LA-UR 93-1965



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SUBMITTED TO The Proceedings of "Future Direction in Particle and Nuclear Physics at Multi-GeV Hadron Facilities".

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SUBMITTED TO: The Proceedings of "Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Facilities" Meeting: BNL, March 4-6, 1993

# Resonances in the $\Sigma NN$ System

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**Abstract**

We first review certain unique aspects of few-body $\Lambda$- hypernuclei and then explore the physics of $\Sigma$-hypernuclei that would produce structure near the $\Sigma$ threshold in few-body elastic scattering and reactions. In particular, we discuss a predicted enhancement in the $\Lambda d$ cross section near the $\Sigma NN$ threshold in terms of poles in the $T = 0$ $YNN$ amplitude. A brief discussion of anticipated poles in the $T = 1$ amplitudes is also given.

## 1 Introduction

The physics of $\Lambda$-hypernuclei has proven to be both novel and puzzling, stretching our intuition and analysis capabilty beyond the unprecedented physics uncovered in the three quarters of a century that we have investigated conventional nuclei. This strange-particle sector of hadronic physics is not just a simple extension of zero-strangeness ($S = 0$) phenomena. The discoveries have proven to be new; the physics is different. With limited manpower and resources, we have uncovered such novel aspects of $\Lambda$-hypernuclei as:

- Striking charge symmetry breaking in the ${}^{4}_{\Lambda}$He-${}^{4}_{\Lambda}$H isodoublet [1, 2],
- Spin inverson in the splitting between the $A = 4$ ground states and spin flip, excited-states [3, 4, 5],
- Obvious anomalous binding of ${}^{5}_{\Lambda}$He [1, 6, 7, 8, 9].

In hypernuclei such significant effects stand out clearly without the need for sophisticated theoretical analysis of the data. Furthermore, $\Lambda N$–$\Sigma N$ coupling appears to play a much more significant role in hypernuclei than does $\Delta N$–$NN$ coupling in conventional nuclei [10]. The hypertriton may be bound only because of the attraction provided by the $\Lambda NN$ three body force [11]. Finally, the discovery of ${}^{6}_{\Lambda\Lambda}$He argues strongly against the existence of any deeply bound H dibaryon [10].

$\Lambda$ hypernuclear physics has been established as a most interesting subject which deserves concentrated effort to understand, and now there exists the prospect of exploring $\Sigma$ hypernuclei as well as the even more exotic $S = -2$ systems. We need hadron machines capable of producing the pion and kaon beams required to create the $\Lambda$, $\Sigma$, $\Xi$, ... hypernuclei that will test our understanding of nonperturbative QCD. Will the models which have been developed from a detailed experimental investigation of the $S = 0$ sector of conventional nuclei extrapolate beyond that domain to describe $S = -1$ and $S = -2$ physics? The challange awaits the facilities to carry forth the experimental program

## 2 The $\Sigma$-Hypernucleus Question

Hayano has just described the experimental work at KEK and BNL [12, 13, 14] which has demonstrated clear structure in the $\Sigma NNN$ system below the $\Sigma$ threshold. These data are supported by the earlier bubble chamber data for the exclusive $K^{-4}He \rightarrow \pi^- \Lambda pd$ reaction [15], recently reanalyzed by Dalitz *et al.* [16]. Let us briefly review the situation. The $\pi^-$ spectra from the $(K,\pi)$ reaction on $^4He$ exhibit narrow structure below the threshold for $\Sigma$ production, whereas the $\pi^+$ spectra do not. Because the $(K^-,\pi^-)$ reaction leads to both $T = 1/2$ and $T = 3/2$ states while the $(K^+,\pi^+)$ reaction leads only to $T = 3/2$ states, and because the spin-flip reaction is small, the structure observed has been interpreted as a bound $^4_\Sigma He$ hypernucleus having the quantum numbers $(T = 1/2, J^\pi = 0^+)$.

Dover and Gal [17] noted a decade ago that, if a bound state were to exist, then the $(T = 0, J = 0)$ state should lie lower in energy than either the $T = 1$ or $T = 2$ states, because of the spin-isospin dependence of the $\Sigma N$ interaction. Following that work, Harada *et al.* predicted the existence of an $A = 4$ $\Sigma NNN$ bound state [18, 19]. Although no other bound states for $A = 2-5$ were predicted, we were motivated to examine the $\Sigma NN$ system in an effort to understand the properties of the scattering amplitude that might lead to observable structure in the physical $\Lambda d$ cross section. For a sufficiently attractive $\Sigma N$ interaction, one would hope to see evidence for a $(T = 0, J = 1/2)$ $\Sigma NN$ bound state, or a low-lying resonance, in the $\Lambda d$ cross section near the threshold for $\Sigma$ production. Furthermore, one can analytically continue the equations into the complex energy plane to seek the positions of the poles that are responsibile for that structure. For this latter exercise, we need not restrict ourselves to $T = 0$ $\Lambda d$ scattering but can extract poles of the $T = 1$ and $T = 2$ systems that are reached in the $^3He(K,\pi)$ reactions studied at the Brookhaven AGS [20].

## 3 Numerical Results

We have explored the structure of the $\Lambda d$ cross section in terms of a Hamiltonian model [21]. Summarizing the formalism briefly, one would say that a Hermitian Hamiltonian which describes the $YNN$ system is defined on the first Riemann sheet of the complex energy plane, while the resonance poles of the scattering amplitude lie on the second Riemann sheet. To explore the structure in the scattering amplitude on the second sheet, one must analytically continue the eigenvalue problem onto that part of the second sheet where the resonance poles reside; this leads to an eigenvalue problem for a non Hermitian Hamiltonian and, therefore, to the complex eigenvalues associated with a resonance [22]. In the problem at hand, with a cut corresponding to both the $\Lambda NN$ and $\Sigma NN$ thresholds, there are four sheets. If the $YN$ interaction produces a pole in the $\Lambda d$ amplitude below the $\Sigma NN$ threshold (on the bottom sheet of the $\Lambda NN$ branch cut but the top sheet of the $\Sigma NN$ branch cut, labeled [bt] [1]), then one would anticipate narrow structure in $\Lambda d$ scattering *below* the $\Sigma NN$ threshold, corresponding to a pole which might be interpreted as a $\Sigma$ bound state because the real part of its eigenvalue would be less than the threshold for producing a $\Sigma$. In contrast, if the $YN$ interaction produces a pole above the $\Sigma NN$ threshold (on the bottom sheet of the $\Lambda NN$ branch cut but on the first sheet of the $\Sigma NN$ branch cut, again the [bt] sheet), then the effect of this pole will still be to produce structure in the $\Lambda d$ cross section *below* the $\Sigma NN$ threshold. This occurs because, for energies above the $\Sigma NN$ threshold, the pole is screened from the physial region by the branch cut arising from the threshold. In either case, enhancement in the $\Lambda d$ cross section corresponds to an eigenstate of the $YNN$ system. (To actually see structure above the $\Sigma NN$ threshold, there should be a pole above the $\Sigma$ production threshold on the second sheet of both the $\Lambda NN$ and $\Sigma NN$ branch cuts, *i.e.*, [bb].)

[1] We have adopted the convention of [23] for the labeling of the Riemann sheets corresponding to the $\Lambda NN$ and $\Sigma NN$ thresholds, although we have in this problem additional sheet structures from the $\Lambda d$ threshold and other branch points coming from poles in the $YN$ t matrix.

We illustrate this for two different $^3S_1$ separable potential models: 1) SRW [24] and 2) TGE-B [25]. Both models produce only resonances above the $\Sigma N$ threshold (2131 MeV) as is illustrated in Table 1. (We have used $m_N = 939$ MeV, $m_\Lambda = 1115$ MeV, and $m_\Sigma = 1192$ MeV.) In each case we use the SRW $^1S_0$ interaction. The TGE-B potential is somewhat stronger than the SRW potential, this can be seen when the the $\Lambda N$-$\Sigma N$ coupling is set to zero, because the TGE-B model supports a true (zero width) $\Sigma N$ bound state under that condition while the SRW potential does not [21, 23]. The parameters for the $^1S_0$ and $^3S_1$-$^3D_1$ $NN$ potentials ($P_D = 4\%$) are those used in our study of $\Lambda N$-$\Sigma N$ coupling in the hypertriton [11].

Table 1
The position of the poles of the $\Lambda N - \Sigma N$ amplitude that lie close to the $\Sigma N$ threshold for the $^3S_1$ $YN$ interactions considered.

| Potential | Sheet | Pole position |
|---|---|---|
| SRW | [tb] | $2132.5 - 0.4i$ |
| TGE-B | [bt] | $2131.7 - 5.4i$ |

In the $YNN$ calculation, both models produce narrow structure only in a single partial wave ($J^\pi = \frac{1}{2}^+$), as one would expect of a true resonance [21]. (The cross sections for higher partial waves exhibit a broad enhancement above the $\Sigma$ threshold, which is due to the opening of a new channel.) The structure is, of course, more pronounced in the inelastic cross section than in the total elastic cross section. In each case the structure is more or less symmetric and lies below the threshold for $\Sigma$ production [21], although in the case of the SRW model the total elastic cross section falls sharply near the threshold suggesting that there is some shadowing by the branch cut; that is, the SRW pole lies above the $\Sigma NN$ threshold. In Table 2 we compare the positions of the poles for the two models as well as provide the positions of the poles in the two-body amplitudes for comparison. (The energies of the resonances are given relative to the $\Lambda N$ and $\Lambda NN$ thresholds.)

Table 2
The position of the poles of the $YNN$ amplitude near the $\Sigma NN$ threshold and the position of the resonance pole in the $YN$ amplitude for comparison.

| | Two-Body | | Three-Body | |
|---|---|---|---|---|
| Potential | Sheet | Position | Sheet | Position |
| SRW | [*tb*] | $78.5 - 0.4i$ | [*bt*] | $79.5 - 1.2i$ |
| TGE-B | [*bt*] | $77.7 - 5.4i$ | [*bt*] | $75.5 - 8.9i$ |

Although the TGE-B model does not produce a pole below the $\Sigma N$ threshold, the presence of the third baryon enhances the overall attraction enough to effectively bind the $\Sigma NN$ system. The pole lies below threshold. The structure in the cross section is characteristic of a resonance that is not screened from view by any threshold cut, a rounded peak in contrast to a cusp-like structure. The SRW model does not produce a pole below the $\Sigma N$ threshold either, but for this model the three body $YNN$ pole also lies above the threshold for $\Sigma$ production. That is, the attraction is not sufficient to support a "bound state." Nonetheless, the structure in the cross section lies *below* the threshold for $\Sigma$ production. Thus, we see that whether the $\Sigma NN$ pole lies above or below the threshold for $\Sigma$ production, the structure in the $\Lambda d$ cross section appears below the $\Sigma NN$ threshold.

Although there is no $\Lambda d$ coupling to the $T = 1$ $YNN$ channel, so that we cannot calculate elastic scattering for such an isospin channel, we can search for the poles in the $T = 1$ $YNN$ amplitude. We have initiated such a search. Because of the spin-isospin dependence of the $YN$ interaction, we expect the $T = 1$ poles to lie "higher" in energy; that is, we anticipate that the real part of the eigenvalue will lie above that for the corresponding $T = 0$ eigenvalue. For that reason we have begun the search with the TGE-B model, adding the $T = 3/2$ $YN$ interactions corresponding to the scattering lengths and effective ranges specified by the the Nijmegen group [26]. Our initial efforts to find the $T = 1$ pole have not produced a definitive answer. The pole appears to be located (above the $\Sigma NN$ threshold) in such a position that we must alter our contour rotation prescription in order to be able to analytically continue in such a manner as to "see" the pole. However, the fact that the $T = 1$ pole seems to lie higher in energy than the $T = 0$ pole for this model is consistent with the analysis of the spin-isospin dependence of the $YN$ interaction by Dover and Gal.

## 4 Summary

The physics of $\Lambda$-hypernuclei has proven to be novel and much more than a mere extension of that found in coventional, non-strange systems. The structure seen in the $^4$He($K^-,\pi$) reactions is yet another example of physics that differs from the physics of the $S = 0$ sector. This structure is not due to a cusp effect, as one finds in the $nn$-$td$ system or in the two-body $YN$ ($\Lambda N$-$\Sigma N$) system [23], but it is most likely a structure associated with poles in the scattering amplitude.

Whether there exists a true $\Sigma$-hypernuclear "bound state" is not important. The structure observed in the $^4$He($K^-,\pi^-$) reaction is most likely corresponds to an eigenstate of the $YNNN$ Hamiltonian. We have illustrated this for the $YNN$ system, where we have shown that one would expect to see structure in the $T = 0$ $\Lambda d$ cross section below the threshold for $\Sigma$ production whether the pole in the scattering amplitude lies 1) below the $\Sigma$ threshold (what one might wish to label as a bound state) or 2) above that threshold (what one might wish to label as a resonance). In the case of the $YNN$ system, the spin-isospin dependence of the $YN$ interaction does make it appear that any T=1 pole will lie above the threshold for $\Sigma$ production, a conclusion that is not settled for T=0. However, one would nonetheless antiticpate structure of some type below the $\Sigma$ threshold in the $^3$He($K^-,\pi$) spectra.

## 5 Acknowledgements

The work of B. F. Gibson was performed under the auspices of the U. S. Department of Energy. That of I. R. Afnan was supported by the Australian Research Council. The authors thank B. C. Pearce for assistance in determining the positions of the poles of the $YN$ amplitudes and S. B. Carr for help in calculating the $\Lambda N$ cross sections.

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