L'I.S. FBS dell'INFN: stato dei progetti in corso e prospettive future

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Istituto Nazionale di Fisica Nucleare

Outline

Outline

I.S. Few-Body Systems

Aims

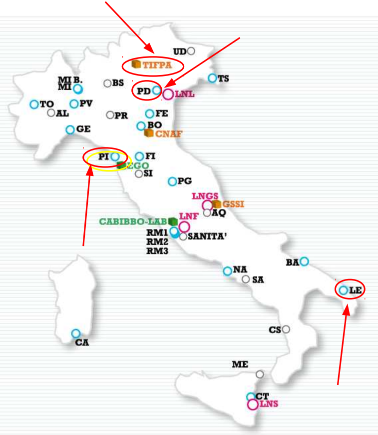
- Development of accurate methods to study the bound and continuum states of few-body systems using realistic interactions
- Development of more and more accurate nuclear potentials and electroweak currents
- Study of the properties of light and medium-light nuclear systems in radioactive ion beams
- Study of strange nuclear systems (hypernuclei), also in systems with A>4
- Perform accurate calculations of reactions of astrophysical interest
- Study of universal properties and of Efimov physics in atomic and nuclear few-body systems
- Study of fundamental symmetries in few-nucleon systems

`https://web.infn.it/CSN4/IS/Linea3/FBS/`

I.S. Few-Body Systems

Composizione dell'I.S. FBS

- Lecce: L. Girlanda
- Padova: L. Canton
- Pisa:
  - A. Kievsky, L.E. Marcucci, MV, J. Dohet-Eraly (Post-doc)
  - A. Gnech *PhD Student, GSSI, L'Aquila (Italy)*
  - E. Filandri, A. Nannini *(L.M., Pisa Un.)*
- Trento:
  - W. Leidemann, G. Orlandini
  - F. Ferrari-Ruffino *(ex Ph.D student, Trento Un.)*
  - P. Andreatta *(L.M., Trento Un.)*



Outline

Summary of research projects

Lecce

- Construction of NN & 3N interactions, electroweak currents, dark-matter - nucleon interaction, . . . starting from effective field theory
- Subleading (N4LO) three-nucleon contact interaction
- Luca's talk on Tuesday – → section 4

Padova

- Study of medium-light exotic nuclei
- cluster models – algebraic approaches
- → section 3

Pisa

- 3N & 4N bound and scattering states
- Construction of NN and 3N interactions (→ section 4)

Pisa (cont.)

- Subleading (N4LO) three-nucleon contact interaction (Luca's talk on Tuesday)
- Efimov Physics (see Alejandro's talk)
- Extension to $A = 5, 6$ (see Jeremy's talk)
- Reactions of astrophysical interest & muon capture (see Laura's talk)
- Parity and time-reversal violation (see Alex's talk)

Trento

- Reactions of few-nucleon systems using the Lorentz-integral transform method (→ section 5)
- Study of hypernuclear systems (see Ferrari-Ruffino's talk → Section 6)

Outline

Multichannel algebraic scattering (MCAS) method

Spectrum of unbound nucleus ^{15}F

- ^{15}F decays emitting a proton
- [Phys. Rev. Lett. 96, 072502 (2006)] prediction of narrow resonances $\Gamma = 0.005$ MeV
- Experimentally verified by Mukha et al., [Phys. Rev. C 77, 061303(R) (2008)]

MCAS

- ^{15}F as a $p + {}^{14}$O system
- Inclusion in the calculation many excited states of ^{14}O
- Solution of the coupled channel two-body equations with Sturmians

$$G_0(E)V_c|\Phi_{ci}\rangle = -\eta_{ci}|\Phi_{ci}\rangle$$

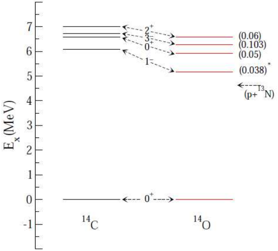
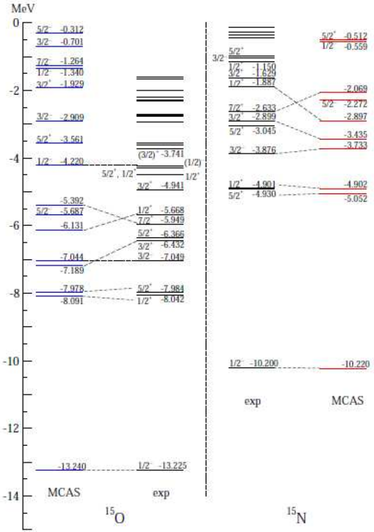


FIG. 1: The low excitation spectra of the mass-14 mirror nuclei, ^{14}C and ^{14}O, used in MCAS calculations. The spin-parities of the states are listed in the middle of the diagram.

Energy levels of ^{15}F

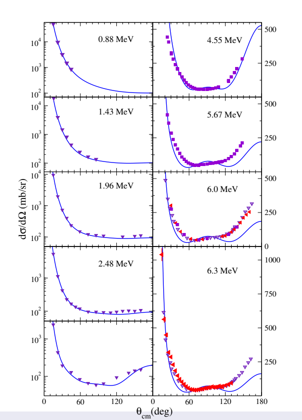
P. R. Fraser, K. Amos, L. Canton, S. Karataglidis, D. van der Knijff, and J. P. Svenne
Australia-South Africa-Italy-Canada Collaboration – [ArXiv:1709.03051]



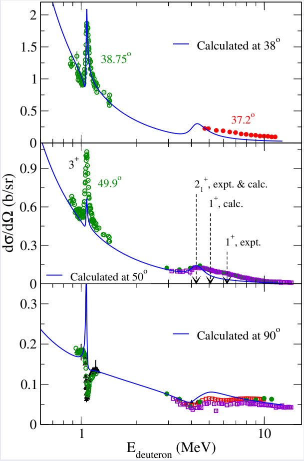
Study of $d + {}^4\mathrm{He}$ scattering

P. R. Fraser, K. Massen-Hane, A. S. Kadyrov, K. Amos, I. Bray, and L. Canton
Australia-South Africa-Italy Collaboration – [Phys. Rev. C **96**, 014619 (2017)]

Angular distribution of the elastic cross section



Energy dependence at fixed angles



Outline

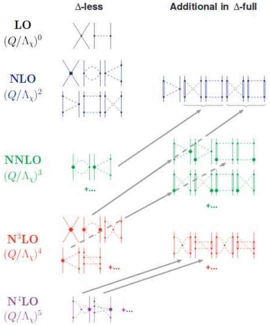
NN and $3N$ interaction from χEFT with Δ d.o.f.

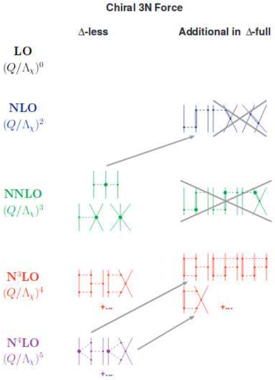
JLab+Argonne+Lecce+Pisa Collaboration

- χEFT framework with inclusion of Δ d.o.f.
- Local version that can be used with GFMC
- Non-local terms “eliminated” via Fierz transformations

- $\mathbf{k} = \mathbf{p}' - \mathbf{p}$
- $\mathbf{K} = (\mathbf{p}' + \mathbf{p})/2$

$$K^m \longrightarrow -\frac{1+\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2}{2}\,\frac{1+\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2}{2}\,\frac{k^m}{2^m}$$



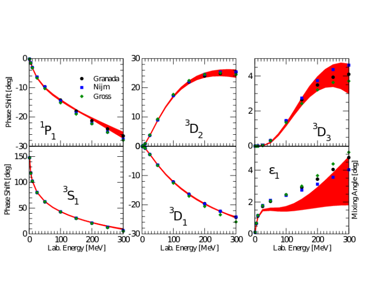


Fit of NN data

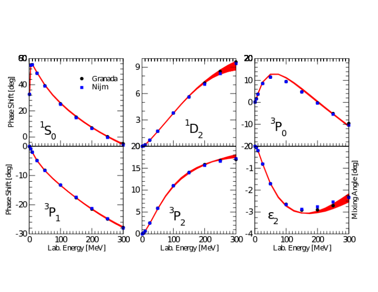
M. Piarulli, L. Girlanda, R. Schiavilla, A. Kievsky, A. Lovato, L.E. Marcucci , S.C. Pieper, MV , and R.B. Wiringa – [PRC **94**, 054007 (2016)]

Comparison with NN experimental data

n − *p* scattering



p − *p* scattering



Different versions

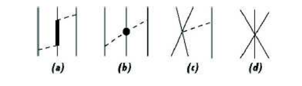
name	order	R_L	R_S	$E_{\max}$	χ^2/datum
	LO	1.0	0.7	125 MeV	59.88
	NLO	1.0	0.7	125 MeV	2.18
	N2LO	1.0	0.7	125 MeV	2.32
NV–Ia	N3LO*	1.0	0.7	125 MeV	1.07
NV–Ib	N3LO*	1.2	0.8	125 MeV	1.05
NV–IIa	N3LO*	1.0	0.7	250 MeV	1.37
NV–IIb	N3LO*	1.2	0.8	250 MeV	1.37

^{3}H & ^{4}He binding energies (no 3NF)

name	order	$B(^3\mathrm{H})$	$B(^4\mathrm{He})$
NV–Ia	N3LO*	7.60	23.96
NV–Ib	N3LO*	7.82	25.15
NV–IIa	N3LO*	7.87	25.28
NV–IIb	N3LO*	7.95	25.80

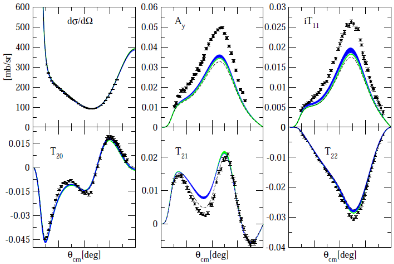
Inclusion of the 3N force

M. Piarulli, A. Baroni, L. Girlanda, A. Kievsky, A. Lovato, E. Lusk, L.E. Marcucci, S.C. Pieper, R. Schiavilla, MV, and R.B. Wiringa – [arXiv:1707.02883]



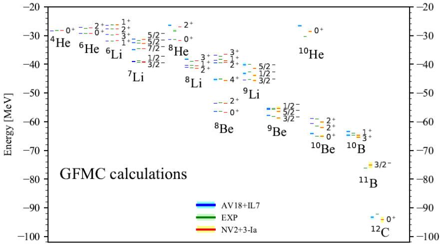
3NF with two parameters c_D and c_E fitted to the ^{3}H BE & $n-d$ a_d scattering length

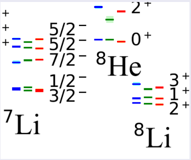
$p-d$ scattering at $E_p = 3$ MeV
green band = NV-Ia & NV-Ib + 3NF   blue band = NV-IIa & NV-IIb + 3NF
black dashed line = NV-Ia

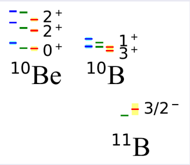


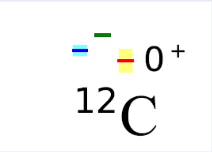
GFMC calculation of light nuclei

NV-Ia + 3NF









Nice reproduction of the energy levels – 3N force fitted using only $A = 3$ data!!!
more studies are in progress ($p - {}^3\mathrm{He}$, $n - {}^3\mathrm{He}$, $d - d$, . . . scattering)

Outline

Lorentz Integral Transform method

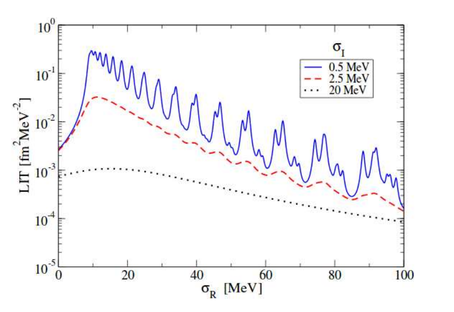
V. Efros, W. Leidemann, G. Orlandini, and N. Barnea, [J. Phys. G **34**, R459 (2007)]

The LIT method in a nutshell

$$
\begin{aligned}
R(E_\gamma) &= \int df |\langle f|D_z|0\rangle|^2 \delta(E_f - E_0 - E_\gamma) \\
L(\sigma = \sigma_R + i\sigma_I) &= \int_{E_{thr}}^{\infty} dE_\gamma \frac{R(E_\gamma)}{(E_\gamma - \sigma_R)^2 + \sigma_I^2} \\
&= \langle 0|D_z \frac{1}{H - E_0 - \sigma^*} \frac{1}{H - E_0 - \sigma} D_z|0\rangle \\
|\tilde{\Psi}(\sigma)\rangle &= \frac{1}{H - E_0 - \sigma} D_z|0\rangle \\
(H - E_0 - \sigma)\, |\tilde{\Psi}(\sigma)\rangle &= D_z|0\rangle \\
L(\sigma) &= \langle \tilde{\Psi}(\sigma)|\tilde{\Psi}(\sigma)\rangle
\end{aligned}
$$

Lorentz Integral Transform method (2)

The problem of the inversion



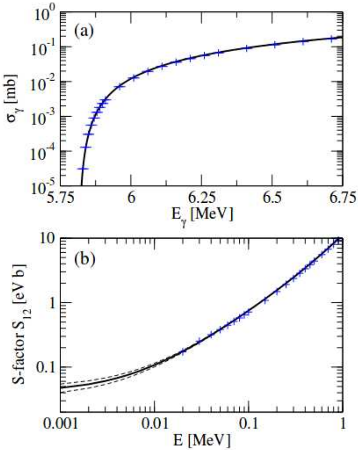
Many applications
EM response of ^{4}He and ^{6}Li
Electric dipole polarizability of medium nuclei using the coupled cluster
Neutrino scattering
See also S. Bacca and S. Pastore [J. Phys. G **41**, 123002 (2014)]

Recent application: $p-d$ capture astrophysical factor

S. Deflorian, V. Efros, and W. Leidemann, [Few-Body Syst **58**, 3 (2017)]

- Reaction under study $p - d \to {}^3\mathrm{He} + \gamma$
- LIT calculation of the inverse reaction $\gamma + {}^3\mathrm{He} \to p + d$
- $\sigma_{\rm capt}(k) = 2E_\gamma^2 \sigma_\gamma(E_\gamma)/3k^2$
- k relative $p - d$ momentum

Benchmark calculation with the MT-I/III interaction



Outline

TIFPA: Study of hypernuclei

Aim: selection of **antisymmetric** states with a non-symmetrized HH basis
→ M. Gattobigio, A. Kievsky, MV, and P. Barletta [PRA **79**, 032513 (2009)]

⇒ We add to $\hat{\mathrm{H}}$ the **Casimir operator** of the **permutation group $\mathbf{S}_N$**, which selects "by himself" the interesting states:

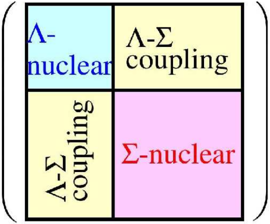
$$\hat{H}' = \hat{H} + \gamma \hat{C}(A) \quad ; \quad \hat{C}(A) = \sum_{i>j} \hat{P}_{ij}$$

Its action on the vectors:

$$\hat{C}(A)\Psi_s = \frac{A(A-1)}{2}\Psi_s = \lambda_s \Psi_s \; ;$$
$$\hat{C}(A)\Psi_m = \lambda_m \Psi_m \; ;$$
$$\hat{C}(A)\Psi_a = -\frac{A(A-1)}{2}\Psi_a = \lambda_a \Psi_a \; ,$$

⇒ with a proper choice of γ the g.s. energy $\mathbf{E}_A^0$ becomes the **lowest eigenvalue of H′** (similar procedure for excited states).

Particle Transition Extension



- **Transition** between **species** (examples: NΛ-NΣ, NN-ΔΔ, ...);
- the **masses** are **state dependent**;
- the **HH** basis is **mass dependent**: need to define transformation from one set of Jacobi weights ζ to another ζ'.

For a basis with $\zeta' \neq \zeta_{\text{phys}} = \zeta$ we follow both ways:

- **coordinate** transformation (present work):

$$H'(\boldsymbol{\eta}_{\zeta'}) = H\left[\boldsymbol{\eta}_{\zeta}(\boldsymbol{\eta}_{\zeta'})\right] = H\left(W_{\zeta\zeta'} \cdot \boldsymbol{\eta}_{\zeta'}\right) \;;$$

- **basis** transformation (in progress):

$$H'(\boldsymbol{\eta}_{\zeta'}) = \mathcal{W}^{\dagger}_{\zeta\zeta'} \cdot H(\boldsymbol{\eta}_{\zeta'}) \cdot \mathcal{W}_{\zeta\zeta'} \;.$$

$\Rightarrow$ The calculation of the $\mathcal{W}$ m.e. is in progress (HH real scaling coefficients).

Convergence Test I

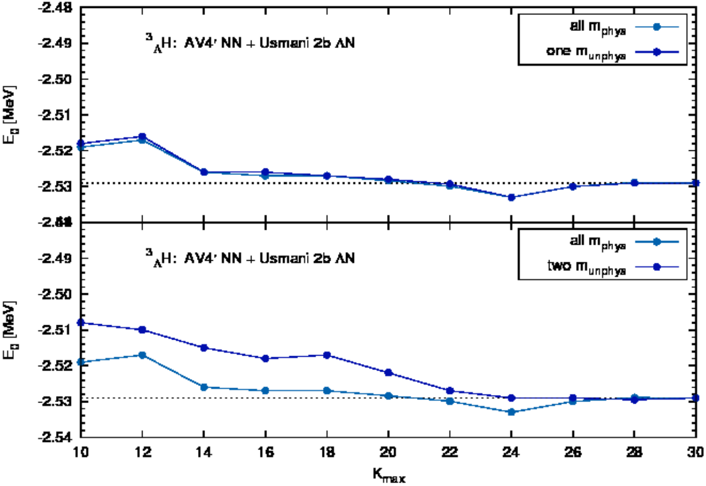
We consider a 3-body system like ${}^{3}_{\Lambda}$H (with no transitions) and **three different Jacobi sets**:

$$\begin{aligned} \boldsymbol{\eta}_0 &= \boldsymbol{\eta}(m_N, m_N, m_\Lambda) \; ; \\ \boldsymbol{\eta}_1 &= \boldsymbol{\eta}(m_N, m_N, m_N) \; ; \\ \boldsymbol{\eta}_2 &= \boldsymbol{\eta}(m_\Lambda, m_\Lambda, m_\Lambda) \; , \end{aligned}$$

and look how convergence is affected by changing the mass parameters.

- We employ semi-realistic **AV4**' NN potential combined with **Bodmer-Usmani** phenomenological ΛN interaction;
- we have implemented the **Lee-Suzuki** effective interaction procedure adapted to the case of unphysical mass parameters.

Convergence Tests II



Some Results

Interaction	System	NSHH	FY	GEM
AV8'	^{2}H		-2.226(1)	
AV8'+gNSC97f	$^3_\Lambda$H	-2.413(3)	-2.415(1)	-2.42(1)
	B_Λ	0.187(3)	0.189(1)	0.19(1)
AV8'	^{3}H	-7.76(0)	-7.76(0)	-7.77(1)
AV8'+gNSC97f	$^4_\Lambda$H	-10.08(2)		-10.10(1)
	B_Λ	2.32(2)		2.33(1)

In Progress:

1. completion of the mass transformations formalism ($\mathcal{W}$ **coefficients**);
2. bound state calculation of ^{3}H with full **NN-NΔ-$\Delta\Delta$** channels;

Future Application: Transitions inside Hypernuclei

	S = 0	S = -1	S = -2	S = -3	S = -4
I = 0	$(NN \to NN)$		$\begin{pmatrix} \Lambda\Lambda \to \Lambda\Lambda & \Lambda\Lambda \to \Xi N & \Lambda\Lambda \to \Sigma\Sigma \\ \Xi N \to \Lambda\Lambda & \Xi N \to \Xi N & \Xi N \to \Sigma\Sigma \\ \Sigma\Sigma \to \Lambda\Lambda & \Sigma\Sigma \to \Xi N & \Sigma\Sigma \to \Sigma\Sigma \end{pmatrix}$		$(\Xi\Xi \to \Xi\Xi)$
I = 1/2		$\begin{pmatrix} \Lambda N \to \Lambda N & \Lambda N \to \Sigma N \\ \Sigma N \to \Lambda N & \Sigma N \to \Sigma N \end{pmatrix}$		$\begin{pmatrix} \Lambda\Xi \to \Lambda\Xi & \Lambda\Xi \to \Sigma\Xi \\ \Sigma\Xi \to \Lambda\Xi & \Sigma\Xi \to \Sigma\Xi \end{pmatrix}$	
I = 1	$(NN \to NN)$		$\begin{pmatrix} \Xi N \to \Xi N & \Xi N \to \Lambda\Sigma & \Xi N \to \Sigma\Sigma \\ \Lambda\Sigma \to \Xi N & \Lambda\Sigma \to \Lambda\Sigma & \Lambda\Sigma \to \Sigma\Sigma \\ \Sigma\Sigma \to \Xi N & \Sigma\Sigma \to \Lambda\Sigma & \Sigma\Sigma \to \Sigma\Sigma \end{pmatrix}$		$(\Xi\Xi \to \Xi\Xi)$
I = 3/2		$(\Sigma N \to \Sigma N)$		$(\Sigma\Xi \to \Sigma\Xi)$	
I = 2			$(\Sigma\Sigma \to \Sigma\Sigma)$		

Outline

Conclusions

Collaboration with many experimental groups

- Reactions of astrophysical interest (LUNA, TH, TUNL, ORNL, . . .)
- Electromagnetic reactions (JLab)
- Hypernuclei (DaΦNE, . . .)
- Exotic nuclei (ISOLDE, GANIL, . . .)

Future projects & collaborations

- Efimov physics and Nuclear Physics
- Double β decay, dark-matter interactions, EDM: application of the interaction derived from EFT in heavy nuclei (STRENGTH)
- Generalized parton distributions in light nuclei (NINPHA)
- Electroweak reactions with LIT (MANYBODY)
- Exotic nuclei (SPES)
- . . .