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Search for the H-dibaryon resonance in ^{12}C(K^-, $K^+\Lambda\Lambda X$)

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The H-dibaryon resonance was sought by a $\Lambda\Lambda$ invariant mass spectrum that was obtained by the ^{12}C(K^-, $K^+\Lambda\Lambda X$) reactions. We observed a bump near the $\Lambda\Lambda$ threshold, as reported by the previous experiment (KEK E224), with better statistics. Data were compared with results of a cascade model calculation including $\Lambda\Lambda$ final state interactions consistent with the newly measured binding energy of $^{\ 6}_{\Lambda\Lambda}$He. No significant enhancements above levels of the model predictions were observed. The resulting upper limit for the production cross section of the H with a mass range between the $\Lambda\Lambda$ and ΞN threshold is found to be 2.1 ± 0.6 (stat.) ± 0.1 (syst.) μb/sr at a 90% confidence level.

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The H dibaryon ($uuddss$, $I = J = 0$) has attracted much attention in relation to confinement phenomena in QCD [1,2]. With the observation of $^{\ 6}_{\Lambda\Lambda}$He (the NAGARA event) and the precise measurement of its binding energy, the KEK experiment E373 obtained a lower limit of the H-dibaryon mass of 2223.7 MeV/c^2 [3], which is much closer to the two-Λ threshold than the previously obtained value, 2203.7 MeV/c^2 [4]. These results, together with results suggesting the existence of $^{\ 4}_{\Lambda\Lambda}$H (deuteron plus $\Lambda\Lambda$ system) reported by the BNL E906 [5], were regarded as nearly conclusive evidence for ruling out the existence of a bound H dibaryon. However, the H dibaryon is predicted as a resonance by some models [6,7], and this has provided motivation to continue the experimental search for it.

The KEK E224 Collaboration [8] first reported an enhancement near the $\Lambda\Lambda$ threshold in ^{12}C(K^-, $K^+\Lambda\Lambda X$) reactions above the phase space of ^{12}C(K^-, $K^+\Lambda\Lambda^{10}$Be) at $P_{K^-} = 1.66$ GeV/c. Because of its limited statistics, they could not draw a definite conclusion on the nature of the enhancement, but suggested that the enhancement is due to either an H-dibaryon resonance or a strongly attractive $\Lambda\Lambda$ final state interaction (FSI) or both of these. The interaction energy of $\Lambda\Lambda$($\Delta B_{\Lambda\Lambda}$) can be obtained from the binding energy of the double-Λ hypernucleus. The $\Delta B_{\Lambda\Lambda}$ of $^{\ 6}_{\Lambda\Lambda}$He obtained from the NAGARA event is $1.01 \pm 0.20\ ^{+0.18}_{-0.11}$ MeV [3], and on the basis of this result, it has been concluded that the $\Lambda\Lambda$ interaction is weakly attractive. For this reason, study of the $\Lambda\Lambda$ invariant mass spectrum near the threshold is interesting.

In this paper, we report new experimental results on the $\Lambda\Lambda$ measurement with doubled statistics compared with the previous experiment. We also compared the $\Lambda\Lambda$ mass spectrum with model calculations including $\Lambda\Lambda$ final state interactions. The experiment was carried out [9] using the 1.67 GeV/c separated K^- beam at the KEK 12 GeV proton synchrotron (KEK-PS).

Figure 1(a) shows a layout of the experimental setup. The K^- was identified with a beam-line spectrometer composed of five proportional chambers (BPC1-5), a set of time-of-flight

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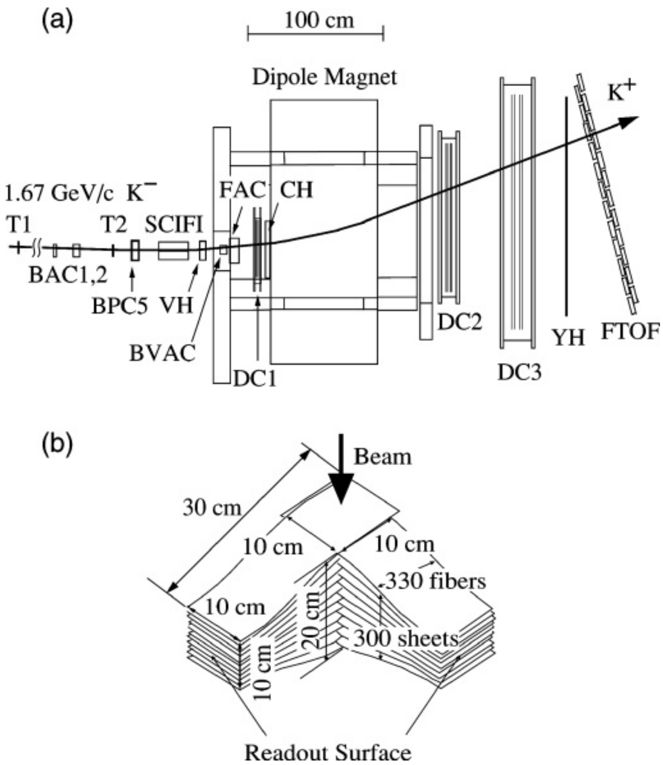

FIG. 1. Top view of KEK E522 experimental setup (a) and schematic drawing of the scintillating fiber active target (b).

counters (T1, T2), and two aerogel Cerenkov counters (BAC1, 2) with a refractive index n of 1.03.

The momenta of the outgoing particles were measured with a K^+ spectrometer that consists of a dipole magnet with the field strength of 1 T, three hodoscopes (VH, CH, YH), three drift chambers (DC1, DC2, DC3), two aerogel Cerenkov counters with $n = 1.04$ (FAC) and $n = 1.05$ (BVAC), and a forward time-of-flight counter (FTOF). The momentum resolution ($\Delta P/P$) of the scattered particle was measured as 0.5% at the region of 1 GeV/c. The mass of scattered particles was reconstructed by momentum, time of flight, and flight length. The region between 0.4 and 0.6 GeV/c^2 was selected as the K^+ region. Contamination of π^+ and protons in this region for the momentum of $0.9 < P_{K^+} < 1.3$ GeV/c was estimated as 10%.

During the run in 2002, an approximately $9 \times 10^9 K^-$ beam was injected into a scintillating fiber (SCIFI) active target. A schematic view of the SCIFI target is shown in Fig. 1(b). It consists of 600 sheets of plastic scintillating fibers [10]. Each fiber is 30 cm long and has a 300×300 μm cross section. The three-dimensional active volume of the SCIFI target is $10 \times 10 \times 20$ cm, which acts as a visual track detector observing both the (K^-, K^+X) reactions and decay of hyperons (Ξ^- and Λ) produced in the target. Images of charged particle tracks were obtained with four stages of image intensifier tubes (IITs) that were arranged in U and V coordinates, thereby enabling three-dimensional reconstruction of the tracks. Intensified track images were recorded using two sets of charged-coupled device (CCD) cameras (Eastman Kodak ES310 Megaplus) and the data

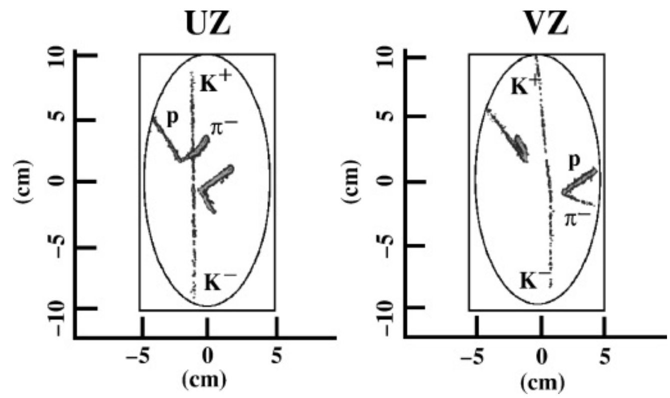

FIG. 2. Typical image of the $\Lambda\Lambda$ in the scintillating fiber active target.

were compressed and stored in the Versa Module Eurocard (VME)-based data-acquisition system [11]. The track width defined by the distribution of each pixel of a track weighted by its brightness around the fitted straight line was 296 μm for a minimum ionizing particle.

In total, 45 934 (K^-, K^+) events in the K^+ momentum region, $0.9 \leqslant P_{K^+} \leqslant 1.3$ GeV/c, were scanned by human eyes and classified according to their topological categories, as defined by the number of charged prongs, kinks, and decayed particles from the neutral particles such as Λs (V-topology).

Of the above event sample, 214 two-V-topology events were observed, among which 28 events had a charged prong from the (K^-, K^+) reaction vertex. Present data analyses are based on the events having two-V topology. A typical event

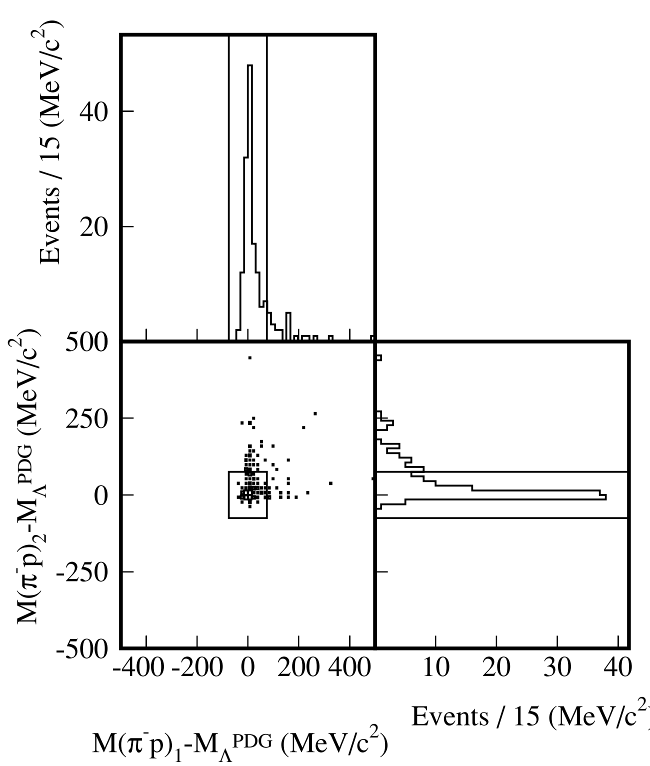

FIG. 3. Reconstructed mass distribution of two-Λ candidates.

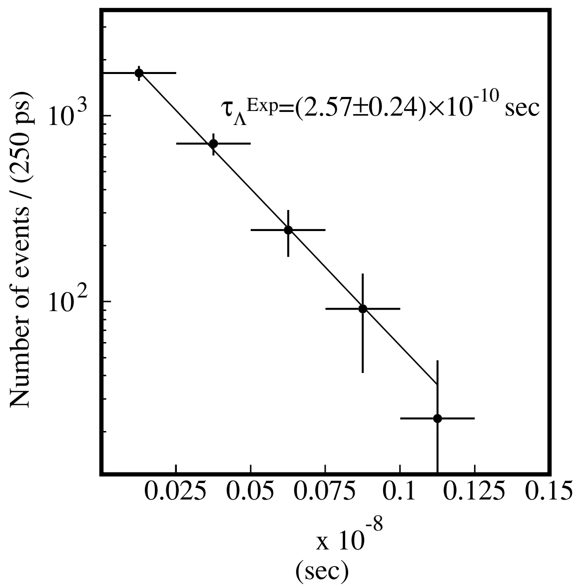

FIG. 4. Proper time of two-Λ data. Efficiency was corrected.

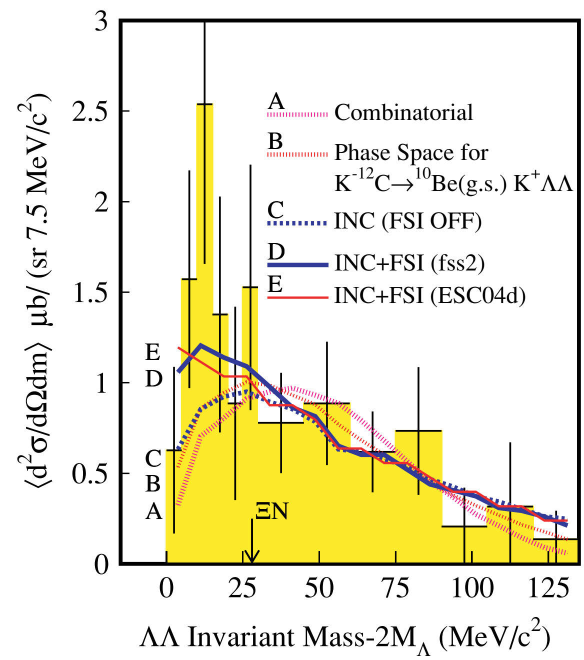

FIG. 5. (Color) ΛΛ invariant mass spectrum compared with theoretical predictions and with experimentally deduced backgrounds. Binning was done corresponding to the different resolutions, 5 and 15 MeV/c^2. Error bars are statistical only.

of ^{12}C$(K^-, K^+\Lambda\Lambda)$ reaction is shown in Fig. 2. Figure 3 shows the mass distribution of the two-Λ candidate events, in which the mass resolution is 15 MeV/c^2, which was estimated by fitting the distributions. The indicated two lines denote ±75 MeV/c^2 gates from the known Λ mass. The kinematic calculation was performed using empirical range-energy relations that are calibrated with a set of Ξ^--decaying events ($\Xi^- \to \Lambda\pi^-$).

Figure 4 shows the distribution of lifetimes for the two-Λ data. The fitted value from the distribution is $\tau_\Lambda^{\rm EXP} = (2.57 \pm 0.24) \times 10^{-10}$ s, which is consistent with the present world data, $\tau_\Lambda^{\rm PDG} = (2.631 \pm 0.020) \times 10^{-10}$ s [12] within the error.

For identification of proton and pion, we first assigned them using the brightness and thickness of the tracks. Subsequently, the reconstructed mass was compared with two sets of hypotheses on π^--p and p-π^-. Then, the set which gave a closer value to the known Λ mass was accepted if they were separated from each other by more than two times the Λ mass resolution. A simulation study shows that 94.4 ± 5.4 (stat.)% of the data for the measured tracks can be correctly identified by the above procedure. The simulation images were produced by GEANT [14] using the measured response function of the scintillating fibers.

The momentum of the Λ was deduced by measuring the range of stopped protons or pions. Then, a kinematic fit [15] for the hypothesis on the Λ-decay ($\Lambda \to \pi^- p$) was performed. The reconstructed ΛΛ-mass resolution is 5 MeV/c^2 below the ΞN threshold and 15 MeV/c^2 for the higher mass region, as estimated by fitting the differences between simulated and reconstructed masses. The ΛΛ mass resolution below the ΞN threshold is slightly improved over the previous one.

To improve mass resolution of the ΛΛ, the following conditions were required.

(i) Track lengths must be longer than 4 mm for both protons and pions.
(ii) Flight lengths of Λ must be longer than 1.5 mm.
(iii) Reconstructed $\pi^- p$ invariant masses must be in the gate, $|M_{\pi^- p} - M_\Lambda^{\rm PDG}| < 75$ MeV/c^2.

Here $M_{\pi^- p}$ denotes the invariant mass of a π^- and proton, and $M_\Lambda^{\rm PDG}$ denotes the present world data of Λ mass.

Efficiency ($\eta_{\Lambda\Lambda}^{\rm SCIFI}$) of the analysis was deduced by analyzing 8000 events of simulated GEANT-image data. Data were mixed with those simulation events, and then randomly analyzed during the data analysis. The efficiency was determined and corrected.

Figure 5 shows the ΛΛ invariant mass spectrum. The production cross section for ΛΛ production was estimated by using the relation

$$\langle d\sigma^{\Lambda\Lambda}/d\Omega \rangle = \langle d\sigma^{(K^-,K^+)}/d\Omega \rangle \times (Y^{\Lambda\Lambda}/Y).$$

Here the cross section of (K^-, K^+) reactions with the carbon nuclei $\langle d\sigma^{(K^-,K^+)}/d\Omega \rangle$ was taken as 99 ± 4 μb/sr, which was measured in the past experiment at the KEK [13]. The yield of (K^-, K^+) events with the carbon nuclei in the SCIFI target, Y, is given by $Y = 0.72N$.[1] Here N represents the observed number of (K^-, K^+) reactions determined by the

[1]This ratio is taken from the nuclear mass number A dependence of the target for the (K^-, K^+) cross sections. It is given by $(d\sigma/d\Omega)_A = (d\sigma/d\Omega)_p \times A^{0.38\pm0.03}$ [13]. Here the SCIFI target is assumed to be made of $(\mathrm{CH})_n$, and other materials such as clads and paints [22] were neglected. The effect of these materials changes by 2% the cross section results.

scanning. The yield of $\Lambda\Lambda$ can be expressed as

$$Y^{\Lambda\Lambda} = N^{\Lambda\Lambda}/\mathrm{Br}^2(\Lambda \to \pi^- p)\,\eta^{\mathrm{SCIFI}}_{\Lambda\Lambda}.$$

Here $N^{\Lambda\Lambda}$ is the number of $\Lambda\Lambda$, $\mathrm{Br}^2(\Lambda \to \pi^- p)$ is the squared branching ratio for the charged decay of a Λ having the value $(0.639 \pm 0.005)^2$, and $\eta^{\mathrm{SCIFI}}_{\Lambda\Lambda}$ denotes the efficiency of the analysis, as described previously.

The production cross section of $^{12}\mathrm{C}(K^-, K^+\Lambda\Lambda X)$ over the momentum region $0.9 \leqslant P_{K^+} \leqslant 1.3$ GeV/c in the angular region of $2^\circ \leqslant \theta^{\mathrm{Lab}}_{K^+} \leqslant 15^\circ$ is found to be 12.8 ± 1.5 (stat.) ± 0.5 (syst.) μb/sr. The systematic error arises from uncertainty of the cutoff efficiencies on short flight lengths, track lengths, and the mass cut of the reconstructed Λ, which are studied by varying cutoff parameters by ±20% from the accepted values.

The data were compared with a "combinatorial background" (pink dotted line: A) that is produced by mixing Λ pairs taken from mutually different events. This data set contains the same acceptance of the real data. The data were also compared with a phase space distribution for the $K^{-12}\mathrm{C} \to {}^{10}\mathrm{Be}$ (ground state; g.s.) $K^+\Lambda\Lambda$ (red dotted line: B) [16], and intranuclear cascade (INC) calculation (blue dotted line: C) [17]. These prediction curves were normalized by using the cross section of the data in which the mass region was larger than 30 MeV/c^2 (approximately ΞN threshold). The three prediction curves—combinatorial, phase space, and INC—are mutually similar. Statistical significances of the enhancements below 30 MeV/c^2 are found to be 2.1 standard deviations with respect to phase space (11.0 events for the signal, 17.7 for the background), and 2.6 standard deviations with respect to the combinatorial (14.1 events for the signal, 14.6 for the background) by defining $S/\sqrt{B+S}$. Here B is the number of background and S is the number of signal events above the background.

We performed INC calculations including FSI using the method in Refs. [18]. Two recent $\Lambda\Lambda$ potential[2] sets were used for the FSI: the resonating group method fss2 (RGM-fss2) by the Kyoto-Niigata group (blue solid line: D) [19] and the extended soft core model 04d (ESC04d) by the Nijmegen group (red solid line: E) [20]. These models reproduce the newly measured binding energy of the NAGARA event. Although data in the mass region 10–15 MeV/c^2 shows a peak, the statistical significance below 30 MeV/c^2 is negligibly small. Excess of the production cross section above the level of the fss2 prediction is 0.9 μb/sr, which is the same order of the value predicted by Aert and Dover for a bound H dibaryon ($M_H \sim 2M_\Lambda$) [21]. The resulting upper limit for the production cross section of H with a mass range between the $\Lambda\Lambda$ and ΞN threshold is found to be 2.1 ± 0.6 (stat.) ± 0.1 (syst.) μb/sr at a 90% confidence level. Here, the difference between the cross sections of the fss2 and the ESC04d is smaller than the systematic error.

In summary, we sought the H-dibaryon resonance through $^{12}\mathrm{C}(K^-, K^+\Lambda\Lambda X)$ reactions using a scintillating fiber active target at the KEK-PS. We observed a bump near the $\Lambda\Lambda$ threshold as reported by the KEK E224 experiment. The statistical significance of the enhancements compared with a phase space and a combinatorial background below 30 MeV/c^2 are 2.1 and 2.6 standard deviations, respectively.

INC model calculations with final state interactions were performed, in which we employed $\Lambda\Lambda$ potentials which are consistent with their interaction energy obtained from the NAGARA event [3]. No significant enhancement above the levels predicted by INC with a FSI calculation was observed. The upper limit for the production cross section of the H with a mass range between the $\Lambda\Lambda$ and ΞN threshold is found to be 2.1 ± 0.6 (stat.) ± 0.1 (syst.) μb/sr at a 90% confidence level.

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[2] Here, the $\Lambda\Lambda$ potentials employed are not directly taken from the theories but are parametrized with two- or three-Gaussian functions to reproduce the phase shifts of the models.

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