Σ Hyperons in the Nucleus

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A search for Σ hypernuclear states in p-shell hypernuclei has been performed with the Moby Dick spectrometer and the low energy separated beam (LESB-2) at the Brookhaven Alternating Gradient Synchrotron (BNL AGS). Unlike some previously published reports, no narrow states have been observed for targets of ^{6}Li and ^{9}Be in $(K^-, \pi^\pm)$ reactions, either for bound state or continuum regions. Together with the previously reported $J = 0$, $T = 1/2$ bound state in $^4_\Sigma$He, these results demonstrate the crucial role of isospin in Σ hypernuclei.

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The existence of narrow Σ hypernuclear states has been the subject of experimental and theoretical study for more than 20 years [1]. They were first suggested by Bertini *et al.* [2], in a pioneering experiment with a (K^-, π^-) reaction on a ^{9}Be target at the CERN PS. This finding was quite unexpected since the widths of Σ states were believed to be large due to strong Σ-Λ conversion. The reporting of such narrow structures in the continuum, with an apparent similarity to the Λ region, raised the hope that Σ states might indeed be very narrow.

This report stimulated a number of further experiments with a specially created short kaon beam at the CERN PS [3,4]. They were closely followed by experiments at the Japanese High Energy Facility (KEK) [5] and at the Brookhaven National Laboratory Alternating Gradient Synchrotron (BNL AGS) [6]. These experiments suffered from limited statistics and their interpretations were mutually contradictory. This resulted in much confusion [7,8].

On the other hand, a report of a bound state created by the $(K^-_{\mathrm{stop}}, \pi^-)$ reaction on ^{4}He by Hayano [9] was subsequently confirmed at the BNL AGS in an in-flight experiment [10]. The purpose of this Letter is to present new results for targets of ^{6}Li and ^{9}Be, and to present a coherent picture of Σ production for all three targets [11]. These experiments constitute a data base against which a number of theoretical descriptions of the fundamental hyperon-nucleon interaction may be compared.

The experiments were carried out at the C6 beam line of the Low Energy Separated Beam (LESB-2) of the BNL AGS. Negative kaons of 600 MeV$/c$ were incident on metallic targets of ^{9}Be and ^{6}Li; except for the liquid helium target, the experimental arrangements were similar to that used in the ^{4}He studies. The π^- and π^+ reaction products were analyzed with the Moby Dick spectrometer, set at an angle of 4°. The usual particle identification used with the Moby Dick spectrometer, consisting of time-of-flight and Lucite Čerenkov counters, was supplemented by a muon-range telescope which tagged events, assumed to be pions, that ranged out in a 20 cm iron block placed at the rear of Moby Dick [10]. To further improve the discrimination, corrections were made to account for path variations in the magnetic trajectories. The effectiveness of these background suppressions is the key to obtaining data with a statistical quality much higher than in previous experiments, especially for the (K^-, π^-) reaction. The avoidance of tagging, coupled with the relatively high kaon fluxes available from LESB-2, resulted in an order-of-magnitude increase in precision of the present experiment. The excellent particle identification, which allows us to discriminate decisively among electrons, muons, and pions, has already been shown in our previously published Letter on ^{4}He [10].

Kaon decays are a serious background problem with $(K^-, \pi^\pm)$ studies. Missing mass cuts were chosen to limit the contribution of two-body kaon decays in the Λ region with a minimum loss of real events. Near 600 MeV$/c$, the three-body decays K_{e3} and $K_{\mu 3}$ are a problem in the quasifree region of Σ excitation; however, three-body pionic decays appear only at momenta below about 400 MeV$/c$. The particle identification methods described above strongly minimized their contributions in the (K^-, π^-) spectra. Empty target runs were used to subtract the small remaining contributions. For the (K^-, π^+) spectra, there are no decay backgrounds, except for the three-body pionic channels below 400 MeV$/c$. There are, however, target-related backgrounds arising

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principally from kaon charge exchange and scattering reactions giving rise to kaon decays. From Monte Carlo estimates, the charge exchange reactions give rise to a flat background cross section of about 1.5 (μbarn/sr)/MeV. K^- elastic scattering is estimated to contribute less than 0.5 (μbarn/sr)/MeV.

Because of the limited momentum acceptance of Moby Dick, the regions of pion momentum were carefully selected to highlight regions of interest. These were centered on the threshold and quasifree regions. The momentum acceptance was measured with kaon decays and also with a set of (K^-, π^+) runs on a polyethylene target. The two methods gave consistent results, but the decay studies were used to determine an acceptance curve because of their superior statistics. The analysis was constrained to decays originating in the target region. The K_{e3} decays from empty target runs from the (K^-, π^-) sets were selected for this purpose, and the results were fit by least squares to a product of the error function and its complement: $[\mathrm{erf} \times (1 - \mathrm{erf})]$. With proper parameters determined from experiment, the resulting shape allowed an excellent representation of the decay data. A typical acceptance correction curve is shown in Fig. 1 for one of the spectra in the ^{9}Be experiment.

Figure 2, an overlay of the CERN and BNL data on ^{9}Be, demonstrates the advantages of the higher beam intensities and the background suppressions described above. The present measurements have order-of-magnitude more events. Whereas 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. Although the resolution in the present experiment—4 MeV—is slightly broader than the 3 MeV achieved in the CERN experiment, the difference is not significant compared to the claimed peak width of 8 MeV [2]. The lack of confirmation of two narrow states and the statistical quality of the BNL experiment are clear from Fig. 2. Since the other reported states are based on data statistically no better than those shown by Ref. [2], we suggest that the reality of those claims is also unlikely.

The data shown here for ^{9}Be and ^{6}Li were taken in runs close together in time and separated from the ^{4}He data. Calibrations of the overall system efficiencies were carried out at several intervals during the experiments, which took place over several years. These were done by measurements of the (K^-, π^+) cross section on hydrogen, using a polyethylene (CH_2) target. The average of these measurements, 774 μbarn/sr, agrees well with the value of 760 μbarn/sr near 600 MeV/c reported by Armenteros [12]. The internal consistency of our calibration measurements, however, was no better than 20% across these data sets, taken at different times. We therefore assign a systematic error of $\pm 20\%$ to the values displayed here.

The results of the present experiment are shown in Fig. 3 and in Table I. Note that the excitation energies are referred to zero at the threshold of Σ^0 emission for the (K^-, π^-) reaction and Σ^- for the (K^-, π^+) reaction. The data for all targets are shown on identical cross section and energy scales in the figure to facilitate comparison. The indicated cross sections differ somewhat from those previously reported [1,10,11] and reflect our present knowledge of the systematic errors involved in the various particle identification cuts and in the drift chamber efficiencies.

Table I lists the integrated cross sections over the range of excitation energy from -20 to 80 MeV. A subtraction to account for the "Λ tail" has been made for the π^- spectra over that range. For this a Gaussian form, centered at the Λ quasifree energy and normalized to the spectrum below $E = -20$ MeV, was used. The (K^-, π^+) spectra

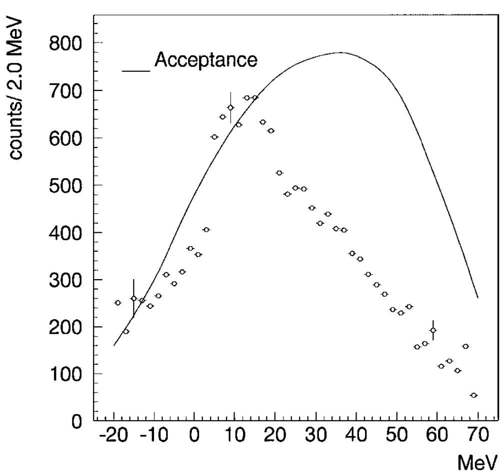

FIG. 1. Acceptance-corrected spectrum of the ^{9}Be(K^-, π^-) reaction as a function of excitation energy. The data shown are drawn from the ^{9}Be portion of the experiment, with the acceptance-correction curve superposed. The systematic error to be attached to the acceptance correction is 20%.

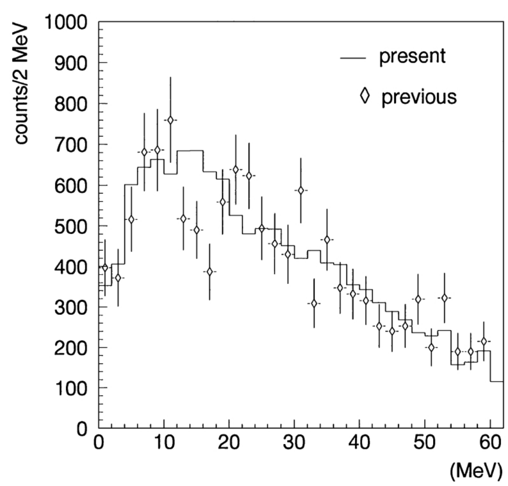

FIG. 2. A direct comparison of the CERN and BNL results for ^{9}Be(K^-, π^-). The histogram represents the BNL measurement; the CERN data and their error bars were scaled up by about a factor of 10 to allow comparison to the present experiment.

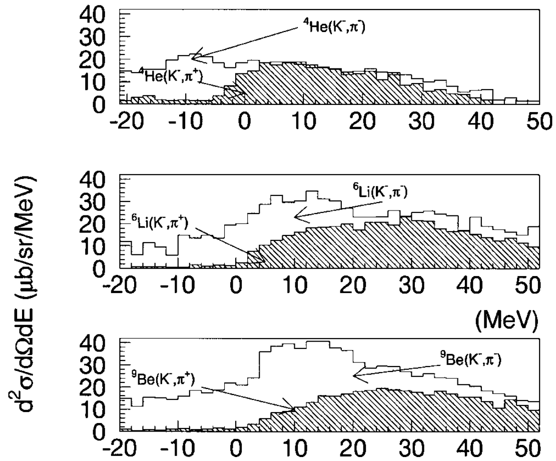

FIG. 3. Excitation spectra and cross sections obtained for targets of ^{4}He, ^{6}Li, and ^{9}Be. Note the similarities and trends with mass number in these spectra.

were fit to a phenomenological function consisting of the form erf $\times$ (1 $-$ erf), and the (K^-, π^-) spectra were fit with the same function with an added Gaussian to represent the enhancement evident for all targets. These functions were used to extend the integration over regions in the tails of the acceptance, where corrections would have been larger than a factor of 2.5. The enhancement is included in the integrated cross section of the table. According to the global fits of Gopal *et al.* [13], the ratios of the cross sections for the two channels would be expected to be about 1.4 compared to the values 1.1, 1.6, and 1.8 for our ^{4}He, ^{6}Li, and ^{9}Be data, respectively. An error of 30% has been assigned to these integrated cross sections.

The plots show a consistent picture for the trends of Σ production in $A = 4$, 6, and 9. They constitute a database for incorporation into the various models of the fundamental hyperon-nucleon interaction. The characteristic features of these spectra are remarkable. To show these in more detail, the spectra are replotted and superposed in the region of the threshold for the two reaction channels in Fig. 4.

First, there is an obvious isospin dependence evident in the comparison of the (K^-, π^-) 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 ^{4}He to 14 MeV for ^{9}Be. Finally, there is a progressive broadening and shift to higher energies of the (K^-, π^+) spectrum. It should be noted that the presence of s-shell nucleon-hole components results in a shift of the continuum excitation in the (K^-, π^-) spectra for ^{6}Li and ^{9}Be, as compared to that for ^{4}He.

An important contribution to the understanding of $^4_\Sigma$He has been made by Harada [14], who has published a description of the entire ^{4}He spectrum from the Λ threshold into the Σ continuum region. Any theoretical analysis must, of course, take into account the interference between Λ and Σ amplitudes in a coupled-channel calculation for the (K^-, π^-) reaction. As has been previously pointed out [8], the results indicate a very large isospin dependence in the Σ-nucleus potential. Bearing in mind that $T = 1/2$ cannot contribute to the (K^-, π^+) reaction, the comparison of the two reaction channels for production in ^{4}He indicates a practically pure $T = 1/2$ bound state for ^{4}He.

The presence of an isospin dependence in reaction theory is characterized by a "Lane" term [15]. Harada suggests that there is such a term in the Σ-nucleus potential. The $1/A$ dependence of that term reduces the likelihood of observing bound states for $A > 5$. The data further suggest a strong repulsive potential in the $T = 3/2$ channel. This large isospin dependence is indicated in the dramatic differences between the (K^-, π^-) and (K^-, π^+) reactions indicated in Figs. 3 and 4.

In examining Figs. 3 and 4, one is tempted to interpret the targets in terms of an alpha particle cluster model which provides a common basis for understanding the continuum region. Either a cluster model or a continuum shell model is needed to explain these data, which are not describable in terms of the usual quasifree models using the impulse approximation incorporating Fermi broadening.

TABLE I. The measured cross sections integrated over the excitation energy between -20 and 80 MeV.

Target	Reaction	(μbarns/sr) at 0°
^{4}He	(K^-, π^-)	735 $\pm$ 220
^{4}He	(K^-, π^+)	702 $\pm$ 210
^{6}Li	(K^-, π^-)	1530 $\pm$ 460
^{6}Li	(K^-, π^+)	970 $\pm$ 290
^{9}Be	(K^-, π^-)	1520 $\pm$ 460
^{9}Be	(K^-, π^+)	843 $\pm$ 260

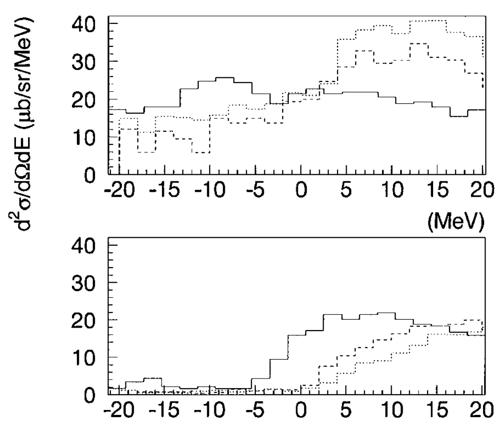

FIG. 4. A detailed comparison of the threshold regions of the targets and reaction channels of the present experiment. The upper portion shows the (K^-, π^-) and the lower portion shows the (K^-, π^+) reactions. The solid lines describe ^{4}He, the dashed lines describe ^{6}Li, and the dotted lines describe ^{9}Be. This figure facilitates comparison of the systematic features for these reactions.

The conclusions to be drawn from this paper can be summarized as follows.

(1) With statistical precision and background rejection superior to previously published work, we do not observe the existence of narrow continuum Σ states in $(K^-, \pi^\pm)$ reactions on targets of ^{9}Be, ^{6}Li, or ^{4}He.

(2) There are sharp and systematic differences between (K^-, π^-) and (K^-, π^+) reactions which demonstrate a large isospin term in the Σ-nuclear potential. That conclusion is also supported by an analysis of Σ^- atom data [16].

(3) There is a reasonable description of a virtually pure $T = 1/2$ isospin bound state in ^{4}He. That description implies a potential with a $1/A$ Lane term, suggesting that bound states will be unlikely for heavier systems.

(4) There are systematic and regular features in the Σ continuum region which call for a systematic theoretical treatment in both the cluster model and the continuum shell model.

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