Fundamendal physics studies in few-nucleon systems: the FBS project

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Outline

1. I.S. FBS – Few-Body Systems
2. HPC project: PV in few-nucleon systems
3. Other studies

I.S. Few-Body Systems

Aims

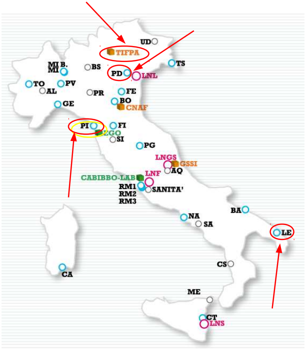
- Development of accurate methods to study the bound and continuum states of few-body systems using realistic interactions
- Development of more and more accurate nuclear potentials and electroweak currents
- Study of the properties of light and medium-light nuclear systems in radioactive ion beams
- 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

Groups

- 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.)*



CINECA resources for 2017

- Galileo: 250,000 hours
- Marconi/A1: 350,000 hours
- Marconi/A2: 300,000 hours

HPC project: PV in few-nucleon systems

Weak low-energy current-current Lagrangian at quark level

$$\mathcal{L} = \frac{G_F}{\sqrt{2}}\left(J_W^\dagger J_W + J_Z^\dagger J_Z\right)$$

- $J_W = \cos\theta_C J_W^{u\to d} + \sin\theta_C J_W^{u\to s}$
- $J_W^{u\to d} \equiv J_W^1$: $\Delta S = 0,\ \Delta T = 1$
- $J_W^{u\to s} \equiv J_W^{1/2}$: $\Delta S = -1,\ \Delta T = 1/2$
- $J_Z = \alpha J_Z^{u\to u} + \beta J_Z^{d\to d} + \cdots$
- $J_Z = J_Z^0 + J_Z^1$
- J_Z^0: $\Delta S = 0,\ \Delta T = 0$
- J_Z^1: $\Delta S = 0,\ \Delta T = 1$

Lagrangian describing low energy $\Delta S = 0$ processes

$$\mathcal{L} = \frac{G_F}{\sqrt{2}}\left[\cos^2\theta_C (J_W^1)^\dagger J_W^1 + \sin^2\theta_C (J_W^{1/2})^\dagger J_W^{1/2} + (J_Z^1)^\dagger J_Z^1 + (J_Z^1)^\dagger J_Z^0 + (J_Z^0)^\dagger J_Z^1 + (J_Z^0)^\dagger J_Z^0\right]$$

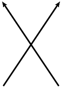
- Symm. product $(J_W^1)^\dagger J_W^1$: $\Delta T = 0\ \&\ 2$
- Symm. product $(J_W^{1/2})^\dagger J_W^{1/2}$: $\Delta T = 1$: suppressed by a factor $\tan^2\theta_C \approx 0.04$
- Interest: quark-quark weak interaction
- $\Delta T = 1$ component: dominated by neutral currents (?)
- Several discrepancies theory-experiment in hyperon non-leptonic decays $\Lambda \to p + \pi^-$, etc.

Effective field theory approach to nuclear PV

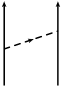
Chiral symmetry

- Group G=$SU(2)_R \times SU(2)_L$
- Since m_u, $m_d \ll 1$ GeV, $\mathcal{L}_{QCD}$ is approximately invariant under G
- $\mathcal{L}$ of hadrons made of u, d constrained by this symmetry
- Violation of chiral symmetry at quark level also dictates violation at hadron level
  - quark mass, EM interaction, weak interaction of quarks → PV interaction
  - [Weinberg, 1990], [Bernard, Kaiser, & Meissner (1995)], [Ordonéz, Ray, & van Kolck (1996)], [Epelbaum, Meissner, & Gloeckle (1998)], . . .
  - PV Lagrangian up to NLO [Kaplan & Savage, 1992]
  - PV Lagrangian up to N2LO [MV *et al.*, 2014]
  - Order of magnitude $\sim G_F f_\pi^2 \sim 10^{-7}$
- **Simplified approach, valid at low energies: Pionless EFT**

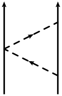
order Q



order Q^{-1}



order Q^{1}



. . .

- h_π^1 πNN coupling constant believed to be suppressed (after 40 years of exper. efforts)
- LQCD estimate: $(1.099 \pm 0.505) \times 10^{-7}$ [Wasem, 2012]

Pionless PV contact potential

Gardner, Haxton, Holstein, `1704:02617`

$$
\begin{aligned}
V_{CT}^{PV}(\mathbf{r}) \;=\;& \Lambda_0^{{}^1S_0-{}^3P_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}}{2m_N}\frac{\delta^3(\mathbf{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)+\frac{1}{i}\frac{\boldsymbol{\nabla}}{2m_N}\frac{\delta^3(\mathbf{r})}{m_\rho^2}\cdot i(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\right)\\
+\;& \Lambda_0^{{}^3S_1-{}^1P_1}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}}{2m_N}\frac{\delta^3(\mathbf{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)-\frac{1}{i}\frac{\boldsymbol{\nabla}}{2m_N}\frac{\delta^3(\mathbf{r})}{m_\rho^2}\cdot i(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\right)\\
+\;& \Lambda_1^{{}^1S_0-{}^3P_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}}{2m_N}\frac{\delta^3(\mathbf{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\tau_{1\,z}+\tau_{2\,z})\right)\\
+\;& \Lambda_1^{{}^3S_1-{}^3P_1}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}}{2m_N}\frac{\delta^3(\mathbf{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)(\tau_{1\,z}-\tau_{2\,z})\right)\\
+\;& \Lambda_2^{{}^1S_0-{}^3P_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}}{2m_N}\frac{\delta^3(\mathbf{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1\otimes\boldsymbol{\tau}_2)_{20}\right)
\end{aligned}
$$

$\Lambda_0^{{}^1S_0-{}^3P_0}$, . . .: LECs to be determined

$S-P$ transitions: [Danilov, 1965] – From general properties of the Lagrangian: [Girlanda, 2008]

Large N_c analysis

[Schindler, Springer, & Vanasse, 2016]

$$\begin{aligned}
\Lambda_0^+ \equiv \frac{3}{4}\Lambda_0^{^3S_1-^1P_1} + \frac{1}{4}\Lambda_0^{^1S_0-^3P_0} &\sim N_c \\
\Lambda_2^{^1S_0-^3P_0} &\sim N_c, \\
\Lambda_0^- \equiv \frac{1}{4}\Lambda_0^{^3S_1-^1P_1} - \frac{3}{4}\Lambda_0^{^1S_0-^3P_0} &\sim 1/N_c \\
\Lambda_1^{^1S_0-^3P_0} &\sim \sin^2\theta_W \\
\Lambda_1^{^3S_1-^3P_1} &\sim \sin^2\theta_W
\end{aligned}$$

$1/N_c^2 = 1/9$, $\sin^2\theta_W/N_c \sim 1/12$ 3 LECs suppressed

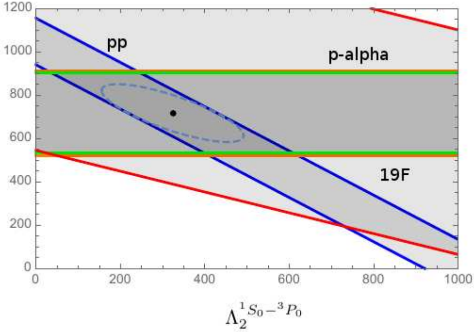
LQCD calculation of $\Lambda_2^{^1S_0-^3P_0}$ in progress [Tiburzi, 2012], [Kurth *et al.*, 2016]

Experiments

- Longitudinal asymmetry $A_L(pp)$ in $\vec{p}p$ elastic scattering
  - $A_L(\vec{p}p) = (-0.97 \pm 0.20) \times 10^{-7}$, $E_p = 13.6$ MeV Bonn 1991
  - $A_L(\vec{p}p) = (-1.53 \pm 0.21) \times 10^{-7}$, $E_p = 45$ MeV PSI 1980
  - $A_L(\vec{p}p) = (+0.84 \pm 0.34) \times 10^{-7}$, $E_p = 221$ MeV TRIUMF 2003
- Longitudinal asymmetry $A_L(p\alpha)$ in $\vec{p}\alpha$ elastic scattering
  - $A_L(\vec{p}\alpha) = (-3.3 \pm 0.9) \times 10^{-7}$, $E_p = 46$ MeV PSI 1985
- γ angular asymmetry A_γ in ^{19}F γ–decay
  - $A_\gamma(^{19}F) = (-8.5 \pm 2.6) \times 10^{-5}$ Seattle 1993
  - $A_\gamma(^{19}F) = (-6.8 \pm 1.8) \times 10^{-5}$ Mainz 1987
- γ circular polarization P_γ in ^{18}F γ–decay
  - $P_\gamma(^{18}F) = (-7 \pm 20) \times 10^{-4}$ Caltech 1988
  - $P_\gamma(^{18}F) = (3 \pm 6) \times 10^{-4}$ Florence 1985
- Asymmetry A_γ in $\vec{n} + p \to d + \gamma$
  - $A_\gamma(\vec{n}p) \lesssim 1 \times 10^{-8}$ ORNL, data analysis in progress
- Longitudinal asymmetry A_L in $\vec{n} + {}^3\mathrm{He} \to p + {}^3\mathrm{H}$
  - $A_L(\vec{n}{}^3\mathrm{He})$ ORNL, data analysis in progress

Description of the experimental data with only two parameters

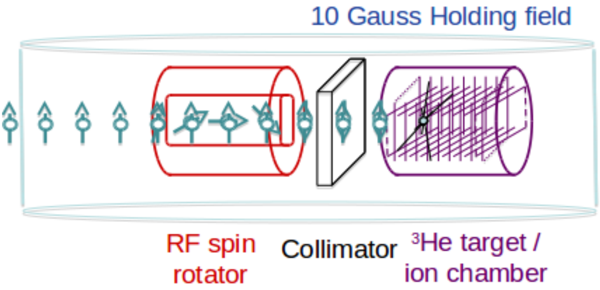
$$
\begin{aligned}
\frac{2}{5}\Lambda_0^+ + \frac{1}{\sqrt{6}}\Lambda_2^{{}^1S_0-{}^3P_0} &= 419 \pm 43 & A_L(\vec{p}p)\\
\Lambda_0^+ &= 715 \pm 195 & A_L(\vec{p}\alpha)\\
\Lambda_0^+ &= 718 \pm 184 & A_\gamma({}^{19}F)
\end{aligned}
$$



“central values”

- $\Lambda_0^+ = 717 \pm 153$
- $\Lambda_2 = 324 \pm 164$

n3he experiment at ORNL

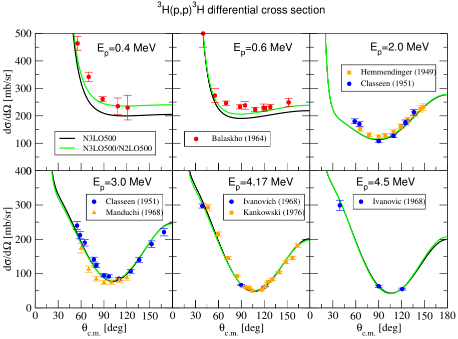


- Spallation Neutron Source: 10^8 n/sec/cm^2 ultracold neutrons $E_n \sim$ meV
- $p + {}^3\mathrm{H}$ emitted with 0.765 MeV
- target of $^3\mathrm{He}$ works also as a detectors mesuring the protons and $^3\mathrm{H}$
- Data taken in 2015 & 2016; now data analysis in progress
- Which is the prediction using the pionless contact potential?

Calculation of the $n + {}^3\mathrm{He} \to p + {}^3\mathrm{H}$ longitudinal asymmetry (1)

Step 1: scattering wave functions

- initial state $(n - {}^3\mathrm{He})$ $q \approx 0$: ${}^1S_0$, ${}^3S_1$
- final state $(p - {}^3\mathrm{H})$ $q = 0.165$ fm^{-1}:
  - $J = 0$: ${}^1S_0$, ${}^3P_0$
  - $J = 1$: ${}^3S_1 - {}^3D_1$, ${}^1P_1 - {}^3P_1$
- Solution of $H\Psi = E\Psi$ expanding on a basis, enforcing the right b.c.
- $H = T + V_{NN} + W_{NNN}$ PC strong interaction potentials
- Derived from χ EFT: [Entem & Machleidt, 2003]
- OpenMP code running on Galileo & Marconi



Calculation of the $n + {}^3\mathrm{He} \to p + {}^3\mathrm{H}$ longitudinal asymmetry (2)

Step 2: Computation matrix elements of the PV potential

PC		PV	
${}^1S_0 \to {}^1S_0$	$T^0_{00,00}$	${}^1S_0 \to {}^3P_0$	$T^1_{00,11}$
${}^3S_1 \to {}^3S_1$	$T^0_{01,01}$	${}^3S_1 \to {}^1P_1$	$T^1_{01,10}$
		${}^3S_1 \to {}^3P_1$	$T^1_{01,11}$

- $T^J_{LS,L'S'} = \langle \Psi^J_{LS} | V_{PV} | \Psi^J_{L'S'} \rangle$
- Monte Carlo multidimensional integration with a MPI code on Marconi/KNL

$$T^J_{LS,L'S'} = \int d^3r_1 \cdots d^3r_4 F(\boldsymbol{r}_1, \ldots, \boldsymbol{r}_4) \approx \frac{1}{N} \sum_c \frac{F(c)}{W(c)}$$

- $c \equiv \boldsymbol{r}_1, \ldots, \boldsymbol{r}_4$
- $W(c)$ suitable weight factor (importance sampling)

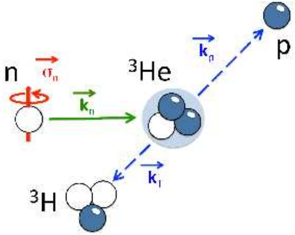
Results

PV asymmetry

$$A_L(\vec{n}^3\mathrm{He}) = a_+\Lambda_0^+ + a_2\Lambda_2^{{}^1S_0-{}^3P_0}$$

- Difficult integration due to the $\delta(\mathbf{r})$ appearing in V_{PV}

$$\delta(\mathbf{r}) \to \frac{\Lambda^3}{(2\pi)^{\frac{3}{2}}} e^{-\frac{1}{2}(\Lambda r)^2}$$



- First case: $\Lambda = 5$ GeV
- $500,000$ integration points
- $a_+ = (0.72 \pm 0.20) \times 10^{-3}$
- $a_2 = (0.09 \pm 0.10) \times 10^{-5}$

Preliminary result

$$A_L(\vec{n}^3\mathrm{He}) = (0.52 \pm 0.15) \times 10^{-7}$$

- Check the dependance on Λ, PC interaction, etc

Other studies

- Study of hypernuclei (TIFPA)
  - HPC code [Ferrari-Ruffino *et al.*, 2017] `arXiv:1701.06399`
- CP violation → EDM in light nuclei
  - Experiments for measuring the EDM of charge particles (p, ^{2}H, ^{3}H, ^{3}He, . . . nuclei) under study:
  - BNL: Pure electric ring (Storage Ring EDM Coll.)
    - `https://www.bnl.gov/edm/Proposal.asp`
  - Jülich: a new E/B ring or using the existing COSY ring (JEDI Coll.)
    - `http://collaborations.fz-juelich.de/ikp/jedi/`
- Dark-matter interactions with nuclei
  - Dark-matter-nucleons & dark-matter-pions interactions parametrized via a general EFT . . .
  - Analysis of the Darkside experiment (^{40}Ar)
  - In collaboration with Colleagues of the STRENGTH I.S.

Collaborators

- J. Dohet-Eraly, E. Filandri, A. Kievsky & L.E. Marcucci - *INFN & Pisa University, Pisa (Italy)*
- A. Gnech - *GSSI, L'Aquila, (Italy)*
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- R. Schiavilla - *ODU & Jefferson Lab. Newport News (USA)*

Thank you!