No-core shell model for hypernuclei

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Strangeness in nuclear many-body systems

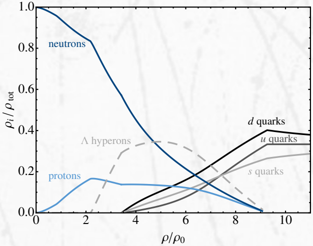
Interdisciplinary subject connecting particle physics, nuclear physics and astrophysics.

Related topical questions include:

- interaction of (anti)kaons with the nuclear medium
  - possible existence of deeply-bound K^-–nuclear states?
  - antikaons in dense matter?
- interaction of hyperons with the nuclear medium
  - S=-1 Λ hypernuclei, Σ-hypernuclei?
  - S=-2 $\Lambda\Lambda$-hypernuclei, Ξ hypernuclei
  - hyperons in dense nuclear matter and neutron stars?

Role of strangeness in dense nuclear matter?

- **admixtures of Λ and Σ hyperons in dense baryonic matter in neutron stars?**
- at baryon densities $\rho \gtrsim (2-3)\rho_0$,
  Λ hyperons can take role of neutrons if energetically favourable



(Hell, Weise, arXiv:1402:4098 [nucl-th])

- presence of hyperons results in considerable softening of EOS incompatible with recent astrophysical constraints – by reducing the maximum neutron star mass much below $2M_\odot$

Study of hypernuclei

- improve understanding of YN interaction
  - provide important constraints on YN interaction
  - precise experimental data on hypernuclear spectroscopy
  - supplement (very sparse) hyperon–nucleon scattering data base
- new precision experiments at J-PARC, J-Lab, FAIR, . . .
- modern developments of YN interaction
  - based on SU(3) chiral EFT
  - require advanced many-body computational methods to confront with hypernuclear structure measurements

Ab initio calculations of light hypernuclei

- given microscopic NN (+NNN) and YN interactions, calculate the energy spectra of A-body hypernuclear system with controllable approximations
- calculations so far limited to A=3,4 hypernuclear systems (Faddeev, Faddeev–Yakubovsky equations)
- recent developments in computational many-body methods

Our aim:

- develop a method applicable to heavier A≥5 hypernuclei
- study available boson-exchange and chiral YN interaction models

No-core shell model for hypernuclei

Ab initio

- all particles are active (no rigid core)
- exact Pauli principle
- realistic 2- and 3-body interactions (accurate description of *NN* and *YN* data)
- controllable approximations

- Hamiltonian is diagonalized in a *finite* A-particle harmonic oscillator basis
- NCSM results converge to exact results

No-core shell model for hypernuclei

- two independent NCSM formulations developed:

Slater-determinant HO basis

+ starting with atisymmetrized basis
+ second quantization methods
− c.m. degree of freedom present ⇒ huge basis

relative Jacobi-coordinate HO basis

+ c.m. d.o.f. removed
  ⇒ smaller basis
  ⇒ larger model space possible
− the basis has to be antisymmetrized

Input V_{NN}, V_{NNN}, and V_{YN} potentials

NN+NNN interaction

- chiral N3LO NN potential
  (Entem, Machleidt, PRC 68 (2003) 041001)
- chiral N2LO NNN potential
  (Navrátil, FBS 41 (2007) 14)

YN interaction

- phenomenological meson-exchange Jülich04 potential
  (Haidenbauer, Meißner, PRC 72 (2006) 044005)
- chiral LO potential
  NLO version recently developed (Haidenbauer *et al.*, NPA 915 (2013) 24)

$\Lambda N - \Sigma N$ mixing explicitly taken into account:

$$V_{YN} = \begin{pmatrix} V_{\Lambda N-\Lambda N} & V_{\Lambda N-\Sigma N} \\ V_{\Sigma N-\Lambda N} & V_{\Sigma N-\Sigma N} \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & m_\Sigma - m_\Lambda \end{pmatrix}$$

S-shell hypernuclei: ${}^{3}_{\Lambda}\mathrm{H}$

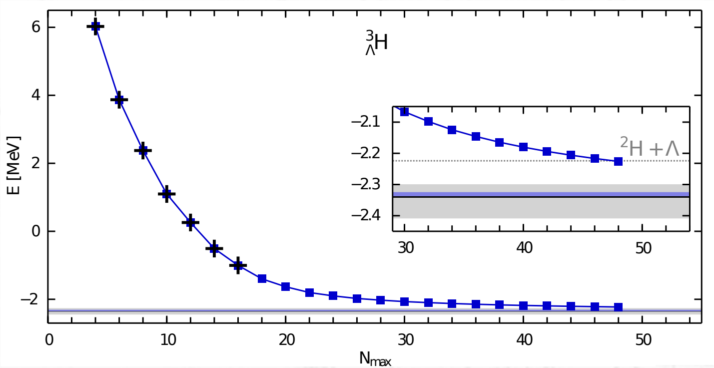


Figure: Ground state energy of ${}^{3}_{\Lambda}\mathrm{H}$ as a function of the size of the model space, with bare chiral LO @ 600 MeV interactions.

S-shell hypernuclei: $nn\Lambda$ bound state?

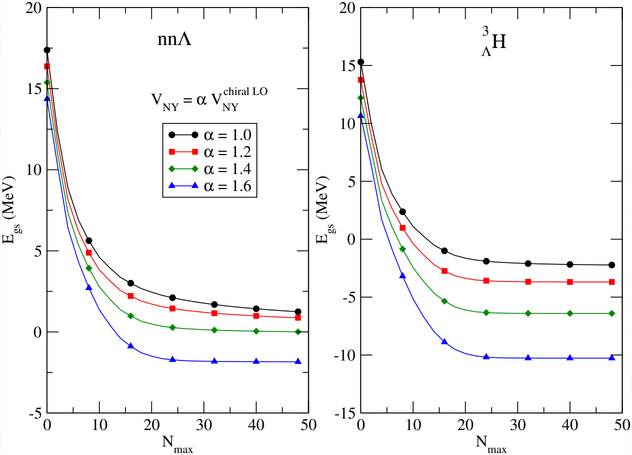


Figure: Ground state energy of $nn\Lambda$ and $^{3}_{\Lambda}$H as a function of the size of the model space, with scaled chiral LO @ 600 MeV interactions.

S-shell hypernuclei: ${}^4_\Lambda$H, ${}^4_\Lambda$He

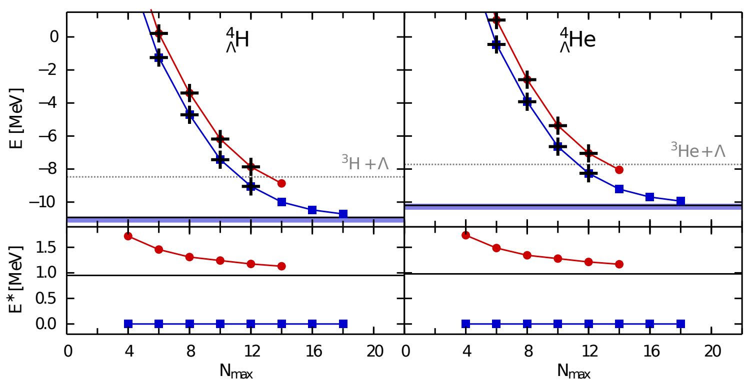


Figure: Ground state (blue) and excited state (red) energy of ${}^4_\Lambda$H and ${}^4_\Lambda$He as a function of the size of the model space, with chiral LO @ 600 MeV interactions.

S-shell hypernuclei: $\Lambda N - \Sigma N$ mixing in $^4_\Lambda$He

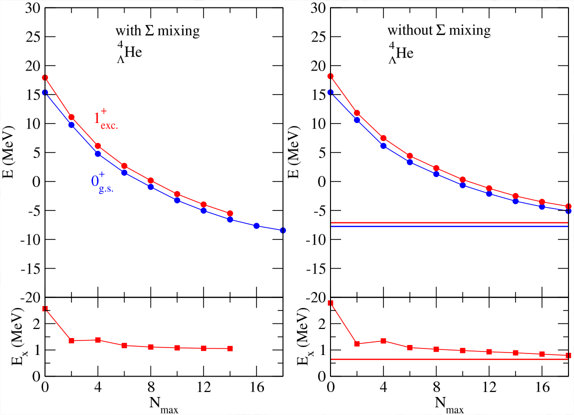


Figure: Ground state (blue) and excited state (red) energy of $^4_\Lambda$He with and without $\Lambda N - \Sigma N$ mixing as a function of the size of the model space, with chiral LO @ 600 MeV interactions.

P-shell hypernuclei: $^{7}_{\Lambda}$Li

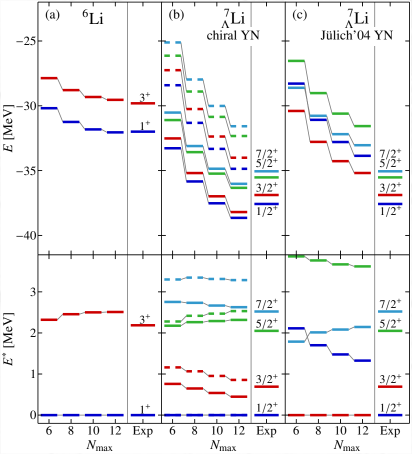


Figure: Calculations of $^{7}_{\Lambda}$Li with chiral LO @ 600@MeV (solid lines) and 700 MeV (dashed lines) and Jülich04 YN interactions.

P-shell hypernuclei: ${}^{9}_{\Lambda}\mathrm{Be}$

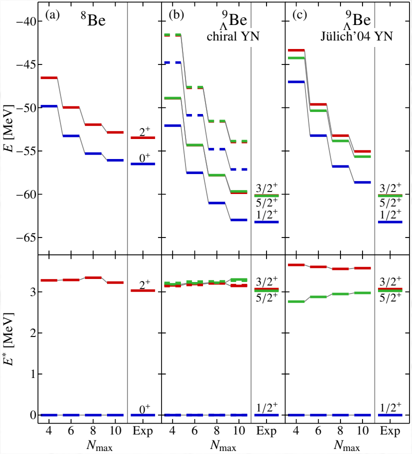


Figure: Calculations of ${}^{9}_{\Lambda}\mathrm{Be}$ with chiral LO @ 600@MeV (solid lines) and 700 MeV (dashed lines) and Jülich04 YN interactions.

P-shell hypernuclei: $^{13}_{\Lambda}C$

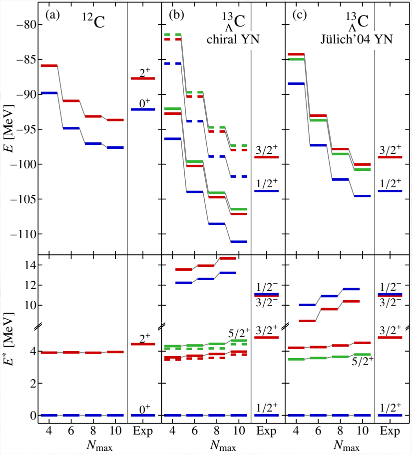


Figure: Calculations of $^{13}_{\Lambda}C$ with chiral LO @ 600@MeV (solid lines) and 700 MeV (dashed lines) and Jülich04 YN interactions.

Summary

Calculations of light hypernuclei within NCSM

- reliable *ab initio* calculations of p-shell hypernuclei with microscopic interactions are now possible
- systematic study of p-shell hypernuclei improves understanding of YN interactions
- LO chiral YN interactions are consistent with measured low-lying energy levels of light hypernuclei
- indication of deficiencies for higher relative partial waves of LO chiral YN interactions – study of YN interaction at NLO desirable

Gazda, Mareš, Navrátil, Roth, Wirth; Few-Body Systems, 55 (2014) 857.
Wirth, Gazda, Navrátil, Calci, Langhammer; submitted to PRL, arXiv:1403.3067 [nucl-th].