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Enhanced ΛΛ Production near Threshold in the ^{12}C(K^-, K^+) Reaction

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Abstract

Enhanced production of $\Lambda\Lambda$ pairs, above levels predicted by a two-step process model, has been observed near threshold (in the mass range 2.23-2.26 GeV/c^2) in the ^{12}C(K^-, K^+) reaction at 1.66 GeV/c using a scintillating fiber target. The differential cross section for $\Lambda\Lambda$ production in the momentum region $0.95 \le p_{K^+} \le 1.3$ GeV/c averaged over the range $2.3^\circ \le \theta_{K^+} \le 14.7^\circ$ was found to be 7.6 ± 1.3 μb/sr, and that for the enhancement was found to be approximately 3 μb/sr.

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While most applicable theories predict the H-dibaryon ($uuddss$) to be stable with respect to strong decay, it has not yet been unambiguously observed experimentally. Many recent experimental results indicate that the existence of a deeply-bound H (bound by more than about 30-50 MeV) is very unlikely [1]. The observation of several double-Λ hypernuclear events in nuclear emulsion suggests that the H-dibaryon is very loosely bound, or unbound, relative to $2m_\Lambda$ [2]. Recent theoretical estimates [3] show that the H-dibaryon could exist as a resonance-like state decaying into $\Lambda\Lambda$ close to the $\Lambda\Lambda$ threshold.

Several decades ago, a heavy-liquid bubble chamber experiment [4] was performed using 2.1 GeV/c K^- to search for an H-dibaryon resonance in a $\Lambda\Lambda$ invariant mass plot. Two separate experiments, one using Σ^- hyperon-nucleus interactions at 300 GeV/c [5] and one using hadronic Z^0 boson decays into $\Lambda\Lambda$ or $\bar{\Lambda}\bar{\Lambda}$ [6], were recently carried out. There was, however, no conclusive evidence of the H-dibaryon resonance in those experiments. It should be noted that the K^- beam momentum of 2.1 GeV/c used in the first of these experiments is too high to produce a low-energy Ξ^- particle, which is thought to participate with high probability in H-dibaryon formation, and that the latter two experiments using much higher energies could only detect the H-dibaryon signal if it were to appear as a sharp and strong peak in the $\Lambda\Lambda$ invariant mass spectrum.

In this Letter, we report on enhanced $\Lambda\Lambda$ production close to the threshold in the ^{12}C(K^-, K^+) reaction. $\Lambda\Lambda$ production in the (K^-, K^+) reaction with a nuclear target originates chiefly from the intermediate Ξ^- and meson-induced two-step processes, such as $K^-p \to \Xi^-K^+$; $\Xi^-p \to \Lambda\Lambda$ and $K^-p \to \pi^0\Lambda; \pi^0p \to \Lambda K^+$. In a previous study [7], we found that $\Lambda\Lambda$ production in the ^{12}C(K^-, K^+) reaction can be understood as being mainly due to intermediate meson-induced two-step processes, and that roughly half of the total $\Lambda\Lambda$ production above $p_{K^+} = 0.95$ GeV/c could be attributed to Ξ^--induced reactions. This sizable contribution of the Ξ^--induced two-step processes has been studied with respect to the possible formation of the H-dibaryon resonance decaying into $\Lambda\Lambda$. Our experiment has much better sensitivity for the observation of a possible H-dibaryon resonance near the threshold in the $\Lambda\Lambda$ invariant mass spectrum than the three experiments mentioned above.

Our experiment was carried out using a separated 1.66 GeV/c K^- beam at the KEK proton synchrotron. The heart of the experiment is a novel 4π detector consisting of $0.5 \times 0.5\text{mm}^2$ plastic scintillating fibers. The scintillating fiber (SCIFI) detector acts as a primary interaction target and visual track detector for recognizing (K^-, K^+) reactions and subsequent decays of hyperons produced in the effective volume of $8 \times 8 \times 10$ cm^3. The SCIFI target was observed using two sets of the image intensifier tubes (IIT), which were arranged orthogonally along the X and Y directions. The beam corresponds to the Z direction. The intensified image was recorded using a CCD camera and digitized with a flash ADC. Including the analysis of the SCIFI data caused the contamination of π^- and $\bar{p}$ to be reduced to less than 0.01 %. The momenta of outgoing particles were measured with a K^+ spectrometer of approximately 5 m length, consisting of a dipole analyzing magnet with a field integral of 1.08 T·m, 12 drift-chamber planes, two Cherenkov counters, and three hodoscope counters for timing and triggering purposes. The momentum resolution $(\Delta p/p)$ was 0.5% (rms) at 1.2 GeV/c, and the background ratio of π^+ to K^+ was estimated to be less than 0.2 % [8].

The average number of track clusters for a minimum-ionizing particle was approximately 0.55/mm along the particle track, and the size of a single cluster was typically 180 μm (rms). The track residual, defined as the distribution of the distance between the fitted straight track and each cluster, weighted by the brightness of each cluster, was about 290 μm. The details of the experimental setup are described elsewhere [7,8].

A total of eight thousand (K^-, K^+) events above $p_{K^+} \geq 0.95$ GeV/c were scanned by eye and categorized according to their event topologies, defined by the number of charged prongs, kinks and Λ particles. Scanning for events with two V topologies revealed 71 events corresponding to the ^{12}C$(K^-, K^+)\Lambda\Lambda X$ reaction. Out of these 71 events, 63 events each have no additional charged prong, while the remaining 8 events have one stopping prong from the (K^-, K^+) primary vertex. The data analysis is based on reconstructing events with two V topology tracks. Candidates were first geometrically constructed from the SCIFI images obtained from two perpendicularly oriented views (corresponding to the two sets of IIT).

Λ candidates were selected by requiring that $| m_V - m_\Lambda |$ be less than 70 MeV/c^2, where m_V is the reconstructed mass and m_Λ is the known mass of the Λ particle, as shown in Fig.1(a). Next, hypothesizing the decay $\Lambda \rightarrow p\pi^-$, a kinematic fit was performed to obtain the momentum of the Λ particle with its known mass. To demonstrate the quality of this Λ sample, the mean lifetime of Λ particles for the sample of $\Lambda\Lambda$ events is compared with that for a sample of one-Λ events in Fig.1(b). The mean lifetimes of the Λ particles for both samples are consistent with the present world data (τ_Λ=2.64 $\pm$ 0.26 $\times$ $10^{-10}s$ for a $\Lambda\Lambda$ sample). Finally, only 35 events with decay protons of track length greater than 2 mm were retained [9].

Quasifree Ξ^- production in the (K^-, K^+) reaction at 1.66 GeV/c is characterized by a sharp peak of the K^+ momentum distribution at $\sim$ 1.1 GeV/c. The double differential cross section for the ^{12}C$(K^-, K^+)\Lambda\Lambda X$ reaction with respect to the K^+ momentum shown in Fig.2 [10] exhibits a significant peak in the region of the quasifree Ξ^- production. This peak indicates a sizable contribution from Ξ^--induced reactions. An estimate obtained from an intranuclear cascade model calculation [11] on intermediate meson-induced reactions is represented by the overlaid dashed line.

The finite size of our SCIFI detector makes the observation of the decay of Λ particles very close to the production point and the observation of Λ particles with long lifetimes less likely. The detection efficiency for any given event depends on the kinematic quantities which characterize its topology. In order to calculate the detection efficiency of the SCIFI target, we used a Monte Carlo simulation based on real data. Since we have no *a prior* knowledge regarding the Λ momentum distribution for $\Lambda\Lambda$ production, this simulation relies entirely on real data for each event. The sizes of the errors for the individual events vary greatly and the Monte Carlo data were generated with Gaussian probability. In addition, we assumed azimuthal symmetry of the Λ production angle with respect to the K^- beam track. Keeping the polar angle between the two Λ particles fixed, we made a random rotation of the Monte Carlo event with respect to the beam direction. This randomization minimizes the possible variation of detection efficiency near the corner of the SCIFI detector.

The detection efficiency for the two Λ decays in the SCIFI target, $\eta_{SFD}^{\Lambda\Lambda}$, is given by $Br^2(\Lambda \rightarrow p\pi^-) \cdot \eta_{\Lambda\Lambda}$. The branching ratio for charged particle decay of the $\Lambda\Lambda$ pair was taken into account by using the factor $Br^2(\Lambda \rightarrow p\pi^-) = (0.639 \pm 0.005)^2$ [12]. The scanning efficiency, $\eta_{\Lambda\Lambda}$, was deduced from the Monte Carlo simulation described above. The corrected number of events for the $^{12}C(K^-, K^+)\Lambda\Lambda X$ reaction is $35/\eta_{SFD}^{\Lambda\Lambda} = 441 \pm 75$. The differential cross section integrated over the K^+ momentum region ($950 \leq p_{K^+} \leq 1300$ MeV/c) was thus found to be $\langle d\sigma/d\Omega_L \rangle_{^{12}C(K^-,K^+)\Lambda\Lambda X} = 7.6 \pm 1.3$ μb/sr.

Figure 3 displays the $\Lambda\Lambda$ invariant mass spectrum. The invariant mass resolution was determined by fitting Gaussian distributions of the individual measurements with a standard deviation corresponding to the experimental error. The error here is largely due to uncertainties in determining the magnitude of the Λ momentum, which depends strongly on the range measurement of stopping proton from Λ decay. The invariant mass resolution calculated using sample data below the mass 2.26 GeV/c^2. It was found to be approximately 6 MeV/c^2.

The $\Lambda\Lambda$ invariant mass spectrum in Fig.3 displays a significant enhancement near the threshold. We performed an intranuclear cascade model calculation to understand the origin of this peak. In this calculation, the positions of nucleons were generated randomly within a sphere with the requirement that the distance between two nucleons be larger than 0.81 fm. The nuclear density distribution employed was that of a harmonic oscillator shell-model, and the local Fermi momentum was determined using the local-density approximation. The nuclear binding energy was taken into account, and off-shell kinematics were used. Total and differential cross sections for K^--induced reactions were taken from a parametrization based on the experimental data [13].

The total contribution of two-step processes is represented by the dashed line in Fig.3, with the individual contributions from Ξ^- and π^0-induced reactions represented by the dotted and dashed-dotted lines, respectively. The total cross section ($\sigma(E_{\Xi^-})$) for the $\Xi^- p \rightarrow \Lambda\Lambda$ reaction was taken from the prediction of the Nijmegen D model (r_c=0.5 fm). This cross section is approximately 2 mb at $p_{\Xi^-} \sim 0.5$ GeV/c. The total cross section for the

$\pi^0 p \rightarrow \Lambda K^+$ reaction was taken from a parametrization of existing experimental data for the $\pi^- p \rightarrow \Lambda K^0$ reaction [14]. To establish some confidence in the reliability of our intranuclear cascade model calculation, the shape of the invariant mass distribution was calculated using the approximate Kopylov-Komolova shape formula, which corresponds to the phase space for the $K^{-12}C \rightarrow K^+\Lambda\Lambda^{10}Be$ 4-body reaction. We assume here, for simplicity, that the remaining nucleus ^{10}Be is in the ground state, and we use a K^+ momentum distribution taken from real data. This function carries only shape information, and hence the integral of this function was normalized to the result of the intranuclear cascade model calculation. The two results are quite consistent. However, neither of them reproduces the peak near the threshold.

The enhancement of the invariant mass near the threshold is suggestive of either the possible existence of a $\Lambda\Lambda$-resonance which could be identified with an H-dibaryon resonance state [3], a strongly-attractive $\Lambda\Lambda$ final state interaction (FSI), or a complementary signal resulting from both contributions. The observed K^+ momentum spectrum shown in Fig.2 for $\Lambda\Lambda$ production implies a sizable contribution from the Ξ^--induced two-step (K^-, K^+) process. However, the observed opening angle distribution near the threshold is forward peaked, as indicated by the dotted histograms in Fig.4(a). This fact suggests that it is unlikely that the enhancement results directly from the $\Xi^- p \rightarrow \Lambda\Lambda$ conversion process, since if this were the case, the opening angle would tend toward larger angles adjacent to $\pi/2$.

The formation of an H-dibaryon resonance, as shown in Fig.4(b), could be accompanied by significant enhancement. The statistical significance of the enhancement (14.9 events) below 2.261 GeV/c^2 is 4.9 standard deviations on the basis of the intranuclear cascade model calculation for the background (9.3 events). The differential cross section for the enhancement ($\sim 3\mu$b/sr) is approximately 6 times larger than the value predicted by Aerts and Dover for bound H production ($m_H \sim 2m_\Lambda$) [15]. On the other hand, the FSI could be significant close to the threshold in the case of a strongly-attractive $\Lambda\Lambda$ interaction. However, the observed spectrum intensity, in excess of that predicted by the two-step process model, probably cannot be fitted with a large negative value for the $\Lambda\Lambda$ scattering length [16], whereas, assuming no resonance state exists, the best-fit parameter ($a_{\Lambda\Lambda} = -2.5$ fm) is comparable with that for $^1S_0$ Λn interaction [9].

In conclusion, enhanced production of $\Lambda\Lambda$ pairs, above levels predicted by a two-step process model, has been observed near the threshold (in the mass range 2.23-2.26 GeV/c^2) in the ^{12}C(K^-, K^+) reaction at 1.66 GeV/c using a scintillating fiber target. The differential cross section for $\Lambda\Lambda$ production in the momentum region $0.95 \leq p_{K^+} \leq 1.3$ GeV/c averaged over the range $2.3^o \leq \theta_{K^+} \leq 14.7^o$ was found to be 7.6 ± 1.3 μb/sr, and that for the enhancement was found to be approximately 3 μb/sr. The enhancement of the invariant mass indicates either the possible existence of a $\Lambda\Lambda$ resonance, which is referred to as an H-dibaryon resonance state, a strongly-attractive $\Lambda\Lambda$ final state interaction, or both. Unfortunately, we cannot make a definite identification due to the limited statistical significance of our data.

It is therefore necessary to search for the $\Lambda\Lambda$-resonance state near the threshold. At BNL-AGS, a (K^-, K^+) experiment (E906) [17] is now underway with a cylindrical drift chamber system, and it is expected to achieve statistical significance two orders of magnitude higher than that in our experiment for $\Lambda\Lambda$ events. It is also probable that such studies could be carried out in the context of the strangeness physics program envisioned for the upcoming Japan Hadron Facility (JHF).

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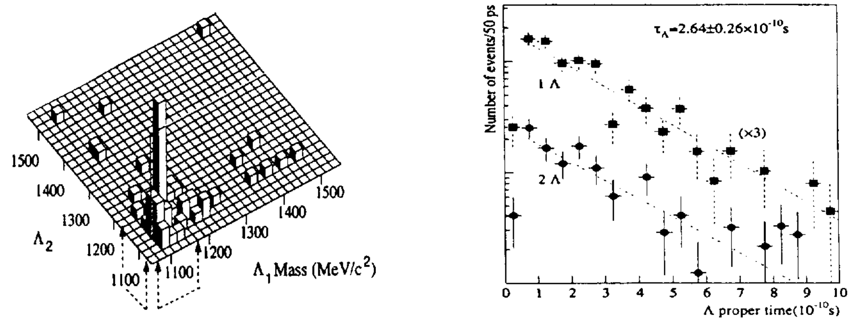
FIGURES



(a) (b)

FIG. 1. (a) Reconstructed mass distribution of V topology tracks for the decay $\Lambda \rightarrow p\pi^-$. Λ candidates are selected by the mass cut indicated by the arrows (see text). (b) Proper time distribution of the Λ candidates for both one-Λ and two-Λ events. The results of the lifetime fit are represented by the overlaid dashed lines.

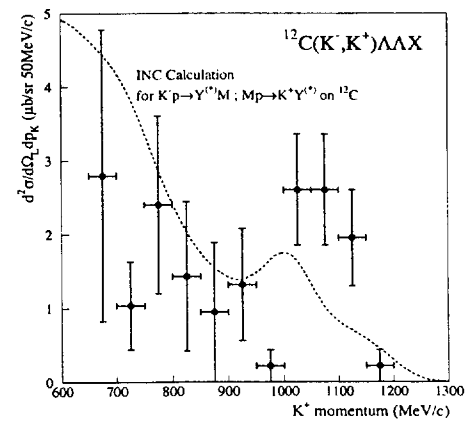


FIG. 2. Differential cross section for the $^{12}C(K^-,K^+)\Lambda\Lambda X$ reaction with respect to the K^+ momentum. The dashed line indicates the prediction of an intranuclear cascade model calculation for intermediate meson-induced two-step processes.

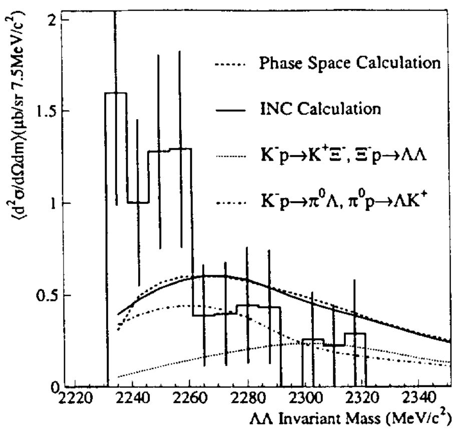
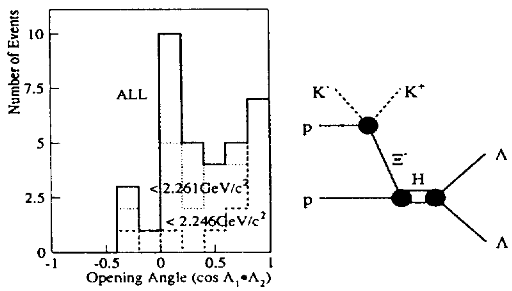


FIG. 3. The $\Lambda\Lambda$ invariant mass spectrum compared with theoretical estimates of the phase-space calculation (dashed line) for the $K^{-12}C \to K^+\Lambda\Lambda^{10}Be$ reaction and an intranuclear cascade model calculation (solid line) for intermediate π^0-induced (dashed-dotted line) and Ξ^--induced (dotted) two-step processes.



(a) (b)

FIG. 4. (a) The opening angle distribution for $\Lambda\Lambda$ production. (b) The forward peaking of events near the threshold suggests that the enhancement in Fig.3 could be due to a doubly-strange H dibaryon decaying strongly into $\Lambda\Lambda$.