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We have observed a clear peak below the Σ^+-production threshold in the ^{4}He(K^-, π^-) reaction at 600 MeV/c and $\theta_{K\pi} = 4°$. This is confirmation of the existence of the bound state of ${}^{4}_{\Sigma}$He, which was reported in the ^{4}He(stopped K^-, π^-) reaction. As in the case of stopped kaons, no such peak was found in the ^{4}He(K^-, π^+) spectrum. Quantitatively reliable parameters for this level have been established. The binding energy and the width of the bound state are 4.4 $\pm$ 0.3(stat) $\pm$ 1(syst) MeV and 7.0 $\pm$ 0.7(stat)$^{+1.2}_{-0.0}$(syst) MeV, respectively. [S0031-9007(98)05364-2]

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It has long been debated whether there exist any bound states of hypernuclei containing the Σ hyperon. In the experiment E905, performed at the Brookhaven National Laboratory Alternating Gradient Synchrotron (BNL-AGS), we have unambiguously confirmed the existence of a ${}^{4}_{\Sigma}$He bound state, originally claimed in the ^{4}He(stopped K^-, π^-) reaction [1]. The state appears as a clear peak in the Σ bound region in the in-flight ^{4}He(K^-, π^-) reaction.

Very little information concerning the ΣN interaction is known. From early work with He bubble chambers at the zero gradient synchrotron (see Ref. [2]) it was known that its magnitude was comparable to the ΛN interaction, and that a dominant role was played by Σ-Λ conversion. Later, more quantitative estimates of the Σ-nucleus potential were made on the basis of an analysis of Σ^--atom x-ray data by Batty *et al.* [3]. They estimated the potential at the center of a nucleus to be $-(25-30)$ MeV for the real part and $-(10-15)$ MeV for the imaginary part, with a form proportional to the nuclear density. Thus, it was believed that the conversion width would be too broad to obtain spectroscopic information. Subsequent reanalyses [4,5] of the Σ^--atom x-ray data were performed with a potential form nonlinear in the nuclear density. In these the real part has become very shallow or even repulsive [4], so that formation of any bound states is very unlikely. However, the Σ^--atom x-ray data are sensitive only to the potential depth near the nuclear surface, and do not probe the nuclear interior.

In this context, it was surprising that the Saclay-Heidelberg group reported narrow structures ($\Gamma < 8$ MeV) in the unbound region of the ^{9}Be(K^-, π^-) spectrum in 1980 [6]. After several inconclusive attempts to establish similar narrow structures at CERN, BNL, and KEK [7], a recent BNL-AGS experiment, E887, concluded that there were no narrow structures in the unbound region [8]. This conclusion was based on very high-statistics data on ^{9}Be($K^-, \pi^\pm$) and ^{6}Li($K^-, \pi^\pm$).

The one candidate of a bound Σ hypernucleus which appears to merit further consideration is that originally reported in the ^{4}He(stopped K^-, π^-) reaction [1]. However, in that case, there are large backgrounds to be subtracted in order to obtain the peak position and the width of the state [9,10]. Because of the ambiguity in the K^- orbital from which K^- is absorbed, theoretical calculations have uncertainties on the interpretation of the experimental spectrum [11,12]. Such ambiguities and backgrounds make it difficult to rule out alternative interpretations by Dalitz and Deloff [11], who have suggested that the observed structure represents a threshold cusp associated with the opening of the Σ^0 and Σ^+ channels. Afnan and Gibson [13] have investigated the few-body systems using separable NN and ΛN-ΣN potentials in Fadeev equations, and have shown that the apparent threshold cusp phenomenon in the three-body system can be associated with a resonance pole in the scattering amplitude. Thus there is considerable theoretical support for the idea of a Σ hyperon bound state in a light hypernucleus. It is important to have information on such bound states of Σ hypernuclei in order to determine the potential form in the interior.

In contrast to the (stopped $K^-, \pi^\pm$) reactions, the reaction mechanism is rather simple in the in-flight ($K^-, \pi^\pm$) reactions, so that a comparison with theoretical calculations is more reliable. Furthermore, the decay backgrounds dominating the stopped kaon reaction are out of range in the pion momentum of the in-flight reaction.

A first attempt to obtain the in-flight ^{4}He($K^-, \pi^\pm$) spectra was carried out at BNL-AGS as E774 in 1991. In this experiment, multiplicity tagging was employed to reduce backgrounds in the bound state region, with a consequent large penalty in statistical quality. In that tagged (K^-, π^-) spectrum, a peak structure at $B_{\Sigma^+} = 4 \pm 1$ MeV with a width about 10 ± 2 MeV was reported [10]. However, the statistical quality was inadequate to establish convincingly the existence of the bound state.

In the present experiment, the quality of the particle identification in our detector system has been greatly improved, so that we do not need tagging to suppress the experimental background. Our statistical precision is thereby greatly improved. Further, the systematic error in our excitation energy determination has been reduced by comparing the Σ^- and Σ^+ peak positions obtained from polyethylene calibration runs from (K^-, π^+) and (K^-, π^-) reactions.

The experiment E905 was carried out at the C6 kaon-separated beam line of the BNL-AGS in 1996. The incident K^- beam at 600 MeV/c was focused on a liquid ^{4}He target. The beam size at the target was 3.4 cm (rms) in horizontal and 0.5 cm (rms) in vertical. The typical beam intensity was 4×10^4 K^-/spill in every 3.6 sec with the π^-/K^- ratio of $\sim$17. The last part of the beam line (QDQQ) was used to measure the incident K^- momentum. Seven sets of drift chambers were installed in the beam line for the tracking. Two scintillation counters upstream and downstream of the beam spectrometer were used to identify the K^- by a time-of-flight (TOF) measurement. A Lucite Čerenkov counter was installed just upstream of the target to suppress pions in the beam trigger.

Liquid ^{4}He with a density of 0.13 g/cm^3 was contained in a cryostat of 5.08 cm in diameter and 20.32 cm long. After energy losses in the trigger counters, tracking chambers, and the liquid ^{4}He, etc., the beam momentum at the center of the target was reduced to 588 MeV/c.

The pions from the ($K^-, \pi^\pm$) reactions were detected by using the Moby Dick spectrometer. It consisted of a QQDQQ system, eight sets of tracking drift chambers, two scintillation counters, and a range telescope, or "muon" counter. This telescope was used to identify the muon contamination in the pions. The nominal central momenta of the spectrometer were set at 466 MeV/c for the ^{4}He(K^-, π^-) reaction and 460 MeV/c for the ^{4}He(K^-, π^+) reaction. In the settings, the Σ-production thresholds were near the center of the momentum acceptance (-5 to $+7.5\%$ in $\Delta p/p$) of the spectrometer.

In this momentum region, the main backgrounds come from three-body decays of the incident K^-: $K_{\mu 3}(K^- \rightarrow \mu^- \pi^0 \bar{\nu}_\mu)$ and $K_{e3}(K^- \rightarrow e^- \pi^0 \bar{\nu}_e)$. Therefore, the identification of pions against muons and electrons is essential in the (K^-, π^-) reaction. For the (K^-, π^+) reaction, there is no contribution from these decays. The pions from the three-body decays of $K^- \rightarrow \pi^- \pi^- \pi^+$ and $K^- \rightarrow \pi^- \pi^0 \pi^0$ contribute only near the low-momentum edge of our momentum acceptance. Two-body decays are out of range in the present momentum acceptance. The spectrometer was located at the scattering angle of 4°, where the reaction vertex information is effective in suppressing K^- decay-in-flight backgrounds. A possible physical background process from the reactions in the target is the ($K^-, \bar{K}^0$) charge-exchange reaction producing $\pi^\pm$ via the $\bar{K}^0 \rightarrow \pi^+ + \pi^-$ decay. However, the momentum distribution is almost flat in the acceptance region, and the magnitude is a few percent level of the quasifree Σ production.

The muon counter was a plastic scintillation counter, in front of which a 10-in.-thick iron block was installed. With that thickness, an estimated 95% of pions will stop in the iron block. After correcting flight paths and particle momenta, the final TOF resolution for pions was $\sigma_t =$ 170 ps. As shown in Fig. 1, π^-'s are clearly separated from the electrons from the K_{e3} decay when we suppress the μ^-'s with the muon counter. The contamination of electrons and μ^-'s into π^-'s is estimated to be less than 1% in the present analysis.

The incident K^- momentum and the emitted $\pi^\pm$ momentum were obtained through the tracking by using the second-order transport matrices. The energy scales of two spectrometers were calibrated in zero-degree beam runs with and without various target materials in the beam line. The energy calibration on the production thresholds of Σ particles were carried out by using a CH_2 target

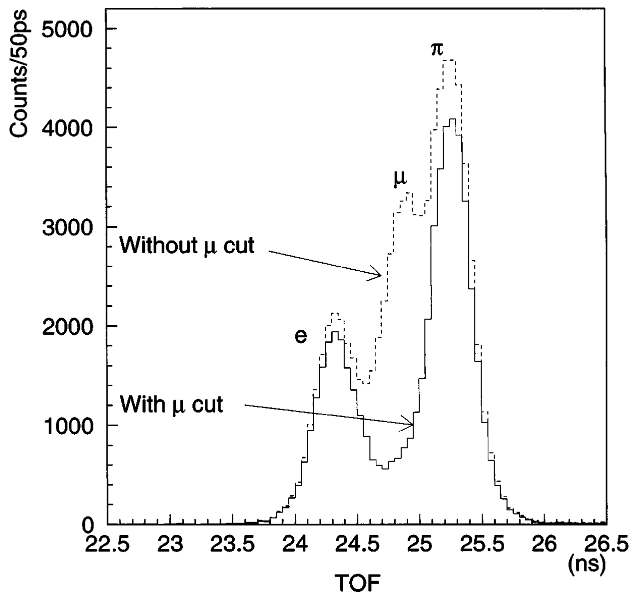

FIG. 1. The time-of-flight spectra for the (K^-, π^-) reaction measured in the Moby Dick spectrometer. A solid-line histogram shows the TOF spectrum with muon suppression by using a muon counter. The dashed line is the TOF spectrum without muon suppression.

for the reactions $K^- p \rightarrow \pi^+ \Sigma^-$ and $K^- p \rightarrow \pi^- \Sigma^+$, in which small adjustments of the energy offsets by the amount of $\pm 1 \times 10^{-3}$ in $\Delta p/p$ were applied.

Since the liquid ^{4}He target was long in the beam direction, energy loss corrections for an incident kaon and an emitted pion were performed by using a reaction point obtained from the tracking event by event. The correction parameters were optimized by using the large peak corresponding to the production of ${}^4_\Lambda\mathrm{He}_{\mathrm{g.s.}}$ in the (K^-, π^-) reaction measured with the Moby Dick momentum setting at 550 MeV/c. Small corrections for the imperfect transport matrices used in the momentum reconstruction were also applied by using the same data. The final energy resolution obtained for the peak was 3.63 ± 0.12 MeV (FWHM).

The momentum acceptance curve of the Moby Dick spectrometer was obtained from the measured momentum spectrum of electrons from the K_{e3} decay. The momentum distribution of the electrons at the entrance of the spectrometer is assumed to be flat in the momentum acceptance region of the spectrometer, and confirmed by a Monte Carlo simulation. The cross sections were obtained with the acceptance normalized to a central value of 18 msr for the spectrometer, after correction for cut efficiencies. They were compared with the (K^-, π^+) reaction value of Armenteros *et al.* [14]. We obtained 903 ± 40(statistical only) μb/sr(lab) about 15% higher than the Armenteros value.

Contributions from the structural materials of the target holder and Mylar insulation were evaluated by making empty target runs. In Fig. 2(a), horizontal vertex distributions as measured by tracking are shown with the liquid ^{4}He target filled and empty (cross-hatched). The contribution of the cylindrical container walls is clearly seen. The contributions of the front and back windows of the target are also apparent, and are easily rejected by vertex cuts. In Fig. 2(b), the π^- spectra of the (K^-, π^-) reaction with/without the liquid ^{4}He in a cryostat are shown after the vertex cuts. It should be noted that the background level is less than 8% and the signal distribution is almost flat in the central region of interest.

In Fig. 3, the excitation energy spectra of the $^4\mathrm{He}(K^-, \pi^{\mp})$ reactions are shown. The acceptance of the spectrometer and the effect of the pion decay-in-flight were corrected for each event. In this figure, the small contributions from the cryostat materials are not subtracted.

For the $^4\mathrm{He}(K^-, \pi^-)$ reaction, both the Σ^0 and Σ^+ productions contribute to the spectrum. Since the cross section for the $(K^- n \rightarrow \pi^- \Sigma^0)$ reaction is considerably larger than that for the $(K^- p \rightarrow \pi^- \Sigma^+)$ reaction at this energy [14], the excitation energy spectrum of the (K^-, π^-) reaction is plotted for $-B_{\Sigma^0}$ in order to compare the spectrum shape of the quasifree Σ production with that of the $^4\mathrm{He}(K^-, \pi^+)$ reaction. In the (K^-, π^+) reaction, only the Σ^- production contributes to the quasifree spectrum.

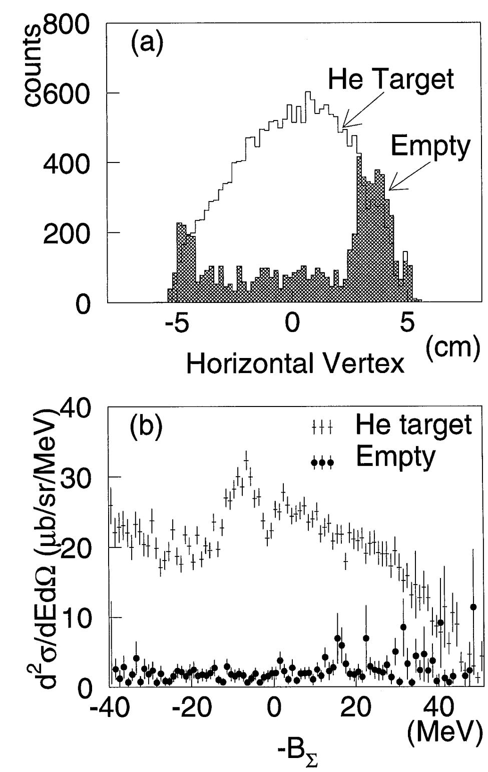

FIG. 2. (a) The distributions of horizontal vertex positions in the (K^-, π^-) reaction with and without the liquid ^{4}He in a cryostat. With an empty cryostat (hatched), contributions from the cryostat walls are clearly seen. (b) Excitation energy spectra of the (K^-, π^-) reaction with and without the liquid ^{4}He in a cryostat, after the vertex cuts. The contribution from the empty cryostat is negligibly small.

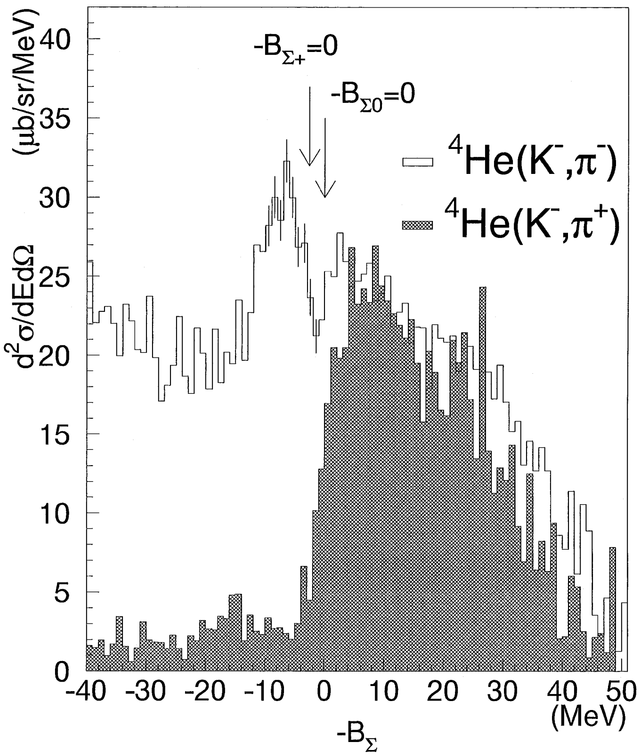

FIG. 3. Excitation energy spectra of ^{4}He(K^-,π^-) and ^{4}He(K^-,π^+) at 600 MeV$/c$ K^- momentum measured at 4°. The binding energy threshold for the (K^-,π^-) reaction is that of Σ^0 production, and Σ^- for the (K^-,π^+) reaction. The threshold for the Σ^+ production is also indicated by an arrow. Statistical error bars are shown in the region of the peak. Small contributions from the cryostat materials are not subtracted.

As shown in the figure, the quasifree Σ^- production is clearly seen in the (K^-,π^+) spectrum in the excitation energy region of $0 < -B_{\Sigma^-} < 50$ MeV. The spectrum shape of the (K^-,π^-) reaction in this energy region is very similar to that of the (K^-,π^+) reaction, except near the threshold energy ($-B_\Sigma = 0$ MeV). The cross section at the quasifree peak in the (K^-,π^+) reaction is $\sim$25 (μb/sr)/MeV, which is in good agreement with the calculation done by Harada and Akaishi [15] before the experiment.

A clear peak is seen in the (K^-,π^-) spectrum at about $-B_{\Sigma^0} = -7$ MeV. As shown in the figure, the peak structure is statistically very significant. No such peak is observed in the (K^-,π^+) spectrum, which is consistent with the observation in the (stopped $K^-,\pi^\mp$) reactions. Since the ^{4}He(K^-,π^-) reaction can populate both $T = 3/2$ and $T = 1/2$ states, while the ^{4}He(K^-,π^+) reaction can produce only a $T = 3/2$ final state, the experimental data suggest this $^4_\Sigma$He bound state has $T = 1/2$. The existence of this $T = 1/2$, $S = 0$ bound state in $^4_\Sigma$He was first predicted by Harada *et al.* [16]. The unique nature of this state is due to the large isospin dependence in their potential. The $T = 1/2$ state is attractive while the $T = 3/2$ state is strongly repulsive. The existence of a central repulsion in the Σ-nucleus potential reduces the overlap between the Σ wave function and the core nucleus, which results in the reduction of the conversion width due to the $\Sigma N \rightarrow \Lambda N$ process.

A small enhancement at about $-B_\Sigma = -15$ MeV in the (K^-,π^+) spectrum is a contribution from protons in the cryostat Mylar sheets. The same background could also contribute to the (K^-,π^-) spectrum through the reaction $K^- p \rightarrow \pi^- \Sigma^+$. It is, however, negligible because the cross section is smaller than that of the $K^- p \rightarrow \pi^+ \Sigma^-$ reaction [14].

As seen in Fig. 3, the bound state peak rests on a large continuum. The magnitude of this continuum is too large to explain with the one-step Λ-quasifree process alone. It is likely that we need to take into account two-step processes and other complex processes in such a high-excitation region well above the Λ-production threshold. Since we have no available theoretical models for such processes at this moment, we applied three phenomenological shapes to fit the tail: an exponential tail, a Gaussian tail, and a constant. From these fits, we found that the peak position was rather stable, while the peak width was somewhat dependent on the background shapes. The threshold energy for the Σ^+ production is lower than the Σ^0 production by 2.65 MeV, and the binding energy of the $^4_\Sigma$He system should be measured for the B_{Σ^+}. Thus, we obtain the binding energy of 4.4 ± 0.3(stat) $\pm$ 1(syst) MeV and the width (FWHM) of 7.0 ± 0.7(stat)$^{+1.2}_{-0.0}$(syst) MeV. The experimental energy resolution is taken into account in extracting the width. The integrated cross section for the peak is about 100 μb/sr.

These values may be compared with those reported from the latest stopped kaon analysis of Outa *et al.* [9]. They obtained $B_{\Sigma^+} = 2.8 \pm 0.7$ MeV and $\Gamma_\Sigma = 12.1 \pm 1.2$ MeV. The binding energy is thus reasonably consistent, while the width is significantly narrower. Comparing with the theoretical calculation by Harada *et al.* [16], the present values are in good agreement with $B_{\Sigma^+} = 4.6$ MeV and $\Gamma_\Sigma = 7.9$ MeV for their SAP-1 potential, which was constructed to be an S matrix equivalent to the Nijmegen model-D potential.

In summary, we have confirmed the existence of the $^4_\Sigma$He bound state in the ^{4}He(K^-,π^-) reaction at 600 MeV$/c$ and $\theta_{K\pi} = 4°$. The binding energy and the width of the state are $4.4 \pm 0.3 \pm 1$ MeV and $7 \pm 0.7^{+1.2}_{-0.0}$ MeV, respectively. No bound state was found in the ^{4}He(K^-,π^+) reaction, which suggests the state has $T = 1/2$ and $S = 0$, as predicted by Harada *et al.* [16].

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