$g_A$ Quenching Information from Neutrino Scattering

Saori Pastore
νEclipse Workshop
Knoxville, TN, August 2017

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
Electroweak Reactions

* $\omega \sim 10^2$ MeV: Accelerator neutrinos
* $\omega \sim 10^0$ MeV: EM decay, $\beta$-decay
* $\omega \lesssim 10^1$ MeV: Astrophysical $\nu$’s, Stopped-$\pi$’s expt
\( \omega \sim \text{MeV: single } \beta \text{ decay} \)

\[ g_{A}^{\text{eff}} \approx 0.70 \ g_{A} \]

quenching required to bring theory in agreement with expt

Rates \( \propto g_{A}^{2} \)

Fig. from Chou et al. PRC47(1993)163
Neutrinoless Double Beta Decay

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

$\rightarrow$

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

$\rightarrow$

implications in

matter-antimatter imbalance

* detectors’ active material $^{76}\text{Ge}$ *

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

1 ton of material to see (if any) $\sim 5$ decays per year

* also, if nuclear m.e.’s are known, absolute $\nu$-masses can be extracted *

Rates $\propto g_A^4$

2015 Long Range Plane for Nuclear Physics
Neutrinoless Double Beta Decay

J. Engels & J. Menendez - Rep. on Prog. in Physics 80(2017)046301
Neutrinoless Double Beta Decay

* $\beta$ decay energy and momentum are set by the Q-value $\sim$ MeV

* $0\nu\beta\beta$ decay the scales is set by the interparticle distance of the two decay nucleon $\sim$ 100 MeV

\[
GT \propto \sigma_1 \cdot \sigma_2 \tau_1^+ \tau_2^+ / r_{12}
\]
$g_A$ Quenching from Neutrino Scattering

* Does the $g_A$ problem persist at moderate momenta?
* How does the $g_A$-quenching affect $0\nu\beta\beta$-decay matrix elements?

* Data at moderate momenta from $\nu$-scattering very valuable
* LSND (stopped pions) data available on $^{12}C$; $C(\nu_e, e^-)N$, $C(\nu_\mu, \mu^-)N$
Nuclear Physics

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

⇒

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

http://www.cpepweb.org

http://www.cpepweb.org
Nuclear Interactions

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

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

where \( v_{ij} \) and \( V_{ijk} \) are two- and three-nucleon operators based on EXPT data fitting and fitted parameters subsume underlying QCD.

* 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

(\( \pi N \Delta \)) by Maria Piarulli et al.
PRC91(2015)024003
Energy Spectrum and Shape of Nuclei

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

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

Lovato et al. PRL111(2013)092501
Nuclear Currents

1b

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

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

* In Impulse Approximation IA nuclear currents are expressed in terms of those associated with individual protons and nucleons, \( \rho_i \) and \( \mathbf{j}_i \), 1b-operators

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

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

* Villars, Myiazawa, Chemtob, Riska, Schiavilla, Marcucci, …
Electromagnetic Currents from Chiral Effective Field Theory

\[ \text{LO} : j^{(-2)} \sim eQ^{-2} \]

\[ \text{NLO} : j^{(-1)} \sim eQ^{-1} \]

\[ \text{N^2LO} : j^{(-0)} \sim eQ^0 \]

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

\[ \text{N^3LO} : j^{(1)} \sim eQ \]

unknown LEC's


* analogue expansion exists for the Axial nuclear current - Baroni et al. PRC93 (2016)015501 *
Magnetic Moments and M1 Transitions

EXPT

GFMC(1b)
GFMC(1b+2b)

\( \omega \sim \text{MeV}: \text{single } \beta \text{ decay} \)

\[ g_{A}^{\text{eff}} \simeq 0.70 g_{A} \]

\textbf{quenching} required to bring theory in agreement with expt

We use \( g_{A} = 1.2723 \) from PDG

Fig. from Chou et al. \textit{PRC47(1993)163}
Single beta decay in $A \leq 10$ Nuclei

$g_A = 1.2723$ from PDG

in preparation

* Two-body currents are found to provide a small (negligible) contribution
  * Significant reduction from correlations
  * no quenching required - limited to the light systems we studied
Single beta decay in $A \leq 10$ Nuclei

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in preparation

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

\begin{eqnarray*}
\text{Axial} & \propto & \tau_1^+ \tau_2^+ \sigma_1 \cdot \sigma_2 \\
\text{Tensor} & \propto & \tau_1^+ \tau_2^+ S_{12}
\end{eqnarray*}

\textbf{WITH}

Emanuele Mereghetti & Dekens & Cirigliano & Graesser & Wiringa \textit{et al.}

* Preliminary *
Summary and Outlook

We discussed the role played by correlations and many-body currents in $\beta$- and $\nu0\beta\beta$-decay m.e.’s of $A \leq 10$ nuclei

* Two-body currents provide negligible quenching in the $\beta$-decay m.e.’s we studied
* Large reduction from correlations found in $\beta$-decay m.e.’s
* $\nu0\beta\beta$-decay involves different energy scale, $g_A$-quenching likely to be different
* Data very valuable at moderate momenta
* GFMC calculations computationally limited to $A = 12$ (data on C valuable)
* AFDMC pushing microscopic picture to $A \sim 40$ (data on O, Ca, LAr valuable)

Outlook

* Understand quantitatively and qualitatively $g_A$ quenching
* Benchmark both single- and double-beta decay m.e.’s
* Characterize two-body currents entering double-beta decay m.e.’s
Outlook
Fundamental Physics with Electroweak Probes of Light Nuclei
June 12 - July 13, 2018
S. Bacca, R. J. Hill, S. Pastore, D. Phillips

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$\omega \sim \text{GeV}$: Accelerator Neutrinos

neutrinos oscillate

$\rightarrow$

they have tiny masses

$=\ 	ext{BSM physics}$

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 *

$\nu$-mass hierarchy, CP-violation, accurate mixing angles

DUNE, MiniBoone, T2K, Minerva ... active material *$^{12}C$, $^{40}Ar$, $^{16}O$, $^{56}Fe$, ...*
$\omega \sim \text{GeV}: \text{Dark Matter Direct Detection}$

Dark Matter Beam Production and Direct detection:

$$\chi + A \rightarrow \chi + A$$

Dark Matter is detected via scattering on nuclei in the detector

Detection of Sub-GeV Dark Matter requires knowledge of nuclear responses

A. A. Aguilar-Arevalo et al. arXiv:1211.2258
Three-body Axial Currents from $\chi$EFT

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 $\Delta$-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 $\Delta$-current

Chemtob, Rho, Towner, Riska, Schiavilla, Marcucci . . .

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

\[ \delta^{N3LO} = \max \left[ Q^4 |\mu^{LO} - \mu^{NLO}|, Q^3 |\mu^{LO} - \mu^{NLO}|, \right. \]
\[ \left. Q^2 |\mu^{NLO} - \mu^{N2LO}|, Q^1 |\mu^{N2LO} - \mu^{N3LO}| \right] \]
\[ Q = \max \left[ \frac{m_\pi}{\Lambda}, \frac{p}{\Lambda} \right] \]

<table>
<thead>
<tr>
<th>m.m.</th>
<th>THEO</th>
<th>EXP</th>
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<tbody>
<tr>
<td>(^9\text{C})</td>
<td>-1.35(4)(7)</td>
<td>-1.3914(5)</td>
</tr>
<tr>
<td>(^9\text{Li})</td>
<td>3.36(4)(8)</td>
<td>3.4391(6)</td>
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* ‘N3LO-\(\Delta\)’ corrections can be ’large’ *

* SNPA and \(\chi\)EFT currents qualitatively in agreement, \(\chi\)EFT isoscalar currents provide better description exp data *

Pastore et al. PRC87(2013)035503
χEFT currents: a closer look

$A = 7$ Captures

<table>
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<th></th>
<th>gs</th>
<th>ex</th>
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<tr>
<td>LO</td>
<td>2.334</td>
<td>2.150</td>
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<tr>
<td>N2LO</td>
<td>$-3.18 \times 10^{-2}$</td>
<td>$-2.79 \times 10^{-2}$</td>
</tr>
<tr>
<td>N3LO(OPE)</td>
<td>$-2.99 \times 10^{-2}$</td>
<td>$-2.44 \times 10^{-2}$</td>
</tr>
<tr>
<td>N3LO(CT)</td>
<td>$2.79 \times 10^{-1}$</td>
<td>$2.36 \times 10^{-1}$</td>
</tr>
<tr>
<td>N4LO(2b)</td>
<td>$-1.61 \times 10^{-1}$</td>
<td>$-1.33 \times 10^{-1}$</td>
</tr>
<tr>
<td>N4LO(3b)</td>
<td>$-6.59 \times 10^{-3}$</td>
<td>$-4.86 \times 10^{-3}$</td>
</tr>
<tr>
<td>TOT(2b+3b)</td>
<td>0.050</td>
<td>0.046</td>
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</table>

* 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 $\beta$-decay

![Graph showing cumulative m.e. / EXP vs. Cutoff MeV for different theoretical contributions.]

* $\sim 2\%$ 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. *PRC*89(2014)024305


Nuclear properties are strongly affected by two-nucleon interactions!
Electromagnetic Currents from Nuclear Interactions (SNPA currents)

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

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

\[ \mathbf{j} = \mathbf{j}^{(1)} \]

\[ + \mathbf{j}^{(2)}(\nu) + \]

\[ + \mathbf{j}^{(3)}(V) \]

Villars, Myiazawa (40-ies), Chemtob, Riska, Schiavilla . . .
see, e.g., Marcucci et al. PRC72(2005)014001 and references therein
Currents from nuclear interactions

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

$^2\text{H}(p,\gamma)^3\text{He}$ capture

Marcucci et al. PRC72, 014001 (2005)
$0\nu\beta\beta$ – decay

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

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

*Preliminary*

![Graph showing double beta-decay m.e.'s](image)

- $\rho_V = \tau^+_1 \tau^+_2 / r_{12}$
- $f \rho_V \ j_i = .063$
- $f \rho_V \ j_i = .0545$
- $\rho_A = 1 \ 2 \ \tau^+_1 \tau^+_2 / r_{12}$
- $f \rho_A \ j_i = -.137$
- $f \rho_A \ j_i = -.19$

* $\frac{<\rho_V>_{corr}}{<\rho_V>_{uncorr}} \sim 0.86$  
* $\frac{<\rho_A>_{corr}}{<\rho_A>_{uncorr}} \sim 0.72$
Magnetic Moments in $A \leq 10$ Nuclei - bis

Predictions for $A > 3$ nuclei

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

- $^9\text{C} (^9\text{Li})$ dominant spatial symmetry $[s.s.] = [432] = [\alpha, ^3\text{He} (^3\text{H}), pp(nn)] \rightarrow$ Large MEC
- $^9\text{Be} (^9\text{B})$ 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.


- **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 $\Delta$-resonances in ‘MEC’ (EM current consistent with the chiral ‘$\Delta$-full’ NN potential developed by M. Piarulli et al. PRC91(2015)024003)
  - Fully consistent $\chi$EFT 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: \(d^S, d_1^V, d_2^V\) could be determined by pion photo-production data on the nucleon

\(d_2^V\) and \(d_1^V\) are known assuming \(\Delta\)-resonance saturation

Left with 3 LECs: Fixed in the \(A = 2 - 3\) nucleons’ sector

- Isoscalar sector:
  * \(d^S\) and \(c^S\) from EXPT \(\mu_d\) and \(\mu_S(3H/3He)\)

- Isovector sector:
  * model I = \(c^V\) from EXPT \(npd\gamma\) xsec.
  * model II = \(c^V\) from EXPT \(\mu_V(3H/3He)\) m.m. ← our choice

Note that:

χEFT operators have a power law behavior → introduce a regulator to kill divergencies at large \(Q\), e.g.,

\[
C_\Lambda = e^{-\left(\frac{Q}{\Lambda}\right)^n},
\]
...and also, pick \(n\) large enough so as to not generate spurious contributions

\[
C_\Lambda \sim 1 - \left(\frac{Q}{\Lambda}\right)^n + ...
\]
Predictions with $\chi$EFT EM currents for $A = 2–3$ systems

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

- $np$ xsec. and $\mu_V(3H/3He)$ 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