Jefferson Lab

The ^{6}He β-decay (^{6}He $\rightarrow$ ^{6}Li $+ e^- + \bar{\nu}$)

Alex Gnech

Collaborators:
R. Schiavilla (ODU & JLAB)
L.E. Marcucci (Univ. of Pisa & INFN Pisa)
M. Viviani (INFN Pisa)

Cake Seminar @JLAB,
February 8th, 2021

Introduction

- β-decay rates of large nuclei smaller than free neutron [1]

g_A quenching

- Two-body currents contribution can explain this [2]
(Studies based on NCSM and CC methods)

- QMC calculations show a different sign for the two-body currents [3]

- They both use χEFT (see next slides)

Tensions between the two calculations

[1] I.S. Towner, Phys. Rep. **155**, 263 (1985)
[2] P. Gysbers, *et al.* Nature Phys. **15**, 428 (2019)
[3] G.B. King, *et al.* Phys. Rev. C **102**, 025501 (2020)

Introduction

$$T_{fi} = \frac{G_F^2}{\pi^2} F(p_e, p_\nu, x_{e\nu}) \ M_{fi}$$

- G_F Fermi constant
- $F(p_e, p_\nu, x_{e\nu})$ phase space factor
- $M_{fi} = \frac{1}{2J_i+1} \sum_{M_i, M_f} | < f|J_5|i > |^2 \Rightarrow$ Nuclear matrix element

Initial and final state calculation ($|f>, |i>$)

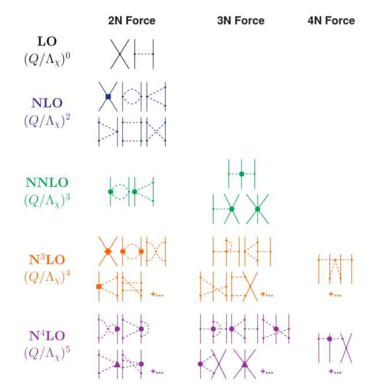
$$H = \sum_i \frac{p_i^2}{2M} + \sum_{i<j} V(i,j) + \sum_{i<j<k} W(i,j,k) + \dots$$

- Nuclear model
  - chiral effective field theory χEFT
- Search for accurate solution of $H\Psi = E\Psi$
  - Variational approach
  - Expansion of Ψ on the basis of Hyperspherical Harmonic (HH) functions [L.E. Marcucci, *et al.*, Front. Phys. **8**, 69 (2020)]

Chiral interaction (χEFT)

$$\text{QCD} \xrightarrow{\text{chiral symmetry}} \chi\text{EFT}$$

- Low Energy Theory ($\Lambda_\chi \sim 1$ GeV)
  - N, π as d.o.f.
  - high energy d.o.f. integrated out $\rightarrow$ Low Energy Constants
- Perturbative expansion ($\propto (Q/\Lambda_\chi)^\nu$)
- Non-relativistic expansion $\Rightarrow$ Nuclear potential
- Regularization with a cutoff ($\Lambda = 400 - 600$ MeV)
- LECs fitted to the experimental data



D.R. Entem, *et al.* Phys. Rev. C **96**, 024004 (2017)

E. Epelbaum, *et al.* Phys. Rev. Lett. **115**, 122301 (2015)

The HH wave function

- Jacobi vectors $\vec{\xi}_1, \ldots, \vec{\xi}_N \Rightarrow$ CoM completely decoupled
- Hyperangular variables $\rho = \sum_{k=1}^{5} (\xi_k)^2$, $\Omega = \{\hat{\xi}_i, \phi_i\}$, $\cos\phi_k = \frac{\xi_k}{\sqrt{\xi_1^2 + \ldots + \xi_k^2}}$

$$T = -\frac{\hbar^2}{m}\left(\frac{\partial^2}{\partial\rho^2} + \frac{D-1}{\rho}\frac{\partial}{\partial\rho} - \frac{L^2(\Omega)}{\rho^2}\right)$$

- Expansion on a base $\Rightarrow$ Hyperspherical Harmonics (HH)

$$L^2(\Omega)\mathcal{Y}_{[K]}(\Omega) = K(K+13)\mathcal{Y}_{[K]}(\Omega)$$

- The variational wave function

$$\psi_A = \sum_{l,[K]} A_{l,[K]} f_l(\rho)\mathcal{Y}_{[K]}(\Omega_{A-1})\Big[\chi_S \otimes \chi_T\Big] = \sum_{[\alpha]} A_{[\alpha]}\Phi_{[\alpha]},$$

- Check convergence on K

The HH wave function

- Sum over the permutations $\Rightarrow$ antisymmetrization

- Transformation Coefficients

$$\sum_{perm} \mathcal{Y}^{KLSTJ}_{[\alpha]}(\Omega_{perm}) = \sum_{[\alpha']} a^{KLSTJ}_{[\alpha],[\alpha']} \mathcal{Y}^{KLSTJ}_{[\alpha']}(\Omega)$$

- Evaluation of the matrix elements

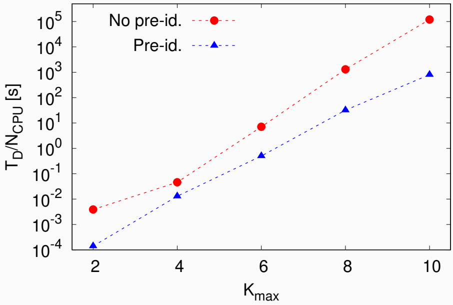
$$H_{\alpha,\beta} = \langle \Phi_{[\alpha]} | H | \Phi_{[\beta]} \rangle$$

  - Kinetic energy immediate
  - Nuclear potential

$$\langle \Phi_{[\alpha]} | \sum_{i<j} V(i,j) | \Phi_{[\beta]} \rangle = \frac{A(A-1)}{2} \sum_{[\alpha'],[\beta']} a_{[\alpha],[\alpha']} a_{[\beta],[\beta']} V_{[\alpha'],[\beta']}(1,2)$$

$\Rightarrow$ By using the sum over the permutations and the TC

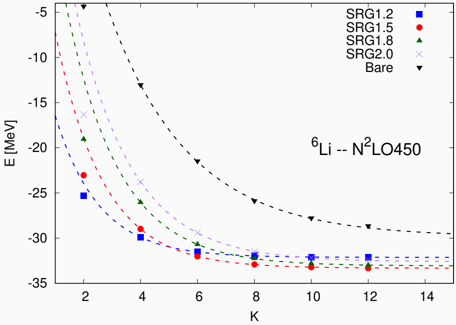
Computing...



- $T_D =$ time for computing all the $\langle \Phi_\alpha | \sum_{i<j} V(i,j) | \Phi_\beta \rangle$ with $K(\alpha) = K(\beta)$
- Exponential behavior
- Blue use a new algorithm

[A.G., L.E. Marcucci and M. Viviani, Phys. Rev. C **102**, 014001 (2020)]

Convergence studies



	^{6}Li	^{6}He
SRG1.2	-32.13(2)	-28.87(3)
SRG1.5	-33.33(3)	-30.17(4)
SRG1.8	-33.07(1)	-30.08(2)
SRG2.0	-32.62(7)	-29.73(2)
Bare	-29.8(4)	-27.6(3)
Exp.	-31.99	-29.27

Note that it is a rough estimate!

Final extrapolation

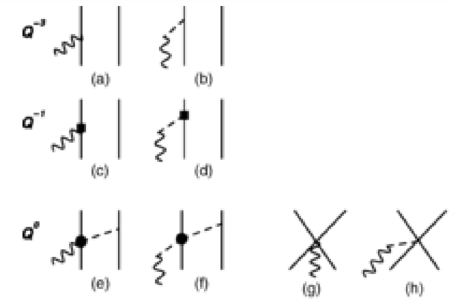
	B_{full}[2]	$B(\infty)$[2]	Ref. [1]
N3LO500-SRG1.2 (^{6}Li)	31.78	31.81(1)	31.85(5)
N3LO500-SRG1.5 (^{6}Li)	32.79	32.91(2)	33.00(5)
N3LO500-SRG1.8 (^{6}Li)	32.25	32.68(9)	32.8(1)
N2LO450-bare (^{6}Li)	28.51	30.2(3)	
N2LO450-bare (^{6}He)	26.07	27.5(4)	

- All the energies are in MeV
- Results of Ref. [1] from No Core Shell Model
- Experimental value $B_{^6\mathrm{Li}} = 31.99$ MeV and $B_{^6\mathrm{He}} = -29.27$

[1] E.D Jungerson, P. Navrátil and R.J. Furnstahl, PRC **83**, 034301 (2011)

[2] A.G., L.E. Marcucci and M. Viviani, Phys. Rev. C **102**, 014001 (2020)

Nuclear axial currents (J_5)



A. Baroni, *et al.*, Phys. Rev. C **93**, 015501 (2016)

- Q^{-3} Gamow-Teller (GT) $\Rightarrow$ $g_A \approx 1.27$
- Q^{-1} Relativistic Corrections (RC)
- Q^0 One pion exchange (OPE) $\Rightarrow$ c_3, c_4 from Nuclear Potential
- Q^0 Contact Term (CT) $\Rightarrow$ $z_0(c_D, c_3, c_4)$
  Fitted on the $^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \bar{\nu}$

Preliminary results

$$\text{RME} = \frac{\sqrt{2J_f + 1}}{g_A} \frac{< J_f M | J_5 | J_i M >}{< J_i M, 10 | J_f M >}$$

	LO(GT)	NLO(RC)	N2LO(OPE)	N2LO(CT)	Tot.
SRG1.2	2.342	−0.020	−0.040	−0.039	2.244
SRG1.5	2.335	−0.022	−0.028	−0.044	2.242
SRG1.8	2.320	−0.022	−0.018	−0.047	2.234
SRG2.0	2.321	−0.023	−0.012	−0.047	2.239
bare	2.299	−0.022	0.003	−0.049	2.231
Exp.					2.1609(40)

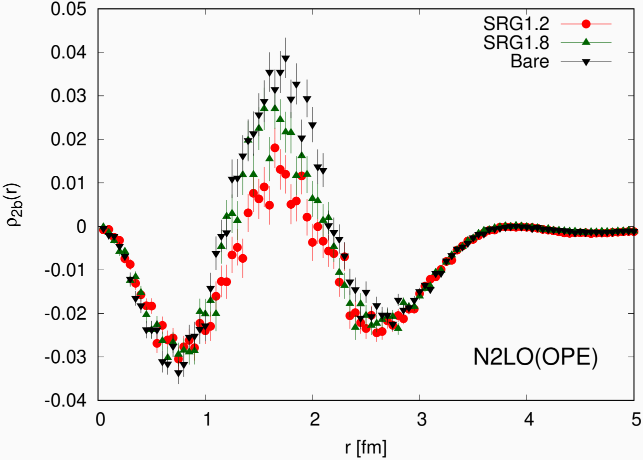
- $\text{RME}(K = 12) \simeq \text{RME}(\infty)$
- Preliminary results consistent with [1]
- Sign of CT is the same as QMC calculations [2]
- Large variability on OPE contribution

[1] P. Gysbers, *et al.* Nature Phys. **15**, 428 (2019)

[2] G.B. King, *et al.* Phys. Rev. C **102**, 025501 (2020)

Two-body density

$$\rho_{2b}(r) \propto < J_f M | \sum_{i<j} \delta(r - r_{ij}) J_5(ij) | J_i M > \quad \mathrm{RME}(2b) = \int_0^\infty \rho_{2b}(r) dr$$



Conclusions and perspectives

- Overview of the HH method
  - Inclusion of three-body forces
  - Scattering states
- Study of electro-weak interactions in light nuclei
  - Beta-decay
  - Muon capture reaction
  - Electromagnetic transition in $A = 6$ nuclei
- Study of electro-weak interactions in medium-mass nuclei
  AFDMC (in coll. with A. Lovato)

Acknowledgments

Jefferson Lab

NERSC National Energy Research Scientific Computing Center

Cluster form factor $\alpha + d$

$$\frac{f_L(r)}{r} = \langle \Psi^{(L)}_{\alpha+d} | \Psi_{^6\mathrm{Li}} \rangle, \qquad |\Psi^{(L)}_{\alpha+d}\rangle = \left[(\Psi_\alpha \otimes \Psi_d)_S \, Y_L(\hat{r}) \right]_J$$

with $S = 1$, $J = 1$ and $L = 0$ ($^3S_1$)