THE STORY OF Σ HYPERNUCLEI—A MODERN FABLE

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The reality of Σ hypernuclei has been the subject of intense concern among experimenters and theoreticians for more than 20 years. The possible existence of Σ hypernuclei was first suggested by a pioneering experiment on a 9Be target at the CERN PS. There were reported to be two narrow (Γ < 8 MeV) peaks in the continuum region. This finding was quite unexpected since the widths of Σ states were believed to be large due to the strong conversion process. It is obvious that if such relatively long-lived systems were confirmed unambiguously by experiment, their masses and widths provide important constraints on the ΣN effective interaction and its relation to the ΛN and NN interactions. Since the Σ carries isospin, the role of isospin and isospin conservation in hadronic reactions could be explored.

This report stimulated a number of subsequent experiments at the BNL-AGS and KEK, along with further experiments with a specially created short kaon beam at the CERN PS. Experimental data were reported for different targets at different momenta and at different conditions. Various tagging techniques were employed to suppress backgrounds, but always at the expense of a reduction in statistical quality. Because of problems with resolution and statistics, contradictions among the different sets of data resulted more often in clouding the issues than clarifying them. Thus, up until a few years ago, there was no statistically clear confirmation of this surprising finding. In the last few years, however, a series of definitive experiments has been performed at the BNL-AGS in an effort to resolve the discrepancies and settle the controversy. Besides repeating the initial experiment on Be, a target of 6Li was run. The earlier stopped kaon data on 4He was repeated in an in-flight experiment, and the suggestion of a Σ bound state, with virtually pure isospin, confirmed. We now have a better understanding of the role of isospin in the nucleon-hyperon interaction and the importance of three body forces in hypernuclei. According to that understanding, it is unlikely that Σ states for Λ > 5 will ever be seen. In this review, a critique of the past BNL experiments is presented and conclusions on the status of the Σ database drawn. As it is with the fables of old, this modern story also has a moral and it can be derived by paraphrasing and combining two old ones: “Seek and ye shall find; but beware, lest what ye find be only in the eye of the beholder.”

Since the advent of in-flight studies of hypernuclei initiated at CERN in the 1970’s, they have been used to draw conclusions about the baryon-baryon interaction. After a series of fruitful studies on the nuclear structure of p-shell Λ, experimenters naturally turned to the Σ hyperon to discover details of the spin-isospin character of the interaction. The report of Bertini et al.1, reporting narrow Σ states in beryllium, started a flurry of activity; it was deemed of particular interest to compare the spin-orbit splitting of Λ and Σ hypernuclei.

Of course, the very existence of Σ hypernuclei was always in question because of the presence of the strong conversion from Σ to Λ hyperons in the nuclear medium. Special features would have to exist in the radial and spin-isospin dependence of the hyperon-nucleon potential to suppress that strong conversion. Such considerations made the reported observations, with their possibilities in providing interesting information on the nature of the interaction, very exciting.

In an effort to bolster the experimental evidence for Σ hypernuclei, a modified
beamline at CERN was constructed so that the lowest practical $K^-$ beam could be achieved. Because of the increased mass of the $\Sigma$ over the $\Lambda$, the beam momentum needed for minimum momentum transfer is reduced. Thus the CERN-Heidelberg collaboration hoped to take advantage of a new short beamline with which they investigated targets of carbon and oxygen.

In the initial report of Bertini et al. 1, two peaks, with FWHM's of less than 8 MeV, were reported at an excitation 80 MeV above the $\Lambda$ hypernuclear threshold region. The spectrum bore a strong resemblance to the $\Lambda$ region. The presence of such peaks, in the continuum above $\Sigma$ binding, stimulated the hope that $\Sigma$ states may indeed be very narrow.

This work encouraged much theoretical and further experimental effort; the outcome of this effort, however, led to contradictory interpretations of such fundamental quantities such as the $\Sigma$-nucleon spin-orbit splitting. Follow-up experiments by Bertini et al.2,3, Yamazaki et al.4, and Piekarz et al.5 advanced claims for observing narrow states for the p-shell nuclear targets of $^6\text{Li}, ^{12}\text{C},$ and $^{16}\text{O}$. They were led to make a number of conflicting predictions of the $\Sigma$-nucleon spin-orbit splitting and well depth. One characteristic of these early works was the necessity to use tagging techniques, or the observation of secondary particles, to enhance the signal above the background of kaon decay. The problem is particularly severe for the $\pi^-$ experiments; on the other hand, the double charge exchange for $(K^-, \pi^+)$ suppresses decay signals. Thus most reported $\Sigma$ states were for the $(K^-, \pi^+)$ reaction. The use of tagging, however, resulted in an order-of-magnitude reduction in statistics.

The somewhat confusing situation was first summarized in the review of Dover, Millener, and Gal 6. They point out that a rough estimate for the width of a $\Sigma$ state localized in a well of imaginary depth $W_\Sigma$ is $2 W_\Sigma$, or about 15 to 20 MeV, based on the earlier estimates of Batty et al.7.

Figure 1, taken from the review of Dover et al.6 shows the relevant squares of Fermi-averaged amplitudes for the elementary $\Sigma$ production processes. The strong momentum dependence was used in the CERN and BNL experiments to draw conclusions about the nature of the apparent peaks in the $(K^-, \pi^\pm)$ data. These cross sections are constructed from the amplitudes for $\Sigma$ production by Gopal8, and the elementary cross sections were also used for system efficiency calibrations because of the ease with which a $(K^-, \pi^+)$ peak on a hydrogenous target could be seen.

A subsequent experiment with stopping kaons was reported9 for a $^4\text{He}$ target. This result supported an earlier He bubble chamber experiment10, and suggested observed structure near threshold as evidence for a bound $\Sigma$ state. The stopped kaon data is shown in figure 2, taken from Hayano et al.9. The large backgrounds unavoidable in the stopped kaon work make the structure hard to see. An effort was subsequently carried on as part of AGS E774 to provide an in-flight experimental verification of the bound state11. The statistical quality of the verification was not sufficient to settle the issue.

In this review, I will not describe in more detail the CERN and KEK results of the earlier years. They were contradictory and could not be reconciled; they were typically characterized by a very small number of events, especially after tagging.
Figure 1. The ratios of Fermi-averaged cross sections in charge and isospin bases, taken from Dover, Gal, and Millener.

Figure 2. Observation of a suggested bound state in the stopped kaon \((K^-, \pi^-)\) reaction on \(^4\text{He}\) at KEK from the report of Hayano et al. 9

No evidence for statistical significance was presented for these experiments. In any case, it is impossible for an outsider to assess possible problems and to offer sensible criticisms of these experiments, done many years ago. Furthermore, the CERN experiments were undertaken at a time when the CERN PS was being phased out for hypernuclear studies. The experimenters were given a very short time to use this short kaon beam line, which was designed to match the low momentum suitable for \(\Sigma\) substitutional state production. This turns out to be a common problem for
Figure 3. A direct comparison of the CERN and BNL results for $^9$Be. The statistical errors shown are for the CERN data; the histogram represents the BNL measurement.

hypernuclear work—too little and too late. One longs for a dedicated facility, like the proposed Japanese Hadron Facility, to do this work.

I will therefore confine my remarks to more recent BNL work and the insight it provides. I will also discuss several older published BNL-AGS experiments in an effort to render some consistency to this often confusing subject.

The first figure I show in the set of the new BNL experiments is an overlay of the CERN and BNL data on $^9$Be. While the CERN experiment was done at 720 MeV/c, the BNL work at 600 MeV/c has a lower momentum transfer, which would be expected to enhance any coherent excitation. While the resolution achieved in the BNL experiment—4 MeV—is slightly broader than the 3.0 MeV achieved in the CERN experiment, the difference is not significant compared to the claimed peak width of 8 MeV. The lack of confirmation of narrow states, and the statistical quality of the BNL experiment, are clear from figure 3.

I now describe how the superior statistics and background suppression were achieved. These most recent experiments were carried out at the C6 beam line of the Low Energy Separated Beam (LESB-2) of the Brookhaven National Laboratory Alternating Gradient Synchrotron (BNL-AGS). Negative kaons of 600 MeV/c were incident on a metallic targets of Be and $^6$Li, and on a liquid helium target. The $\pi^-$ and $\pi^+$ reaction products were analyzed with the Moby-Dick spectrometer, set at a lab reaction angle of 4 deg. The usual particle identification used with Moby-Dick, consisting of time-of-flight and Čerenkov counters, was supplemented by a muon-range telescope which tagged events, presumably pions, which ranged out in a 20 cm iron block. The effectiveness of these background suppressions are shown in figure 4.

A number of complementary runs were taken to make up for the limited momentum acceptance of the Moby-Dick spectrometer over the range of significant $\Sigma$ production. These included ($K^-, \pi^+$) at 460 MeV/c, ($K^-, \pi^-$) at 438 MeV/c, and ($K^-, \pi^-$) at 550 MeV/c. Further, calibration runs were taken with a 2.28 gm/cm$^2$ polyethylene target to check against previously measure elementary kaon production cross sections on protons, and to study spectrometer acceptance. The
acceptance was further studied by kinematically isolating decays in the target region. The absolute Moby-Dick solid angle acceptance of 18 msr is believed known to an accuracy of 15%, based on these and previous studies. The plots to be presented here are missing mass spectra, with the excitation energy zero chosen to correspond to Σ⁰ production in the (K⁻, n⁻) reaction.

Following on the inadequate result of the E774 check on the bound state in He suggested by the stopped kaon experiment at KEK, Nagae et al. led the collaboration with an in-flight experiment at BNL with Moby-Dick. It was the last experiment ever done with that venerable spectrometer. With the improved timing and an improved muon filter provided by the Japanese, the in-flight experiment provided a striking confirmation of the KEK stopped kaon experiment.

These last BNL results show a consistent picture of the progression of Σ excitations for A=4, 6, and 9. These are displayed in Figure 5. They constitute a data base which is a challenge for theorists to incorporate in their knowledge of the fundamental hyperon-nucleon interaction. The characteristic features of these spectra are remarkable. First, there is an obvious isospin dependence in the comparison of the (K⁻, n⁻) and (K⁻, π⁺) spectra. Second, there is a progressive shift in the appearance of an enhancement in the (K⁻, π⁻) spectrum with mass number, ranging from -10 MeV for He to 14 MeV for Be (note that all excitation energies are referred to 0 on a Σ⁰ scale). Finally, there is a progressive broadening and shift to higher energies of the (K⁻, π⁺) spectrum. Any theoretical analysis must, of course, take account of the interference between Λ and Σ amplitudes in a coupled channels calculation for the π⁻ reaction.

A important contribution to the understanding of ⁴He has been made by Harada and his collaborators. As they point out, the results indicate a very large isospin dependence in the Σ -nucleus potential. The ⁴He π⁻ results indicate a practically pure T=1/2 bound state in ⁴He . Harada suggests a large “Lane” term in the potential; the 1/A dependence in that term indicates that we will not have bound
states for $A>5$. Hence a $\Sigma$ spectroscopy does not exist for the p-shell and beyond. Harada suggests there is a strong repulsive potential for the $T = 1/2$ part of the potential, and that repulsion is absent for $T = 3/2$ part; that suggests a region of relatively low conversion in the tail of the nuclear density, where a bound state orbital may exist. This large isospin difference is just what the BNL data indicate in the figures above. Harada further suggests that there is a sizeable three-body force due to the $\Sigma$ and this shows up in the binding energy systematics of hypernuclei. A complete fit was reported by Harada, covering the region from the $\Lambda$ threshold to beyond the $\Sigma$ thresholds.

What is perhaps not so clear is the extension of these ideas to systems heavier than helium and the reconciliation of shell model and cluster descriptions of these heavier hypernuclei.

The shell model calculations have perhaps been, up to now, hampered by lack of a consistent data base of cross sections. This has been made clear to me by my review of earlier BNL experiments. I want here to describe two problem areas and how they have been (maybe) resolved. These problems are well illustrated by a comparison of Piekarz et al. and Tang et al. The next figures illustrate the problem.

The first is the very large difference in the cross sections for lithium in the two sets (nearly a factor of 4 for nuclei differing by only one mass unit—that is, $^6\text{Li}$ and $^7\text{Li}$). I learn from theoretically minded friends that it is simply not possible to fit

Figure 5. Excitation spectra obtained for targets of He, $^6\text{Li}$, and Be. Note the similarities and trend with mass number in these spectra.
Figure 6. Spectra of Piekarz et al. obtained for the reaction \((K^-, \pi^+)\) on \(^6\text{Li}\) at 600 MeV/c. The cross section scale is in \(\mu\text{barns}/\text{sr}\).

Figure 7. The data of Tang et al. using the \((K^-, \pi^+)\) reaction on a target of \(^7\text{Li}\) at 715 MeV/c. The cross section scale is in \(\text{mb}/\text{sr}\). The large bump near zero is a target impurity.

The large cross sections reported by Tang with a shell model with reasonable pick-up amplitudes. The answer is that Tang et al. normalized to the amplitudes of Gopal, whereas in Piekarz, the cross sections are normalized by reference to Armenteros. While there is no reason to doubt that the Gopal amplitudes show the general trend of the data, near 600 MeV/c they provide cross sections a factor of two larger than the relevant measurements of Armenteros.

Figure 8 demonstrates the very large discrepancy between the measured cross sections and those predicted the the Gopal amplitudes. When that is taken into account, and considering the difference in beam momenta, the sets are consistent.

The second embarrassment (at least to the BNL group) is the report in Piekarz et al.\(^5\) of "narrow" states produced by the \((K^-, \pi^+)\) on \(^6\text{Li}\); the states are seen...
clearly in fig. 13. The disappearance of those “states” at 9 and 13 degrees was ascribed to the forward angle dominance of the Δ L=0 component and its virtual disappearance at 9 or 13 degrees. It is difficult to argue that these bumps are not significant statistically.

It is important to point out that the bumps seen in figure 6 are visible also in the spectrum of figure 7. In comparing these, note that the bump near zero in the latter spectrum should be ignored. It is a target impurity.

A clue to explaining these bumps is that the spectrometer setting for both experiments is precisely zero (it is explained in the references that a zero setting corresponds to an average over the spectrometer acceptance, resulting in an effective value of 3.7 degrees). At zero angle, however, it is not possible to make a vertex cut on the tracks of the emitted reaction pions; it therefore not possible to isolate contributions of pions coming from the timing scintillator and Čerenkov veto upstream of the target. We learned in the subsequent Σ experiments described earlier that very large contributions are seen from upstream elements; these are removed by using a non-zero spectrometer angle and a vertex cut to isolate the target contribution.

I suggest therefore that unscattered pions from these elements would have appropriate momenta to account for the broad peaks seen. Such a contribution may as well appear in Tang’s spectrum. Data from both of these experiments should be therefore treated with caution because of the above reasons.

The conclusions to be drawn from the present work can be summarized as follows:
1) There are no compelling reasons to believe there are narrow continuum Σ states seen in any hypernuclei above mass number 4.
2) There are sharp and systematic differences between (K⁻, π⁻) and
which demonstrate a large isospin term in the $\Sigma$-nuclear potential.

3) There is a reasonable description of a virtually pure $l=1/2$ isospin state in helium. That description implies a potential with a $1/\Lambda$ term, suggesting that bound states will not appear for heavier systems.

4) There systematic and regular features in the $\Sigma$ continuum region which call for a systematic treatment, whether in the cluster model or the continuum shell model.

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References

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