Production of ${}_{\Lambda\Lambda}^{4}\mathrm{H}$ Hypernuclei

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An experiment demonstrating the production of double-Λ hypernuclei in (K^-, K^+) reactions on ^{9}Be was carried out at the D6 line in the BNL alternating-gradient synchrotron. The technique was the observation of pions produced in sequential mesonic weak decay, each pion associated with one unit of strangeness change. The results indicate the production of a significant number of the double hypernucleus ${}_{\Lambda\Lambda}^{4}\mathrm{H}$ and the twin hypernuclei ${}_{\Lambda}^{4}\mathrm{H}$ and ${}_{\Lambda}^{3}\mathrm{H}$. The relevant decay chains are discussed and a simple model of the production mechanism is presented. An implication of this experiment is that the existence of an $S = -2$ dibaryon more than a few MeV below the $\Lambda\Lambda$ mass is unlikely.

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We report on results from the alternating-gradient synchrotron (AGS) experiment E906 which was designed to observe the production of double-Λ hypernuclei [1,2]. The observational procedure used was the detection of pairs of decay pions, each one indicating one unit of strangeness change in sequential mesonic weak decay of a $\Lambda\Lambda$ system. The pions are tracked in the cylindrical detector system (CDS) [3] comprised of cylindrical drift chambers in a solenoidal magnetic field surrounding a beryllium target.

The (K^-, K^+) reaction may be viewed as starting with the conversion of a proton to a Ξ^- in the target nucleus. The Ξ^- in turn may convert into a pair of Λ's by interaction with a proton, either in the nucleus in which it was produced or by subsequent interaction with a neighboring nucleus. In work at KEK [4], one doubly strange hypernucleus was reported; earlier examples from Prowse [5] and Danysz *et al.* [6] have been in the literature for some time. These emulsion experiments have uncovered, at best, a handful of possible candidates and have exhibited the usual ambiguities in the target nuclei associated with emulsion experiments. Counterexperiments have reported an excess of events over the background in the region of bound Ξ^-'s or $\Lambda\Lambda$'s, but provide no definitive identification [7].

The present experiment was carried out at the AGS D6 line [8], using the beam line and its associated spectrometer to momentum analyze the incoming K^- and outgoing K^+, respectively. The setup, with the exception of the target region, is identical to that previously employed in several double strangeness experiments, and has been extensively described in the literature [9]. This experiment used the CDS, located in the D6 target region. The CDS is a cylindrical detector system consisting of a solenoidal magnet (0.5 T), the volume of which is filled with a system of drift chambers surrounded by an azimuthally segmented hodoscope [3]. A schematic drawing of the CDS is shown in Fig. 1. The chamber materials were chosen to minimize multiple scattering along the path from the beryllium target (1.27 cm high, 5.08 cm wide, and 15.24 cm thick) at the center of the CDS to the hodoscope at its outer radius (30 cm). The chamber volume is subdivided into 12 layers of two different types—axial layers, whose sense wires are parallel to the beam axis, and stereo layers, with sense wires inclined at angles ranging from 3.4° to 5.8°.

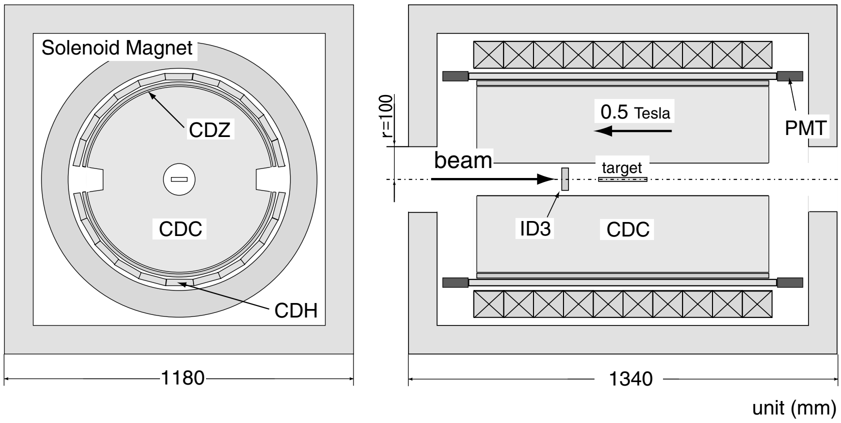

FIG. 1. Schematic front and side views of the CDS; ID3, CDC, and CDZ refer to chambers, PMT to photomultipliers, and CDH to a scintillation hodoscope.

The magnetic field is uniform to 0.5% throughout the enclosed volume (30 cm radius, 100 cm length) and is antiparallel to the beam direction. Most of the chamber volume is devoted to tracking the out-of-beam particles. The component of the momentum in the xy plane (transverse momentum, P_t) was deduced from the curvature of the track in that plane. The projection of the track on the z axis was obtained from stereo-wire-layer information in the drift-chamber volume. Combining these measurements, we obtained the total momentum vector. The hodoscope was used for both triggering and time-of-flight measurement within the CDS, so that complete particle identification by charge and mass was achieved.

Data were also recorded with a series of spatially separated polyethylene slabs to study vertex reconstruction and resolution using (π^-, p) elastic scattering at 450 MeV$/c$. The targets were used for momentum calibration, using Σ^+ decay from the $p(K^-, \pi^-)\Sigma^+$ reaction. The momentum so measured, at 185 MeV$/c$, confirmed the design value to an accuracy of 1 MeV$/c$. The momentum resolution of CDS was also calculated over the range 20 to 300 MeV$/c$ by simulations which included tracking chamber resolution (250 μm rms), multiple scattering, and target thickness correction uncertainties due to tracking errors. The overall three-dimensional positional accuracy for vertex determination was estimated as 3 mm. From all these contributions to the resolution, a rms uncertainty of 4 MeV$/c$, at 100 MeV$/c$, was predicted. This result was confirmed by fitting the Σ^+ decay mentioned above, as well as by fitting decays of the twin Λ hypernuclei ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ at 114 and 133 MeV$/c$, respectively, in the Be target. The reconstruction efficiency of the CDS was typically in the range of 65%.

The data set on which the analysis is based consists of those events in which Ξ^- production from a beryllium target took place in coincidence with the detection of two negatively charged tracks in the CDS. A loose chi-square-per-degree-of-freedom cut of <4 was imposed on the tracking. This set was further subjected to the requirement that the distance of closest approach (DCA) between the two tracks be less than 2.0 cm, and that the associated vertex be within the target. The pion pairs were ordered with respect to their measured momenta; the pion with the higher momentum is labeled "π_H" while the one with the lower is labeled "π_L." Since π^-'s emitted into small polar angles are almost entirely of fast Ξ^--decay origin, event pairs with π_H polar angles less than 60° were rejected. A further restriction which is important in background reduction is the rejection of all events whose Ξ "missing mass" exceeds 1343 MeV$/c^2$. This cut removed about half of the remaining events—those corresponding to high excitations in the quasifree Ξ spectrum.

An important issue is the adjustment applied to pion momenta for energy loss in the target. We deduced the vertex using DCA with a precision limited by the tracking resolution. This is strictly applicable only to pions coming from a true vertex, i.e., *pions from double-*Λ *or twin single-*Λ *hypernuclear events*. (The former category, with our spatial resolution, is indistinguishable from the latter.) For nonintersecting events, such as fast Ξ^- decay or $\Lambda + {}_{\Lambda}X$, the vertex from DCA is meaningless, and the measured momenta were subjected to large energy loss adjustments of up to 30 MeV$/c$, with a mean adjustment of $\sim$10 MeV$/c$. Thus, backgrounds such as Ξ decay or single hypernuclear decay were smeared out.

During the production run in 1998, the typical K^- flux at 1.8 GeV$/c$ was 2.0×10^6 per spill, with a K^-/π ratio of 0.5. An integrated flux of 0.9×10^{12} kaons on the beryllium target was accumulated, leading to 1.1×10^5 triggers.

Doubly strange nuclear systems can decay in a number of ways. In very light systems the dominant mode is mesonic, with a single pion emitted in every weak conversion. In such a reaction, each decay may or may not result in the release of nucleons, but, of the emitted charged particles, only π's can escape the target consistently with sufficient energy to be detected by the CDS.

The main source of background for the two π^- data is expected to come from Ξ^- decay, which results in

$p + \pi^- + \pi^-$ about 64% of the time (the rest of the time the final state includes neutral particles). An extensive simulation of quasifree Ξ^- production in the CDS was carried out. The quasifree Ξ^- events appear in our experiment as two negative tracks in the CDS when the proton is not detected, either because it is outside the geometric acceptance or, for low momentum Ξ^-'s, because it never leaves the target. The events in which all three tracks were detected were limited to about 800 in number, about 5% of the two π^- set (before applying cuts as described above). They were analyzed to compare to our simulation which includes the geometry and response of the CDS. The shape comparison was satisfactory, and the simulated spectrum magnitude was fixed by the three-track data. The simulation then provided a reliable measure of the Ξ^- background magnitude and shape in the two-track data.

Figure 2 contains a two-dimensional scatter plot of the pion pair events, obtained as described above, binned in 3 MeV/c cells. The box size shown is proportional to the cell population.

The pion spectrum will exhibit a sharp peak in a two-body decay from a system at rest, or nearly at rest, such as a double- or single-Λ hypernucleus. A correlated signal, which appears as such a peak in both pion spectra, is interpreted as a pair of single-Λ hypernuclei if the momenta match known decays of single-Λ systems. It is regarded as a candidate for a double-Λ hypernucleus when only one of the lines matches a known decay momentum [2,10–13]. Figure 3, adapted from Ref. [2], indicates where known single-Λ hypernuclear lines are expected as well as where $\Lambda\Lambda$ decay lines are anticipated as a function of the $\Lambda\Lambda$ pairing energy $\Delta B_{\Lambda\Lambda}$.

Inspection of the plot indicates two regions of event concentration; one near (104, 114) and one near (114, 133) in the pion momentum axes. The right-hand side of the figure shows projections of the data regions in the indicated bands of 12 MeV/c width (3σ in CDS resolution) on the P_H and P_L axes. Histogram I displays the higher momentum pion distribution with the lower pion momentum between 97 and 109 MeV/c, while II shows the lower pion momentum distribution, with the upper pion cut between 107 and 119 MeV/c. The event concentration projected in I and II we attribute to ${}_{\Lambda\Lambda}^{4}\mathrm{H}$ as explained below, while those projected in III and IV are attributed to the decays,

$$ {}_{\Lambda}^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi_L^- \qquad (114.3\ \mathrm{MeV}/c), \tag{1} $$

$$ {}_{\Lambda}^{4}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi_H^- \qquad (132.9\ \mathrm{MeV}/c). \tag{2} $$

The existence of these twin hypernuclei is evidence that Ξ^-'s of appreciable kinetic energy are initiating reactions. Also indicated in the projected spectra I to IV are the appropriate backgrounds from quasifree Ξ^- production, determined from the three particle tracks as described above. A clear excess of signal over Ξ^- background is observed in these spectra.

We direct attention to two structures in Fig. 2, a relatively wide peak centered near 114 MeV/c in I, and the correlated narrow low-momentum peak near 104 MeV/c in II. The latter prominent peak has no clear explanation in the literature. It is the conjunction of this feature with the wide peak in I that points strongly to the existence of ${}_{\Lambda\Lambda}^{4}\mathrm{H}$ in our data sample. The broadening near 114 MeV/c is attributed to the presence of more than a single contribution and the peak at 104 MeV/c to a particular decay mode of the doubly strange hypernucleus. We develop this argument as follows.

Consider the following possible sequences, some of which are combinations of single-Λ decays. The decay momenta, known from emulsion experiments to typically better than 1 MeV/c, are near those of the correlated peaks. These are listed below as processes (3) and (4),

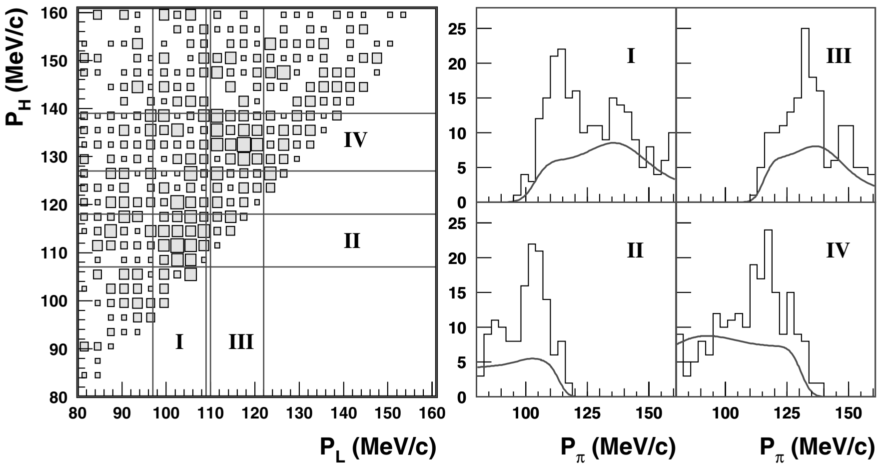

FIG. 2. The momenta of π_H and π_L, in MeV/c, plotted against each other (left). The event concentration associated with the ${}_{\Lambda\Lambda}^{4}\mathrm{H}$ doubly strange hypernucleus is located near (114, 104). The plots on the right, I and II, are projections on the y and the x axis, respectively, with the indicated limits. The projections shown in III and IV are attributed to ${}_{\Lambda}^{4}\mathrm{H}$ and ${}_{\Lambda}^{3}\mathrm{H}$. The overlayed curves for I–IV are the measured quasifree Ξ^--decay backgrounds, normalized to the expected number of such events in the data.

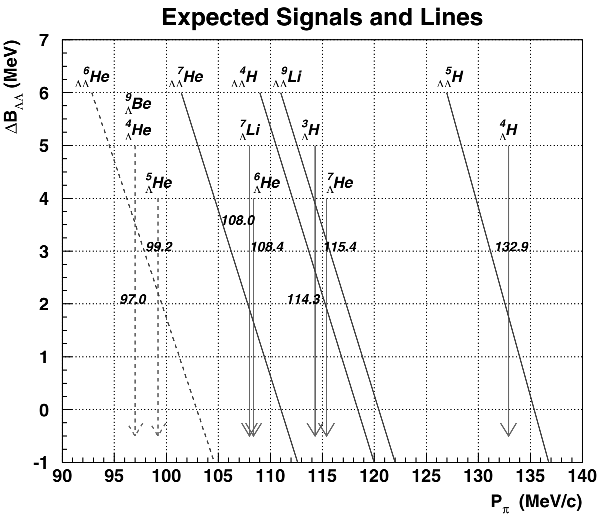

FIG. 3. The characteristic π momenta of the singly and doubly strange hyperfragments expected to be produced in this experiment. Dashed lines represent three-body decay; the inclined lines show the dependence of the pion momenta on the assumed $\Lambda\Lambda$ pairing energy. This figure was adopted from Ref. [2] and modified.

(5) and (6), and (7) and (8):

$$ {}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi_H^- \qquad (114.3\ \mathrm{MeV}/c), \tag{3}$$

$$ {}^{6}_{\Lambda}\mathrm{He} \rightarrow {}^{6}\mathrm{Li} + \pi_L^- \qquad (108.4\ \mathrm{MeV}/c), \tag{4}$$

$$ {}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi_H^- \qquad (114.3\ \mathrm{MeV}/c), \tag{5}$$

$$ {}^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{H} + p + \pi_L^- \qquad (\sim 98\ \mathrm{MeV}/c). \tag{6}$$

In (4) is listed a possible two-body decay of ${}^{6}_{\Lambda}\mathrm{He}$ which might populate low-lying excited states of ${}^{6}\mathrm{Li}$ as well as the ground state. However, this two-body decay has not been reported in the standard compilations because of inherent difficulties in handling two-prong events [11]. Most of the strength in (4) is expected to go to highly excited states of ${}^{6}\mathrm{Li}$ resulting in three-body decays with π^- momenta below 100 MeV$/c$ [14]. Thus, this decay cannot explain the sharp feature near 104 MeV$/c$ of II in Fig. 2. Similarly, the three-body decay of (6) is well below the sharp structure of II in Fig. 2, although it might account for some background below that peak.

The decay chain

$$ {}^{9}_{\Lambda\Lambda}\mathrm{Li} \rightarrow {}^{9}_{\Lambda}\mathrm{Be}^*[2^+] + \pi_H^- \qquad (113\ \mathrm{MeV}/c), \tag{7}$$

$$ {}^{9}_{\Lambda}\mathrm{Be} \rightarrow {}^{9}\mathrm{B} + \pi_L^- \qquad (97\ \mathrm{MeV}/c), \tag{8}$$

could account for the 114 MeV$/c$ signal in I of Fig. 2, but clearly the π_L^- momentum in (8) lies well below the peak of interest in II of Fig. 2. The π_H^- momentum in (7) depends on the pairing energy $\Delta B_{\Lambda\Lambda}$ in ${}^{9}_{\Lambda\Lambda}\mathrm{Li}$, taken here as $\sim$3 MeV. In general, such heavy hypernuclear systems tend to favor nonmesonic decays, for which the present experiment has practically no sensitivity.

The only other possibilities are sequential decays of ${}^{4}_{\Lambda\Lambda}\mathrm{H}$,

$$ {}^{4}_{\Lambda\Lambda}\mathrm{H} \rightarrow {}^{4}_{\Lambda}\mathrm{He} + \pi_H^- \qquad (\sim 114\ \mathrm{MeV}/c), \tag{9}$$

$$ {}^{4}_{\Lambda}\mathrm{He} \rightarrow {}^{3}\mathrm{He} + p + \pi_L^- \qquad (97\ \mathrm{MeV}/c), \tag{10}$$

and, in particular, a decay into a possible excited state of ${}^{4}_{\Lambda}\mathrm{He}$,

$$ {}^{4}_{\Lambda\Lambda}\mathrm{H} \rightarrow {}^{4}_{\Lambda}\mathrm{He}^* + \pi_L^- \qquad (\sim 104\ \mathrm{MeV}/c) \tag{11}$$

$$ {}^{4}_{\Lambda}\mathrm{He}^* \rightarrow {}^{3}_{\Lambda}\mathrm{H} + p, \tag{12}$$

$$ {}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi_H^- \qquad (114.3\ \mathrm{MeV}/c). \tag{13}$$

The resonance in (11) and (12) has not been observed experimentally, but its existence is indeed plausible [15]. The light hypernucleus, ${}^{4}_{\Lambda}\mathrm{He}^*$, when in the resonant state of interest, is rather extended spatially. A narrow, P-wave, resonance can be modeled [16] in a reasonably sized potential, whose depth is constrained by the known energies of the ground state $(0^+, 1^+)$ pair of levels. The emission into this quasi-three-body decay is [12] expected to constitute more than half the total decay of the parent ${}^{4}_{\Lambda\Lambda}\mathrm{H}$, and the calculated widths [15] permit sufficient competition with Λ escape from ${}^{4}_{\Lambda}\mathrm{He}^*$. The determination of a separable peak momentum for the first of these decay chains would constitute a measurement of $\Delta B_{\Lambda\Lambda}$ in ${}^{4}_{\Lambda\Lambda}\mathrm{H}$.

The signals from systems (3) and (4), (5) and (6), and (7) and (8) are thus small or virtually nonexistent, and the limited statistics of the present data set preclude discussion of possible small signals. The absence of a strong signal from ${}^{5}_{\Lambda\Lambda}\mathrm{H}$, which we originally expected to dominate the spectrum near 135 MeV$/c$ [2], compels us to reexamine the possible mechanisms driving these systems, from production to fragmentation.

A simple model which views the ${}^{9}\mathrm{Be}$ nucleus as consisting of a pair of α particles (i.e., a ${}^{8}\mathrm{Be}$ nucleus) held together by a weakly bound neutron is suggested. A Ξ^- can be considered incident on one of the α's, the other α and the neutron acting essentially as spectators. The final state reached will depend on the kinetic energy of the incident Ξ^-; most collisions with appreciable energy will result in the ejection from the struck ${}^{4}\mathrm{He}$ of a neutron, as well as the conversion of one of the protons, with the Ξ^-, into two Λ's. The end product, if an $S = -2$ nucleus at all, is then more likely to be ${}^{4}_{\Lambda\Lambda}\mathrm{H}$ than ${}^{5}_{\Lambda\Lambda}\mathrm{H}$. Even if the initiating Ξ^- is at rest, the Q value is probably too large to permit the copious formation of ${}^{5}_{\Lambda\Lambda}\mathrm{H}$. Of course, more massive compound nuclei and, hence, more massive hypernuclei can result from nuclear interactions of Ξ^-'s, but not at rates discernible in the present data set.

The production rate of $\Lambda\Lambda$ hypernuclei may be estimated from inspection of II in Fig. 2. The peak in that figure contains about 34 events above a background, one-half of which is attributable to quasifree cascade decays. After suitable corrections for tracking and cut efficiencies, and CDS solid angle acceptance, we estimate a production of about 400 ${}_{\Lambda\Lambda}^{4}\mathrm{H}$ events, or about 0.0048 per quasifree cascade produced in our experiment. Since the estimate relies on assumptions about the unknown neutral mode decay fractions of the members of the production chain, it should be considered as only an order-of-magnitude estimate.

The observation of numerous $\Lambda\Lambda$ hypernuclei in this experiment argues against the existence of an $S = -2$ dibaryon with a mass less than a few MeV below that of a $\Lambda\Lambda$ system. We observe the weak decay of such a system which presumably could not compete against the strong $\Lambda\Lambda \rightarrow H$ reaction.

In summary, strong evidence for the production of ${}_{\Lambda\Lambda}^{4}\mathrm{H}$ in (K^-, K^+) on ^{9}Be is presented. This conclusion follows from finding an appropriately broadened π_H line at the expected momentum, and from the fact that this candidate line is dominantly paired with π_L decay modes that can be expected from the sequential decays of ${}_{\Lambda\Lambda}^{4}\mathrm{H}$. The combination of the broad π_H^- feature near 114 MeV$/c$ and the correlated, narrower peak in the π_L^- spectrum constitutes the best evidence for such a conclusion. The pairing energy of the Λ's within the mass 4 double hypernucleus, i.e., a deuteron plus two Λ's, is not well determined in the present experiment. Future experiments with more data, better resolution, and other targets could probably uncover several $S = -2$ species and determine the important $\Lambda\Lambda$ interaction energies in each species. Given the limitations of our data set, such an experiment is the only way to observe the more massive $S = -2$ species with the CDS.

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