pi\pi} \sim L_{\pi\pi}\, \tau_{1,+}\, \tau_{2,+}\, \frac{\boldsymbol{\sigma}_1 \cdot \mathbf{q}\, \boldsymbol{\sigma}_2 \cdot \mathbf{q}}{m_\pi\, (\mathbf{q}^2 + m_\pi^2)^2}$$

$$\upsilon_{\pi} \sim L_{\pi}\, \tau_{1,+}\, \tau_{2,+}\, \frac{\boldsymbol{\sigma}_1 \cdot \mathbf{q}\, \boldsymbol{\sigma}_2 \cdot \mathbf{q}}{m_\pi^3\, (\mathbf{q}^2 + m_\pi^2)}$$

$$\upsilon_{\text{NN}} \sim L_{\text{NN}}\, \tau_{1,+}\, \tau_{2,+}\, \frac{\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2}{m_\pi^3}$$

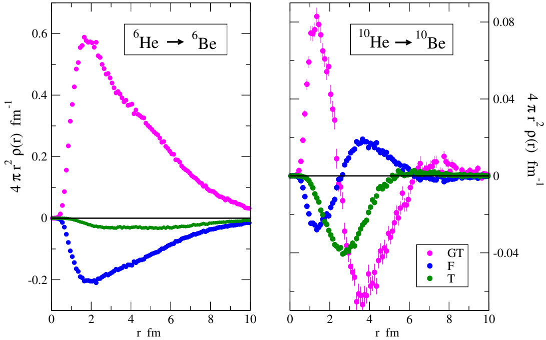
$L_{\pi\pi}$, L_{π}, L_{NN} encode hadronic and model dependent particle physics

* Cirigliano & Dekens & Mereghetti & Walker-Loud in arXiv:1710.01729

IN COLLABORATION WITH
Emanuele Mereghetti & Wouter Dekens & Cirigliano & Carlson & Wiringa

PRC97(2018)014606

F, GT, and T Transition Densities



* $\Delta T = 0$

^{6}He(1)→^{6}Be(1)
^{8}He(2)→^{8}Be*(2)
^{10}Be(1)→^{10}C(1)

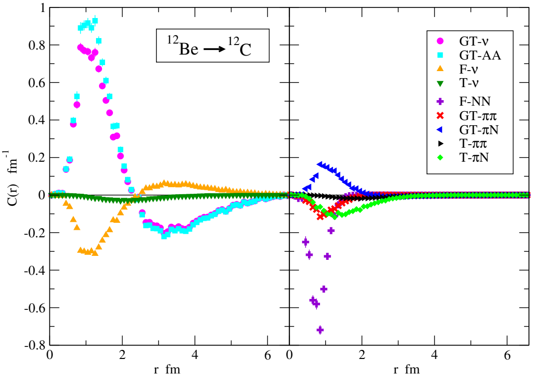
* $\Delta T = 2$

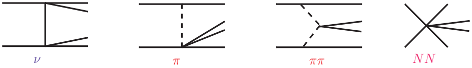
^{8}He(1)→^{8}Be(0)
^{10}He(3)→^{10}Be(1)
^{12}Be(2)→^{12}C(0)

$$\mathrm{F}= \tau_{1,+}\,\tau_{2,+}\ \ ;\mathrm{GT} = \tau_{1,+}\,\tau_{2,+}\,\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\ \ ;\mathrm{T}= \tau_{1,+}\,\tau_{2,+}\,S_{12}$$

PRC97(2018)014606

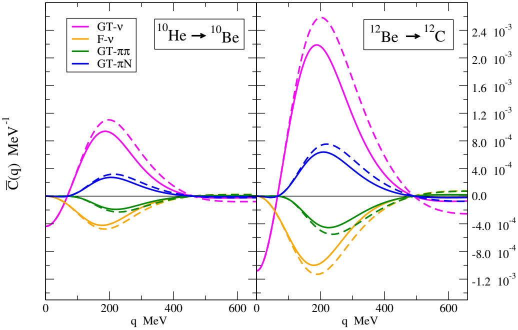
Double beta-decay Matrix Elements





PRC97(2018)014606

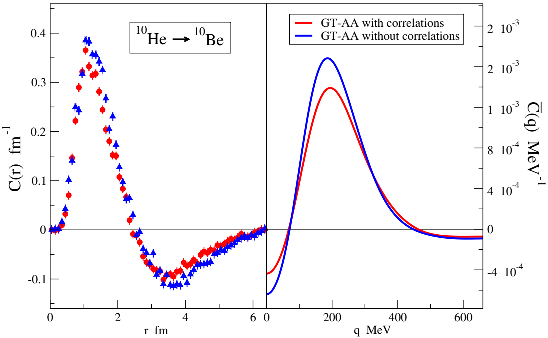
Momentum Dependence and Sensitivity to N2LO effects
i.e., ‘dipole’ nucleonic form factors and $\upsilon_\nu^{\mathrm{N2LO-loop}}$



* Peaks at $\sim$ 200 MeV
* Form factors on/off $\rightarrow \sim$ 10% variation same size as $\upsilon_\nu^{\mathrm{N2LO-loop}}$ from Cirigliano *et al.* arXiv:1710.01729
* $A = 10$ highly suppressed w.r.t. $A = 12$ (clusterization matter?)
* $A = 12$ ‘most similar’ to experimental cases

PRC97(2018)014606

Sensitivity to 'pion-exchange-like' correlations

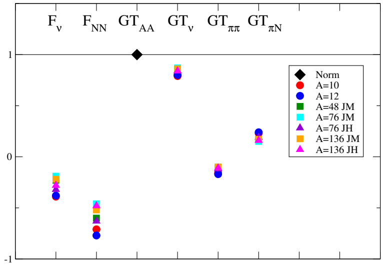


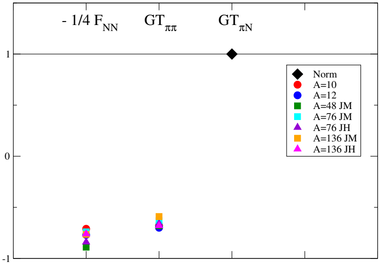
* no 'pion-exchange-like' correlation operators U_{ij}
* yes 'pion-exchange-like' correlation operators U_{ij}
* $\sim 10\%$ increase in the matrix elements corresponds to a 'g_A-quenching' of ~ 0.95
* as opposed to ~ 0.83 found in $A = 10$ single beta decay

* Correlations reduce the m.e.'s (also true for μ's and GT's) *

PRC97(2018)014606

Comparison with calculations of larger nuclei





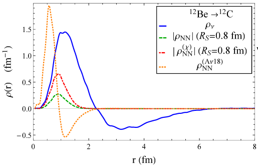
JM = Javier Menendez private communication
JH = Hyvärien *et al.* PRC91(2015)024613

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

PRC97(2018)014606

The contact!

Impact on $0\nu\beta\beta$ nuclear matrix elements



VMC calculation
w. AV18 potential

- assuming $C_1 = C_2$ & extract from AV18

$$M_{F\nu} = 0.191 \quad M_{GT\nu} = 0.400 \quad M_{F,NN} = 0.460$$

$\mathcal{O}(1)$ correction!

- need consistent treatment of weak and strong interactions

Courtesy of Emanuele Mereghetti

* renormalization requires to introduce a counter term at leading order

$$\upsilon_\nu = \upsilon_\nu^{\mathrm{LO}} + \upsilon_{CT}$$

* υ_{CT} is 'partially' determined by the isospin breaking NN potential ($\propto (\tau_{1,z} + \tau_{2,z})$)

Mereghetti & Dekens & Cirigliano & Graesser & de Vries & van Kolck & Pastore

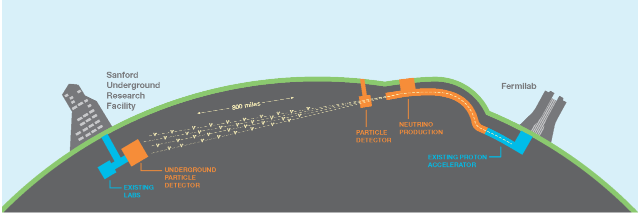
arXiv:1802.10097

$e - A$ and $\nu - A$ Scattering

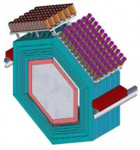
- How do nuclei interact with electrons and neutrinos in the GeV energy regime and how can calculations of these interaction cross sections be improved?

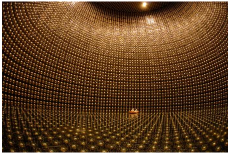
i.e.

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



LBNF





Minerνa

T2K

Factorization: Short-Time Approximation

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

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

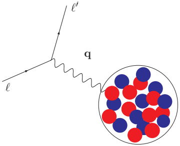
At short time, expand $P(t) = e^{i(H-\omega)t}$ and keep up to 2b-terms

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

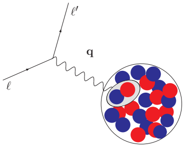
and

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

1b



2b

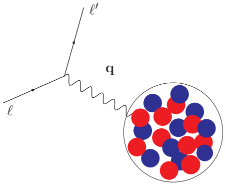


WITH
Carlson & Gandolfi (LANL) *et al.*

Factorization I: The Plane Wave Impulse Approximation (PWIA)

In PWIA:

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



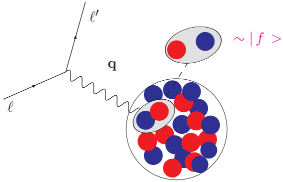
$$R_\alpha(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) \langle 0|O^\dagger_\alpha(\mathbf{q})|f\rangle\langle f|O_\alpha(\mathbf{q})|0\rangle$$

$$O_\alpha(\mathbf{q}) = O_\alpha^{(1)}(\mathbf{q}) = 1\text{b}$$

$$|f\rangle \sim e^{i(\mathbf{k}+\mathbf{q})\cdot\mathbf{r}} = \text{free single nucleon w.f.}$$

Factorization II: The Short-Time Approximation (STA)

In STA:



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

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

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

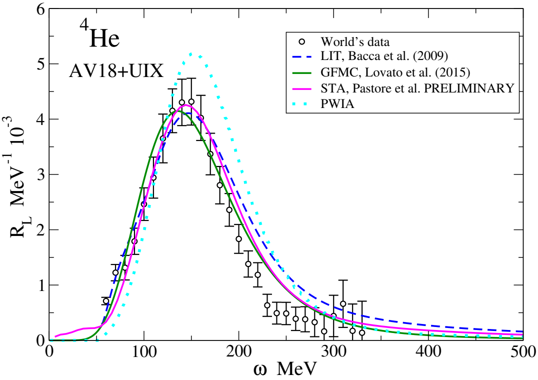
$$|f\rangle \sim |\psi_{p,P,J,M,L,S,T,M_T}(r,R)\rangle = \text{correlated two} - \text{nucleon w.f.}$$

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

* $R_\alpha(q,\omega)$ requires only direct calculation of g.s. $|0\rangle$ w.f.'s *

* STA can be implemented to accommodate for more two-body physics, *e.g.*, pion-production induced by e and ν

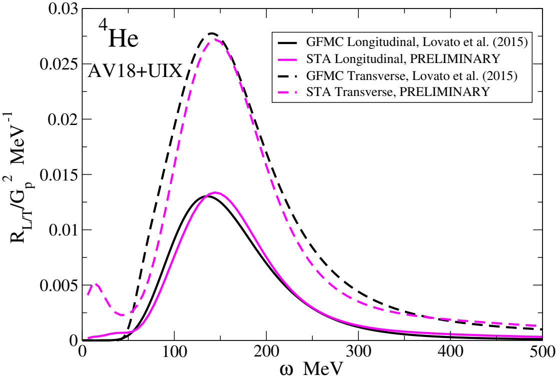
The Short-Time Approximation



Longitudinal Response function at $q = 500$ MeV

Preliminary results

The Short-Time Approximation



Longitudinal vs Transverse Response Function at $q = 500$ MeV

Preliminary results

Summary and Outlook

Two-nucleon correlations and two-body electroweak currents are crucial to explain available experimental data of both static (ground state properties) and dynamical (cross sections and rates) nuclear observables

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

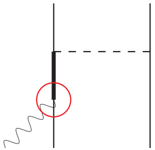
* Calculations of $\beta-$ and $\beta\beta-$decay m.e.'s in $A \leq 12$ indicate two-body physics (currents and correlations) is required

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

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

EXTRA SLIDES

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

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

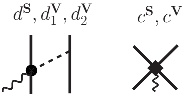
$$|\Psi_V\rangle = \left[\mathcal{S} \prod_{i<j} (1 + U_{ij} + \sum_{k \neq i,j} U_{ijk}) \right] \left[\prod_{i<j} f_c(r_{ij}) \right] |\Phi_A(JMTT_3)\rangle$$

* 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)

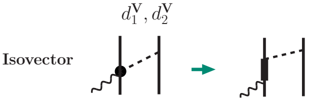
Lomnitz-Adler, Pandharipande, and Smith NPA361(1981)399

Wiringa, PRC43(1991)1585

Electromagnetic LECs



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



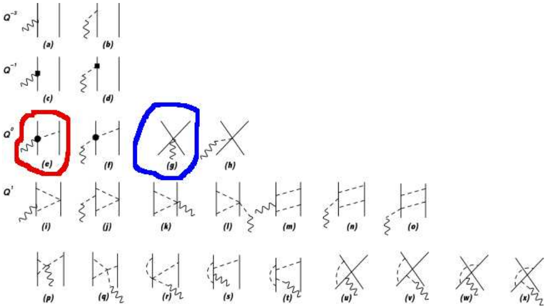
$d_2^V = 4\mu^* h_A / 9 m_N (m_\Delta - m_N)$ and
$d_1^V = 0.25 \times d_2^V$
assuming Δ-resonance saturation

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.

Two-body Axial Currents from χEFT



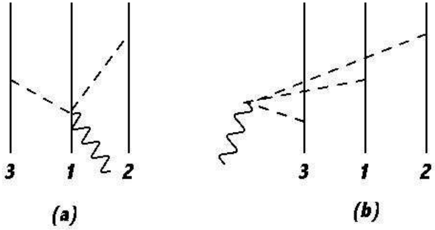
c_D

* fitted to GT m.e. of tritium beta-decay
* for both χEFT potentials and AV18+UIX
* because of N4LO two-body currents c_D value changes

	N3LO		N4LO	
Λ	500	600	500	600
c_D	–0.353	–0.443	–1.847	–2.030

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

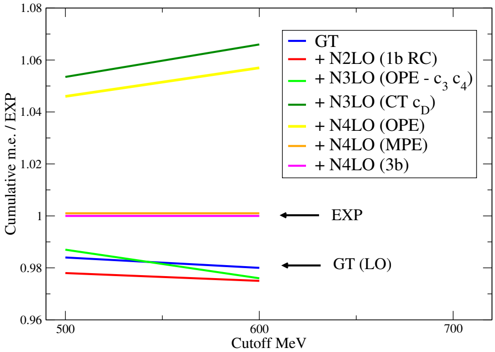
Three-body Axial Currents from χEFT



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

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

$A = 7$ 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

Comparison with calculations of larger nuclei

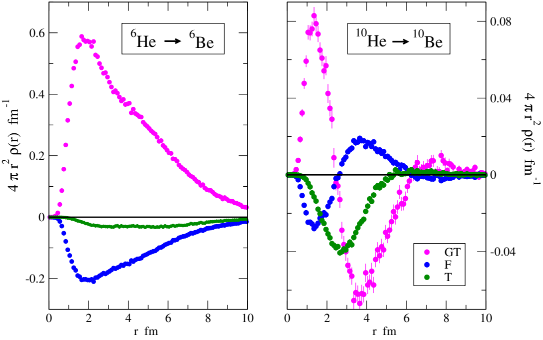
$(T_i) \to (T_f)$		F		GT			
		ν	NN	AA	ν	$\pi\pi$	πN
^{8}He(2)→^{8}Be(0)		-0.63	-1.37	1	0.71	-0.28	0.38
^{10}He(3)→^{10}Be(1)		-0.39	-0.71	1	0.79	-0.16	0.23
^{12}Be(2)→^{12}C(0)		-0.38	-0.77	1	0.80	-0.17	0.24
^{48}Ca →^{48}Ti	Men	-0.23	-0.60	1	0.86	-0.11	0.17
^{76}Ge →^{76}Se	Men	-0.19	-0.46	1	0.87	-0.10	0.15
	Hyv	-0.32	-0.63	1	0.84	-0.12	0.19
^{136}Xe →^{136}Ba	Men	-0.22	-0.52	1	0.86	-0.10	0.17
	Hyv	-0.28	-0.48	1	0.84	-0.11	0.16

$(T_i) \to (T_f)$		F	GT	
		NN	$\pi\pi$	πN
^{8}He(2)→^{8}Be(0)		3.38	-0.76	1
^{10}He(3)→^{10}Be(1)		2.86	-0.68	1
^{12}Be(2)→^{12}C(0)		3.08	-0.70	1
^{48}Ca →^{48}Ti	Men	3.55	-0.68	1
^{76}Ge →^{76}Se	Men	2.97	-0.63	1
	Hyv	3.34	-0.66	1
^{136}Xe →^{136}Ba	Men	3.06	-0.59	1
	Hyv	3.03	-0.68	1

Men = Javier Menendez private communication
Hyv = Hyvärien *et al.* PRC91(2015)024613

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

F, GT, and T Transition Densities



* $\Delta T = 0$

^{6}He(1)→^{6}Be(1)
^{8}He(2)→^{8}Be*(2)
^{10}Be(1)→^{10}C(1)

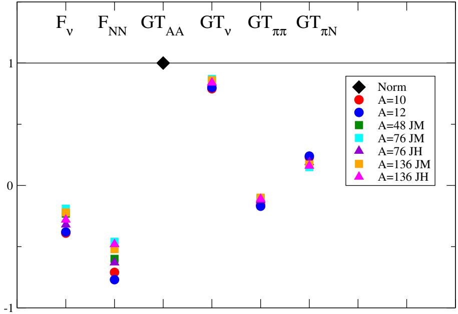
* $\Delta T = 2$

^{8}He(1)→^{8}Be(0)
^{10}He(3)→^{10}Be(1)
^{12}Be(2)→^{12}C(0)

$$F = \tau_{1,+}\,\tau_{2,+} \;\; ; GT = \tau_{1,+}\,\tau_{2,+}\,\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \;\; ; T = \tau_{1,+}\,\tau_{2,+}\,S_{12}$$

arXiv:1710.05026

Comparison with calculations of larger nuclei



$(T_i) \to (T_f)$	F	GT	
	NN	$\pi\pi$	πN
^{10}He(3)→^{10}Be(1)	2.86	-0.68	1
^{12}Be(2)→^{12}C(0)	3.08	-0.70	1
^{48}Ca →^{48}Ti JM	3.55	-0.68	1
^{76}Ge →^{76}Se JM	2.97	-0.63	1
JH	3.34	-0.66	1
^{136}Xe →^{136}Ba JM	3.06	-0.59	1
JH	3.03	-0.68	1

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

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

arXiv:1710.05026