BRIEF REPORTS

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Cascade hypernuclei in the (K^-,K^+) reaction on ^{12}C

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Cascade hypernuclei have been studied in the (K^-,K^+) reaction on a scintillating fiber target. The experimental result is compared with a theoretical calculation in order to extract information concerning the Ξ^- nucleus potential. [S0556-2813(98)01108-X]

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The study of $S=-2$ hypernuclei is of great importance not only for understanding baryon-baryon interactions in a unified way within the SU(3) octet, but also for investigating multistrangeness systems, such as strange matter [1]. However, the data of $S=-2$ systems are very limited, whereas there is a relatively large amount of information on $S=-1$ hypernuclei.

As for Ξ^- hypernuclei, there have been a few events attributed to the formation of Ξ^- hypernuclei in the interactions of mesons with emulsion nuclei [2]. These events were reconstructed in order to extract the binding energy of Ξ^- and, as a result, a phenomenological Woods-Saxon potential with parameters $V_0^{\Xi}=-24\pm4$ MeV, $R=1.1\times A^{1/3}$ fm and $a=0.65$ fm was found to fit the data [3]. However, since all of the events only showed the emission of two hyperfragments from the interaction point of the mesons, they do not always assure kinematically that nuclear bound states of Ξ^- were formed. Moreover, if there are any missing neutrals, such as neutrons, they might lead to an erroneous estimate of a deeper binding energy of Ξ^- than the real one.

A recent KEK experiment [4] found two events in which a pair of Λ hyperfragments are emitted in the back-to-back direction after Ξ^- capture by light nuclei in the emulsion target. In both cases, one of the hyperfragments was identified as being ${}^{4}_{\Lambda}$H due to its π^- decay; the partner was ${}^{9}_{\Lambda}$Be. From a kinematical reconstruction, the binding energy of the Ξ^- (B_{Ξ}) was estimated to be 0.54 ± 0.20 MeV for the first event. For the second event, it was interpreted as a $\Xi^- - {}^{12}$C bound system decaying into either (a) ${}^{4}_{\Lambda}\mathrm{H}+{}^{9}_{\Lambda}\mathrm{Be}$, (b) ${}^{4}_{\Lambda}\mathrm{H}+{}^{9}_{\Lambda}\mathrm{Be}^*$, or (c) ${}^{4}_{\Lambda}\mathrm{H}^*+{}^{9}_{\Lambda}\mathrm{Be}$. The binding energy of the $\Xi^- - {}^{12}$C system was estimated to be (a) $3.70^{+0.18}_{-0.19}$ MeV, (b) $0.62^{+0.18}_{-0.19}$ MeV, or (c) $2.66^{+0.18}_{-0.19}$ MeV.

Considering the small binding energy of Ξ^- deduced for the first event, the initial Ξ^- state can be interpreted as being a Ξ^- atomic state. On the other hand, the Ξ^- state for the second event is either an atomic state or a nuclear one, depending on whether the produced hyperfragments are excited or not. One should note that these are the first observations of clearly identified Ξ^- bound systems. Based on these events, Yamamoto analyzed the well depth of the Ξ^--nucleus potential and obtained $V_0^{\Xi}=-(16-17)$ MeV [5], which seems to be substantially weaker than the estimate given in Ref. [3].

It has been proposed that the (K^-,K^+) reaction will lead to the direct formation of Ξ^- hypernuclei [3]. Recent calculations [6,7] also show a sizable cross section for the Ξ^- hypernuclear bound states, where the Ξ^- binding energy and the cross section depend rather sensitively upon the well depth of the Ξ^--nucleus potential; the $0s_{1/2}$ bound state strength has been calculated to be 0.83 and 0.11 % of the quasifree Ξ^- production for $V_0^{\Xi}=-24$ and -12 MeV, respectively.

In view of the above situation of experiment and theory on Ξ^- hypernuclei, we carried out the (K^-,K^+) reaction on a scintillating fiber (SCIFI) target at KEK, aiming at direct observations of the Ξ^- hypernuclear states. The primary motivation of the experiment was to search for the H dibaryon [8]. One advantage of using a scintillating target is that we can reduce the background processes by looking at the tracks of the charged particles around the reaction vertices, as described below.

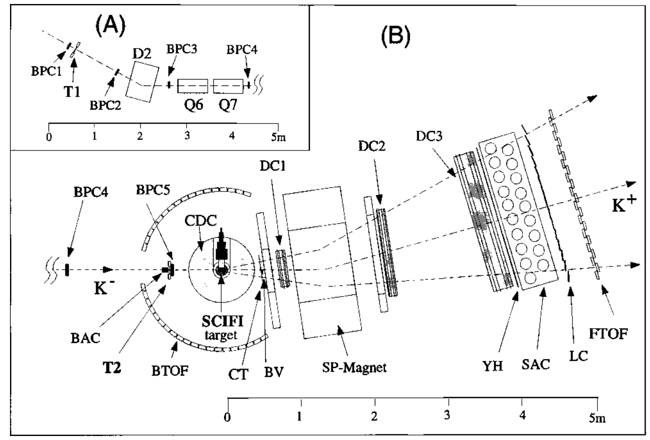

FIG. 1. Schematic drawing of the experimental setup: (a) Beamline elements and detectors upstream of the target and (b) SCIFI target and K^+ tagging spectrometer.

The experiment was carried out at KEK-PS using separated K^- beams with $P_{K^-}\sim1.66$ GeV/c on a scintillating fiber active target ($8\times8\times10$ cm^3). The experimental setup is shown in Fig. 1. The typical K^-/π^- ratio was 1/4 at an intensity of $2\times10^4K^-$/spill($\sim$2 sec). The SCIFI target was comprised of 0.5-mm-thick plastic scintillating-fiber sheets. Each sheet is composed of 0.5×0.5 mm^2 fibers with the fibers in successive sheets running alternately in the X and Y directions, enabling the construction of a three-dimensional tracking system for the charged particles. The light output from each fiber was amplified by one of two image-intensifier tubes (X and Y directions). The incident K^- mesons were identified with an aerogel Cherenkov detector (BAC). Combined with the time-of-flight (TOF) information between the $T1$ and $T2$ scintillators, the contamination of π^- and $\bar{p}$ was reduced to less than 0.01%. Note that the incident kaon decays into pions within the target were rejected by looking at the tracks in the SCIFI target. The beam momentum was measured by using eight planes of multiwire proportional chambers (BPC1-5) with a resolution of $\Delta p/p=0.5\%$ (rms). The outgoing K^+ mesons were clearly identified by a magnetic spectrometer with wire chambers and trigger counters. The particle trajectories were measured by 12 planes of drift chambers (DC1-3). The time-of-flight was measured using a FTOF hodoscope and $T2$ scintillator. A vertical hodoscope (YH) comprised of six plastic scintillators defined the geometrical acceptance of the spectrometer (0.09 sr; ±0.21 rad in the horizontal direction and ±0.12 rad in the vertical one, except for the polar angle $\theta\leqslant0.063$ rad). Lucite (LC) and aerogel Cherenkov (SAC) detectors discriminated kaons from protons and pions, respectively. Further details of the experimental setup as well as the trigger system are described elsewhere [8].

Figure 2 shows the reconstructed mass spectrum of the outgoing particles. The mass resolution for K^+ is 18.5 MeV/c^2 (rms) at $P_{K^+}=1.1$ GeV/c, which is consistent with the momentum and TOF resolution. In order to obtain a clean mass spectrum, a small χ^2 in the track fitting was required to reject background due to decays of K^+ and π^+

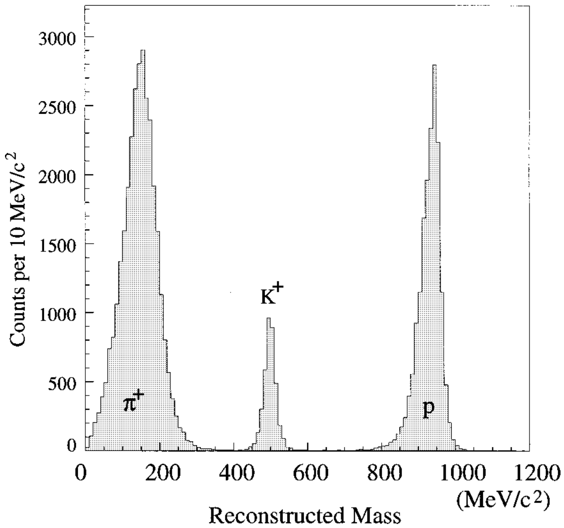

FIG. 2. Mass spectrum of the outgoing particles.

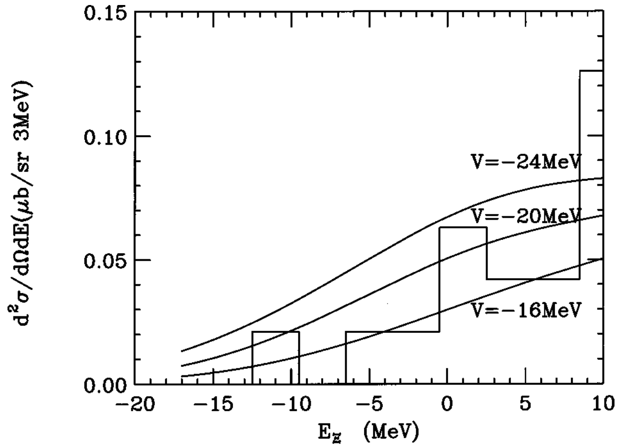

FIG. 4. Expanded view of the missing-mass spectrum around the bound region as a function of the excitation energy (E_Ξ) of Ξ^- in ${}^{12}_{\Xi}$Be. See text concerning the solid lines.

or scattering in the materials in the spectrometer. In addition, the pulse-height information of the TOF counters was used to reduce the background due to accidental hits and nuclear interactions in the counters. The K^+ momentum spectrum was obtained by selecting the events in the mass range from 430 to 570 MeV/c^2. The background due to the misidentification of π^+ as K^+ was estimated to be less than 0.2% by extrapolating the tail of the π^+ peak. The reconstruction efficiency for K^+ in the momentum range $1.6 > P_{K^+} > 0.95$ GeV/c is constant.

Figure 3 shows the missing-mass spectrum as a function of the excitation energy (E_Ξ) of the $\Xi^- + {}^{11}$B system, namely, ${}^{12}_{\Xi}$Be hypernuclei. The absolute energy scale was determined within ± 0.5 MeV by observing the peak position of Ξ^- (1321 MeV) and Ξ^{*-} (1535 MeV) productions from the hydrogen in SCIFI. The missing-mass resolution is

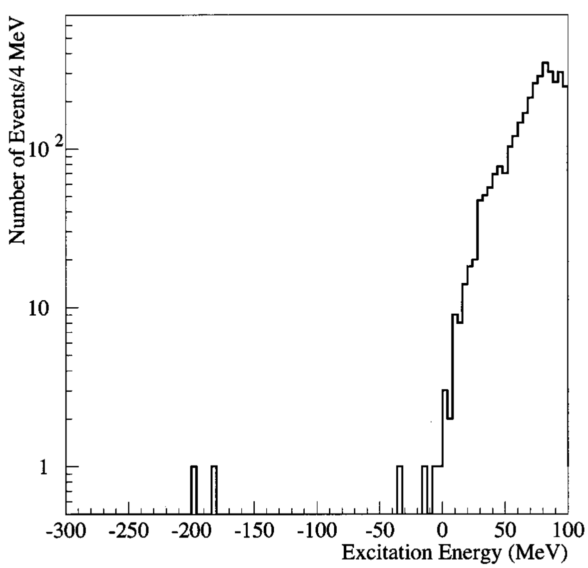

FIG. 3. Missing-mass spectrum for the ^{12}C(K^-,K^+)X reaction as a function of the excitation energy (E_Ξ) of Ξ^- in ${}^{12}_{\Xi}$Be for all events below 100 MeV.

5.6 MeV/c^2 (rms) for the reaction $K^- + p \to K^+ + \Xi^-$. We have analyzed the SCIFI data in order to reduce the background events. First, events having secondary interaction vertices in the SCIFI target (0.08 interaction length) were rejected. One of those is the $\overline{K^0} - K^0$ conversion process, $[K^- + (p) \to \overline{K^0} + (n), \overline{K^0} \to K^0, K^0 + (p) \to K^+ + (n)]$, which can be clearly identified by the SCIFI data. Second, the background caused by false tracking has been rejected by requiring that the tracks of K^- and K^+ at the target predicted by the tracking chambers should be consistent with those observed in the SCIFI data. The spectrum shown in Fig. 3 was thus obtained by rejecting these background events.

The events in the "unbound" region are mainly due to quasifree and free Ξ^- production. The events in the "bound" region are the signal of either $\Lambda\Lambda$, Ξ^- hypernuclei, or H production. The events with a large binding energy ($B_\Xi = 36$, 184, and 197 MeV, where $B_\Xi = -E_\Xi$) have been investigated in more detail as possible candidates of H production [8]. The conclusion is that there are no clear events for H production.

Figure 4 shows an expanded view of the missing-mass spectrum around the bound region. Here, the vertical scale is plotted in terms of the cross section, which was deduced by comparing the yields with the data in Ref. [8]. In order to obtain information concerning the Ξ^--nucleus potential, the experimental data were compared with the theoretical spectra (solid curve), of which the framework is briefly described below.

Based on the DWIA framework shown in Refs. [6,7], the theoretical lab differential cross section $d^2\sigma(\theta)/d\Omega_L dE_\Xi$ was calculated for both bound and unbound Ξ^- production. The Woods-Saxon Ξ^- well depth (V_0^Ξ) has been changed as a parameter with $R = 1.1A^{1/3}$ fm and $a_\Xi = 0.65$ fm being fixed. The proton wave function in the ^{12}C target is generated by the conventional Woods-Saxon potential with $V_0^N = -50$ MeV, $R = 1.1A^{1/3}$ fm, and $a_N = 0.65$ fm. As for the $K^- p \to \Xi^- K^+$ elementary cross section, a recent experimental value [9] is employed: $\alpha (d\sigma/d\Omega)_{K^-p\to\Xi^-K^+} = 0.73 \times (35\pm5) \sim 26$ μb/sr, where the coefficient α accounts for the transformation between two-body and A-body frames.

In the Woods-Saxon potential model, the Ξ^- bound states are predicted as follows, depending on the Ξ^- well depth:

$V_0^{\Xi} = -24$ MeV:

$$E_{\Xi} = -10.5 \text{ MeV}(s_{\Xi}) \quad \text{and} \quad -1.2 \text{ MeV}(p_{\Xi}),$$

$V_0^{\Xi} = -20$ MeV:

$$E_{\Xi} = -8.1 \text{ MeV}(s_{\Xi}) \quad \text{and} \quad -0.2 \text{ MeV}(p_{\Xi}),$$

$V_0^{\Xi} = -16$ MeV: $E_{\Xi} = -6.0$ MeV(s_{Ξ}),

$V_0^{\Xi} = -12$ MeV: $E_{\Xi} = -3.9$ MeV(s_{Ξ}).

It should be also noted that the Ξ state widths due to the $\Xi^- p \rightarrow \Lambda\Lambda$ conversion are predicted to be very small in comparison with the Σ case, $\Gamma_{\Xi}^{\text{conv}} \cong 1.7$ MeV(s_{Ξ}) and 0.9 MeV(p_{Ξ}), when one uses the Nijmegen model-*D* interaction. Thus, if the energy resolution is good enough, some bound states are expected to be observed as distinguishable peaks. One may refer to Fig. 2 of Ref. [7] for the theoretical (K^-,K^+) spectra with a clear peak structure.

In the present case, however, we have to take the present experimental energy resolution ($\sigma = 9.5$ MeV) as a smearing width when we draw the theoretical excitation spectra, and accordingly, the bound peak structure disappears. The calculated results with a varied well depth (V_0^{Ξ}) are also shown by the solid lines in Fig. 4. The theoretical spectra are generated by partially integrating the differential cross section $d^2\sigma/d\Omega dE_{\Xi}$ over the solid angle which corresponds to the actual detector acceptance.

In the present experiment, only a few events are obtained within the relevant bound-state region. Moreover, because the missing-mass resolution is not so good, it seems rather hard to extract definite information concerning the Ξ^- bound state. In spite of the poor statistics, it is interesting to compare the theoretical cross section to the experimental spectrum for a particular region including and near to the Ξ^- bound states in more detail. It is remarked here that both the bound-state and continuum strengths were estimated using the Kapur-Peierls method in a unified way [6,7], so that smearing into the bound region is properly realized in the theoretical spectra. In order to make a quantitative comparison, we estimated the summed cross section for $E_{\Xi} \leqslant 7$ MeV to be

$$\Delta\sigma^{\text{exp}} = 0.21 \pm 0.07 \ \mu\text{b/sr}.$$

The corresponding theoretical values were obtained by integrating over the same energy region:

$$\Delta\sigma^{\text{cal}} = 0.44 \ \mu\text{b/sr} \quad \text{for} \quad V_0^{\Xi} = -24 \text{ MeV},$$

$$0.32 \ \mu\text{b/sr} \quad \text{for} \quad V_0^{\Xi} = -20 \text{ MeV},$$

$$0.19 \ \mu\text{b/sr} \quad \text{for} \quad V_0^{\Xi} = -16 \text{ MeV}.$$

Here, one may think about possible theoretical uncertainties in these predictions. It should be noted that the distorted-wave impulse approximation (DWIA) treatment [10] can well reproduce the experimental cross sections for the $^{12,13}\text{C}(K^-,\pi^-)^{12,13}_{\Lambda}\text{C}$ reaction at $P_{K^-} = 800$ MeV/c [11] and those for the $^{12}\text{C}(\pi^+,K^+)^{12}_{\Lambda}\text{C}$ reaction at $P_{\pi^+} = 1040$ MeV/c($P_{K^+} \simeq 700$ MeV/c) [12] within an accuracy of less than 30% as far as the available differential cross section is concerned. The K^- and K^+ momenta concerned here are different from the above-mentioned cases, however, the larger kaon momenta certainly favor the DWIA treatment employed here in the same manner. Thus, it is reasonable to suppose that the uncertainties in the theoretical predictions are within a similar boundary. On the basis of this consideration, we can make a conclusive remark based on the above comparison: the case with $V_0^{\Xi} = -24$ MeV is clearly outside of the three standard deviations with respect to the experimental value.

In conclusion, although it is not very easy to deduce a definite Ξ^- well depth, the present comparison of both the excitation spectra (Fig. 4) and the summed cross section $\Delta\sigma(E_{\Xi} \leqslant 7$ MeV) near the Ξ^- threshold region suggests that the potential-well depth for Ξ^- should be less than, for example, 20 MeV. This conclusive remark concerning V_0^{Ξ} seems to be consistent with the twin hypernuclear production event [4], for which Yamamoto *et al.* [5] deduced $V_0^{\Xi} = -(16-17)$ MeV, but is not compatible with the result derived from an analysis of old emulsion data ($V_0^{\Xi} = -24$ MeV) [3].

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