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# Reaction $K^{-}p\to\pi^0\pi^0\Lambda$ from $p_{K^-}=514$ to 750 MeV/$c$

S. Prakhov,[1] B. M. K. Nefkens,[1] C. E. Allgower,[2] V. Bekrenev,[3] W. J. Briscoe,[4] M. Clajus,[1] J. R. Comfort,[5] K. Craig,[5] D. Grosnick,[6] D. Isenhower,[7] N. Knecht,[8] D. Koetke,[6] A. Koulbardis,[3] N. Kozlenko,[3] S. Kruglov,[3] G. Lolos,[8] I. Lopatin,[3] D. M. Manley,[9] R. Manweiler,[6] A. Marušić,[1] S. McDonald,[1] J. Olmsted,[9] Z. Papandreou,[8] D. Peaslee,[10] N. Phaisangittisakul,[1] J. W. Price,[1] A. F. Ramirez,[5] M. Sadler,[7] A. Shafi,[4] H. Spinka,[2] T. D. S. Stanislaus,[6] A. Starostin,[1] H. M. Staudenmaier,[11] I. Supek,[1,2] and W. B. Tippens[1]

(Crystal Ball Collaboration)

[1]*University of California Los Angeles, Los Angeles, California 90095-1547, USA*
[2]*Argonne National Laboratory, Argonne, Illinois 60439-4815, USA*
[3]*Petersburg Nuclear Physics Institute, Gatchina 188350, Russia*
[4]*The George Washington University, Washington, D.C. 20052-0001, USA*
[5]*Arizona State University, Tempe, Arizona 85287-1504, USA*
[6]*Valparaiso University, Valparaiso, Indiana 46383-6493, USA*
[7]*Abilene Christian University, Abilene, Texas 79699-7963, USA*
[8]*University of Regina, Saskatchewan, Canada S4S OA2*
[9]*Kent State University, Kent, Ohio 44242-0001, USA*
[10]*University of Maryland, College Park, Maryland 20742-4111, USA*
[11]*Universität Karlsruhe, Karlsruhe 76128, Germany*
[12]*Rudjer Boskovic Institute, Zagreb 10002, Croatia*

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Reaction $K^{-}p\to\pi^0\pi^0\Lambda$ was measured at eight incident $K^-$ momenta between 514 and 750 MeV/$c$ using the Crystal Ball multiphoton spectrometer. The reaction dynamics are displayed in total cross sections, Dalitz plots, invariant-mass spectra, production angular distributions, and the $\Lambda$ polarization. The $\pi^0\pi^0\Lambda$ production is dominated by the $\pi^0\Sigma^0(1385)$ intermediate state; no trace of other light $\Sigma^*$ states is observed, and the role of the $f_0(600)$ meson appears to be insignificant. A striking similarity is seen between $K^{-}p\to\pi^0\pi^0\Lambda$ and $\pi^{-}p\to\pi^0\pi^0 n$; this can be understood as a consequence of dynamical flavor symmetry.

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An important objective of nuclear physics is an understanding of the mechanism by which energy is changed into mass. One of the simplest processes to study is $\pi^0$ production in reactions such as

$$K^{-}p\to\pi^0\pi^0\Lambda. \qquad (1)$$

In the isobar model [1], meson production is dominated by the excitation and decay of resonances in intermediate states, baryonic as well as mesonic ones. For the description of many nuclear reactions at moderate energies, one needs the occurrence of a strong $S$-wave dipion interaction, now called the $f_0(600)$ resonance, but better known as the $\sigma$ mesonic state with $I,J^P=0,0^+$. The $f_0$ is expected to play a significant role in $\pi^0$ production via the sequential process $K^{-}p\to\Lambda^*\to f_0(600)\Lambda\to\pi^0\pi^0\Lambda$, which would be the meson-resonance route. The other option is the process $K^{-}p\to\Lambda^*\to\pi^0\Sigma^0(1385)\to\pi^0\pi^0\Lambda$ with the baryon-resonance route. The most reliable way to probe the resonance routes of $\pi^0$ production in reaction (1) is the examination of the Dalitz plot of the $\pi^0\pi^0\Lambda$ final state.

In QCD calculations, the $s$ quark has the same strong interaction as the $d$ quark, except for the effect of the mass-difference term, which reflects the fact that $m_s-m_d\approx150$ MeV. This is the famous flavor symmetry of QCD that is used to relate the masses of various baryonic and mesonic states. For instance, for every $N^*$ state, we expect a $\Lambda^*$ of the same spin and parity but about 150 MeV heavier, as is observed [2]. We like to explore the possible occurrence of dynamical flavor symmetry in a tree-body final state. Specifically, we want to investigate whether the main features of the $K^{-}p\to\pi^0\pi^0\Lambda$ reaction are closely parallel to those of $\pi^{-}p\to\pi^0\pi^0 n$ [3]. Dynamical flavor symmetry has already been observed in the simple two-body final-state reactions $K^{-}p\to\eta\Lambda$ and $\pi^{-}p\to\eta n$ [4].

There are no recent measurements of reaction (1); the old data date back to the bubble-chamber era with large uncertainties in the results [5,6]. In this article we present results of the first extensive measurement of the $K^{-}p\to\pi^0\pi^0\Lambda$ reaction at eight incident $K^-$ momenta between 514 and 750 MeV/$c$, corresponding to center-of-mass (c.m.) energies 1569–1676 MeV. The chief objectives of the experiment are to determine the dominant features of the reaction mechanism and to measure the total cross sections for reaction (1) with good precision. In this energy range, there are three well-established $\Lambda^*$ states: the three-star $\Lambda(1600)\frac{1}{2}^+$ with $\Gamma\approx150$ MeV, the four-star $\Lambda(1670)\frac{1}{2}^-$ with $\Gamma\approx35$ MeV, and the four-star $\Lambda(1690)\frac{3}{2}^-$ with $\Gamma\approx60$ MeV. Of special interest is a search for evidence of the $\Lambda(1600)\frac{1}{2}^+$ state in the $\pi^0\pi^0\Lambda$ cross-section energy dependence. The above three $\Lambda^*$ states are the flavor analogs of the $N(1440)\frac{1}{2}^+$ (or the Roper resonance), the $N(1535)\frac{1}{2}^-$, and the $N(1520)\frac{3}{2}^-$, respectively. Therefore, the salient features of reaction (1) in the energy

 

TABLE I. Summary of the results for reaction $K^- p \to \pi^0\pi^0\Lambda$. Content of rows: (1) beam momentum and its spread; (2) number of $K^- p \to \pi^0\pi^0\Lambda$ candidates; (3) total cross section $\sigma_t(K^- p \to \pi^0\pi^0\Lambda)$, where the uncertainties are statistical only.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $p_{K^-} \pm \sigma_p$ [MeV/$c$] | $514\pm10$ | $560\pm11$ | $581\pm12$ | $629\pm11$ | $659\pm12$ | $687\pm11$ | $714\pm11$ | $750\pm13$ |
| $N_{\rm Exp}$ | 766 | 1613 | 2475 | 2993 | 3173 | 3627 | 4029 | 7837 |
| $\sigma_t(K^- p \to \pi^0\pi^0\Lambda)$[mb] | $0.65\pm0.03$ | $0.78\pm0.03$ | $0.74\pm0.02$ | $0.85\pm0.02$ | $0.80\pm0.02$ | $0.83\pm0.02$ | $0.87\pm0.02$ | $1.09\pm0.02$ |

range under discussion can be compared to the features of $\pi^- p \to \pi^0\pi^0 n$ at c.m. energies that are equivalent to the $N^*$ production.

Our measurements of $K^- p \to \pi^0\pi^0\Lambda$ were performed at Brookhaven National Laboratory with the Crystal Ball (CB) multiphoton spectrometer, which was installed in the C6 beam line of the Alternating Gradient Synchrotron. The Crystal Ball consists of 672 optically isolated NaI(Tl) crystals that cover 93% of $4\pi$ steradians. A momentum-analyzed $K^-$ beam was incident on a 10-cm-long liquid hydrogen target located in the center of the CB. The mean values $p_{K^-}$ of the incident momentum spectra and the momentum spread $\sigma_p$ determined at the target center are listed in Table I. The precision in determining the mean momenta is 2–3 MeV/$c$. More details about the CB detector, its resolutions, the triggering system, and the data analyses can be found in Refs. [3,4,7–9].

The $\Lambda$ hyperon is identified in the CB by its decay to $\pi^0 n$. The candidates for reaction

$$K^- p \to \pi^0\pi^0\Lambda \to 3\pi^0 n \to 6\gamma n \tag{2}$$

were searched for in the neutral six-cluster and seven-cluster events. The software threshold of the cluster energy was 20 MeV. The seventh cluster is assumed to be from the neutron. All six-cluster and seven-cluster events were subjected to a kinematic fit to test the hypothesis of being reaction (2). The $z$ coordinate of the primary vertex and the decay length of the $\Lambda$ were free parameters in the kinematic fit. The effective number of constraints for the fitted hypothesis was three and five for six-cluster and seven-cluster events, respectively. The kinematic fit was performed for every possible pairing combination of six photons to form three $\pi^0$'s, one being the $\pi^0$ from the $\Lambda$ decay. For six-cluster events, there are 45 such permutations of the six photons. In case of seven-cluster events, this number is seven times larger, since the neutron cluster is also involved in the permutations. Events for which at least one pairing combination satisfied the hypothesis of reaction (2) at the 5% confidence level (C.L.) (i.e., with a probability greater than 5%) were accepted as $\pi^0\pi^0\Lambda$ event candidates. The pairing combination with the largest C.L. was used to reconstruct the kinematics of the reaction. The number of experimental events selected as $\pi^0\pi^0\Lambda$ candidates at each beam momentum is listed in Table I as $N_{\rm Exp}$.

To determine the acceptance, a Monte Carlo (MC) simulation of $K^- p \to \pi^0\pi^0\Lambda \to 3\pi^0 n$ events was performed according to phase space. The simulation was made for each experimental momentum, using the experimental beam-trigger events as input for the kaon-beam distributions. The MC events were then propagated through a full GEANT (version 3.21) simulation of the CB detector, folded with the CB resolutions and trigger conditions, and analyzed the same way as the experimental data. Based on the analysis of simulated data, the average detection efficiency for phase-space-distributed $K^- p \to \pi^0\pi^0\Lambda \to 3\pi^0 n$ events, after applying our selection criteria, varies from 20.1% at $p_{K^-}=514$ MeV/$c$ to 17.3% at $p_{K^-}=750$ MeV/$c$. To study the acceptance dependence on the invariant masses, we used the Dalitz plot of $m^2(\pi^0\pi^0)$ vs $m^2(\pi^0\Lambda)$. For studying the acceptance dependence on the production angles, we used the dipion production angle (the two $\pi^0$'s that are not from the $\Lambda$ decay), the direction of which in the overall c.m. system is just opposite to the $\Lambda$ direction. The overall acceptance for the $\pi^0\pi^0\Lambda$ Dalitz plot was found to be almost uniform for each beam momentum. The largest dependence of the CB acceptance was found to be on $\theta^*$, which is the angle between the $2\pi^0$ direction and the beam direction in the overall c.m. system. The CB acceptance decreases by a factor of three from backward to forward angles $\theta^*$. The dependence of the Dalitz plot acceptance on $\theta^*$ has been investigated as well. At small $\theta^*$, the acceptance decreases for small $m^2(\pi^0\pi^0)$. To take into account these features in the CB acceptance, we compared two methods for the acceptance evaluation. In the first method, the experimental cos $\theta^*$ distribution was corrected by its acceptance. In the second method, the data were divided into four equal intervals in cos $\theta^*$, and the Dalitz plot for each interval was corrected by the individual acceptance. The largest difference in the acceptance evaluation for the two methods was less than 4.5%. The second method of acceptance evaluation was used for the calculation of our total cross sections.

There are two sources of background events that contaminate the $\pi^0\pi^0\Lambda$ data samples; they must be subtracted before the acceptance correction. The first background is the $K^- p \to \pi^0\Sigma^0 \to \pi^0\gamma\Lambda \to 5\gamma n$ reaction, which can produce six-cluster events by splitting a single-photon cluster or by detecting the neutron in the CB. This background process was estimated by determining the probability for the simulated $K^- p \to \pi^0\Sigma^0$ events to be misidentified as $\pi^0\pi^0\Lambda$ candidates. As an input for the simulation of this background, we used the $K^- p \to \pi^0\Sigma^0$ differential cross sections that we have measured at each beam momentum in the same experiment. We estimate that the fraction of the $\pi^0\Sigma^0$ background in our $\pi^0\pi^0\Lambda$ data is 3–4%. The second source of background are processes that are not kaon interactions in the liquid hydrogen target. The major fraction of those are $K^-$ decays in the beam. This type of event was investigated using the data taken with the empty target. The fraction of this background varies from ~12% at $p_{K^-}=514$ MeV/$c$ to ~6% at $p_{K^-}=750$ MeV/$c$.

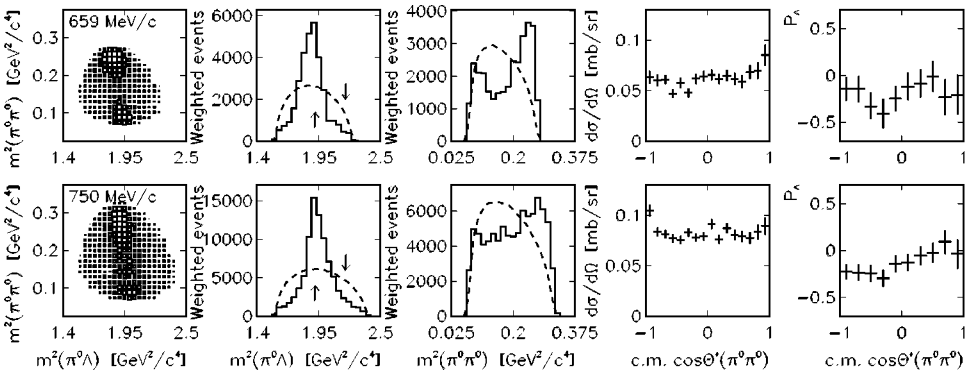


FIG. 1. Kinematics distributions for $K^- p \to \pi^0\pi^0\Lambda$ at $p_{K^-}=659$ and 750 MeV/$c$: Dalitz plots of $m^2(\pi^0\pi^0)$ vs $m^2(\pi^0\Lambda)$; both projections of the Dalitz plots; the cos $\theta^*$ distributions in units mb/sr; the $\Lambda$ polarization $P_\Lambda$. The dashed curves in the $m^2(\pi^0\Lambda)$ and $m^2(\pi^0\pi^0)$ spectra are the $\pi^0\pi^0\Lambda$ phase-space distributions normalized to the number of the experimental events. The arrow in the $m^2(\pi^0\Lambda)$ spectra pointing up marks the $\Sigma^0(1385)$ mass, and the arrow pointing down marks the mass of the one-star $\Sigma(1480)$.

In Fig. 1 we show the $\pi^0\pi^0\Lambda$ experimental distributions obtained for two beam momenta, 659 and 750 MeV/$c$, after background subtraction and acceptance correction. The distributions for the full data set can be found in Ref. [9]. Figure 1 includes the Dalitz plots of $m^2(\pi^0\pi^0)$ vs $m^2(\pi^0\Lambda)$, the projections of the plots on both axes, the cos $\theta^*$ distributions for the dipion production angle, and the $\Lambda$ polarization. Since the invariant mass of the $\pi^0\Lambda$ system is calculated for each of the $\pi^0$'s, every event has two entries in a Dalitz plot. The experimental spectra for $m^2(\pi^0\Lambda)$ and $m^2(\pi^0\pi^0)$ are compared to the corresponding phase-space distributions (shown by the dashed curves), which are normalized to the number of experimental events.

The manifestation of the $\Sigma^0(1385)$ state is clearly seen in the $m^2(\pi^0\Lambda)$ spectra. The Breit-Wigner mass of the $\Sigma^0(1385)$ in the $m^2(\pi^0\Lambda)$ spectra is marked by the arrow pointing up. The location and width of our $\Sigma^0(1385)$ peak is in good agreement with the known parameters of this hyperon [10]. The mass of the one-star $\Sigma(1480)$, which is an exotic hyperon resonance candidate [11], is marked in the $m^2(\pi^0\Lambda)$ spectra by the arrow pointing down. In our data, we do not see a trace of either this controversial state or other light $\Sigma^*$ states. A visual examination of the Dalitz plots and their projections is sufficient to see that the $f_0(600)$-meson contribution is insignificant. An important feature of the $\pi^0\pi^0\Lambda$ data for all beam momenta is a strong asymmetry in the density of the events as a function of the $\pi^0\pi^0$ invariant mass. The number of $\pi^0\pi^0\Lambda$ events with a large $m(\pi^0\pi^0)$ is considerably larger than with a small one. The likely explanation for such an asymmetry is the interference of the transition amplitudes. Note that process $K^- p \to \Lambda^* \to \pi^0\Sigma^0(1385) \to \pi^0\pi^0\Lambda$ involves two $\pi^0\Sigma^0(1385)$ amplitudes due to the coupling of each of the two $\pi^0$'s in the final state to the $\Lambda$ by the $\Sigma^0(1385)$ isobar. The interference of these two $\pi^0\Sigma^0(1385)$ amplitudes distorts the $\Sigma^0(1385) \to \pi^0\Lambda$ decay angular distribution from the specific shape defined by the initial $\Lambda^*$ state. Another interesting feature of the $\pi^0\pi^0\Lambda$ events becomes apparent when the data are divided into subsets for different cos $\theta^*$. A strong correlation between the shape of the $m(\pi^0\pi^0)$ spectrum and the dipion production angle is found. The features observed for the $\pi^0\pi^0\Lambda$ data have a striking similarity to the features of the $\pi^- p \to \pi^0\pi^0 n$ reaction produced at c.m. energies between the $N(1440)\frac{1}{2}^+$ and $N(1535)\frac{1}{2}^-$ [3]. To illustrate these similarities, we compare, in Fig. 2, the $\pi^0\pi^0\Lambda$ Dalitz plots obtained for forward and backward dipion angles $\theta^*$ to the corresponding $\pi^0\pi^0 n$ Dalitz plots.

The cos $\theta^*$ spectra shown in Fig. 1 are in units of mb/sr, so that they can be considered as the differential cross sections of reaction (1). The $\Lambda$ polarization has been obtained from its decay asymmetry $P(\cos\theta^*)=3(\Sigma_i \cos\beta_i)/[\alpha_\Lambda N(\theta^*)]$, where the definition of angle $\beta$ is similar to the one of Ref. [12]. The weak-decay asymmetry parameter $\alpha_\Lambda$ was set equal to 0.645.

Our results for the total cross section of reaction (1) are given in Table I. The uncertainties listed for the total cross sections are statistical only. To calculate the cross sections, we used the branching ratio 0.358 for the $\Lambda \to \pi^0 n$ decay [10]. Our results for $\sigma_t(K^- p \to \pi^0\pi^0\Lambda)$ are shown in Fig. 3 as a function of the beam momentum. The energy dependence of $\sigma_t(K^- p \to \pi^0\pi^0\Lambda)$ has a broad shoulder around the $\Lambda(1600)\frac{1}{2}^+$ state. The strong rise at $p_{K^-}=750$ MeV/$c$ is due

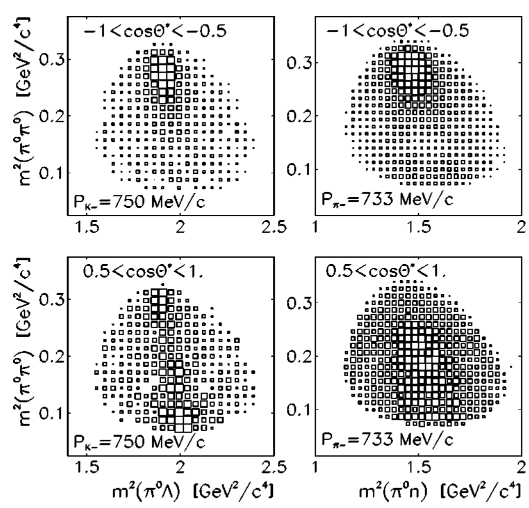


FIG. 2. Comparison of the $\pi^0\pi^0\Lambda$ (left) and $\pi^0\pi^0 n$ (right) Dalitz plots obtained for backward (top) and forward (bottom) dipion production angles.

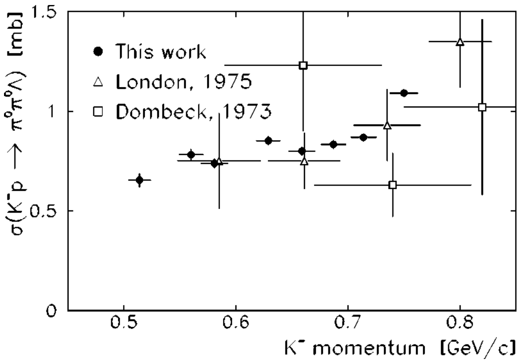


FIG. 3. Total cross section $\sigma_t(K^-p \to \pi^0\pi^0\Lambda)$ as a function of the beam momentum. Our results are compared to the old measurements of this channel, see Refs. [5,6].

to the onset of the $\Lambda(1670)\frac{1}{2}^-$ and $\Lambda(1690)\frac{3}{2}^-$ resonances. In the same figure we also show the results of the old measurements [5,6] of reaction (1). Our measurement favors the results of Ref. [6]; however, the statistical uncertainties of the old experiments are too large.

The systematic uncertainty in our total cross sections is estimated to be about 7%. The major contributions to this uncertainty are the acceptance evaluation, the background subtraction, the calculation of the number of incident kaons, and the evaluation of the fraction of good events lost due to pileup in the CB. An independent measurement of reactions $K^-p \to \pi^0\Lambda$ and $K^-p \to \overline{K}^0 n$ in the same experiment [9] shows good agreement with the published bubble-chamber data [13] for the total as well as differential cross sections; it supports the reliability of our results for $\sigma_t(K^-p \to \pi^0\pi^0\Lambda)$.

In summary, reaction $K^-p \to \pi^0\pi^0\Lambda$ has been measured for eight incident momenta between 514 and 750 MeV/$c$. The experimental Dalitz plots and invariant mass spectra show that $\pi^0\pi^0\Lambda$ production is dominated by the $\pi^0\Sigma^0(1385)$ intermediate state. No trace of the one-star $\Sigma(1480)$ or other light $\Sigma^*$ states was observed. The contribution of the $f_0(600)$ meson to $\pi^0\pi^0\Lambda$ production appears to be insignificant. A strong dependence of the Dalitz plots density on the dipion (or the $\Lambda$) production angle is observed. The total cross section $\sigma_t(K^-p \to \pi^0\pi^0\Lambda)$ rises gradually from 0.65 to 1.1 mb with a hint of a broad shoulder around the $\Lambda(1600)\frac{1}{2}^+$. The magnitude of $\sigma_t(K^-p \to \pi^0\pi^0\Lambda)$ is relatively large. At $p_{K^-}=714$ MeV/$c$, we have $\sigma_t(K^-p \to \pi^0\pi^0\Lambda)/\sigma_t(K^-p \to \pi^0\Lambda) \approx 0.3$. It is similar to ratio $\sigma_t(\pi^-p \to \pi^0\pi^0 n)/\sigma_t(\pi^-p \to \pi^0 n)$ at energies of equivalent range of the dipion invariant masses. Finally, we would like to stress the striking similarity that is seen when comparing our experimental distributions for $K^-p \to \pi^0\pi^0\Lambda$ and the ones for $\pi^-p \to \pi^0\pi^0 n$ [3]. The similarity in the Dalitz plots and the proportionality of the total cross sections for these two processes are an impressive testimony of the applicability of broken $SU(3)$ flavor symmetry to reaction dynamics. Further discussions of the features of $\pi^0\pi^0$ production by $\pi^-$ and $K^-$ are presented in Ref. [2].

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