Correlations
and
two-body currents in (electro)weak processes

Saori Pastore
INT Program INT-17-2a - Neutrinoless Double-beta Decay
Seattle WA - June 2017

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: Double Beta Decay

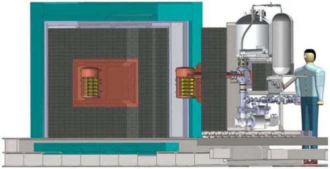
observation of $0\nu\beta\beta$-decay

$\rightarrow$

lepton # $L = l - \bar{l}$ not conserved

$\rightarrow$

implications in
matter-antimatter imbalance



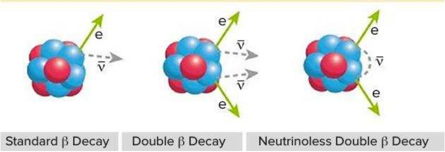
Majorana Demonstrator

* 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) $\sim$ 5 decays per year

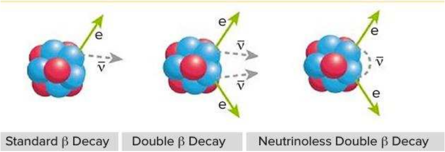
* also, if nuclear m.e.'s are known, absolute ν-masses can be extracted *



2015 Long Range Plane for Nuclear Physics

The question

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



OUTLINE

Role of correlations and many-body currents in

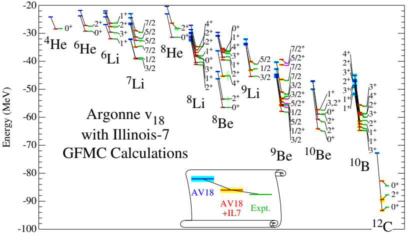
* Single beta-decay in A$\leq$10 nuclei *
* Neutrinoless double beta-decay in $A \leq$12 nuclei *

Nuclear Interactions

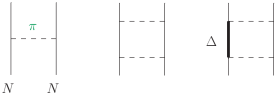
The nucleus is made of A non-relativistic interacting nucleons and its energy is

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

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



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



* AV18+UIX / AV18+IL7 - QMC

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

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

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

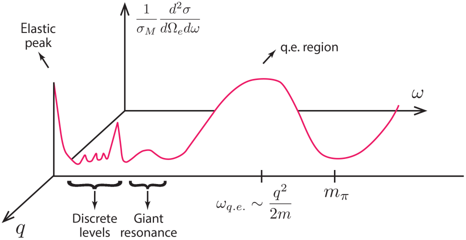
- * single-particle $\Phi_A(JMTT_3)$ is fully antisymmetric and translationally invariant
- * central pair correlations $f_c(r)$ keep nucleons at favorable pair separation
- * pair correlation operators U_{ij} reflect influence of υ_{ij} (AV18)
- * triple correlation operators U_{ijk} reflect the influence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

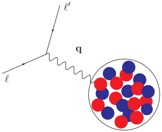
Lomnitz-Adler, Pandharipande, and Smith NPA361(1981)399

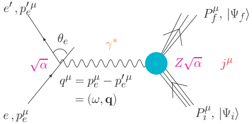
Wiringa, PRC43(1991)1585

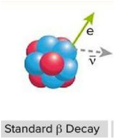
Electroweak Reactions



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

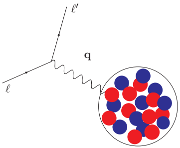




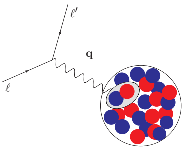


Nuclear Currents

1b



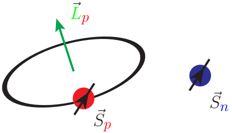
2b



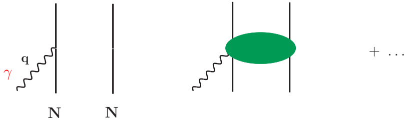
$$\rho = \sum_{i=1}^{A} \rho_i + \sum_{i<j} \rho_{ij} + \ldots\,,$$

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

* 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



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

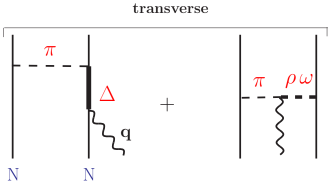
Electromagnetic Currents from Nuclear Interactions (SNPA currents)

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

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

$$\mathbf{j} = \mathbf{j}^{(1)}$$

$$+ \ \mathbf{j}^{(2)}(v) \ +$$



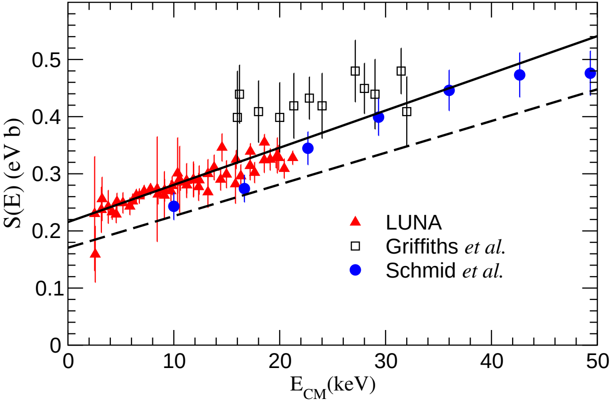
$$+ \ \mathbf{j}^{(3)}(V)$$

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

Currents from nuclear interactions

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

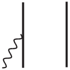
^{2}H(p,γ)^{3}He capture



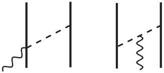
Marcucci *et al.* PRC**72**, 014001 (2005)

Electromagnetic Currents from Chiral Effective Field Theory

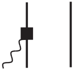
LO : $\mathbf{j}^{(-2)} \sim \mathbf{eQ^{-2}}$



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



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



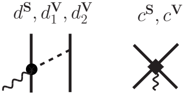
* 3 unknown Low Energy Constants:
fixed so as to reproduce d, ^3H, and ^{3}He magnetic moments

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

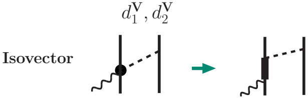
unknown LEC′s →

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 *

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

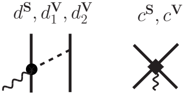
- Isoscalar sector:
  - d^S and c^S from EXPT μ_d and $\mu_S(^3\text{H}/^3\text{He})$
- Isovector sector:
  - c^V from EXPT $npd\gamma$ xsec.

    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

Λ	NN/NNN	$10 \times d^S$	c^S
500	AV18/UIX (N3LO/N2LO)	–1.731 (2.190)	2.522 (4.072)
600	AV18/UIX (N3LO/N2LO)	–2.033 (3.231)	5.238 (11.38)

Electromagnetic LECs



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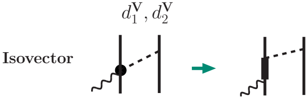

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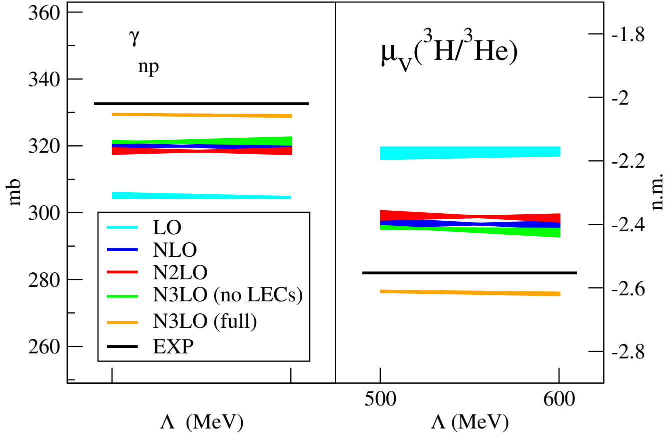
  - Regulator $C(\Lambda) = exp(-(p/\Lambda)^4)$ with $\Lambda = 500-600$ MeV

Λ	NN/NNN	Current	d_1^V	c^V
600	AV18/UIX	I	4.98	-11.57
		II	4.98	-1.025

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]



Piarulli *et al.* PRC(2013)014006

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

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

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

  ……

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

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

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

  ……

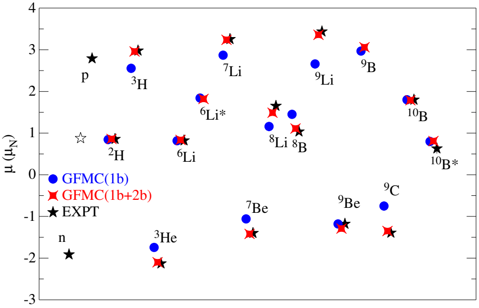
  * Based on EM χEFT currents from PRC80(2009)045502 & PRC84(2011)054008 and consistent χEFT potentials from UT method

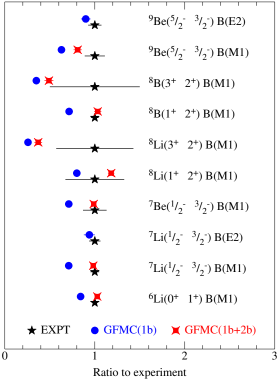
- Phillips (2003-2007)

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

  ……

Magnetic Moments and M1 Transitions

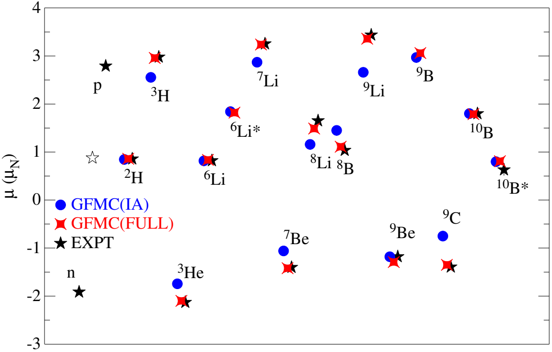




- * 2b electromagnetic currents bring the THEORY in agreement with the EXPT
- * $\sim$ 40% 2b-current contribution found in ^{9}C m.m.
- * $\sim 60 - 70\%$ of total 2b-current component is due to one-pion-exchange currents
- * $\sim$ 20-30% 2b found in M1 transitions in ^{8}Be

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

Error Estimate



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

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

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

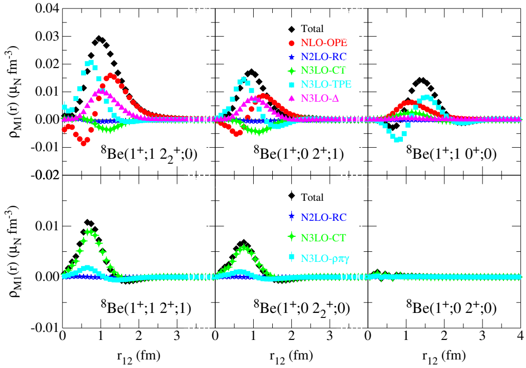
m.m.	THEO	EXP
^{9}C	-1.35(4)(7)	-1.3914(5)
^{9}Li	3.36(4)(8)	3.4391(6)

* ‘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

Two-body M1 transitions densities

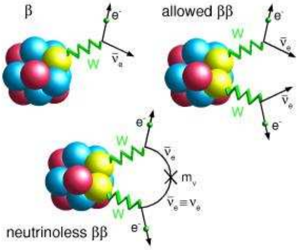


$(J_i,T_i) \rightarrow (J_f,T_f)$	IA	NLO-OPE	N2LO-RC	N3LO-TPE	N3LO-CT	N3LO-Δ	MEC
$(1^+;1) \rightarrow (2_2^+;0)$	2.461 (13)	0.457 (3)	-0.058 (1)	0.095 (2)	-0.035 (3)	0.161 (21)	0.620 (5)

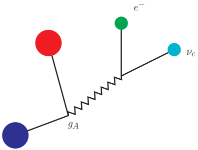
Pastore *et al.* PRC90(2014)024321

$\beta-$decay

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



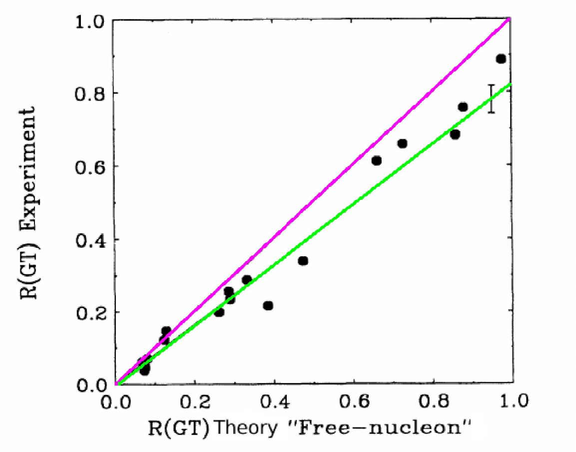
Berna U.



g_A nucleon axial
coupling constant

Preliminary results

Theory vs Experiment: The “g_A problem”



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

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

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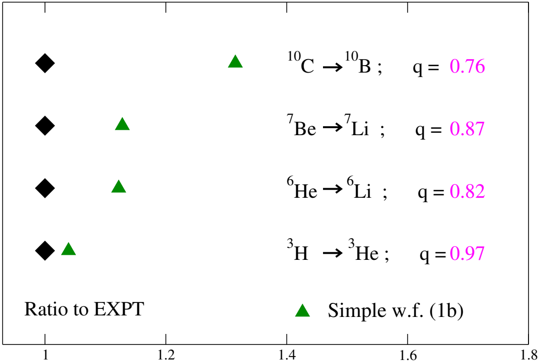
Lomnitz-Adler, Pandharipande, and Smith NPA361(1981)399

Wiringa, PRC43(1991)1585

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

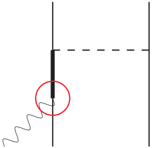


q = quenching from correlations

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

* Preliminary *

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 $A\pi$, $A\rho$, $A\pi\rho$

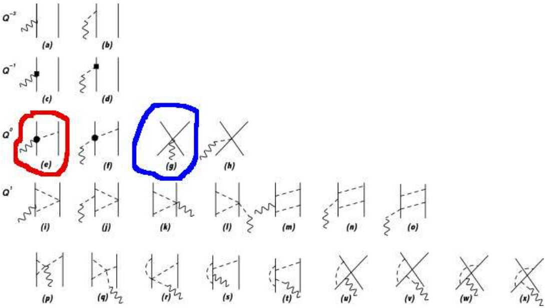
3) $AN\Delta$ coupling fixed to tritium beta-decay

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

Two-body Axial Currents from χEFT

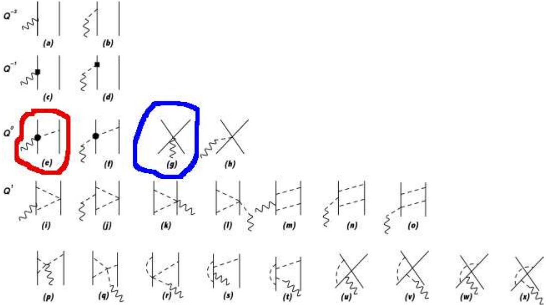


c_3 and c_4

- are saturated by the Δ and $\rho\pi$ d.o.f.
- enter also the χEFT two- and three-nucleon χEFT potential
- are taken them from Entem and Machleidt $c_3 = -3.2\ \text{GeV}^{-1}$, $c_4 = 5.4\ \text{GeV}^{-1}$
  PRC68(2003)041001 & Phys.Rep.503(2011)1

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

Two-body Axial Currents from χEFT



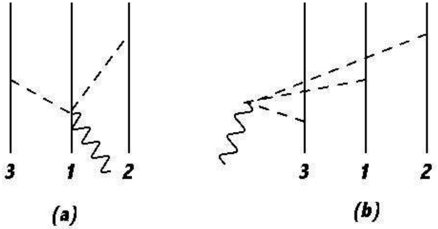
c_D

- 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

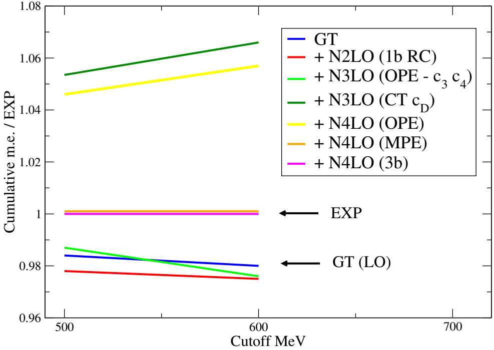
Three-body Axial Currents from χEFT



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

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

Incomplete history

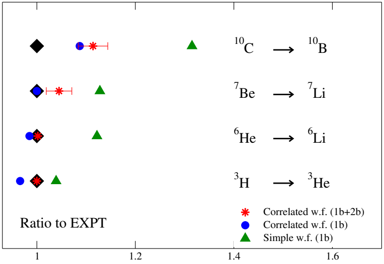
- Park, Min, and Rho *et al.* (90-ies)
  applications to A=2–4 systems including μ-capture, *pp*-fusion, *hep* $\cdot$
- Krebs and Epelbaum *et al.* (2016)
- Klos *et al.* (2015)

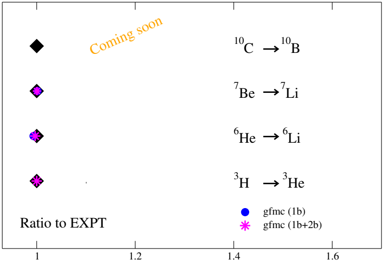
……

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

SNPA currents
VMC Calculations

χEFT currents
GFMC calculations





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 to the quenching, limited to the light systems we studied

χEFT currents: a closer look

$A = 7$ Captures

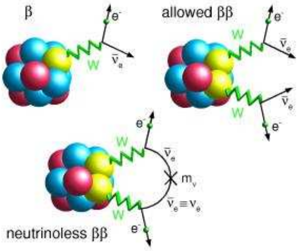
	gs	ex
LO	2.334	2.150
N2LO	-3.18×10^{-2}	-2.79×10^{-2}
N3LO(OPE)	-2.99×10^{-2}	-2.44×10^{-2}
N3LO(CT)	2.79×10^{-1}	2.36×10^{-1}
N4LO(2b)	-1.61×10^{-1}	-1.33×10^{-1}
N4LO(3b)	-6.59×10^{-3}	-4.86×10^{-3}
TOT(2b+3b)	0.050	0.046

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

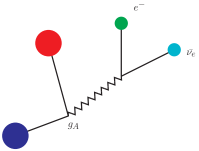
In preparation

$\beta\beta-$decay

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



Berna U.

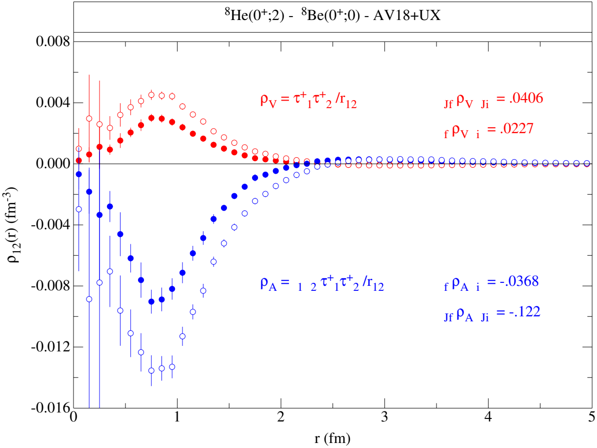


g_A nucleon axial
coupling constant

Preliminary results

Double beta-decay m.e.'s: Correlations

Preliminary



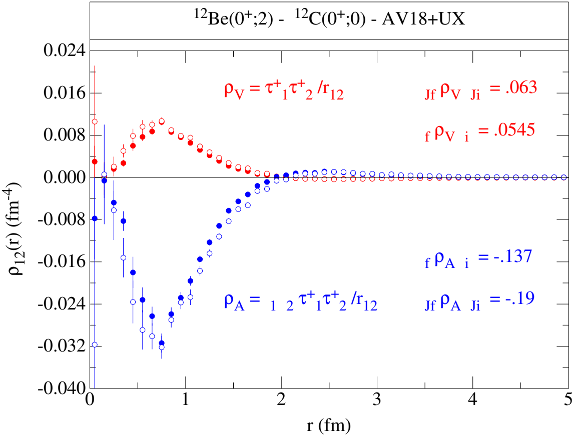
* $< \rho_V >_{\text{corr}} \sim 0.56 < \rho_V >_{\text{uncorr}}$, $q_V = 0.75$

* $< \rho_A >_{\text{corr}} \sim 0.30 < \rho_A >_{\text{uncorr}}$, $q_A = 0.55$

Bob Wiringa *et al.*

Double beta-decay m.e.'s: Correlations

Preliminary

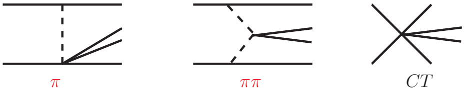


$* < \rho_V >_{\mathrm{corr}} \sim 0.86 < \rho_V >_{\mathrm{uncorr}}$, $\quad q_V = 0.93$

$* < \rho_A >_{\mathrm{corr}} \sim 0.72 < \rho_A >_{\mathrm{uncorr}}$, $\quad q_A = 0.85$

Bob Wiringa *et al.*

Double beta-decay m.e.'s: Two-body currents



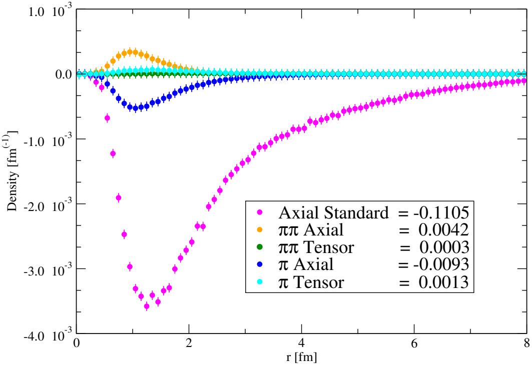
$$
\begin{aligned}
v_{\mathrm{st}} &= L_{\mathrm{st}}\, \tau_{1,+}\, \tau_{2,+} \frac{\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2}{m_\pi\, \mathbf{q}^2} \\
v_{\pi\pi} &= L_{\pi\pi}\, \tau_{1,+}\, \tau_{2,+} \frac{\boldsymbol{\sigma}_1 \cdot \mathbf{q}\, \boldsymbol{\sigma}_2 \cdot \mathbf{q}}{m_\pi\, (\mathbf{q}^2 + m_\pi^2)^2} \\
v_{\pi} &= L_{\pi}\, \tau_{1,+}\, \tau_{2,+} \frac{\boldsymbol{\sigma}_1 \cdot \mathbf{q}\, \boldsymbol{\sigma}_2 \cdot \mathbf{q}}{m_\pi^3\, (\mathbf{q}^2 + m_\pi^2)} \\
v_{\mathrm{CT}} &= L_{\mathrm{CT}}\, \tau_{1,+}\, \tau_{2,+} \frac{\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2}{m_\pi^3}
\end{aligned}
$$

$L_{\pi\pi}$, L_π, L_{CT} are model dependent

WITH

Emanuele Mereghetti & Dekens & Cirigliano & Graesser & Wiringa *et al.*

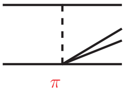
Double beta-decay m.e.'s in ^{6}He$(0^+;2) \to {}^6$Be$(0^+;0)$: A test case I

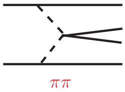


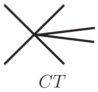
$$\text{Axial} \quad \propto \quad \tau_1^+ \tau_2^+ \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$$

$$\text{Tensor} \quad \propto \quad \tau_1^+ \tau_2^+ S_{12}$$

* Preliminary *



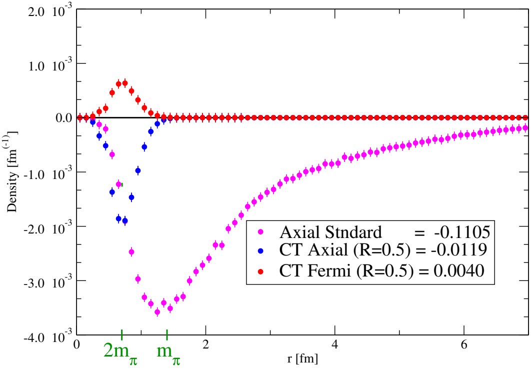




WITH

Emanuele Mereghetti & Dekens & Cirigliano & Graesser & Wiringa *et al.*

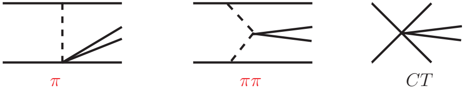
Double beta-decay m.e.'s in ^{6}He(0$^+$;2) → ^{6}Be(0$^+$;0): A test case I



$$\begin{aligned} \text{Axial} &\propto \tau_1^+\tau_2^+\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2 \\ \text{Tensor} &\propto \tau_1^+\tau_2^+ S_{12} \end{aligned}$$

$$C(r) = \frac{e^{-(r/R)^2}}{(\pi)^{3/2} R^3}$$

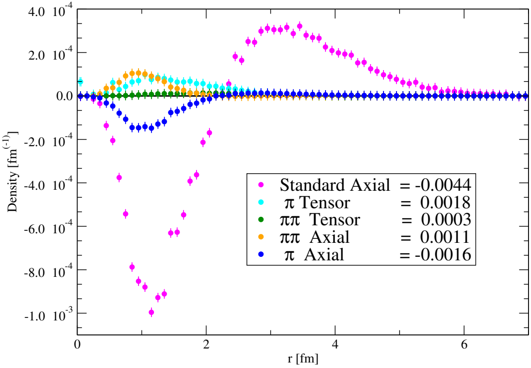
* Preliminary *



WITH

Emanuele Mereghetti & Dekens & Cirigliano & Graesser & Wiringa *et al.*

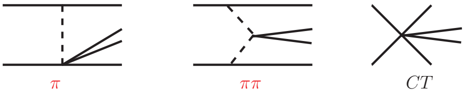
Double beta-decay m.e.'s in ^{8}He(0$^+$;2) → ^{8}Be(0$^+$;0): A test case II



$$\text{Axial} \quad \propto \quad \tau_1^+ \tau_2^+ \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$$

$$\text{Tensor} \quad \propto \quad \tau_1^+ \tau_2^+ S_{12}$$

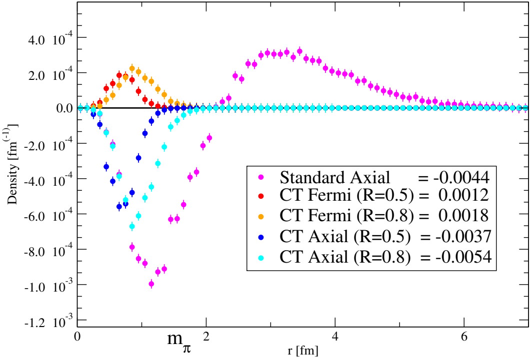
* Preliminary *



WITH

Emanuele Mereghetti & Dekens & Cirigliano & Graesser & Wiringa *et al.*

Double beta-decay m.e.'s in ^{8}He(0^+;2) → ^{8}Be(0^+;0): A test case II

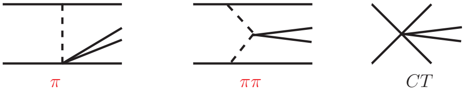


$$\text{Axial} \propto \tau_1^+ \tau_2^+ \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$$

$$\text{Tensor} \propto \tau_1^+ \tau_2^+ S_{12}$$

$$C(r) = \frac{e^{-(r/R)^2}}{(\pi)^{3/2} R^3}$$

* Preliminary *



WITH

Emanuele Mereghetti & Dekens & Cirigliano & Graesser & Wiringa *et al.*

Summary and Outlook

We discussed the role played by correlations and many-body currents in β- and $\upsilon 0\beta\beta$-decay m.e.'s of $A \leq 12$ nuclei

- * Two-body currents (both SNPA and χEFT) provide negligible quenching in the β-decay m.e.'s we studied
- * Correlations provide a quenching q ~ 0.95 in $A = 3$ and q ~ 0.76 in $A = 10$ β-decay m.e.'s
- * Correlations affect $\upsilon 0\beta\beta$-decay m.e.'s leading to a quenching q ~ 0.55 in Standard Axial $A = 8$ and q ~ 0.93 in Standard Fermi $A = 12$
- * A cancellation in the Axial Standard two-body current in $A = 8$ $\upsilon 0\beta\beta$-decay m.e.'s could enhance contributions from Non-Standard two-body currents

Outlook

- * Benchmark both single- and double-beta decay m.e.'s
- * Characterize two-body currents entering double-beta decay m.e.'s
- * Calculate more single- and double-beta decay m.e.'s and study model dependence using AV18+IL7 and Δ-full chiral potential by Piarulli *et al.*