Weak processes in light nuclei

Saori Pastore
Topical Collaboration Meeting
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Washington University in St. Louis
Arts & Sciences

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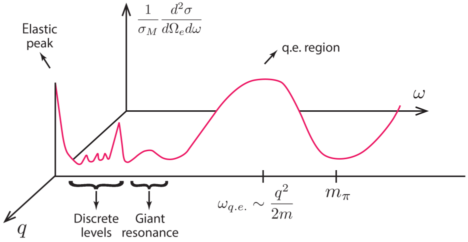
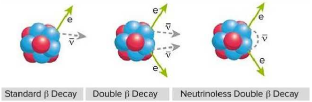
Mereghetti & Dekens & Cirigliano & Graesser (LANL)
de Vries (UMass-Amherst)   van Kolck (AU+CNRS/IN2P3)

Resources: DOE-ALCC 0.39 MNH for “Low Energy Neutrino-Nucleus Interactions”, SP *et al.* 2019

Towards a coherent and unified picture of lepton-nucleus interactions

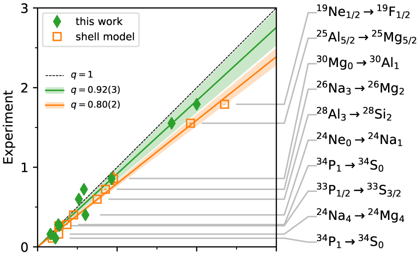


* $\omega \sim$ few MeV, $q \sim 0$: EM-decay, β-decay, $\beta\beta$-decay
* $\omega \sim$ few MeV, $q \sim 10^2$ MeV: μ-capture, Neutrinoless $\beta\beta$-decay
* $\omega \lesssim$ tens MeV: Nuclear Rates for Astrophysics
* $\omega \sim 10^2$ MeV: Accelerator neutrinos, e- and ν-nucleus scattering



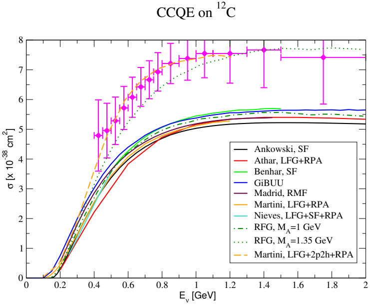
Neutrinos and Nuclei: Challenges and Opportunities

Beta Decay Rate



Gysbers *et al.* Nature Phys.15(2019)

Neutrino-Nucleus Scattering



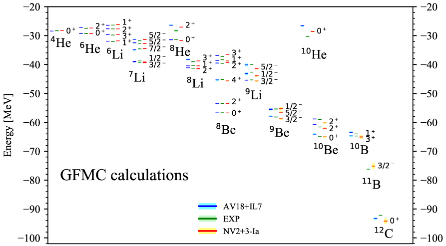
Alvarez-Ruso arXiv:1012.3871

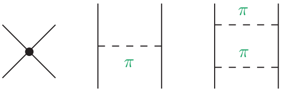
Nuclear Interactions

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





* QMC: AV18+UIX / AV18+IL7
Wiringa+Schiavilla+Pieper et al.

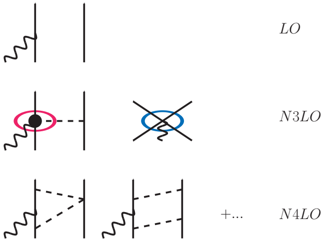
* QMC: NN(N3LO)+3N(N2LO) (π&N&Δ)
Piarulli et al. - Norfolk Potential NV2+3

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

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)



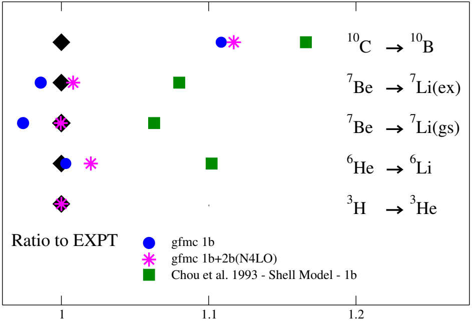
A. Baroni *et al.* PRC93(2016)015501

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 at tree-level in many calculations (Song-Ho, Kubodera, Gazit,Marcucci, Lazauskas, Navratil ...)
* pion-pole at tree-level derived
by Klos, Hoferichter *et al.* PLB(2015)B746

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



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

SP *et al.* PRC97(2018)022501

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

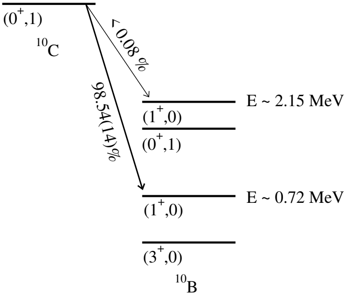
Based on $g_A \sim 1.27$ no quenching factor

GT in ^{3}H is fitted to expt - 2b give a 2% additive contribution to 1b prediction

* similar results were obtained with MEC currents

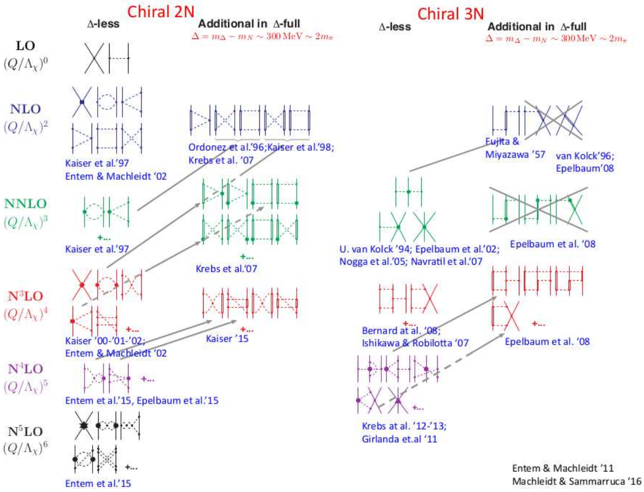
$\ast$ data from TUNL, Suzuki *et al.* PRC67(2003)044302, Chou *et al.* PRC47(1993)163

^{10}B



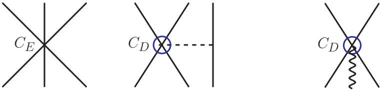
* In ^{10}B, ΔE with same quantum numbers ~ 1.5 MeV
* In $A = 7$, ΔE with same quantum numbers $\gtrsim 10$ MeV

Chiral calculations of beta decay m.e.'s: Nuclear Interaction



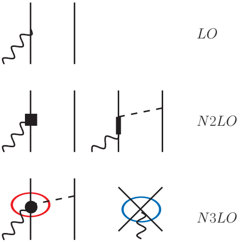
courtesy of M. Piarulli

Nuclear Interactions and Axial Currents



we use

Norfolk chiral 2– and 3–body interactions by Piarulli *et al.* and consistent axial currents up to N3LO (tree-level) by A. Baroni *et al.*



* c_3 and c_4 are taken them from Krebs *et al.* Eur.Phys.J.(2007)A32

* (c_D,c_E) fitted to:

1. trinucleon B.E. and *nd* doublet scattering length **NV2+3 models**

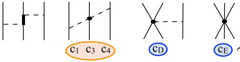
   or

2. trinucleon B.E. and GT m.e. of tritium **NV2+3* models**

Fitting Strategies for (c_D, c_E)

Local chiral 3N potential with Δ's

Inclusion of 3N forces at N2LO:



$\sim \tau_i \cdot \tau_j$

1) Fit to:

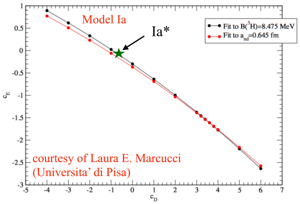
- $E_0(^3\mathrm{H}) = -8.482$ MeV
- $^2a_{nd} = (0.645 \pm 0.010)$ fm

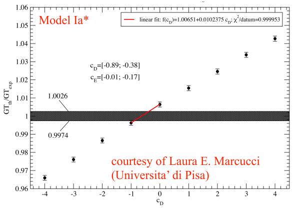
Model	c_D	c_E
Ia	3.666	−1.638
Ib	−2.061	−0.982
IIa	1.278	−1.029
IIb	−4.480	−0.412

2) Fit to:

- $E_0(^3\mathrm{H}) = -8.482$ MeV
- GT m.e. in ^{3}H β-decay

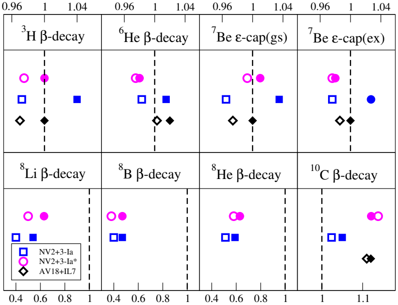
Model	c_D	c_E
Ia*	−0.635(255)	−0.09(8)
Ib*	−4.705(285)	0.550(150)
IIa*	−0.610(280)	−0.350(100)
IIb*	−5.250(310)	0.05(180)





Courtesy of M. Piarulli and the Pisa-group

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



NV2+3-Ia and NV2+3-Ia*; AV18+IL7 from SP *et al.* PRC97(2018)022501

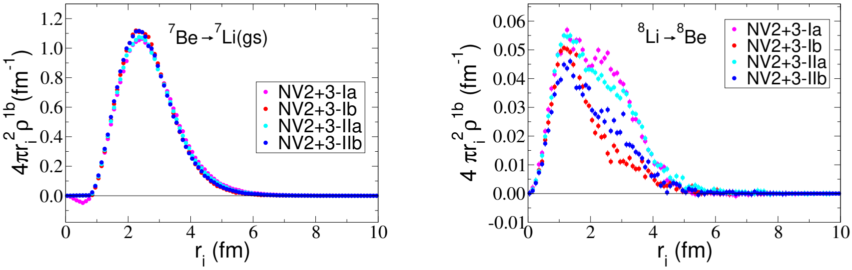
1b (empty symbols) and 2b (full symbols) GFMC predictions

King *et al.* arXiv:2004.05263

* similar results were obtained with MEC currents

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

Single Beta Decay Matrix Element Densities in chiEFT



King *et al.* arXiv:2004.05263

Some Numbers

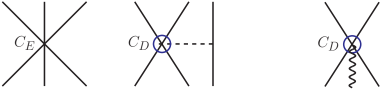
	NV2+3-Ia	NV2+3-Ia*
c_D	3.666	-0.635
c_E	-1.638	-0.090
z_0	0.090	1.035

Contact current

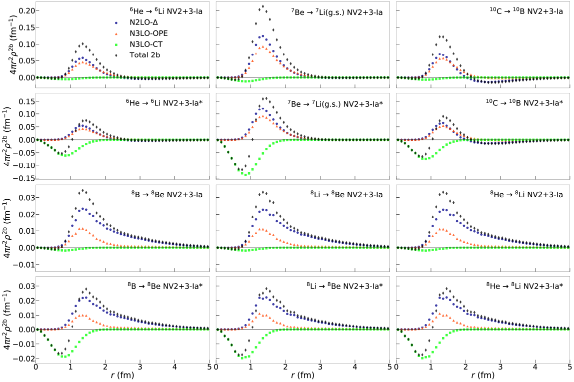
$$\mathbf{j}_{5,a}^{\mathrm{N3LO}}(\mathbf{q};\mathrm{CT}) = z_0\, \mathrm{e}^{i\,\mathbf{q}\cdot\mathbf{R}_{ij}}\, \frac{\mathrm{e}^{-\tilde{r}_{ij}^2}}{\pi^{3/2}}\, \left(\boldsymbol{\tau}_i \times \boldsymbol{\tau}_j\right)_a \left(\boldsymbol{\sigma}_i \times \boldsymbol{\sigma}_j\right) \ ,$$

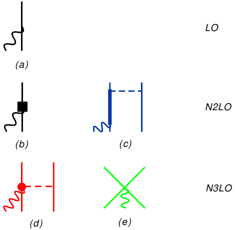
and LECs

$$z_0 \quad = \quad \frac{g_A}{2}\,\frac{m_\pi^2}{f_\pi^2}\,\frac{1}{(m_\pi R_{\rm S})^3}\left[-\frac{m_\pi}{4\,g_A\,\Lambda_\chi}\,c_D + \frac{m_\pi}{3}\,(c_3 + 2\,c_4) + \frac{m_\pi}{6\,m}\right] ,$$



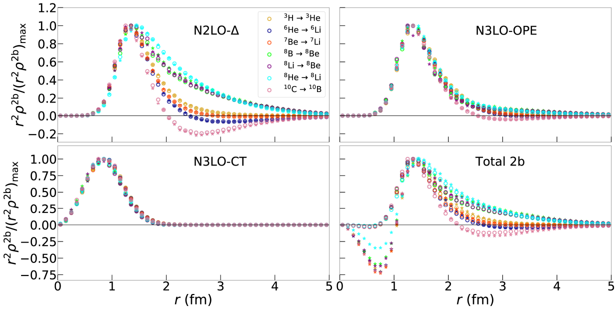
Two-body transition densities: $A = 3 - 10$





King *et al.* arXiv:2004.05263

Two-body transition densities: Scaling

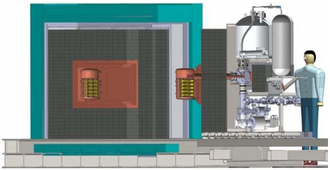


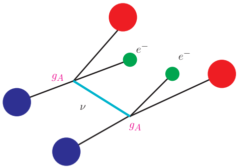
NV2+3-Ia empty circles – NV2+3-Ia* stars

different colors refer to different transitions

King *et al.* arXiv:2004.05263

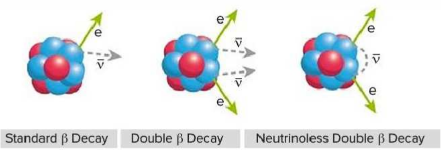
Neutrinoless Double Beta Decay



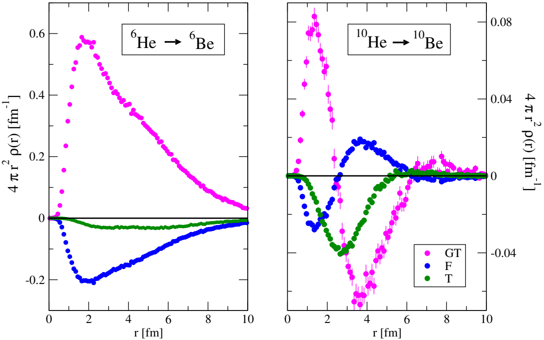


"The average momentum is about 100 MeV, a scale set by the average distance between the two decaying neutrons" cit. Engel&Menéndez

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



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)

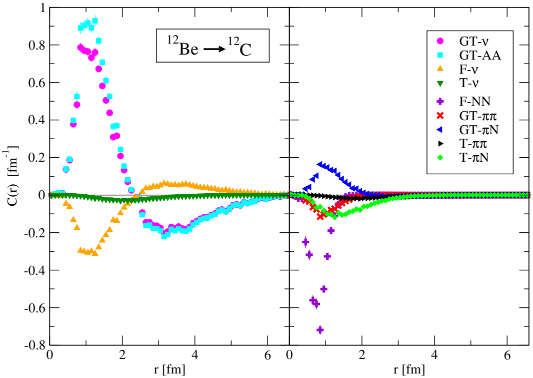
* $\Delta T = 2$

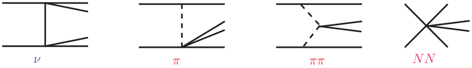
^{8}He(1)→^{8}Be(0)
^{10}He(3)→^{10}Be(1)
^{12}Be(2)→^{12}C(0)

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

SP *et al.* PRC97(2018)014606

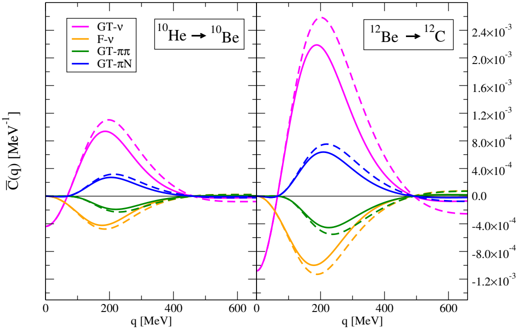
Double beta-decay Matrix Elements





SP *et al.* PRC97(2018)014606

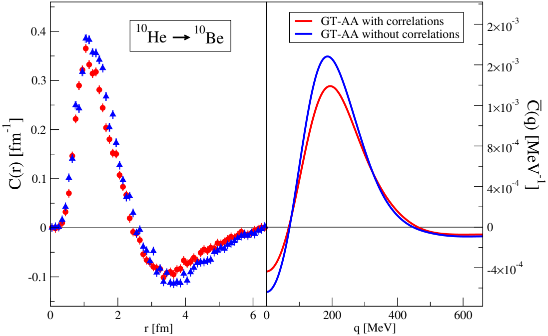
Momentum Dependence and Sensitivity to N2LO effects
i.e., 'dipole' nucleonic form factors and $\upsilon_\nu^{\mathrm{N2LO-loop}}$



- * 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

SP *et al.* 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

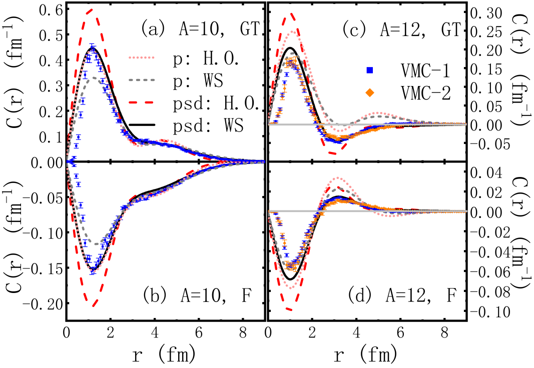
* Correlations reduce the m.e.’s (also true for μ’s and GT’s) *

SP *et al.* PRC97(2018)014606

Benchmark with Shell Model

Model dependence

size's space *p* vs *psd* & H.O. vs W.S. wave functions



X. Wang *et al.* Phys. Lett. B 798 (2019) 134974

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

* We validate the computational framework vs electromagnetic data
* 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 υ-A scattering in $A > 12$ nuclei is in excellent agreement with exact calculations and data

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