Nuclear spectra and weak response: a status report

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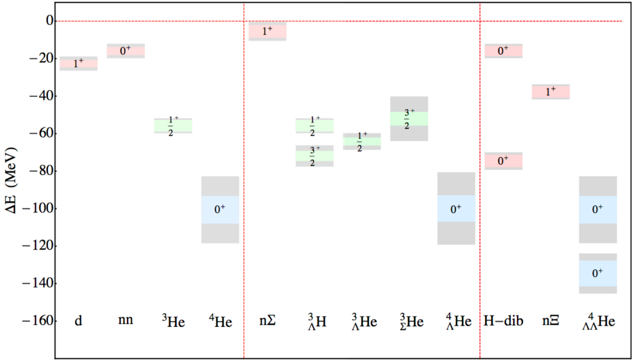
Few-nucleon systems from LQCD

Beane *et al.* (2013); Chang *et al.* (2015); Savage *et al.* (2017)

- NPLQCD spectra calculations ($m_\pi = 806$ MeV)

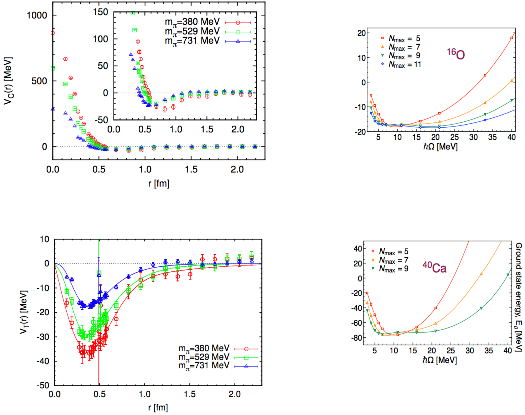


- NPLQCD calculations of magnetic moments and weak transitions in few-nucleon systems also available

$2N$ potential from LQCD and nuclear spectra

Aoki *et al.* (2012); McIlroy *et al.* (2017)

- LQCD calculation of $2N$ potential by HAL collaboration



Outline

- The basic model of nuclear theory
- Chiral $2N$ and $3N$ potentials, nuclear spectra, and neutron matter EOS
- Electroweak currents and (mostly weak) transitions
- Outlook:
  - *Going beyond LO in the $3N$ potentials*
  - *Weak transitions with NV2+3 potential models*

The basic model

- Effective potentials:

$$H = \sum_{i=1}^{A} \frac{\mathbf{p}_i^2}{2\,m_i} + \sum_{i<j=1}^{A} \underbrace{v_{ij}}_{\text{th+exp}} + \sum_{i<j<k=1}^{A} \overbrace{V_{ijk}}^{\text{th+exp}} + \cdots$$

- Assumptions:
  - *Quarks in nuclei are in color singlet states close to those of N's (and low-lying excitations: Δ's, ...)*
  - *Series of potentials converges rapidly*
  - *Dominant terms in v_{ij} and V_{ijk} are due to π exchange*

$$\text{leading } \pi N \text{ coupling} = \frac{g_A}{2\,f_\pi} \tau_a\, \boldsymbol{\sigma} \cdot \boldsymbol{\nabla}\phi_a(\mathbf{r})$$

- Effective electroweak currents:

$$j^{EW} = \sum_{i=1}^{A} j_i + \sum_{i<j=1}^{A} j_{ij} + \sum_{i<j<k=1}^{A} j_{ijk} + \cdots$$

Earlier developers of the basic model . . .

Day 1–2 in the 1977 workshop

WORKSHOP ON NUCLEAR AND DENSE MATTER

May 3 - 6, 1977, Urbana, IL

PROGRAM

Tuesday, May 3

9:00 - 9:30	Registration and Coffee (South Lounge, Physics Building)
9:30 - 10:20	M. H. Kalos - Monte Carlo Methods in the Quantum Many-Body Problem
10:25 - 11:05	G. V. Chester - Monte Carlo Calculations of Nuclear and Neutron Matter
11:10 - 11:30	C. E. Campbell - Comments on Feenberg-Wu Approximation
11:30 - 1:30	Lunch (Levis Faculty Center - 3rd floor)
1:30 - 2:20	S. Rosati - CLuster Expansion & Chain Summation Techniques for Fermion Systems
2:30 - 2:55	S. Fantoni - Recent Calculations on Fermion Systems
3:05 - 3:30	J. Zabolitzky - Convergence Properties of FHNC Methods
3:30 - 4:00	Coffee (South Lounge)
4:00 - 4:45	K. E. Schmidt - Variational Calculations of Liquid ^{3}He with a Complex f
4:50 - 5:30	R. B. Wiringa - Variational Calculations of Nuclear Matter with Realistic Potentials
6:00 - 8:00	Reception (Center for Advanced Study)

Wednesday, May 4

9:00 - 9:30	Coffee (South Lounge)
9:30 - 10:30	B. D. Day - Numerical Calculation and Tests of the Brueckner-Bethe Method
10:40 - 11:30	Comments: C. Mahaux - Quasi-Particle Energies for Intermediate States S. Köhler - Convergence of the Brueckner-Bethe Method C. W. Wong - Comparison of Brueckner and Jastrow Energies at Three-Body Level
11:30 - 1:30	Lunch (Levis Faculty Center - 3rd floor)
1:30 - 2:20	R. Vinh Mau - The Paris Nucleon-Nucleon Potential
2:30 - 2:55	O. Maxwell - Variational Calculations with the Paris Potential
3:05 - 3:30	P. J. Siemens - Optimal Correlation Function for FHNC
3:30 - 4:00	Coffee (South Lounge)
4:00 - 4:20	G. Ripka - Healing and Pauli Effects in Jastrow Theory of Fermi Systems
4:30 - 5:30	H. A. Bethe - Status of the Nuclear Matter Problem
7:00 - 8:00	Cocktails (Levis Faculty Center - 2nd floor)
8:00 -	Workshop Dinner (Levis Faculty Center - 2nd floor)

Day 3–4 in the 1977 workshop

Thursday, May 5

9:00 - 9:30	Coffee (South Lounge)
9:30 - 10:15	D. Pines - Polarization Potentials and Elementary Excitations
10:25 - 11:10	C. Mahaux - Shell Model Theory of Nuclear Matter
11:15 - 11:45	E. J. Moniz - Isobar Propagation in the Nuclear Medium
11:45 - 1:40	Lunch (Levis Faculty Center - 3rd floor)
1:40 - 2:30	G. E. Brown - Pion Nucleus Many-Body Problem
2:40 - 3:00	L. McLerran - Recent Results of Quark Matter Calculations
3:10 - 3:30	F. Coester - Relativistic Many-Body Theories
3:30 - 4:00	Coffee (South Lounge with Physics Colloquium)
4:00 - 5:00	Physics Colloquium - T. C. Koopmans - Approaches of Different Professions to Common Problems

Friday, May 6

9:00 - 9:20	Coffee (South Lounge)
9:20 - 9:50	C. W. Woo - Variational Calculations of Fermi Systems with a New Integral Equation (tentative)
9:55 - 10:30	E. Krotscheck - Formal Properties and Convergence of FHNC
10:40 - 11:05	R. A. Smith - HNC in Spin-Dependent Systems
11:10 - 11:40	J. Clark - Perturbation Theory with Correlated Basis Functions
12:00	Conclusion

All lectures are in Room 144.

Lounge - Room 118.

χEFT formulation of the basic model

- χEFT is a low-energy approximation of QCD
- Lagrangians describing the interactions of π, N, ... are expanded in powers of Q/Λ_χ ($\Lambda_\chi \sim 1$ GeV)
- Their construction has been codified in a number of papers [1]

$$\mathcal{L} = \mathcal{L}^{(1)}_{\pi N} + \mathcal{L}^{(2)}_{\pi N} + \mathcal{L}^{(3)}_{\pi N} + \dots + \mathcal{L}^{(2)}_{\pi\pi} + \mathcal{L}^{(4)}_{\pi\pi} + \dots$$

- $\mathcal{L}^{(n)}$ also include contact $(\overline{N}N)(\overline{N}N)$-type interactions parametrized by low-energy constants (LECs)
- Initial impetus to the development of χEFT for nuclei in the early nineties [2,3]

[1] Gasser and Leutwyler (1984); Gasser, Sainio, and Švarc (1988); Bernard *et al.* (1992); Fettes *et al.* (2000)

[2] Weinberg (1990)–(1992); [3] Park, Min, and Rho (1993) and (1996)

- Time-ordered perturbation theory (TOPT):

$$\langle f \mid T \mid i \rangle = \langle f \mid H_1 \sum_{n=1}^{\infty} \left(\frac{1}{E_i - H_0 + i\,\eta} H_1 \right)^{n-1} \mid i \rangle$$

- Momentum scaling of contribution

$$\underbrace{\left(\prod_{i=1}^{N} Q^{\alpha_i - \beta_i/2} \right)}_{H_1 \text{ scaling}} \times \underbrace{Q^{-(N-N_K-1)}\, Q^{-2N_K}}_{\text{denominators}} \times \underbrace{Q^{3L}}_{\text{loop integrations}}$$

- Each of the N_K energy denominators involving only nucleons is of order Q^{-2}
- Each of the other $N - N_K - 1$ energy denominators involving also pion energies is expanded as

$$\frac{1}{E_i - E_I - \omega_\pi} = -\frac{1}{\omega_\pi}\left[1 + \frac{E_i - E_I}{\omega_\pi} + \frac{(E_i - E_I)^2}{\omega_\pi^2} + \ldots\right]$$

- Power counting:

$$T = T^{LO} + T^{NLO} + T^{N^2LO} + \ldots\,, \quad \text{and} \quad T^{N^n LO} \sim (Q/\Lambda_\chi)^n\, T^{LO}$$

From amplitudes to potentials

Pastore *et al.* (2009); Pastore *et al.* (2011)

- Construct v such that when inserted in LS equation

$$v + v\, G_0\, v + v\, G_0\, v\, G_0\, v + \dots \qquad G_0 = 1/(E_i - E_I + i\,\eta)$$

leads to T-matrix order by order in the power counting

- Assume

$$v = v^{(0)} + v^{(1)} + v^{(2)} + \dots \qquad v^{(n)} \sim (Q/\Lambda_\chi)^n\, v^{(0)}$$

- Determine $v^{(n)}$ from

$$\begin{aligned} v^{(0)} &= T^{(0)} \\ v^{(1)} &= T^{(1)} - \left[v^{(0)}\, G_0\, v^{(0)} \right] \\ v^{(2)} &= T^{(2)} - \left[v^{(0)}\, G_0\, v^{(0)}\, G_0\, v^{(0)} \right] - \left[v^{(1)}\, G_0\, v^{(0)} + v^{(0)}\, G_0\, v^{(1)} \right] \end{aligned}$$

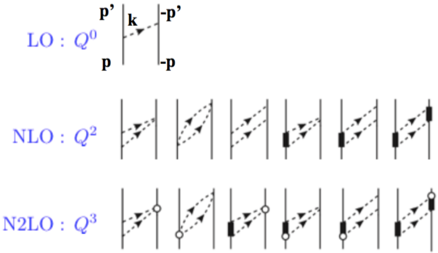
and so on, where

$$v^{(m)}\, G_0\, v^{(n)} \sim (Q/\Lambda_\chi)^{m+n+1}$$

Chiral $2N$ potentials with Δ's

Piarulli *et al.* (2015); Piarulli *et al.* (2016)

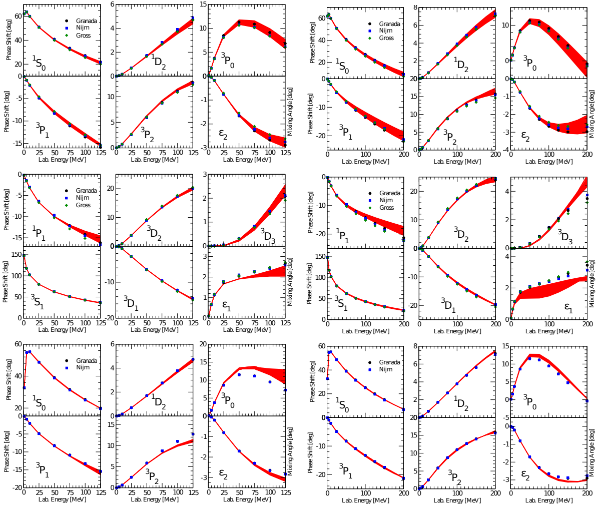
- Two-nucleon potential: $v = v^{\mathrm{EM}} + v^{\mathrm{LR}} + v^{\mathrm{SR}}$
- EM component v^{EM} including corrections up to α^2
- Chiral OPE and TPE component v^{LR} with Δ's



- Short-range contact component v^{SR} up to order Q^4 parametrized by (2+7+11) IC and (2+4) IB LECs
- v^{SR} functional form taken as $C_{R_S}(r) \propto \mathrm{e}^{-(r/R_S)^2}$ with R_S=0.8 (0.7) fm for a (b) models

np ($T = 0$ and 1) and pp phase shifts

Ia-Ib: $E_{\mathrm{lab}} = 125$ MeV IIa-IIb: $E_{\mathrm{lab}} = 200$ MeV



Ab initio methods utilized by our group

- Hyperspherical harmonics (HH) expansions for $A = 3$ and 4 bound and continuum states

$$|\psi_V\rangle = \sum_\mu c_\mu \underbrace{|\phi_\mu\rangle}_{\text{HH basis}} \quad \text{and} \quad c_\mu \;\; \text{from} \;\; E_V = \frac{\langle\psi_V|H|\psi_V\rangle}{\langle\psi_V|\psi_V\rangle}$$

- Quantum Monte Carlo for $A > 4$ bound states

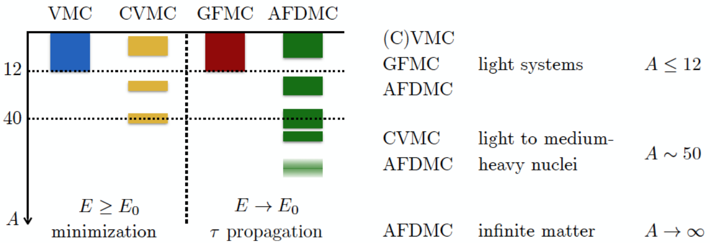
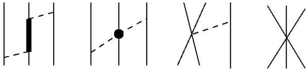


Figure by Lonardoni

Chiral $3N$ potentials with Δ's

Piarulli *et al.* (2018)

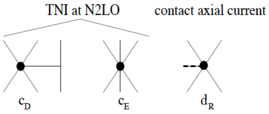
- $3N$ potential up to N2LO[1]:



- c_D and c_E fixed by fitting $E_0^{\rm exp}(^3\text{H}) = -8.482$ MeV and nd doublet scattering length $a_{nd}^{\rm exp} = (0.645 \pm 0.010)$ fm

	without $3N$						with $3N$	
Model	c_D	c_E	$E_0(^3\text{H})$	$E_0(^3\text{He})$	$E_0(^4\text{He})$	$^2a_{nd}$	$E_0(^3\text{He})$	$E_0(^4\text{He})$
Ia	3.666	–1.638	–7.825	–7.083	–25.15	1.085	–7.728	–28.31
Ib	–2.061	–0.982	–7.606	–6.878	–23.99	1.284	–7.730	–28.31
IIa	1.278	–1.029	–7.956	–7.206	–25.80	0.993	–7.723	–28.17
IIb	–4.480	–0.412	–7.874	–7.126	–25.31	1.073	–7.720	–28.17

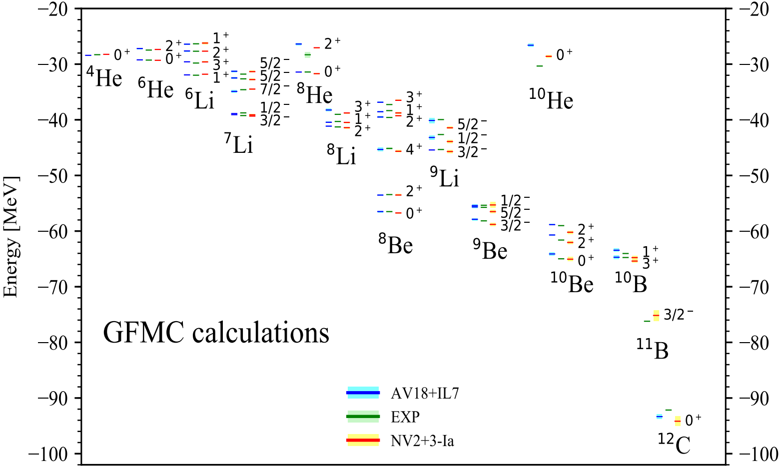
- Alternate strategy: fix c_D and c_E by reproducing $E_0^{\rm exp}(^3\text{H})$ and the GT$^{\rm exp}$ matrix element in ^{3}H β-decay



[1] Epelbaum *et al.* (2002)

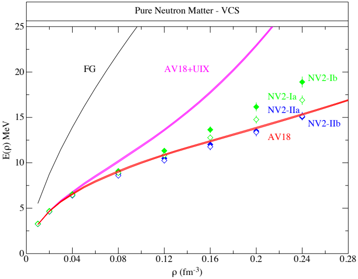
Spectra of light nuclei

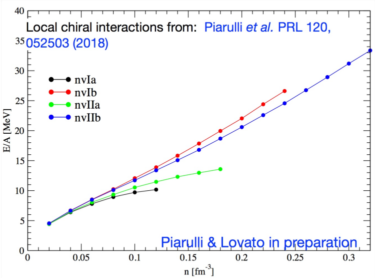
Piarulli *et al.* (2018)

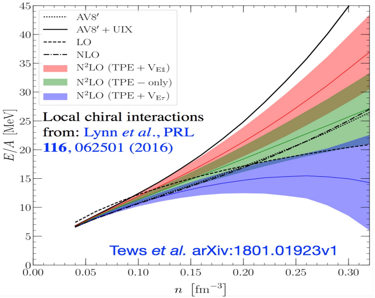


Neutron matter equation of state

Piarulli *et al.*, private communication



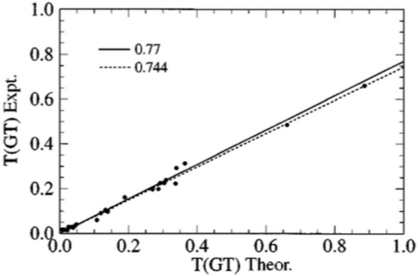




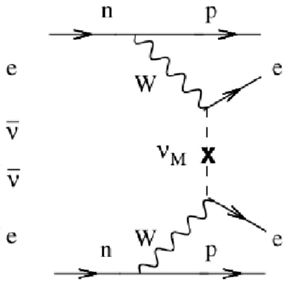
- Sensitivity to $3N$ contact term:
  - $c_E < 0$ repulsive in $A \leq 4$
  - but attractive in PNM
- Cutoff sensitivity:
  - *modest in NV2 models*
  - *large in NV2+3 models*

Nuclear weak interactions at low energies

- Shell model in agreement with exp if $g_A^{\rm eff} \simeq 0.7\, g_A$
- Understanding “quenching” of g_A in nuclear β decays
- Relevant for neutrinoless 2β-decay since rate $\propto\ g_A^4$



Martinez-Pinedo *et al.* (1996)



0ν–2β amplitude

Including electroweak (ew) interactions

Pastore *et al.* (2009,2011); Piarulli *et al.* (2013); Baroni *et al.* (2017)

- Power counting of ew interactions (treated in first order)

$$T_{\rm ew} = T_{\rm ew}^{(-3)} + T_{\rm ew}^{(-2)} + T_{\rm ew}^{(-1)} + \dots \qquad T_{\rm ew}^{(n)} \sim (Q/\Lambda_\chi)^n \, T_{\rm ew}^{(-3)}$$

- For $v_{\rm ew}^{(n)} = A^0 \, \rho_{\rm ew}^{(n)} - \mathbf{A} \cdot \mathbf{j}_{\rm ew}^{(n)}$ to match $T_{\rm ew}$ order by order

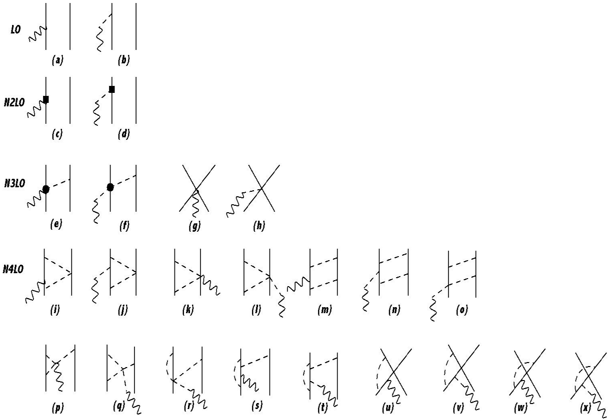
$$\begin{aligned} v_{\rm ew}^{(-3)} &= T_{\rm ew}^{(-3)} \\ v_{\rm ew}^{(-2)} &= T_{\rm ew}^{(-2)} - \left[v_{\rm ew}^{(-3)} \, G_0 \, v^{(0)} + v^{(0)} \, G_0 \, v_{\rm ew}^{(-3)} \right] \\ v_{\rm ew}^{(-1)} &= T_{\rm ew}^{(-1)} - \left[v_{\rm ew}^{(-3)} \, G_0 \, v^{(0)} \, G_0 \, v^{(0)} + \text{permutations} \right] \\ & \quad - \left[v_{\rm ew}^{(-2)} \, G_0 \, v^{(0)} + v^{(0)} \, G_0 \, v_{\rm ew}^{(-2)} \right] \end{aligned}$$

and so on up to $n = 1$

- $\rho_{\rm ew}^{(n)}$ and $\mathbf{j}_{\rm ew}^{(n)}$ (generally) depend on off-the-energy shell prescriptions adopted for $v^{(\leq n)}$ and $v_{\rm ew}^{(\leq n)}$

Nuclear axial currents at one loop

Park *et al.* (1993,2003); Baroni *et al.* (2016); Krebs *et al.* (2017)

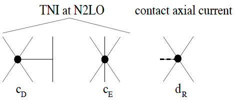


- Some of the contributions—panels (m) and (s)—differ in the Baroni *et al.* and Krebs *et al.* derivations
- 1 unknown LEC in $\mathbf{j}_5$ (4 unknown LECs in ρ_5)

Fitting d_R in the contact axial current

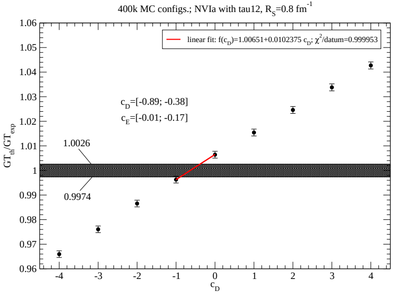
Gardestig and Phillips (2006); Gazit *et al.* (2009)

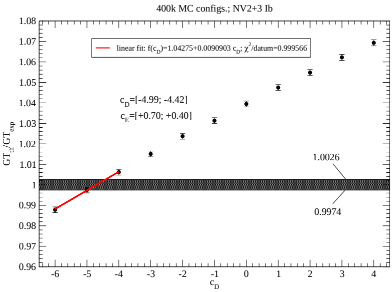
- Correct relation between c_D and d_R



$$d_R = -\frac{m}{4\, g_A\, \Lambda_\chi}\, c_D + \frac{m}{3}\,(c_3 + 2\, c_4) + \frac{1}{6}$$

- Fix c_D via ^{3}H GT m.e. with axial current at N3LO†





† with w.f.'s from either p-space (Entem and Machleidt) or r-space (Piarulli *et al.*) potentials

μ^- capture on ^{2}H and ^{3}He at N3LO

Marcucci *et al.* (2012); Marcucci *et al.* Erratum (2018)

- χEFT predictions with conservative error estimates [1]:

$$\Gamma(^2\mathrm{H}) = (399 \pm 3)\,\mathrm{sec}^{-1} \qquad \Gamma(^3\mathrm{He}) = (1494 \pm 21)\,\mathrm{sec}^{-1}$$

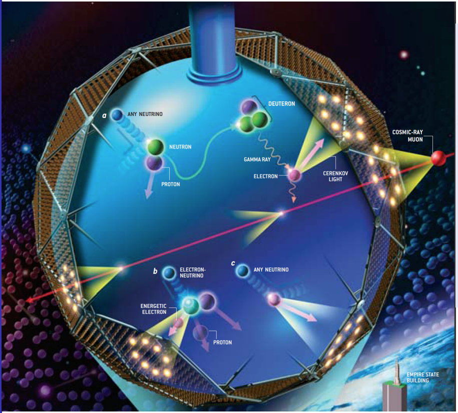
- Errors due primarily to:
  - *experimental error on GT*$^{\mathrm{EXP}}$ *(0.5%)*
  - *uncertainties in EW radiative corrections* [2] *(0.4%)*
  - *cutoff dependence*
- Using $\Gamma^{\mathrm{EXP}}(^3\mathrm{He}) = (1496 \pm 4)$ sec^{-1}, one extracts

$$G_{PS}(q_0^2 = -0.95\, m_\mu^2) = 8.2 \pm 0.7$$

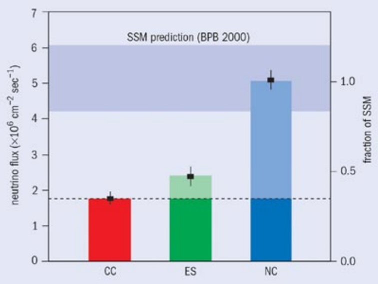
  versus $G_{PS}^{\mathrm{EXP}}(q_0^2 = -0.88\, m_\mu^2) = 8.06 \pm 0.55$ [3] and a χPT prediction of 7.99 ± 0.20 [4]
- Upcoming measurement of $\Gamma(^2\mathrm{H})$ by the MuSun collaboration at PSI with a projected 1% error . . .

[1] Based on Entem and Machleidt potentials; [2] These corrections increase rate by 3%, see Czarnecki *et al.* (2007); [3] From a measurement of $\Gamma^{\mathrm{EXP}}(^1\mathrm{H})$, Andreev *et al.* (2013); [4] Bernard *et al.* (1994), Kaiser (2003)

Low-energy neutrinos



SNO experiment



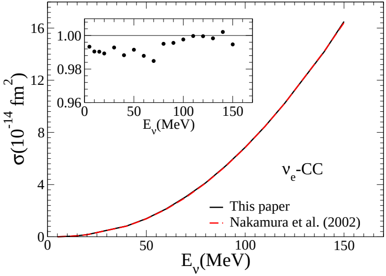
CC from $d + \nu_e \longrightarrow p + p + e^-$

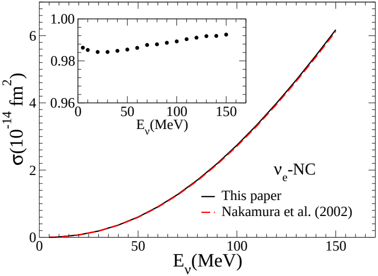
ES from (mostly) $e^- + \nu_e \longrightarrow e^- + \nu_e$

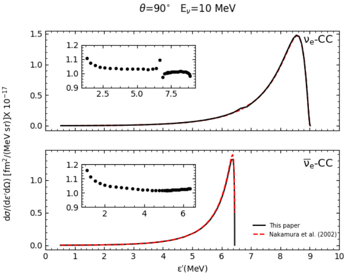
NC from $d + \nu_x \longrightarrow p + n + \nu_x$

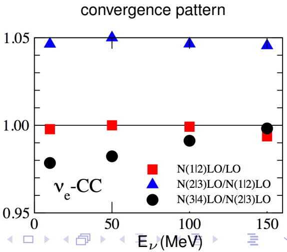
Low-energy inclusive ν-d scattering in χEFT

Baroni and Schiavilla (2017)

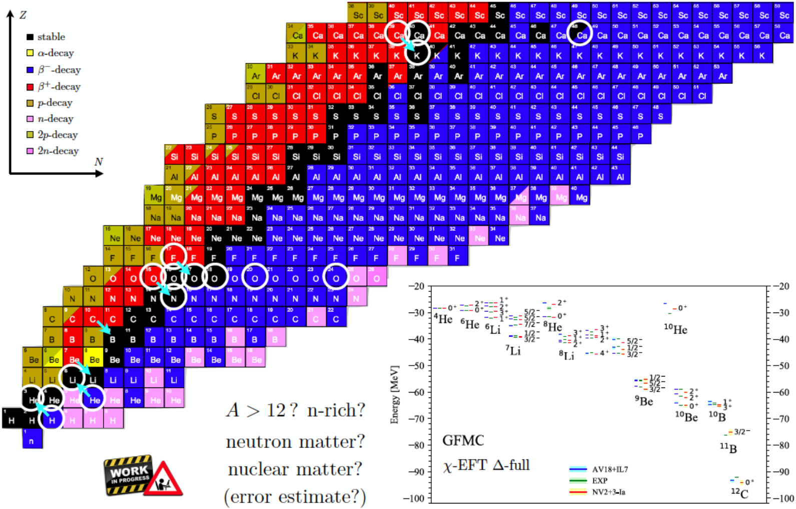








Outlook



$A > 12$? n-rich?

neutron matter?

nuclear matter?

(error estimate?)

M. Piarulli *et al.*, arXiv:1707.02883

Slide by Lonardoni

Subleading contact $3N$ potential

Girlanda *et al.* (2011); Girlanda, private communication

- There are 146 operators with two derivatives ...
- But Fierz identities and relativistic covariance lead to 10 independent operator structures; a possible choice:

$$\sum_{n=1}^{4} V_{ijk}^{(n)} = (E_1 + E_2\, \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j \; + E_3\, \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \; + E_4\, \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j\, \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j) \times \left[C''_{R_S}(r_{ij}) + 2\, \frac{C'_{R_S}(r_{ij})}{r_{ij}} \right] C_{R_S}(r_{jk}) + (j \rightleftharpoons k)$$

$$\sum_{n=5}^{6} V_{ijk}^{(n)} = (E_5 + E_6\, \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j)\, S_{ij} \left[C''_{R_S}(r_{ij}) - \frac{C'_{R_S}(r_{ij})}{r_{ij}} \right] C_{R_S}(r_{jk}) + (j \rightleftharpoons k)$$

$$\sum_{n=7}^{8} V_{ijk}^{(n)} = -2\,(E_7 + E_8\, \boldsymbol{\tau}_j \cdot \boldsymbol{\tau}_k)\, \frac{C'_{R_S}(r_{ij})}{r_{ij}} \left\{ (\mathbf{L} \cdot \mathbf{S})_{ij} \,,\, C_{R_S}(r_{jk}) \right\} + (j \rightleftharpoons k)$$

$$\sum_{n=9}^{10} V_{ijk}^{(n)} = (E_9 + E_{10}\, \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j)\, \boldsymbol{\sigma}_i \cdot \hat{\mathbf{r}}_{ik}\, \boldsymbol{\sigma}_j \cdot \hat{\mathbf{r}}_{jk}\, C'_{R_S}(r_{ik})\, C'_{R_S}(r_{jk}) + (j \rightleftharpoons k)$$

- For consistency $V_{ijk}^{\rm CT2}$ should go along with NN[1] and (multi-pion exchange) $3N$[2] potentials at N4LO ...

[1] Entem *et al.* (2015) and Epelbaum *et al.* (2015); [2] Bernard *et al.* (2008) and (2011)

Projecting in isospin T=1/2 and 3/2 channels

Girlanda, private communication

$$P_{1/2} = \frac{1}{2} - \frac{1}{6}\left(\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j + \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_k + \boldsymbol{\tau}_j \cdot \boldsymbol{\tau}_k\right) \quad \text{and} \quad P_{3/2} = 1 - P_{1/2}$$

- The (single) LO contact term ($\propto c_E$ in standard notation) can be expressed as

$$V^{\rm CT0} = \widetilde{c}_E \, P_{1/2}$$

- The 10 subleading contact terms can be expressed as

$$V^{\rm CT2} = \widetilde{E}_1 \, O_1^{(3/2)} + \sum_{i=2}^{10} \widetilde{E}_i \, O_i^{(1/2)}$$

- There is not much flexibility to constrain the $T = 3/2$ component of the $3N$ contact potential . . .
- But analysis relies on the use of Fierz identities and is valid up to cutoff effects

Reducing the number of subleading LECs

Girlanda, private communication

Implications from large-N_c limit:

- NN contact at LO: C_1, $C_4 \sim N_c$ and C_2, $C_3 \sim 1/N_c$

$$\begin{aligned}\mathcal{L} &= -C_1 N^\dagger N\, N^\dagger N - C_2 N^\dagger \sigma_i N\, N^\dagger \sigma_i N - C_3 N^\dagger \tau_a N\, N^\dagger \tau_a N - C_4 N^\dagger \sigma_i \tau_a N\, N^\dagger \sigma_i \tau_a N \\ &= -\underbrace{(C_1 - 2\,C_3 - 3\,C_4)}_{C_S} N^\dagger N\, N^\dagger N - \underbrace{(C_2 - C_3)}_{C_T} N^\dagger \sigma_i N\, N^\dagger \sigma_i N\end{aligned}$$

- $3N$ contact at LO[1]: D_1, D_4, $D_6 \sim N_c$, but only a single independent operator with associated LEC $\sim N_c$

$$\mathcal{L} = -\sum_{i=1}^{6} D_i\, O_i \qquad O_i = N^\dagger N\, N^\dagger N\, N^\dagger N \ \text{ and 5 more}$$

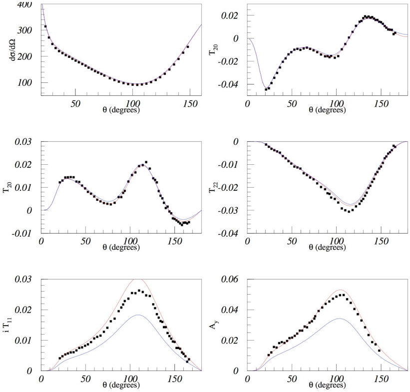
- $3N$ subleading contact[2]: an analysis similar to above shows E_2, E_3, E_5 and E_9 vanish in the large-N_c limit

$$\mathcal{L} = -\sum_{i=1}^{10} E_i\, O_i \qquad O_i = \nabla\left(N^\dagger N\right)\cdot\nabla\left(N^\dagger N\right) N^\dagger N \ \text{ and 9 more}$$

[1] Phillips and Schat (2013); [2] Girlanda, unpublished

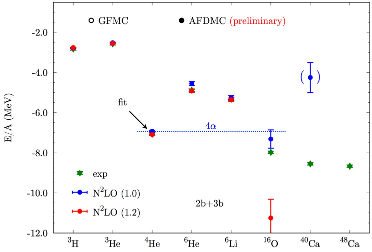
Strategies to constrain the LECs

- Fix c_D via a measured GT m.e. (obvious choice ^{3}H)
- Possible approaches to fix c_E and subleading LECs:
  - *Nd scattering observables at low energies*
  - *Spectra of light- and medium-weight nuclei and properties of nuclear/neutron matter*



Girlanda *et al.* (2018), preliminary

AFDMC for $A = 16$ and 40



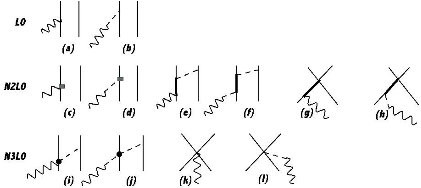
Lynn *et al.* (2016); Lonardoni *et al.*

Weak transitions with NV2+3 potential models

Marcucci *et al.*, unpublished

- Simple at tree level (and calculations are in progress); still a single LEC in the axial current

	Ia	Ib
LO	0.9271	0.9248
N2LO	0.0347	0.0514
N3LOπ	0.0328	0.0453
N3LOc	-0.0433	-0.0706
N4LO(no Δ)	-0.0266	-0.0406



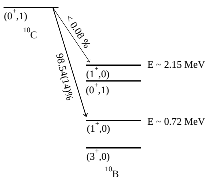
	Ia	Ia	Ib	Ib
c_D	-0.89	-0.38	-4.99	-4.42
c_E	-0.01	-0.17	0.70	0.40

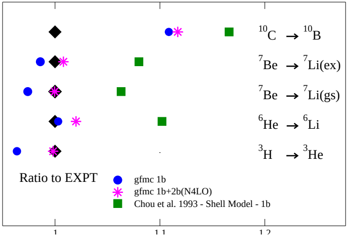
- Ranges in c_D and c_E from (conservative) estimate of error on GT$^{\rm exp}$; these c_E's help in neutron matter EOS
- A major task at N4LO as there are a great many two- and three-body contributions at that order

Weak transitions in $A > 3$ nuclei

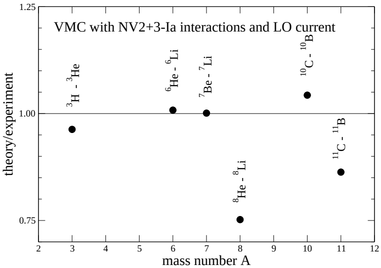
Pastore *et al.* (2018) and unpublished; see also Pastore and Hagen's talks at this workshop

Hybrid GFMC with AV18/IL7→





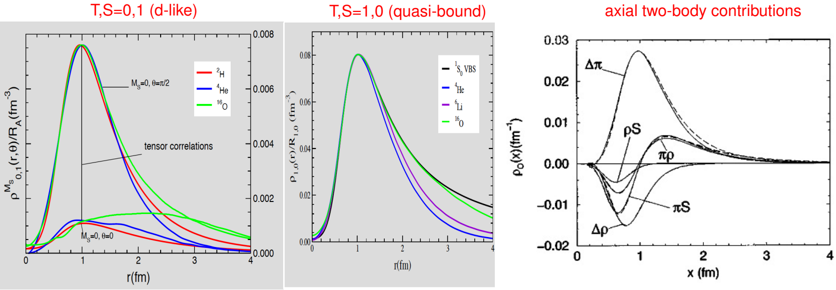
VMC with NV-Ia and LO $\mathbf{j}_5$ →



On two-body axial current contributions . . .

Schiavilla *et al.* (1998)

- Two-body terms primarily convert a $TS = 01$ pn (or $TS = 10$ nn) pair into a $TS = 10$ pp (or $TS = 01$ pn) pair



- Pair wave functions of nuclei in $TS = 01$ and 10 have similar shapes for nucleon separations $\lesssim 2$ fm
- Two-body contributions in nuclei (at least, light ones) are proportional to those in processes $pn(nn) \to pp(pn)$

The HH/QMC team

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