The Strangeness Facets of Few-Body Systems

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What Is Our Goal?

We build computer models of nuclei and nuclear reactions. We take them seriously: we calculate measured observables and attempt to understand the underlying physics.

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CONVENTIONAL NON STRANGE ($S = 0$) NUCLEI

Traditional Model

- Nuclei consist only of nucleons – other degrees of freedom are suppressed
- Nucleons move slowly within nuclei – nonrelativistic dynamics
- Nucleons interact via pairwise forces

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Result

- Enormous simplification !
- Works surprisingly well !!
- Fine tune (!!!) with the addition of
  three-body force (3BF)
  meson-exchange currents (MEC)

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FEW-BODY and LIGHT NUCLEI

^{3}H-^{3}He

- Thy. B(^{3}H) $\simeq$ 7.6 MeV vs. exp. 8.48
  Missing less than 1 MeV out of $< V_{NN} > \simeq 50$
- Other observeables are off correspondingly
  $< r^2_{\text{ch}} >$ is too large
  C_2/C_0 (asympototic norm.) is too small
  E_{C} (Coulomb energy) is too small
- Low energy observables scale with binding energy
  Adding a small **3BF** adjusts most to match experiment; *e.g.*,
  $\langle r^2(^3\text{H})\rangle^{1/2} = 1.58$ fm vs. 1.61 ± 0.04
  $\langle r^2(^3\text{He})\rangle^{1/2} = 1.77$ fm vs. 1.75 ± 0.04
  A small **CSB** force is also needed ($V_{nn} \neq V_{pp}$)
  B(^{3}H) $-$ B(^{3}He) $\simeq$ 648 keV ($= \text{E}_C$) vs exp. 764 keV

^{4}He

- Well described by the pairwise Hamiltonian model augmented by a **3BF** adjusted to reproduce ^{3}H

^{7}Li

- Binding energy misses by 2 MeV out of $< V_{NNN} > \simeq 18$
  A small $T = 3/2$ **3BF** force is needed
- OPE (tensor force) accounts for 75%-80% of the binding energy thru ^{16}O
  The scalar/vector model (*e.g.*, the Walecka model) of nuclei does **not** contain the correct physics

WHY HYPERNUCLEI ?

Do our models developed to describe conventional nuclei and nuclear reactions extrapolate beyond the $S = 0$ realm in which they were developed?

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Novel aspects of Λ hypernuclei

- anomalous binding energies

S=-1 Binding Energy Systematics

The available data on few-body Λ hypernuclei come primarily from emulsion experiments. We emphasize binding energies because the $S = 0$ sector has taught us that binding energies determine the low energy observables. In the study of hypernuclei it is customary to quote the Λ-separation energy:

$$\mathrm{B}_\Lambda({}_\Lambda\mathrm{A}) = \mathrm{B}({}_\Lambda\mathrm{A}) - \mathrm{B}(\mathrm{A\text{-}1})$$

In the non strange sector we observe that the ratio of neutron separation energies for neighboring s-shell nuclei is approximately 3:

- $\mathrm{B_n}({}^3\mathrm{H})/\mathrm{B_n}({}^2\mathrm{H}) \simeq 6/2 = 3$
- $\mathrm{B_n}({}^4\mathrm{He})/\mathrm{B_n}({}^3\mathrm{H}) \simeq 20/6 \approx 3$

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If the physics of all few-baryon systems is similar, then we might anticipate a factor of 3 in the ratio of Λ separation energies for neighboring Λ hypernuclei. Using $B_{\Lambda}({}^{4}_{\Lambda}\mathrm{H}) \simeq$ 2 MeV as our basis, we would then predict

- $\mathrm{B}_{\Lambda}({}^{5}_{\Lambda}\mathrm{He}) \simeq 3{\times}\mathrm{B}_{\Lambda}({}^{4}_{\Lambda}\mathrm{H}) \simeq 6$ MeV,
- $\mathrm{B}_{\Lambda}({}^{3}_{\Lambda}\mathrm{H}) \simeq \frac{1}{3}{\times}\mathrm{B}_{\Lambda}({}^{4}_{\Lambda}\mathrm{H}) \simeq \frac{2}{3}$ MeV.

Simple, central force calculations using $\overline{V}_{N\Lambda}$ fitted to $\mathrm{B}_{\Lambda}({}^{4}_{\Lambda}\mathrm{H})$ plus low-energy scattering data confirm such a simple analysis!

The Real World

The real world is more complex than our naive predictions. The accepted values for the s-shell systems are given in the Table along with the measured γ-ray de-excitation energies for the two species with particle-stable excited states.

Table Hypernuclear Λ-separation energies and excitation energies in MeV

hypernucleus	B_Λ	E_γ
${}^{3}_{\Lambda}$H	0.13±.05	
${}^{4}_{\Lambda}$H	2.04±.04	1.04±.04
${}^{4}_{\Lambda}$He	2.39±.03	1.15±.04
${}^{5}_{\Lambda}$He	3.10±.02	

Experimentally we know that $B_\Lambda({}^{5}_{\Lambda}\mathrm{He}) \simeq 3.1$ MeV [vs. an expectation of ≈ 6 MeV] and $B_\Lambda({}^{3}_{\Lambda}\mathrm{H}) \simeq 0.13$ MeV [vs. an expectation of $\approx \frac{2}{3}$ MeV] . Our $S = 0$ model experience does **not** extrapolate naively to $S = -1$. Explicit NΛ − NΣ (octet-octet) mixing appears to play a large role; in contrast, NN-NΔ (octet-decuplet) mixing does not.

Other Novel Aspects of Hypernuclei

- The small ${}^{3}_{\Lambda}$H Λ-separation energy makes the hypertriton one of the largest halo nuclei known. The radius of the Λ is more than 6 times the radius of the core deuteron.

- The binding energy difference of the $A = 4$ isotopes
  $$\Delta \mathrm{B}_{\Lambda} = 2.39 - 2.04 \approx 0.35 \text{ MeV}$$
  is a direct measure of **CSB** and is some 3 times the **CSB** seen in the ^{3}H - ^{3}He binding energy difference.

- The non identical particle nature of the Λ ($\neq n, p$) suggests new symmetries in hypernuclei:
  - triple s-shell ${}^{5}_{\Lambda}$He and ${}^{6}_{\Lambda\Lambda}$He
  - rotational bands in ${}^{9}_{\Lambda}$Be in addition to those seen in conventional ^{9}Be

- Although $\Lambda \rightarrow p\pi^{-}$ or $\mathrm{n}\pi^{0}$ only, the hypernucleus $\boldsymbol{{}^{4}_{\Lambda}}$**He** has been observed to emit a π^{+}.

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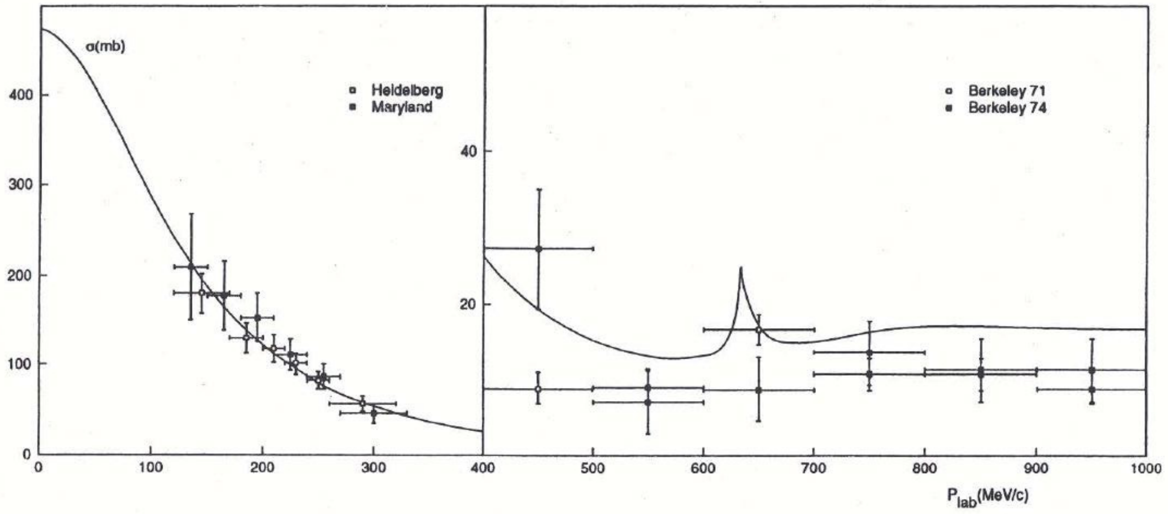
Novel aspects of Λ hypernuclei

- anomalous binding energies
- striking charge symmetry breaking
- sizeable **3BF** effects due to $\mathbf{N\Lambda - N\Sigma}$ mixing
- vanishingly small spin-orbit force
- unexpected π^+ decay of $^{\mathbf{4}}_{\mathbf{\Lambda}}\mathbf{He}$

YN INTERACTION MODELS

- NN interaction is dominated by one pion exchange.
- NN interaction exhibits a strong spin dependence.
- Short range repulsion in NN is important.
- NN-NΔ coupling plays a limited role
- Λ(T=0) × N(T=1/2) implies no one pion exchange.
- Strange mesons (K, K^*, ϕ), which play virtually no role in NN scattering, are essential in YN scattering.
- YN scattering data are meager; one has primarily differential and total cross section measurements.
- $\mathbf{N\Lambda - N\Sigma}$ mixing plays a large role; second order one pion exchange can be large.
- Static $SU(3)$ breaking occurs thru physical baryon and meson masses; dynamic $SU(3)$ breaking can occur thru coupling constants.

ΛN Data



Λp total cross section data for p_{lab} in the range from 0 to 1000 MeV/c compared with predictions from the Nijmegen soft-core potential model.

From J. J. de Swart, P. M. M. Maessen, and Th. A. Rijken in “Properties and Interactions of Hyperons,” edited by B. F. Gibson, P. D. Barnes, and H. Nakai (World Scientific, Singapore, 1994) p. 37.

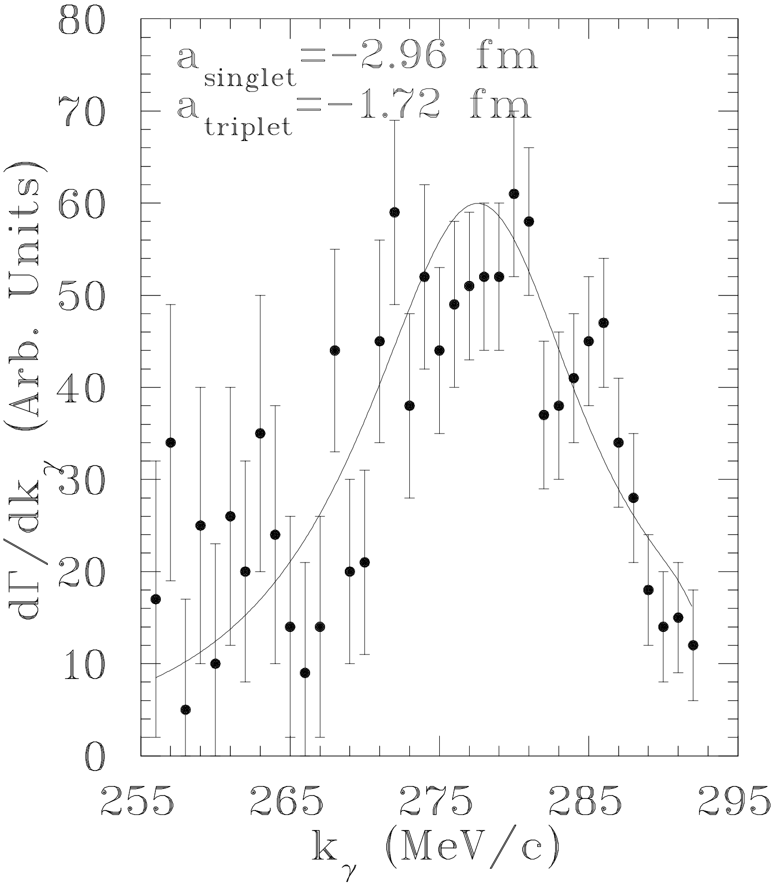
The Λp data have not changed since the bubble chamber work from which these cross sections resulted. There are no Λn cross section data.

Where Can We Go From Here???

- $p + p \to K^+ + \Lambda + p$ to enhance the Λp data base
- Electronic chamber experiments to measure $K^- + d \to \Lambda + \pi^- + p$ to do the same
- JLab $\gamma + d \to K^0 + \Lambda + p$ to do the same
- Stopped $K^- + d \to n + \Lambda + \gamma$ to provide missing Λn data

In each of the first three one must deal with three strongly interacting hadrons in the final state to extract the relatively weak Λp interaction. This does not look promising, given our lack of success in extracting from the $n + d \to n + n + p$ reaction the large n-n scattering length.

Stopped $K^- + d \rightarrow n + \Lambda + \gamma$ can provide missing Λn data



Estimates for Λn spin-singlet and spin-triplet scattering lengths using the differing shapes of the singlet and triplet spectra.

See W. R. Gibbs *et al.*, PRC **61**, 064003 (2000) for a detailed analysis of the data in K. P. Gall *et al.*, PRC **42**, R475 (1990) to extract a Λn scattering lengths.

Can We Impact Nuclear Physics?

- Has HypHI seen ${}^{3}_{\Lambda}\mathrm{n}$?
- Can the s-shell Λ separation energies be confirmed?
- Can the ${}^{3}\mathrm{H} + \mathrm{n} + \mathrm{n}$ resonance pole be constrained by ${}^{6}_{\Lambda}\mathrm{H}$?
- Can one measure $a_{n\Lambda}$?
- Can the p-shell continuum spectra be constrained by corresponding Λ hypernuclear spectra?
- Can we extend the hyper-hydrogen drip line beyond ${}^{6}_{\Lambda}\mathrm{H}$?
- Can we understand Charge Symmetry Breaking in the p-shell mirror pairs?