Conjecture: a possible $nn\Lambda$ resonance

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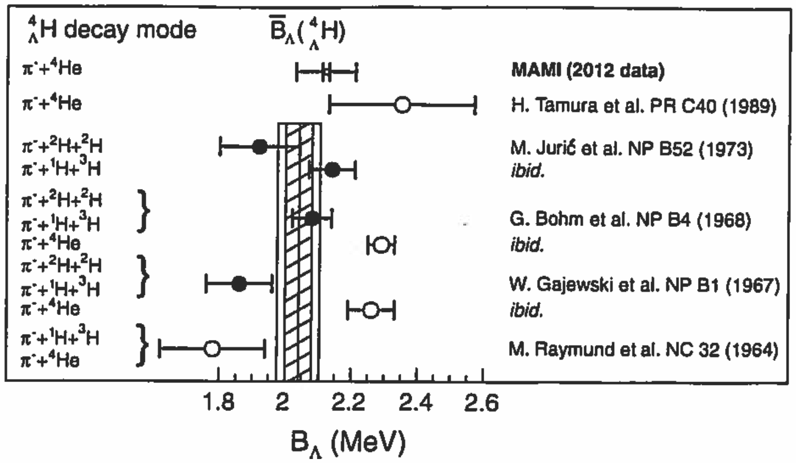

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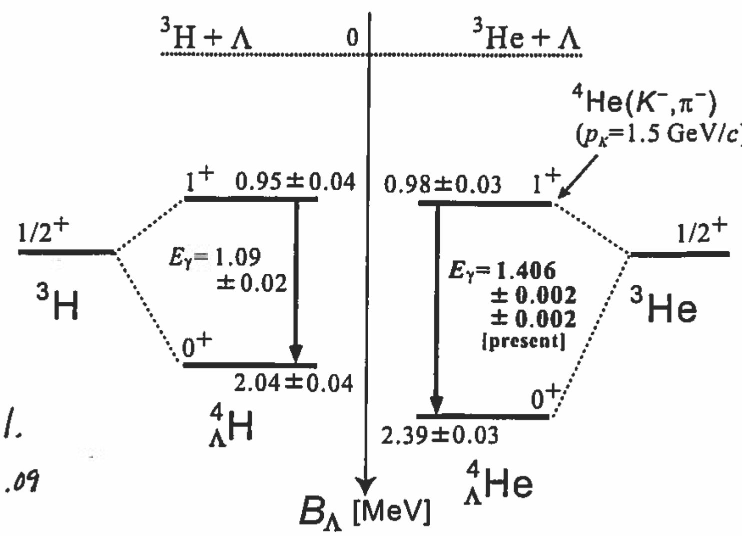

Esser, et al.
2.12 ± .01 ± .09

Background

Question: How can we constrain the $n\Lambda$ interaction, when we have only limited data regarding $p\Lambda$ scattering.?

Few-body hypernuclei:

- Λ hypernuclei provide weak constraints
  - ${}^3_\Lambda$H is weakly bound [$B_\Lambda({}^3_\Lambda\mathrm{H} = 0.13 \pm 0.05$ MeV]; small separation energy implies that it is one of the largest halo nuclei.
  - The A=4 isodoublet seems to exhibit significant Charge Symmetry Breaking, some 2-3 times that in the ^{3}H-^{3}He isodoublet.
  - The uncertainty in the $p\Lambda$ data implies a possible wide range of variation in the $n\Lambda$ interaction.

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  - The A=4 isodoublet seem to exhibit significant Charge Symmetry Breaking, some 2-3 times that in the ^{3}H-^{3}He isodoublet.
  - The uncertainty in the $p\Lambda$ data implies a possible wide range of variation in the $n\Lambda$ interaction.
- The HypHI collaboration reported a bound $nn\Lambda$ system (${}^3_\Lambda$n).
  - C. Rappold *et al.*, Phys. Rev. C **88**, 041001(R) (2013).
  - They observed both two-body and three-body decay modes.
  - ${}^3_\Lambda$n would be the lightest neutron-rich hypernucleus observed.
  - Such a bound state would provide a significant constraint on the $n\Lambda$ interaction; the nn interaction is well known.
  - Such a bound state could be observed directly in a ^{3}H(e,e'K$^+$)${}^3_\Lambda$n experiment at JLab, although a weakly bound system would imply a small cross section.
  - Alternative reactions at J-PARC would be ^{3}H(K$^-$, π^0)${}^3_\Lambda$n and ^{3}He(K$^-$, π^+)${}^3_\Lambda$n.

Background (cont.)

However, a ${}^{3}_{\Lambda}$n bound state has been strongly questioned:

- H. Garcilazo and A. Valcarce, Phys. Rev. C **89** 057001 (2014).
- E. Hiyama *et al.*, Phys. Rev. C **89** 061302 (2014).
- A. Gal and H. Garcilazo, Phys. Lett. **B736**, 93 (2014).

Simple physics suggests that one would not expect a bound state.

- The hypertriton is barely bound and its core is a deuteron.
- A ${}^{3}_{\Lambda}$n bound state would have as a core an unbound di-neutron.

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Could there instead exist a $nn\Lambda$ three-body resonance?

One might still be able to utilize the electro-production reaction (or the HypHI reaction or the J-PARC strangeness-exchange reaction) to constrain the $n\Lambda$ interaction.

Our Three-Body Model for $nn\Lambda$

- pairwise s-wave interactions of rank one separable form

$$V(k,k') = g(k)Cg(k') \qquad g(k) = 1/(k^2+\beta^2)$$

- nn potential strength and range fitted to effective range parameters:

  a_{nn} = -18.9 $\pm$ 0.4 fm and r_{nn} = 2.75 $\pm$ 0.11 fm

- $n\Lambda$ strength and range fitted to the Nijmegen model D values:

  a_s = -2.03 $\pm$ 0.32 fm and r_s = 3.66 $\pm$ 0.32 fm

  a_t = -1.84 $\pm$ 0.10 fm and r_t = 3.32 $\pm$ 0.11 fm

  M. M. Nagels, T. A. Rijken, & J. J. deSwart, PRD **15**, 2547 (1977)

- Separable potentials allow us to simply analytically continue onto the second sheet of the energy plane.

- We search for the resonance poles by examining the eigenvalue specturm of the kernel of the Faddeev equations for the $nn\Lambda$ system

- We earlier used a similar technique to explore $\Lambda - d$ scattering:

  I. R. Afnan and B. F. Gibson, PRC **47**, 1000 (1993).

Potential Resonances in the $n\Lambda$ System

We must analytically continue the Faddeev equations onto the second energy sheet.

- For two identical Fermions interacting via Yamaguchi pairwise potentials, the homogeneous integral equation is of the form

$$\lambda_n(E)\,\phi_{n,k_\alpha}(q,E) = \sum_{k_\beta} \int_0^\infty dq'\; K^{JT}_{k_\alpha,k_\beta}(q,q';E)\;\phi_{n;k_\beta}(q',E)\;, \quad (1)$$

where the kernel of the integral equation is given by

$$K^{JT}_{k_\alpha,k_\beta}(q,q';E) = Z^{JT}_{k_\alpha,k_\beta}(q,q';E)\;\tau_{k_\beta}[E-\epsilon_\beta(q')]\;q'^2\;. \qquad (2)$$

- We analytically continue onto the second energy sheet by utilizing the transformation

$$q \to q\,e^{-i\theta} \qquad q' \to q'\,e^{-i\theta} \qquad \text{with} \qquad \theta > 0\;. \qquad (3)$$

- One limitation on the rotation angle θ is imposed by singularities of the kernel; the Born amplitude $Z^{JT}_{k_\alpha,k_\beta}$ requires that $\theta < \frac{\pi}{2}$, which gives us the region $\Im(E) < 0$ on the second Riemann sheet. The other source of singularity is the quasi-particle propagator $\tau_{k_\beta}[E-\epsilon_\beta(q')]$, but because there are no two-body bound states, this does not limit the rotation.

Results of the Eigenvalue Search

Let us consider a specific example: we utilize the nn and the ${}^1\mathrm{S}_0$ and ${}^3\mathrm{S}_1$ $n\Lambda$ potentials noted previously.

- We searched in the complex energy plane for the largest eigenvalue of the kernel of **1** and found a pole at:

  $$E = -0.154 - 0.753\, i \,\mathrm{MeV} \quad \text{with eigenvalue} \quad \lambda(E) = 1.0000 - 0.0001\, i\, .$$

- Because $\Re(E) < 0$, this pole corresponds to a sub threshold resonance, one that lies below the breakup threshold in a region inaccessible by experiment.

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Because the pole lies just below the breakup threshold, we may ask how easy it might be to convert the pole into an observable resonance or even a bound state.

- We scale the strength of the ${}^1\mathrm{S}_0$ and ${}^3\mathrm{S}_1$ $n\Lambda$ potentials by the factor s.
- We follow the path of the pole as it turns into a "resonance" and then into a bound state.
- We observe that a change in strength of $\sim$4% produces a resonance above the three-body breakup threshold.
- A change of 25% is required to produce a $nn\Lambda$ bound state.

Trajectory of the $nn\Lambda$ "Resonance" Pole

In the figure one follows the trajectory of the "resonance" pole as the strength s of the $n\Lambda$ interaction is increased from a value of 1.0 in increments (Δs) of 0.025. One starts from a sub threhsold resonance at $E = -0.107 - 0.622\,i$ MeV and obtains a resonance around $s \simeq 1.04$ and then a bound state with energy $E = -0.068$ MeV at $s = 1.250$ and $E = -0.195$ MeV for $s = 1.275$.