Non-Symmetrized Hyperspherical Harmonics Method Applied to Light Hypernuclei

Fabrizio Ferrari Ruffino

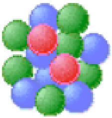
.

September 22, 2015

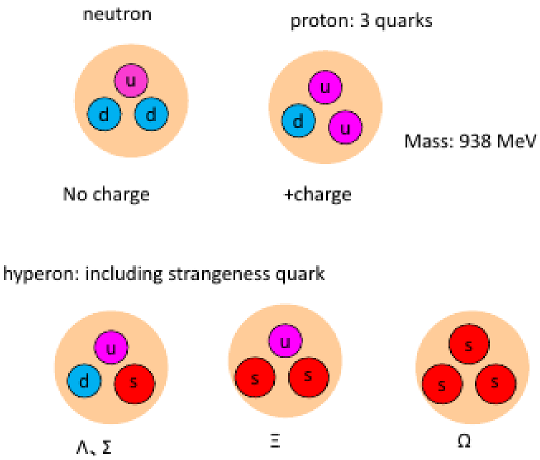
Contents

Nuclei with Strangeness

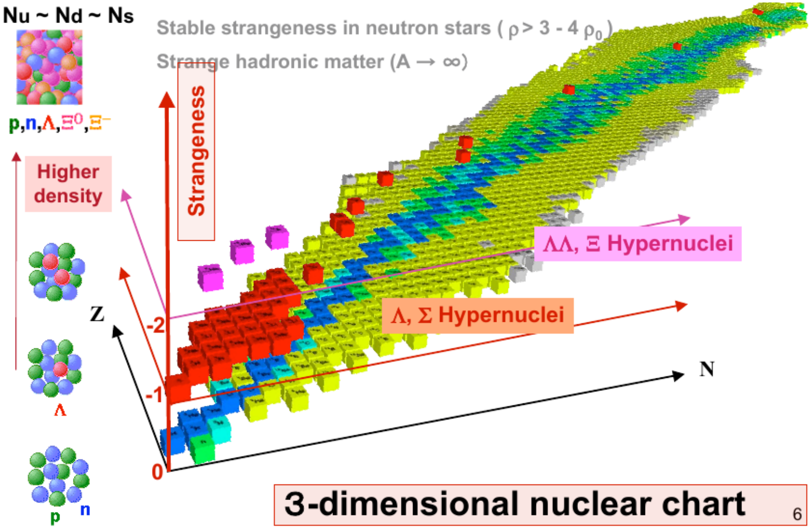
$$m_\Lambda = 1116 \text{ MeV}$$
$$m_{\Sigma^+} = 1189$$
$$m_{\Sigma^0} = 1193$$
$$m_{\Omega^-} = 1673$$



$$\tau_\Lambda = 263\ ps$$
$$\tau_{\Sigma^+} = 80\ ps$$
$$\tau_{\Sigma^0} = 7.4 \cdot 10^{-20} s$$
$$\tau_{\Omega^-} = 82\ ps$$



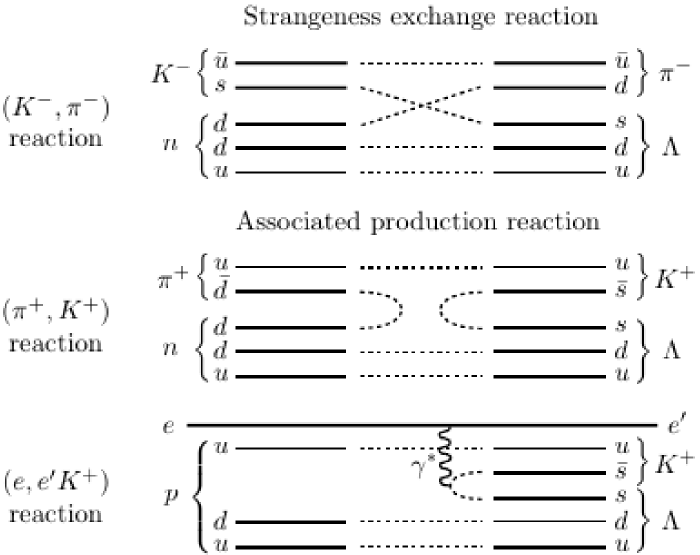
Hypernuclear Chart



[1]

[1] by M. Kaneta inspired by HYP06 conference poster

Production of Hypernuclei

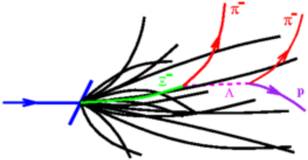


[2]

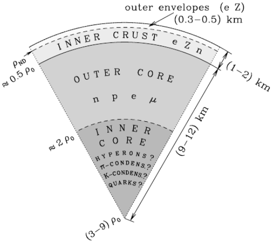
[2] from the PhD thesis of D.Lonardoni, 'From Hypernuclei to Hypermatter..'

Research Directions

SUBNUCLEAR PHYSICS:
weak decay, quark structures ...



NUCLEAR ASTROPHYSICS:
Hyperon puzzle...



$\Rightarrow$ LOW ENERGY NUCLEAR PHYSICS: $\Leftarrow$

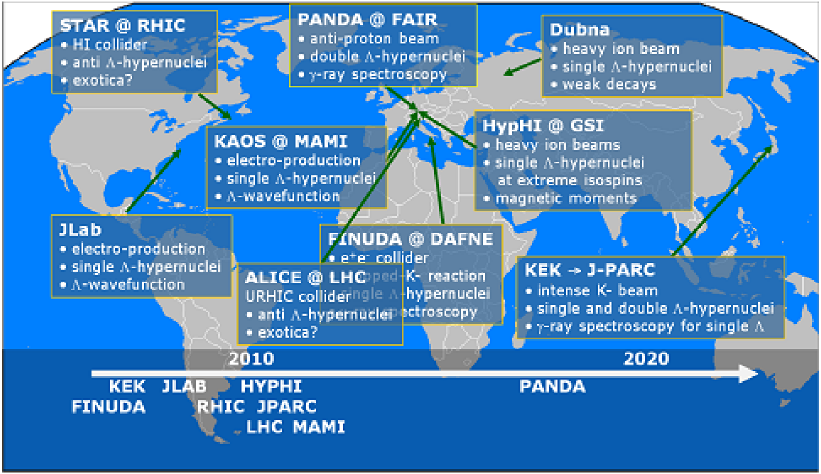
- study of N-Y **interaction** (and Y-Y);
- few-many body **nuclear models** (mainly for bound states);
- Experimental reference: γ**-ray spectroscopy**

Present and Future Perspectives

- Despite exensive investigations, single Λ hypernuclei knowledge is **far** from that of ordinary nuclei;
- Only **one** bound Σ-hypernucleus detected!
- **No** Ξ hypernuclei detected (some indications of weak attraction);
- **No** experimental information about Ω hypernuclei;
- **Four** $\Lambda\Lambda$-hypernuclei energies measured (${}^{6}_{\Lambda\Lambda}$He, ${}^{10}_{\Lambda\Lambda}$Be, ${}^{12}_{\Lambda\Lambda}$Be, ${}^{13}_{\Lambda\Lambda}$B);

$\Rightarrow$ Main goal: **extension** of nuclear chart in all directions!

Experimental investigation in the world



Ab initio method

We consider:

- **A-body** system;
- **A** particle **degrees of freedom**;
- **well-defined** microscopic Hamiltonian;
- internal relative motion treated **correctly.**

Then:

an **ab initio method** enables one to obtain the observable considered by solving the quantum mechanical many body equations, **without any uncontrolled approximation.**

$\Rightarrow$ We can focus on the input **interactions.**

Overview

Several **ab initio** methods:

- Monte Carlo methods;
- Coupled cluster model;
- No core shell model;
- Gaussian expansion method;
- $\Rightarrow$ **Hyperspherical Harmonics method.**

General method for bound states

The starting problem is simple. We find:

- a **basis** for the Hilbert space;
- a well defined particle-particle **interaction**.

$\Rightarrow$ We *build* a truncated $\hat{\text{H}}$ matrix, we *diagonalize* it... It's done!

Problems:

- **selection** of physical states $\rightarrow$ good symmetries;
- good **convergence** / computational weight.

The HH basis

We define **hyperspherical Jacobi coordinates**:

$\Rightarrow$ *hyperradius* ρ + *hyperangles* ϕ_i + *angles*

The A-body kinetic operator is then:

$$\hat{T} = -\frac{1}{2m}\Delta_\rho + \hat{T}_K(\rho) \quad ; \quad \hat{T}_K = \frac{1}{2m}\frac{\hat{\mathbf{K}}_N^2}{\rho^2}$$

where $\hat{\mathbf{K}}_N^2$ is the **grand angular momentum** operator:

$$\hat{\mathbf{K}}_2^2 = -\frac{\partial^2}{\partial\phi_2^2} - 4\cot(2\phi_2)\frac{\partial}{\partial\phi_2} + \frac{1}{\cos^2\phi_2}\hat{l}_1^2 + \frac{1}{\sin^2\phi_2}\hat{l}_2^2$$

The HHs are the **eigenfunctions** of $\hat{\mathbf{K}}_N^2$:

$$\hat{\mathbf{K}}_N^2\mathcal{Y}_{[K_N]}(\Omega_N) = K_N(K_N + 3N - 2)\mathcal{Y}_{[K_N]}(\Omega_N)$$

Non-symmetrized HH method

Problem: Selection of **antisymmetric** states (we deal with fermions):

$\Rightarrow$ We add to Ĥ a special operator which **selects** 'by himself' the interesting states:

$$\hat{H}' = \hat{H} + \gamma \hat{C}(A)$$

where:

$$\hat{C}(A) = \sum_{i>j} \hat{P}_{ij}$$

$\Rightarrow$ No need for explicit symmetrization. In case of Hypernuclei:

$$\hat{C} = \hat{C}_N(A - N_Y) + \hat{C}_Y(N_Y)$$

We are dealing now with **different particles** $\rightarrow$ **extension** of the method.

Some results

$V_{NN} + V_{YN}$	System	NSHH	GEM
AV8'	^{2}H	-2.22	
AV8'+S	$^3_\Lambda$H	-2.41	
	B_Λ	0.19	0.19
AV8'	^{2}H	-2.22	
AV8'+S'	$^3_\Lambda$H	-2.55	
	B_Λ	0.35	0.36
AV8'	^{2}H	-2.22	
AV8'+S"	$^3_\Lambda$H	-2.91	
	B_Λ	0.69	0.72
AV8'	^{3}H	-7.76	
AV8'+S	$^4_\Lambda$H	-10.05	
	B_Λ	2.29	2.33

Present and future goals

1. **Phenomenological** interactions;
    - 2-body potentials
    - 3-body potentials
2. Interactions from **effectve field theory**
3. Study of A>5 systems $\rightarrow$ need for efficient **parallelization**
4. Study of **double** $\Lambda\Lambda$ hypernuclei?
5. Study of hypernuclei with **other hyperons**?

Our group in Trento - Few Body Theory

Supervisors:

- Giuseppina Orlandini
- Winfried Leidemann

PhD students:

- Sergio Deflorian
- Fabrizio Ferrari Ruffino

Collaborators:

- Nir Barnea - The Hebrew University of Jerusalem, Jerusalem, Israel.
- Victor D. Efros - Russian Research Centre 'Kurchatov Institute', Moscow, Russia.
- Sonia Bacca - TRIUMF, Vancouver, Canada.
- Edward L. Tomusiak - University of Saskatchewan, Saskatoon, Canada.