Structure of single Λ Hypernuclei with Gogny type Λ-nucleon forces

Nithish Kumar Covalam Vijayakumar

(TU Darmstadt)

In collaboration with

Luis Robledo

Isaac Vidana

Contents

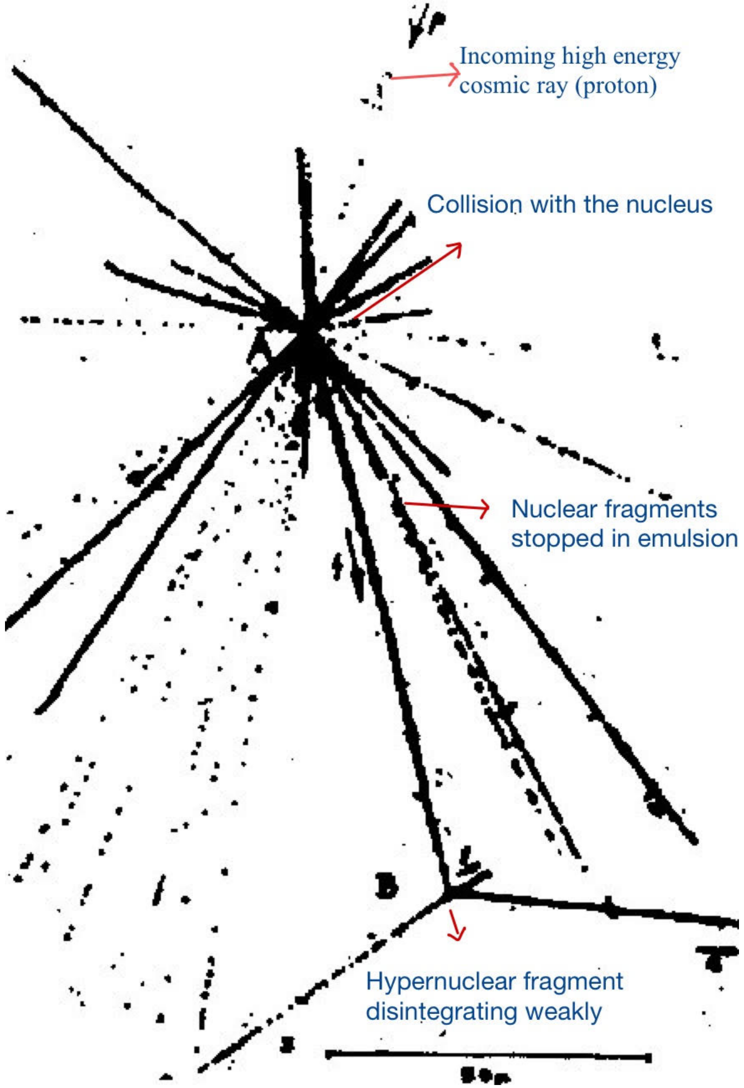
What is a hyperon?

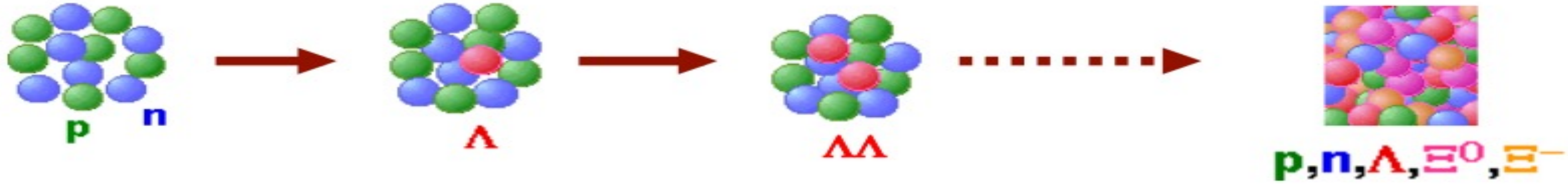
A Hyperon is a baryon made of one, two or three strange quarks

Hyperon	Quarks	$I(J^P)$	Mass (MeV)
Λ	uds	$0(1/2^+)$	1115
Σ^+	uus	$1(1/2^+)$	1189
Σ^0	uds	$1(1/2^+)$	1193
Σ^-	dds	$1(1/2^+)$	1197
Ξ^0	uss	$1/2(1/2^+)$	1315
Ξ^-	dss	$1/2(1/2^+)$	1321
Ω^-	sss	$0(3/2^+)$	1672

What is a hypernucleus?

It is a bound system of nucleons with one or more hyperons (baryons with strangeness content)

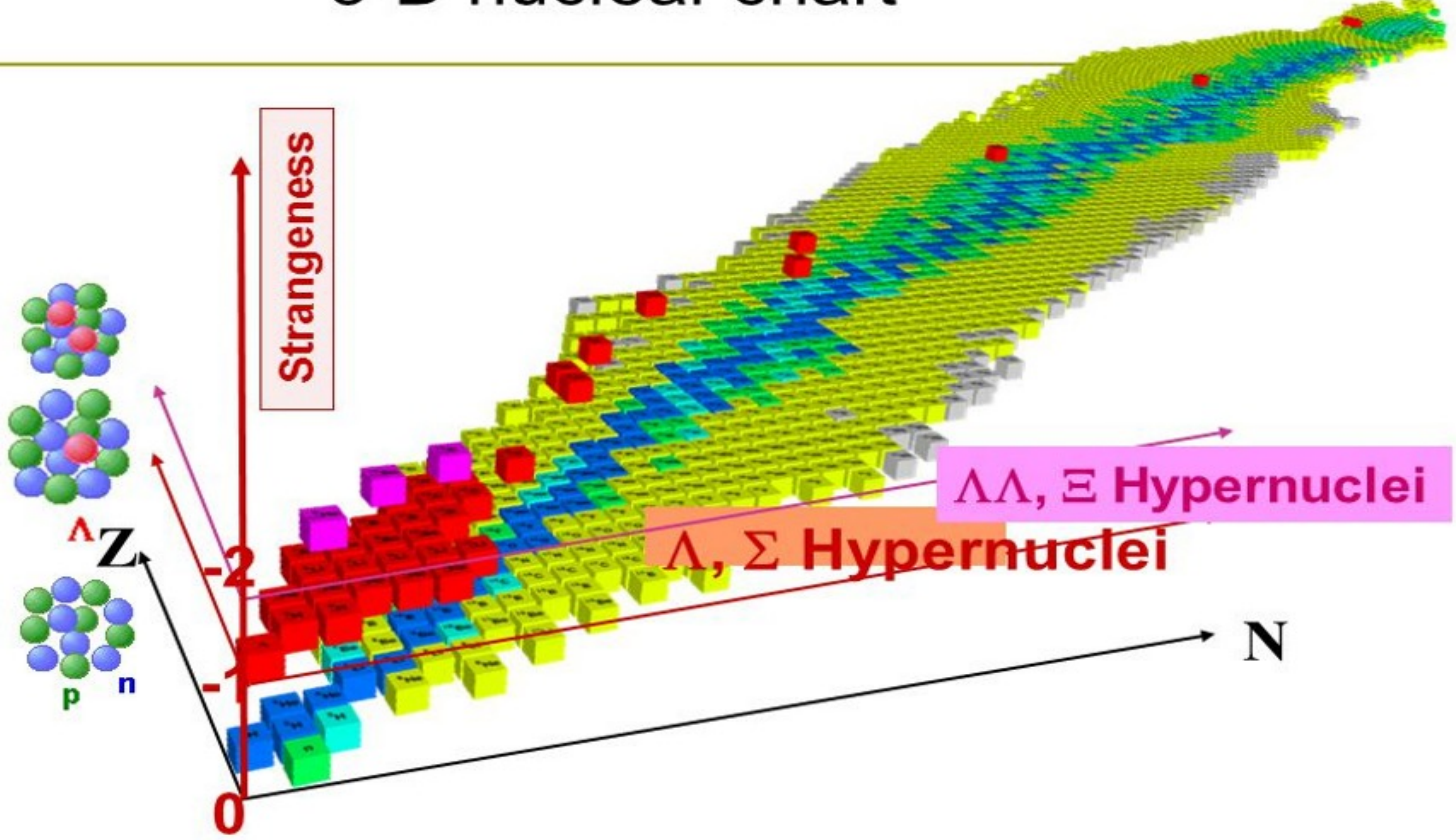




First discovered by two Polish physicists
Marian Danysz and Jerzy Pniewski in 1953

NOMENCLATURE: ${}^{12}_{\Lambda}C$, ${}^{16}_{\Xi}O$, ${}^{10}_{\Lambda\Lambda}Be$

3-D nuclear chart



Experimentally, more than 40 single Λ hypernuclei, and few double Λ and single- Ξ ones have been identified.

No single ∑ hypernuclei have so far experimentally been observed.

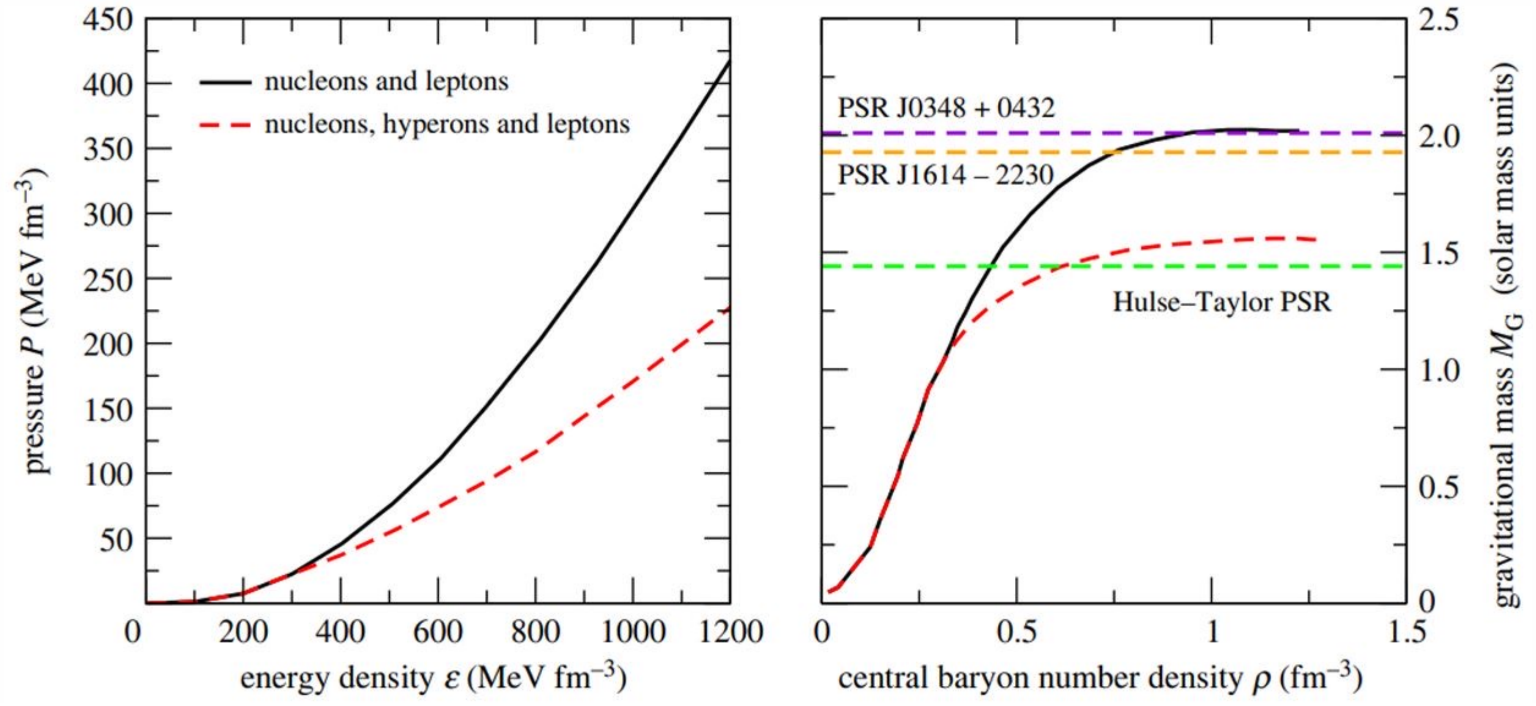
Some motivations for studying hypernuclei

- It is a "laboratory" for extracting hyperon-nucleon and hyperon-hyperon interactions and can improve the current understanding of baryon-baryon interaction.

τ_Λ=252 ps!

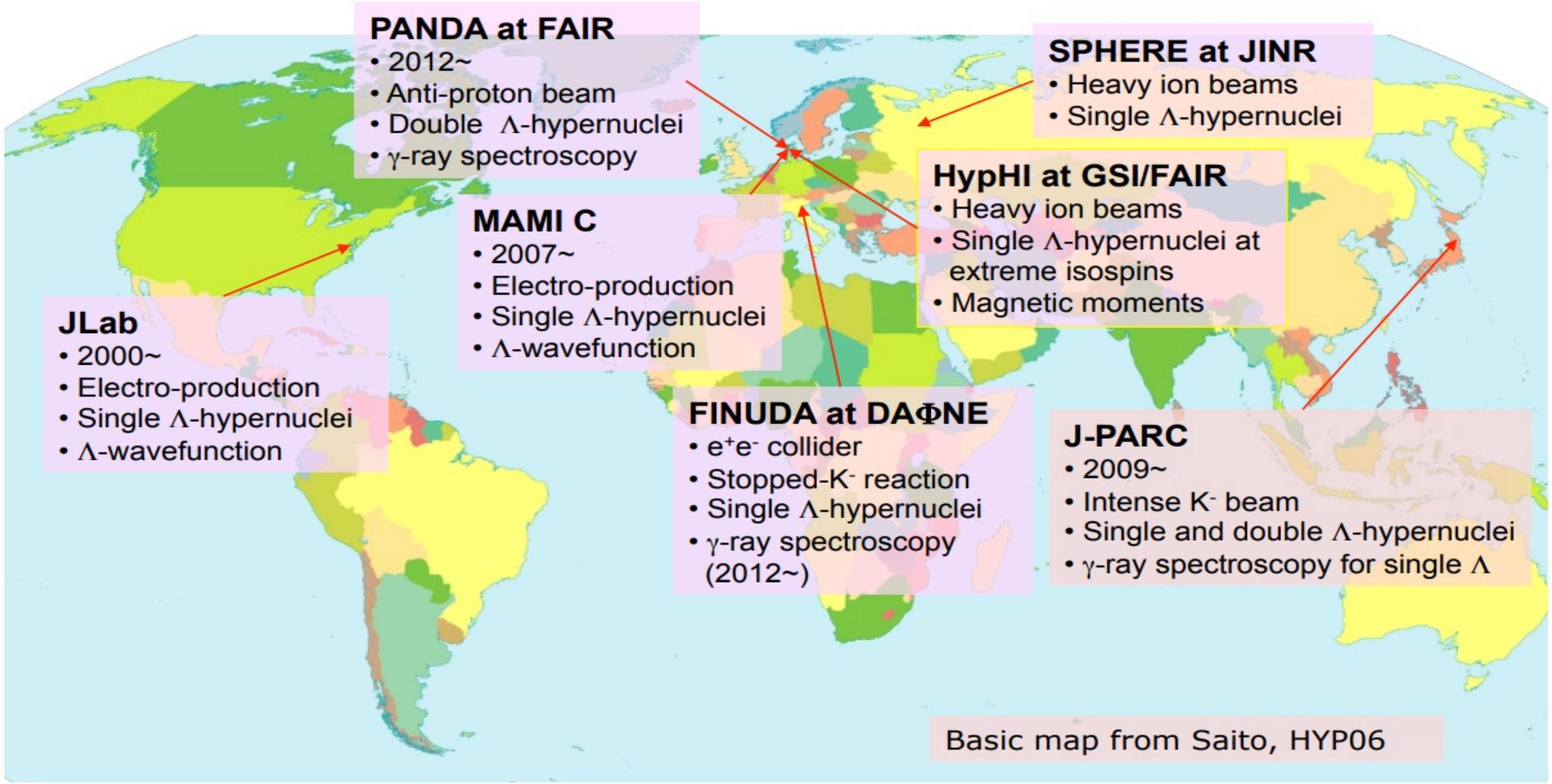
- Hyperon can be used to sample the interior of nuclei e.g. single particle structure.

- Understanding the behaviour of hyperons in nuclear medium is very important in the physics of neutron stars (Hyperon Puzzle).

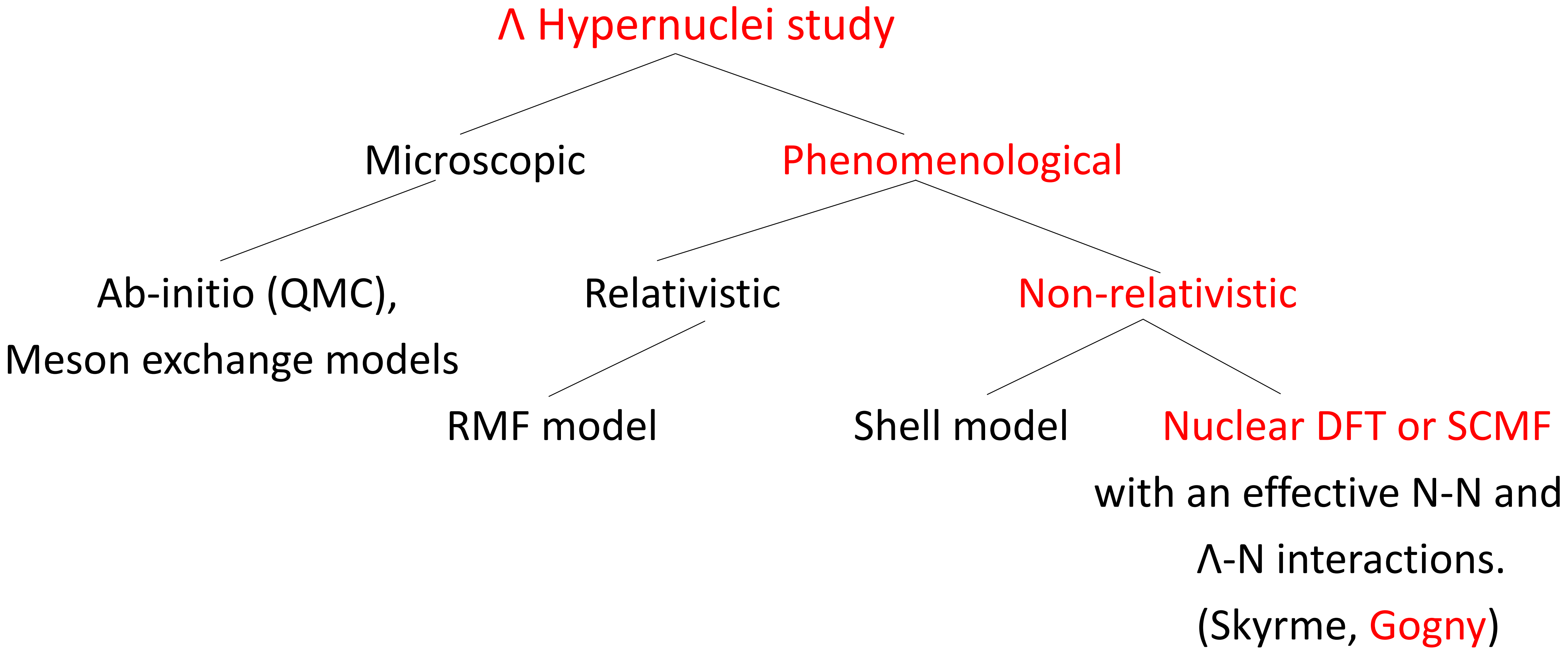


(Isaac Vidaña, Proc. Roy. Soc. A, 474(2217), 20180145, 2018)

International Hypernuclear Network



Theoretical models to study Λ hypernuclei



Hartree-Fock-Bogoliubov (HFB)-Gogny method

- Nuclear DFT
- Phenomenological interaction
- Non-relativistic treatment

$$V(1,2) = \sum_{i=1}^{2} e^{-(\vec{r}_1-\vec{r}_2)^2/\mu_i^2} \left(W_i + B_i P^\sigma - H_i P^\tau - M_i P^\sigma P^\tau\right)$$

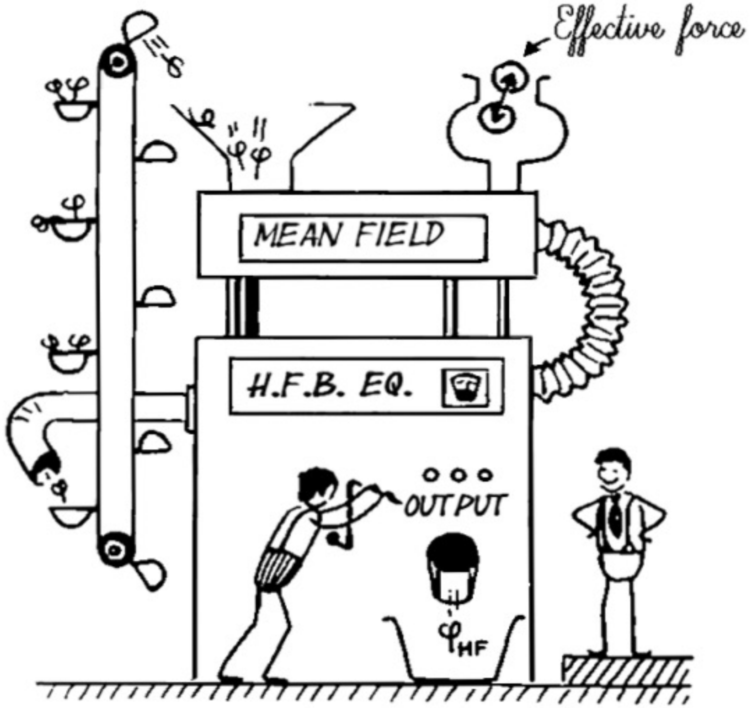
$$+iW_0(\sigma_1+\sigma_2)\vec{k} \times \delta(\vec{r}_1-\vec{r}_2)\vec{k} + V_{\mathrm{Coulomb}}(\vec{r}_1,\vec{r}_2)$$

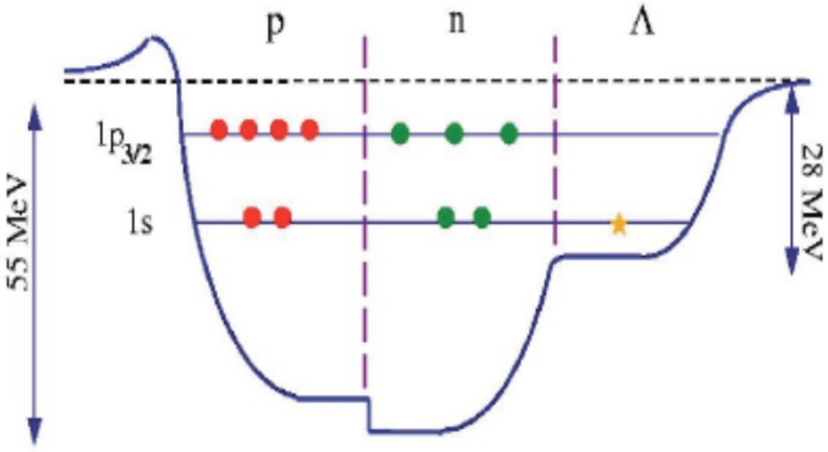
$$+t_3(1+x_0P^\sigma)\delta(\vec{r}_1-\vec{r}_2)\rho^\alpha\left((\vec{r}_1+\vec{r}_2)/2\right)$$

Gogny Force

Finite range force

14 adjustable parameters !





Simple s.p. model of ${}^{12}_{\Lambda}C$

(J.F. Berger et al., The EPJ A 53, Article number: 214, 2017)

Pairing correlations included only for nucleons!

Hamiltonian of hypernuclei

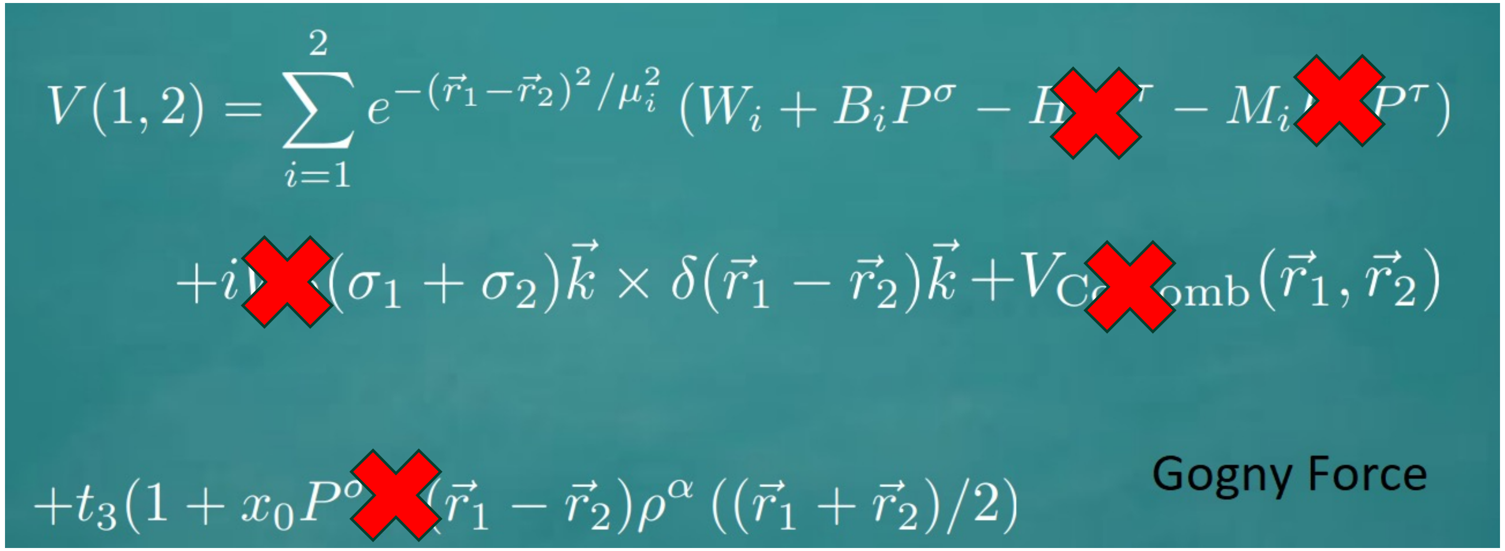
$$\hat{H} = \sum_{i,j} t_{ij}^{N} \hat{a}_i^\dagger \hat{a}_j + \sum_{i,j} t_{ij}^{\Lambda} \hat{c}_i^\dagger \hat{c}_j + \frac{1}{4}\sum_{ijkl} \bar{V}_{ijkl}^{NN} \hat{a}_i^\dagger \hat{a}_j^\dagger \hat{a}_l \hat{a}_k + \sum_{ijkl} V_{ijkl}^{\Lambda N} \hat{a}_i^\dagger \hat{c}_j^\dagger \hat{c}_l \hat{a}_k - \hat{T}_{c.m.}$$

$\bar{V}_{ijkl}^{NN}$: Anti-symmetrised, Gogny D1S parametrisation

$V_{ijkl}^{\Lambda N}$: Only in direct channel, Simplified version of Gogny force

$$V(\vec{r}_1, \vec{r}_2) = \sum_{i=1,2} e^{-(r_{12}/\mu_i)^2} (W_i + B_i \hat{P}_\sigma)$$

Contains 6 unknown parameters !



Fitting protocol and code implementation

Λ-N Gogny interaction parameters

- The 6 unknown parameters (W_1, B_1, W_2, B_2, μ_1 and μ_2) fitted using Simulated Annealing Method (SAM).
- SAM searches for global minimum on the hypersurface of χ^2 functions.
- Chi square is given by,

$$\chi^2 = \frac{1}{N_d - N_p} \sum_{i=1}^{N_d} \left(\frac{M_i^{theo} - M_i^{exp}}{\sigma_i} \right)^2$$

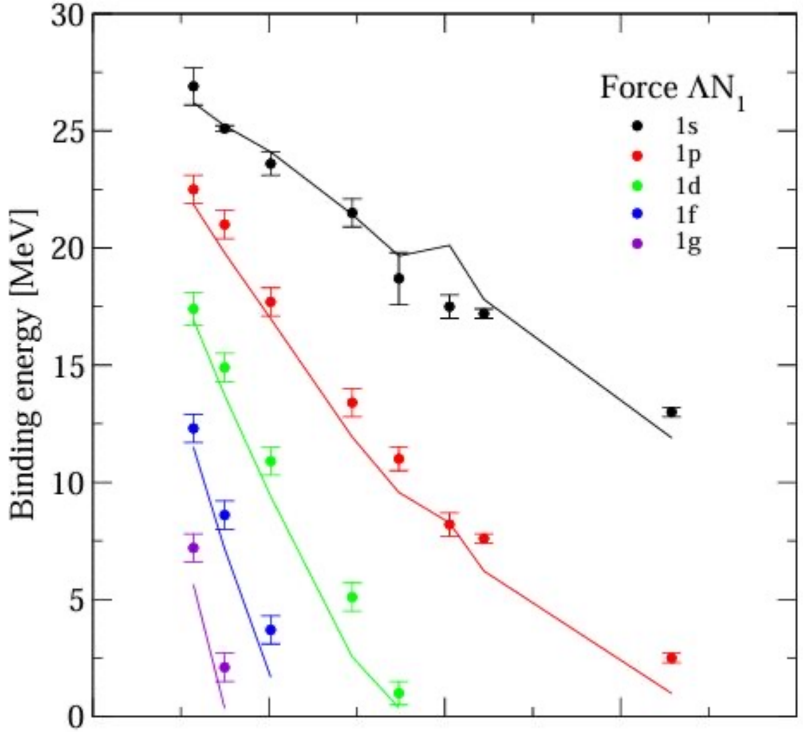
- Chosen observable for fitting is expt. ground state or 1s-shell Λ B.E.´s in 8 medium to heavy hypernuclei.

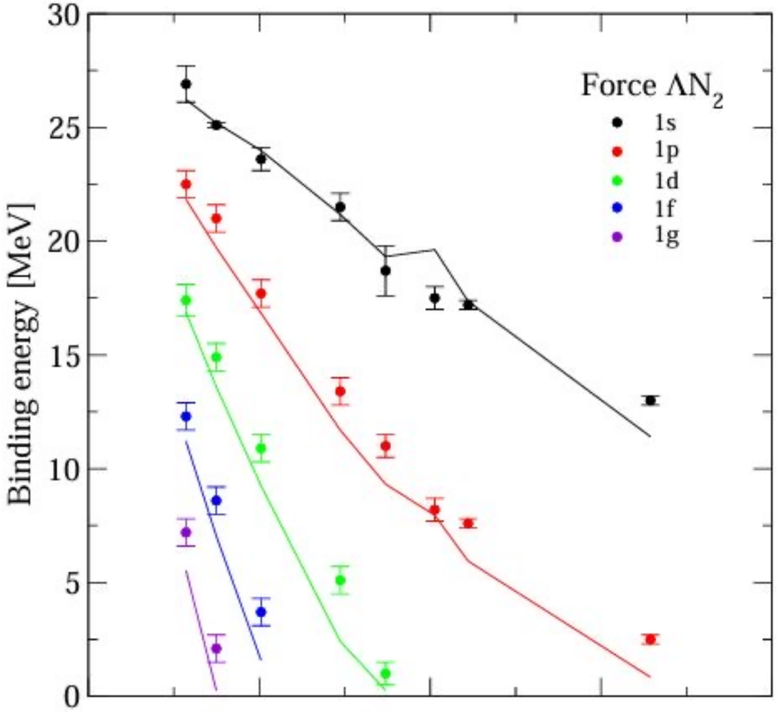
Code implementation:

- Calculations were performed using *HFBaxial* code.
- Incorporated Λ-N Gogny interaction in *HFBaxial* code.
- Concerning SAM fitting protocol, separate bash script code was written.

Results

Binding energy predictions for A=16 to 208



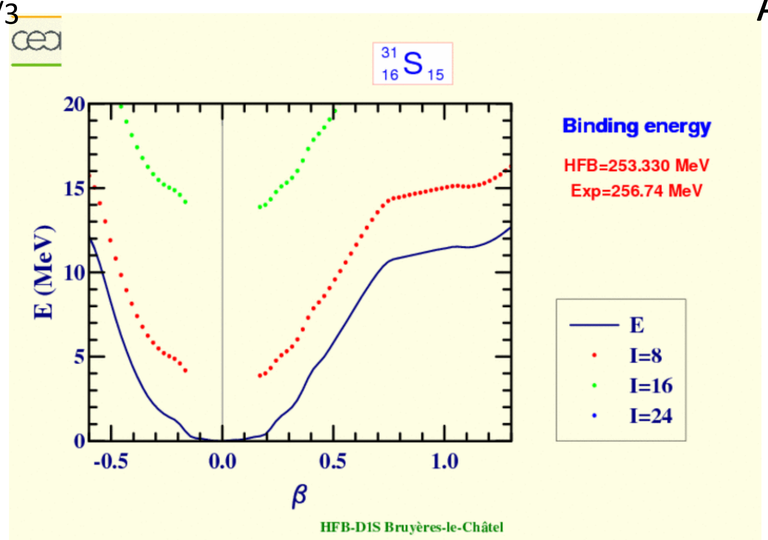


$A^{-2/3}$ $A^{-2/3}$

Expt. B.E. shown for: ${}^{208}_{\Lambda}\mathrm{Pb}$, ${}^{139}_{\Lambda}\mathrm{La}$, ${}^{89}_{\Lambda}\mathrm{Y}$, ${}^{51}_{\Lambda}\mathrm{V}$, ${}^{40}_{\Lambda}\mathrm{Ca}$, ${}^{32}_{\Lambda}\mathrm{S}$, ${}^{28}_{\Lambda}\mathrm{Si}$ and ${}^{16}_{\Lambda}\mathrm{O}$

B.E. prediction for different Λ states are in general reasonable despite using only 1s-shell B.E. in fitting!

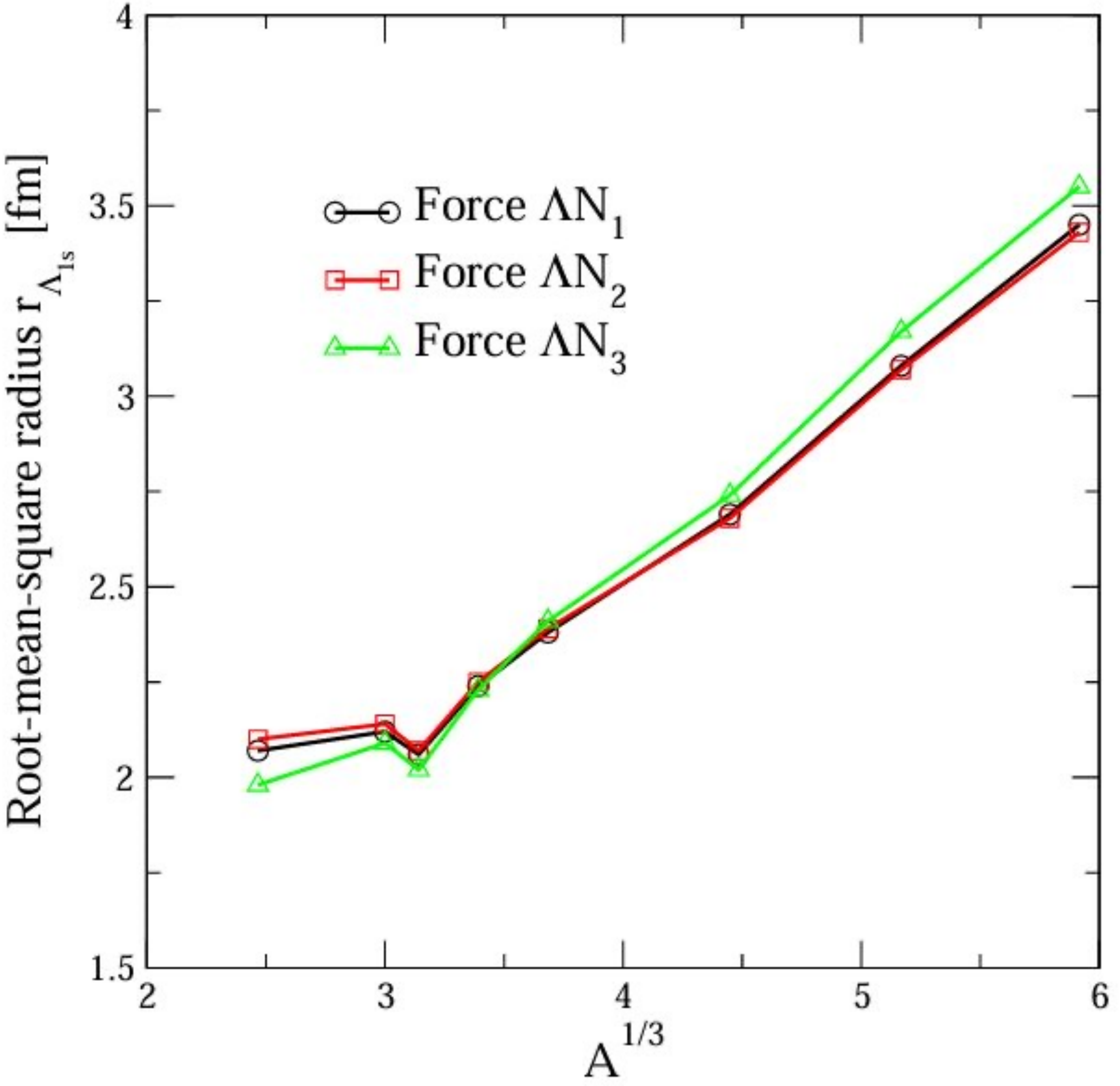
"Kink" observed for ${}^{32}_{\Lambda}S$!



B.E. predictions for ${}^{32}_{\Lambda}S$ could have improved if the fluctuations in β_2 were considered.

(https://www-phynu.cea.fr/science_en_ligne/carte_potentiels_microscopiques/carte_potentiel_nucleaire_eng.html)

Rms radii of ground state Λ orbitals (1s-shell)



$$\langle \hat{r}^2 \rangle^{1/2} = \sqrt{\frac{\langle \Psi | \hat{r}^2 | \Psi \rangle}{\langle \Psi | \Psi \rangle}}$$

r_Λ increases with A of nuclei

Almost a linear dependence in medium to heavy mass regions

Again a "Kink" observed for ${}^{32}_{\Lambda}S$

Global properties of ground state Λ hypernuclei (Λ in 1s-shell)

Quadrupole deformation

Ordinary nuclei	Q_2 (fm^2)
^{15}O	$-1.4 * 10^{-4}$
^{27}Si	25.34
^{31}S	0.15
^{39}Ca	$-1 * 10^{-6}$
^{50}V	-3.00
^{88}Y	-0.15
^{138}La	-0.56
^{207}Pb	-0.40

$\xrightarrow{\Lambda}$

Hypernuclei	Q_2 (fm^2)
$^{16}_{\Lambda}O$	$-1.9 * 10^{-5}$
$^{28}_{\Lambda}Si$	18.70
$^{32}_{\Lambda}S$	$2.3 * 10^{-3}$
$^{40}_{\Lambda}Ca$	$4 * 10^{-6}$
$^{51}_{\Lambda}V$	49.62
$^{89}_{\Lambda}Y$	-0.15
$^{139}_{\Lambda}La$	-0.32
$^{208}_{\Lambda}Pb$	-0.06

Λ tends to make the nucleus less deformed

Conclusions

- First hypernuclear mean field studies performed using Gogny-HFB method.
- Λ − N Gogny interaction was successfully incorporated in HFBaxial code to perform hypernuclei calculations.
- Gogny D1S parameters was used in N-N channel and in the case of Λ−N channel various parameter sets have been obtained using SAM fitting protocol.
- Though we used only ground state or 1s Λ state binding energies of hypernuclei in fitting protocol, the predictions for the other 1L Λ states are quite satisfactory. In addition, rms radii of hyperon was computed.

Outlook

- Density Dependent term of Gogny force can be incorporated in Λ − N interaction.
- Other structure calculations of Λ hypernuclei all over the nuclear chart as well as to extend it to include other type of hyperons can be performed.

Eur. Phys. J. A (2024) 60:67
https://doi.org/10.1140/epja/s10050-024-01278-7
THE EUROPEAN PHYSICAL JOURNAL A
Check for updates
Regular Article - Theoretical Physics

Structure of single Λ-hypernuclei with Gogny-type Λ-nucleon forces

C. V. Nithish Kumar[1,2], L. M. Robledo[2,3], I. Vidaña[4,a]

[1] Dipartimento di Fisica e Astronomia "Ettore Majorana", Università di Catania, Via Santa Sofia 64, 95123 Catania, Italy
[2] Departamento de Física Teórica and CIAFF, Universidad Autónoma de Madrid, 28049 Madrid, Spain
[3] Center for Computational Simulation, Universidad Politécnica de Madrid, Campus de Montegancedo, Bohadilla del Monte, 28660 Madrid, Spain
[4] Istituto Nazionale di Fisica Nucleare, Sezione di Catania, Via Santa Sofia 64, 95123 Catania, Italy

Thank you Grazie