The PTOLEMY experiment: an opportunity for nuclear physics

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The "basic model" of nuclear theory

- Goal of nuclear theory: comprehensive description of nuclear systems
  - NN scattering data: thousands of exp. data ($d\sigma/d\Omega$ ...)
  - Spectra and static properties: binding energies, radii, mag. mom. ...
  - Nucleonic matter EoS: neutron stars ...
- Inputs
  - Degrees of freedom (nucleons, pions, ...)
  - Many-body interactions between the constituents

$$H = \underbrace{\sum_{i=1}^{A} \frac{\mathbf{p}_i^2}{2m_i}}_{\mathrm{One-body}} + \underbrace{\sum_{i<j=1}^{A} v_{ij}}_{\substack{\mathrm{Two-body} \\ \mathrm{NN}}} + \underbrace{\sum_{i<j<k=1}^{A} V_{ijk}}_{\substack{\mathrm{Three-body} \\ \mathrm{NNN}}} + \dots$$

  - Electroweak current operators

$$J^{EW} = \underbrace{\sum_{i=1}^{A} j_i}_{\mathrm{One-body}} + \underbrace{\sum_{i<j=1}^{A} j_{ij}}_{\mathrm{Two-body}} + \underbrace{\sum_{i<j<k=1}^{A} j_{ijk}}_{\mathrm{Three-body}} + \dots$$

Few-nucleon systems: the *ab-initio* approach

A-nucleon system $\leftrightarrow$ H & J^{EW} $\leftrightarrow$ Observable X

- *Ab-initio* method $\rightarrow$ obtain X by solving the relevant quantum many-body equations, without any uncontrolled approximation
- controlled approximations are allowed (expansion on a certain basis)

  $\rightarrow$ converged results = *ab-initio* results
- comparison of *ab-initio* results obtained with different *ab-initio* methods

  $\rightarrow$ benchmark calculations
- comparison of *ab-initio* results with data

  $\rightarrow$ test of H & J^{EW}

  $\rightarrow$ predictions for "un-measurable" observables

How few is "few"? $\Rightarrow$ Few-body $\leftrightarrow$ *ab-initio* methods

$A = 3$ is few!

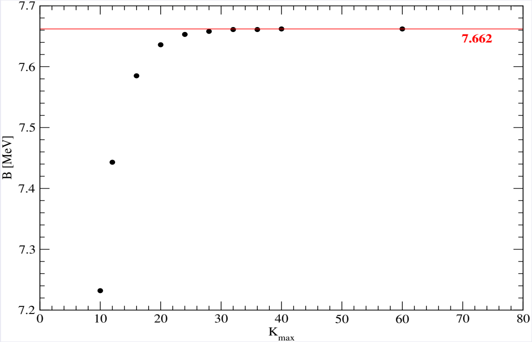
An *ab-initio* approach: the Hyperspherical Harmonics (HH) Method

Bound states

$$\Psi^{JJ_z} = \sum_{\mu} c_\mu \Psi_\mu$$

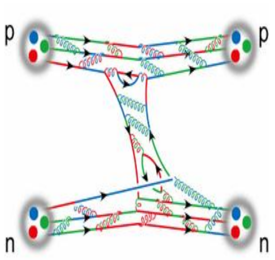
- $\Psi_\mu \rightarrow$ known functions (spin-isospin HH functions)
- Rayleigh-Ritz var. principle: $\delta_c \langle \Psi^{JJ_z} | H - E | \Psi^{JJ_z} \rangle = 0$
  $\Rightarrow$ Solve for E and c_μ

Convergence of the method: B(^{3}H) with first 3 spin-isospin channel – N3LO



$\rightarrow$ bound/scattering states $A \leq 4$, low-energy scattering states (astrophysical interest)

The nuclear Hamiltonian: a little bit of hystory



Nuclear interaction: $V_{NN} + V_{NNN}$

- Until $\simeq$ 20 years ago:
  phenomenological potentials
  - $V_{NN} + V_{NNN}$ semi-phenomenological
  - V_{NN} with $\simeq$ 40 parameters fitted to $A = 2$ data $\rightarrow \chi^2$/datum $\simeq 1$
  - V_{NNN} with 2-3 parameters fitted to $B(A = 3, 4)$

  $\Rightarrow$ **no simple connection to QCD**

  $\Rightarrow$ **no clear relation for H & J^{EW}**
- Then ... chiral effective field theory (χEFT)

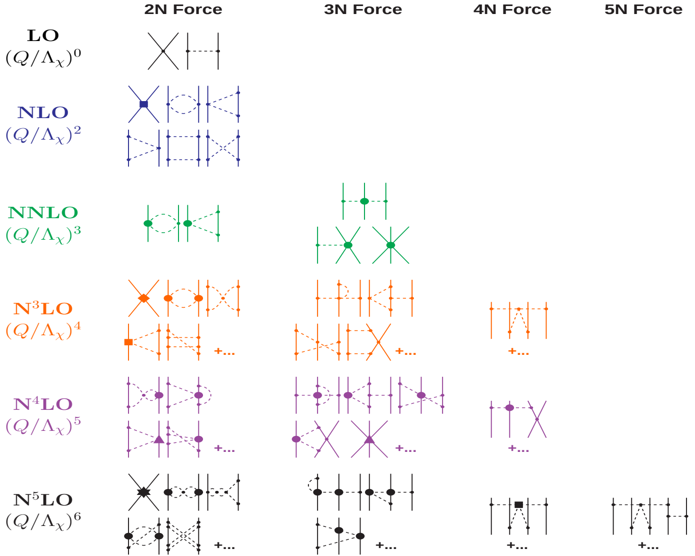
Chiral Effective Field Theory (χEFT): a short summary

- QCD $\rightarrow$ quarks and gluons ("high-energy" d.o.f.)
- Nuclear physics $\rightarrow$ nucleons and pions ("low-energy" d.o.f.)
- EFT $\rightarrow$ processes with $E \simeq p \simeq m_\pi \ll \Lambda_\chi \sim 1$ GeV
  - ⋆ "h-e" d.o.f. integrated out $\rightarrow$ contact interactions with "l-e" d.o.f. and low-energy constants (LECs) obtained from experiment
  - ⋆ perturbative theory: matrix elements $\propto O(p/\Lambda_\chi)^\nu$
- **χEFT $\rightarrow$ EFT with spontaneous breaking of QCD's χ-symmetry**
- Regularization with cutoff function $\rightarrow \Lambda \simeq 414, 450, 500, 600$ MeV

Disadvantage: limited to processes with $E \sim 1 - 2\, m_\pi$

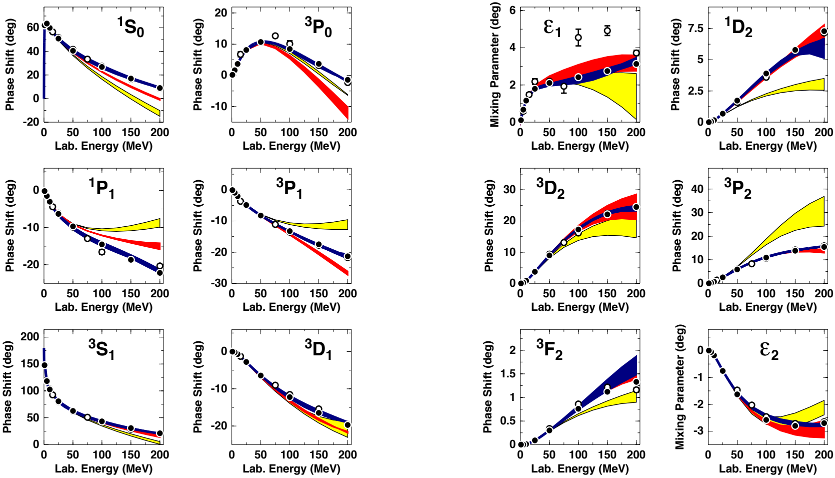
Advantages

- nuclear force "hierarchy" $\rightarrow$ accurate $V_{NN} + V_{NNN}$
- consistent framework for H & J^{EW} (add external EW field among the d.o.f.)



Machleidt and Sammarruca, Physics Scripta **91**, 083007 (2016)

$\Rightarrow$ each $\bullet$ = LECs (20-30) $\rightarrow$ fit to NN data



Yellow=NLO; Red=N2LO; Blue=N3LO

The J^{EW} operator

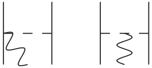
EW operators: $\rho^\gamma, \mathbf{j}^\gamma$; $\rho^{V/A}, \mathbf{j}^{V/A}$ CVC $\Rightarrow \rho^V/\mathbf{j}^V \rightarrow \rho^\gamma/\mathbf{j}^\gamma$

Power counting for $\mathbf{j}^\gamma$

$\mathcal{O}(Q^{-2})$

$$\mathbf{j}^{(-2)} \propto [e_N(1)(\mathbf{p}'_1 + \mathbf{p}_1) + i\mu_N(1)\sigma_1 \times \mathbf{q}] \times \delta(\mathbf{p}'_2 - \mathbf{p}_2) + 1 \leftrightarrow 2$$

$\mathcal{O}(Q^{-1})$

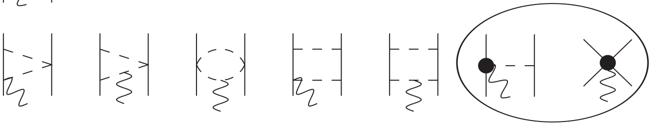


"standard" one – pion – exchange

$\mathcal{O}(Q^{0})$

■ = relativistic corrections

$\mathcal{O}(Q^{1})$



PREDICTIONS $\Leftarrow$ EM observables (many) $\leftarrow$ LECs

Static EM properties for $A = 2, 3$ nuclei

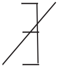
	PhenApp	χEFT	Exp.
$r_c(d)$ [fm]	2.119	2.126(4)	2.130(10)
$Q(d)$ [fm^2]	0.280	0.2836(16)	0.2859(3)
$r_c(^3\mathrm{He})$ [fm]	1.928	1.962(4)	1.973(14)
$r_m(^3\mathrm{He})$ [fm]	1.909	1.920(7)	1.976(47)
$r_c(^4\mathrm{He})$ [fm]	1.639	1.663(11)	1.681(4)

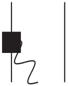
Marcucci *et al.*, JPG **43**, 023002 (2016)

χEFT $\longrightarrow$ **theoretical error!**

Power counting for $\mathbf{j}^A$

$\mathcal{O}(Q^{-3})$ 

$\mathcal{O}(Q^{-2})$ 

$\mathcal{O}(Q^{-1})$ 

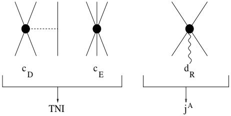
$\mathcal{O}(Q^{0})$  

- $\mathcal{O}(Q^1)$ not shown: loop and 2π-exchange contributions (hughly diagrams!)
- Only one LEC - d_R

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

Gårdestig and Phillips, PRL **96**, 232301 (2006)
Gazit *et al.*, PRL **103**, 102502 (2009)
Marcucci *et al.*, PRL **121**, 049901(E) (2018)

- fit c_D and c_E (in V_{NNN}) to $B(A=3)$ and Gamow-Teller m.e. of tritium β-decay (GT_{Exp})



$\Rightarrow$ **PREDICTIONS for other observables**

Predictions in the weak sector

^{3}H β-decay

$$(1+\delta_R)t_{1/2}f_V = \frac{K/G_V^2}{\langle \mathbf{F}\rangle^2 + f_A/f_V g_A^2 \langle \mathbf{GT}\rangle^2}$$

- $g_A = 1.2723$; $\delta_R = 1.9\%$ outer radiative corrections; $t_{1/2}$=half-life; $f_{V/A}$= Fermi functions
- Exp. values: $K/G_V^2 = (6144.5 \pm 1.9)$ s & $(1+\delta_R)t_{1/2}f_V = (1134.6 \pm 3.1)$ s

$\langle \mathbf{F}\rangle = \langle {}^3\mathrm{He}||\sum_j \tau_{j,+}||{}^3\mathrm{H}\rangle \simeq 0.999$ very stable from theory $\Rightarrow \langle \mathbf{GT}\rangle_{EXP}$

Polarized ^{3}H β-decay: $\overrightarrow{{}^3\mathrm{H}} \rightarrow {}^3\mathrm{He} + \mathrm{e}^- + \overline{\nu}_e$

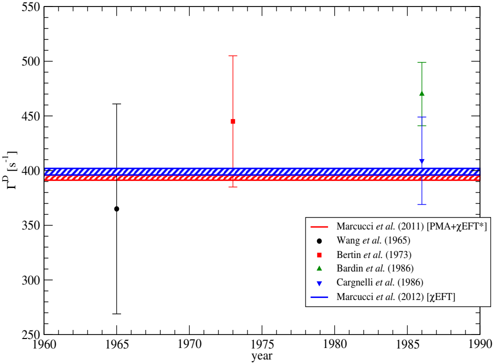
$$\frac{d\omega}{dE_e\, d\Omega_e\, d\Omega_\nu} \propto \xi\, [1 + a\,\vec{\beta}\cdot\hat{\nu} + \hat{P}\cdot(A\vec{\beta} + B\hat{\nu})]$$

- $\hat{P}$=pol. versor; $\hat{\nu} = \mathbf{p}_\nu/E_\nu$; $\vec{\beta} = \mathbf{p}_e/E_e$;
- $\xi \sim \langle \mathbf{F}\rangle^2 + f_A/f_V g_A^2 \langle \mathbf{GT}\rangle^2$; $a\xi \sim \langle \mathbf{F}\rangle^2 - f_A/f_V g_A^2 \langle \mathbf{GT}\rangle^2/3$
- $A\xi$ and $B\xi$: other combinations of $\langle \mathbf{F}\rangle$ and $\langle \mathbf{GT}\rangle$

Calculation: work in progress but NO DATA!

Muon capture on light nuclei: deuteron

$\mu^- + d \rightarrow n + n + \nu_\mu \longrightarrow$ Two hyperfine states (1/2 & 3/2) $\Rightarrow \not{\Gamma}^Q$ & Γ^D



$\Gamma^D = 399(3)\ \text{s}^{-1}$ vs. $\Gamma^D(\text{exp}) \cdots$

MuSun $\rightarrow$ 1.5 % accuracy

Muon capture on light nuclei: ^{3}He (I)

- $\mu^- + {}^3\mathrm{He} \to n + d + \nu_\mu$ (20%) [poor data]
- $\mu^- + {}^3\mathrm{He} \to n + n + p + \nu_\mu$ (10%) [poor data]
- $\mu^- + {}^3\mathrm{He} \to {}^3\mathrm{H} + \nu_\mu$ (70%)

$\mu^- + {}^3\mathrm{He} \to {}^3\mathrm{H} + \nu_\mu$: two hyperfine states, $P(f, f_z) = (1; \pm 1, 0)$ and $(0; 0)$

$$
\begin{aligned}
\cos\theta &= \hat{\mathbf{z}} \cdot \hat{\mathbf{q}} \leftarrow \text{momentum transfer of the lepton pair} \\
\frac{d\Gamma}{d(\cos\theta)} \quad d &= \frac{1}{2}\Gamma_0\left[1 + A_v P_v \cos\theta + A_t P_t\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right) + A_\Delta P_\Delta\right] \\
P_v &= P(1,1) - P(1,-1) \\
P_t &= P(1,1) + P(1,-1) - 2P(1,0) \\
P_\Delta &= P(1,1) + P(1,-1) + P(1,0) - 3P(0,0) \equiv 1 - 4P(0,0)
\end{aligned}
$$

Muon capture on light nuclei: ^{3}He (II)

- Experimental data
  - Γ_0^{EXP}=1496(4) s^{-1}
  - A_v^{EXP}=0.63 $\pm$ 0.09 (stat.)$^{+0.11}_{-0.14}$ (syst.)

Ackerbauer *et al.*, PLB **417**, 224 (1998)

Souder *et al.*, NIMA **402**, 311 (1998)

- Theoretical predictions
  - Γ_0=1492(19) s^{-1}
  - $A_v = 0.5435(6)$
  - $A_t = -0.355(1)$; $A_\Delta = -0.101(2)$

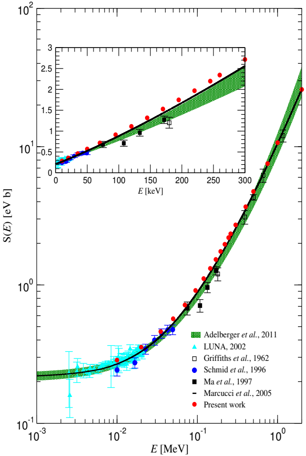
Marcucci *et al.*, PRL **108**, 052502 (2012); Erratum PRL **121**, 049901(E) (2018)

Bottom line

- Theory seems to be ok, but ...
- Need **more** and **more accurate** data in the weak sector to be sure!
- **PTOLEMY can play a role in this game**

An example in the EM sector: the $p + d \to {}^3\text{He} + \gamma$

- interesting for BBN: larger rate $\Rightarrow$ smaller D/H primordial abundance
- on-going measurement by the LUNA Collab. at LNGS
- *ab-initio* study $\Leftarrow$ initial $p + d$ scattering state (only HH method available)



PArthENoPE $\to$ D/H abundance:

$\text{D/H}|_{TH} = (2.46 \pm 0.06) \times 10^{-5}$

$\Omega_b h^2 \to$Planck 2015 & standard N_{eff}

vs.

$\text{D/H}|_{Exp} = (2.53 \pm 0.04) \times 10^{-5}$

Marcucci *et al.*, PRL **116**, 102501 (2016)

Collaboration with LUNA: theory used for simulation/rate estimate but needs to be tested!

Conclusions

- Goal of nuclear theory: comprehensive description of nuclear systems
- Few-body nuclei ($A = 3$) $\rightarrow$ *ab-initio* methods

$\rightarrow$ **test the theoretical framework** (H & J^{EW})

$\rightarrow$ **give solid predictions + theoretical uncertainty** (χEFT)

- But few (poor) data in the weak sector

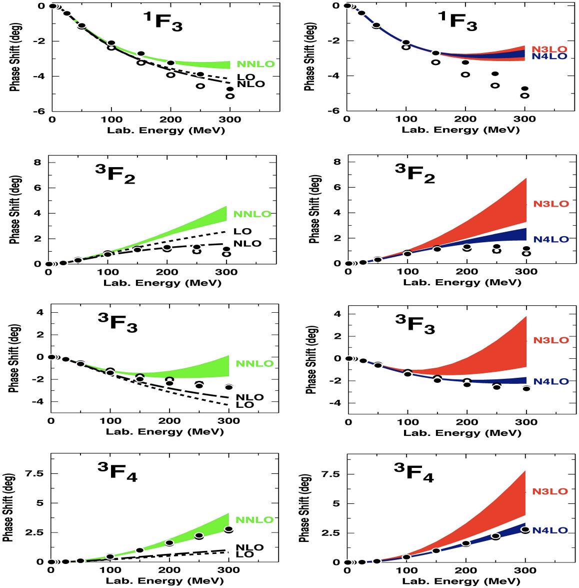
$$\Downarrow$$

The PTOLEMY experiment: a GREAT opportunity for nuclear physics

THANK YOU!


P on-
T ecorvo
O bservatory for
L ight,
E arly-universe,
M assive-neutrino
Y ield

SPARES



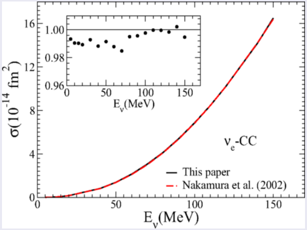
$^1F_3$
NNLO
LO
NLO
$^1F_3$
N3LO
N4LO
$^3F_2$
NNLO
LO
NLO
$^3F_2$
N3LO
N4LO
$^3F_3$
NNLO
NLO
LO
$^3F_3$
N3LO
N4LO
$^3F_4$
NNLO
NLO
LO
$^3F_4$
N3LO
N4LO
Phase Shift (deg)
Lab. Energy (MeV)

The PTOLEMY reaction: $\nu_e + {}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + \mathrm{e}^-$

Preliminary "related" studies

- $\nu_e + d \rightarrow \mathrm{e}^- + p + p$

  Baroni and Schiavilla,
  PRC **96**, 014002 (2017)
  in χEFT



- $\overline{\nu_e} + {}^3\mathrm{He} \rightarrow {}^3\mathrm{H} + \mathrm{e}^+$

  Golak *et al.*,
  PRC **98**, 015501 (2018)
  in PhenApp