$K^- p \to \pi^0\pi^0\Sigma^0$ at $p_{K^-}=514-750$ MeV/c and comparison with other $\pi^0\pi^0$ production

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Reaction $K^- p \to \pi^0\pi^0\Sigma^0$ was measured with the Crystal Ball multiphoton spectrometer at eight K^- momenta from 514 to 750 MeV/c. Dynamics and the energy dependence of the reaction are shown by Dalitz plots, invariant mass spectra, production angular distributions, and total cross sections. The dipion invariant-mass spectra for $K^- p \to \pi^0\pi^0\Sigma^0$ show an enhancement in the low mass region; the opposite is the case for the $K^- p \to \pi^0\pi^0\Lambda$ and $\pi^- p \to \pi^0\pi^0 n$ reactions. There is no direct evidence for a $f_0(600)$-meson contribution to $\pi^0\pi^0$ production. Everywhere $\sigma_t(K^- p \to \pi^0\pi^0\Sigma^0) \ll \sigma_t(K^- p \to \pi^0\pi^0\Lambda)$.

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The study of $\pi\pi$ production has been bolted into prominence by speculation about new opportunities for investigating medium modification [1]. Specifically, a lowering of the mass of the $f_0(600)$ resonance, also known as the σ meson, is expected when it is produced on complex nuclei [2]. Calculations [3] indicate that, if there is early onset of partial chiral restoration, a substantial medium modification is possible, even at low energy. The principal decay of $f_0(600)$ is into two pions. In the data analysis, the $\pi^0\pi^0$ system is preferred, as its isospin I is limited to 0 and 2; while $\pi^+\pi^-$ also has an $I=1$ component, which can be large when near the $\rho(770)$ resonance. To interpret $\pi\pi$ production on complex nuclei properly, the basic $\pi\pi$ production processes by π^- and K^- need to be known.

We report here on the first comprehensive measurement of reaction

$$K^- p \to \pi^0\pi^0\Sigma^0 \tag{1}$$

at p_{K^-} from 514 to 750 MeV/c. This is the final paper on $\pi^0\pi^0$ production of a three-part program involving also reactions $\pi^- p \to \pi^0\pi^0 n$ [4] and $K^- p \to \pi^0\pi^0\Lambda$ [5]. Little is known about reaction (1); there are only a few scattered, very old bubble-chamber data points with huge error bars [6,7]. The difficulty lies in measuring the three neutral particles in the final state with sufficient resolution to suppress the overwhelming background. The use of the Crystal Ball (CB) multiphoton spectrometer has opened new perspectives for studies in hyperon spectroscopy.

The center-of-mass (c.m.) energies covered in our experiment are from 1569 to 1676 MeV. In this range, there are just two well-established Σ^* states: the three-star $\Sigma(1660)\,1/2^+$ with $\Gamma \approx 100$ MeV, and the four-star $\Sigma(1670)\,3/2^-$ with $\Gamma \approx 60$ MeV. The status of other Σ^* states at these energies, like the two-star $\Sigma(1580)\,3/2^-$ and $\Sigma(1620)\,1/2^-$, is controversial. Besides, the $\Sigma(1580)\,3/2^-$ was recently disqualified [8]. The $\pi^0\pi^0\Sigma^0$ final state in our energy range could be produced via the following resonance de-excitation processes:

$$K^- p \to \Sigma^* \to \pi^0\Lambda(1405) \to \pi^0\pi^0\Sigma^0, \tag{2}$$

$$K^- p \to \Sigma^* \to \pi^0\Lambda(1520) \to \pi^0\pi^0\Sigma^0, \tag{3}$$

$$K^- p \to \Sigma^* \to f_0(600)\Sigma^0 \to \pi^0\pi^0\Sigma^0. \tag{4}$$

Note that processes (2) and (4) can be seen at all our momenta, while the threshold for process (3) is $p_{K^-} \approx 705$ MeV/c. Process (4) is of special interest, as the new CB data on $\pi^- p \to \pi^0\pi^0 n$ [4] and $K^- p \to \pi^0\pi^0\Lambda$ [5] do not show direct evidence for the $f_0(600)$ contribution. The $\pi^- p \to \pi^0\pi^0 n$ reaction is dominated by the $\pi^0\Delta^0(1232)\,3/2^+$ intermediate state, while $K^- p \to \pi^0\pi^0\Lambda$ is dominated by $\pi^0\Sigma^0(1385)\,3/2^+$. Since the $\Delta^0(1232)$ and $\Sigma^0(1385)$ are both

TABLE I. Summary of the results for $K^-p \to \pi^0\pi^0\Sigma^0$Content of rows: (1) beam momentum and its spread; (2) number of $K^-p \to \pi^0\pi^0\Sigma^0$ candidates (before background subtraction); (3) total cross section $\sigma_t(K^-p \to \pi^0\pi^0\Sigma^0)$ with the statistical uncertainty.

$p_{K^-} \pm \sigma_p$ (MeV/c)	514 ± 1034	560 ± 11	581 ± 12	629 ± 11	659 ± 12	687 ± 11	714 ± 11	750 ± 13
N_{Expt}	34	118	236	258	321	429	543	1347
$\sigma_t(K^-p \to \pi^0\pi^0\Sigma^0)$ (μb)	35 ± 10	72 ± 11	77 ± 11	93 ± 9	106 ± 9	137 ± 12	151 ± 10	180 ± 10

decuplet states, they are related to each other by flavor symmetry, but not to the $\Lambda(1405)$ or $\Lambda(1520)$, which are SU(3) singlet states.

Reaction $K^-p \to \pi^0\pi^0\Sigma^0$ was measured at eight K^- momenta with the CB detector installed in the C6 beam line of the Brookhaven National Laboratory's Alternating Gradient Synchrotron. Details of the CB detector, K^- and π^- beams, the resolutions, triggering system, and data analyses can be found in Refs. [4,5,9–12]. The mean values p_{K^-} of the incident momentum spectra and the momentum spread σ_p determined at the center of the 10 cm long liquid hydrogen target are listed in Table I. The precision in determining the mean momenta is 2–3 MeV/c.

The Λ hyperon is identified in the CB from the decay into $\pi^0 n$. The candidates for process

$$K^-p \to \pi^0\pi^0\Sigma^0 \to \pi^0\pi^0\gamma\Lambda \to \pi^0\pi^0\pi^0\gamma n \to 7\gamma n \quad (5)$$

were searched for in the neutral seven-cluster events. We assumed that each of the seven clusters was produced by a photon, and the neutron was not detected by the CB. Since the software threshold of the cluster energy was taken to be 20 MeV, the typical energy deposit in the CB from the neutron produced by process (5) was below this threshold. Due to the smallness (below 8%) of the fraction of eight-cluster events for this reaction, we neglected them in our analysis.

All seven-cluster events were subjected to a kinematic fit to test the hypothesis of being reaction (5). The z coordinate of the primary vertex and the decay length of the Λ are free parameters in the kinematic fit. The effective number of constraints for the fitted hypothesis is 4. The kinematic fit is performed for each of 315 possible pairing combinations for seven photons to form three π^0's plus a photon, where one of the π^0's is from Λ decay, and the remaining photon is due to Σ^0 decay. Events for which at least one photon pairing combination satisfies the hypothesis of reaction (5) at the 5% confidence level (C.L.) (i.e., with a probability greater than 5%) are accepted as $\pi^0\pi^0\Sigma^0$ candidates. The photon pairing with the largest C.L. is used to reconstruct the kinematics of the reaction. The number of experimental events selected as $\pi^0\pi^0\Sigma^0$ candidates at each beam momentum is listed in Table I as N_{Expt}.

The acceptance evaluation is based on a Monte Carlo (MC) simulation of the $K^-p \to \pi^0\pi^0\Sigma^0 \to \pi^0\pi^0\gamma\Lambda \to 3\pi^0\gamma n$ events generated according to phase space. The details of the MC procedure and the acceptance evaluation are very similar to the ones described for reaction $K^-p \to \pi^0\pi^0\Lambda$ in Ref. [5]. The features of the CB acceptance for reaction (1) are also similar to the ones for $K^-p \to \pi^0\pi^0\Lambda$. The overall acceptance for the $\pi^0\pi^0\Sigma^0$ Dalitz plots is found to be almost uniform for each beam momentum. The average detection efficiency for phase-space-distributed $K^-p \to \pi^0\pi^0\Sigma^0 \to \pi^0\pi^0\gamma\Lambda \to 3\pi^0\gamma n$ events varies from 14.7% at $p_{K^-}=514$ MeV/c to 11.7% at $p_{K^-}=750$ MeV/c. The largest dependence of the CB acceptance is found to be on θ^*, which is the angle between the dipion (i.e., the two primary π^0's) and the beam direction in the overall c.m. system. The CB acceptance decreases from backward to forward angles θ^* by a factor of 3 for our highest momentum, and by a factor of 2 for the lowest. Also, the acceptance decreases for low $m^2(\pi^0\pi^0)$ at small θ^*. The method of the acceptance correction for the $\pi^0\pi^0\Sigma^0$ events is the same as in Ref. [5].

There are several sources of background events that contaminate the $\pi^0\pi^0\Sigma^0$ data samples. The background should be subtracted prior to the acceptance correction. The first background is from process $K^-p \to \pi^0\pi^0\Lambda \to 3\pi^0 n \to 6\gamma n$, which can produce seven-cluster events as a result of splitting a single-photon cluster or by the detection of the neutron in the CB. This background is estimated by determining the probability for the simulated $K^-p \to \pi^0\pi^0\Lambda$ events to be misidentified as $\pi^0\pi^0\Sigma^0$ candidates. As input to the simulation of this background, we used the $K^-p \to \pi^0\pi^0\Lambda$ spectra that had been measured by us for each beam momentum in the same experiment [5]. We estimate that the fraction of the $\pi^0\pi^0\Lambda$ background in our $\pi^0\pi^0\Sigma^0$ data varies from $\sim$17% at $p_{K^-}=514$ MeV/c to $\sim$8% at $p_{K^-}=750$ MeV/c. The second source of background comes from processes that are not kaon interactions in the liquid hydrogen target, mainly K^- decays in the beam. Such events are investigated using the data taken with the empty target. This background is evaluated to be 11%–17%, depending on the beam conditions. At beam momenta 714 and 750 MeV/c, there is a third source of background that comes from the $3\pi^0\Lambda \to 4\pi^0 n \to 8\gamma n$ events produced in $K^-p \to \eta\Lambda$, for which the total cross section exceeds 1 mb in this energy range [10]. This process contaminates our seven-cluster sample when one of the eight photons is not detected by the CB, or two photon clusters overlap. The simulation of this background is based on the results for the $K^-p \to \eta\Lambda$ reaction obtained in the same experiment [10]. The fraction of the $\eta\Lambda$ background that must be subtracted from the data samples is $\sim$5% at $p_{K^-}=714$ MeV/c and $\sim$17% at $p_{K^-}=750$ MeV/c.

Figure 1 shows various spectra obtained for seven-cluster events at four beam momenta: 581, 687, 714, and 750 MeV/c. In the first column of the figure, we show the $m(\gamma\Lambda)$ invariant-mass spectra for events that are preselected by testing for hypothesis $K^-p \to \pi^0\pi^0\gamma\Lambda \to \pi^0\pi^0\pi^0\gamma n \to 7\gamma n$. Since this hypothesis gives no constraint on the $m(\gamma\Lambda)$ invariant mass to be the Σ^0-hyperon mass, one can see whether a signal from $\pi^0\pi^0\Sigma^0$ events exists, and estimate the magnitude of the background under the Σ^0 peak. In the

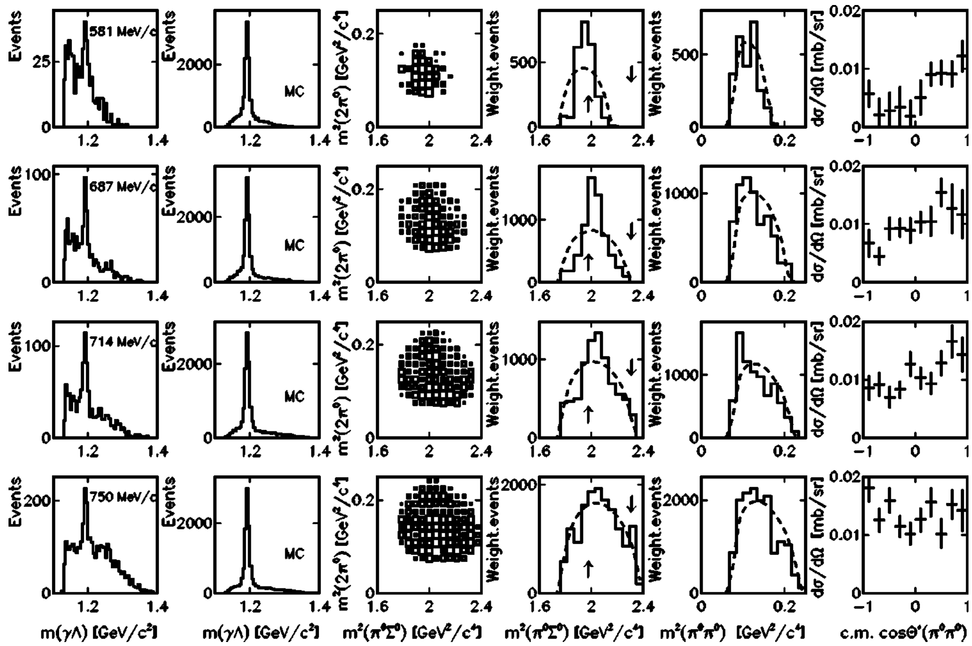

FIG. 1. Spectra for the data at $p_{K^-}=581$, 687, 714, and 750 MeV/c: the $m(\gamma\Lambda)$ invariant-mass spectra for the experimental events (column 1) and Monte Carlo $K^-p \to \pi^0\pi^0\Sigma^0$ events (column 2) preselected by testing for hypothesis $K^-p \to \pi^0\pi^0\pi^0\gamma\Lambda \to \pi^0\pi^0\pi^0\gamma n \to 7\gamma n$; background-subtracted and acceptance-corrected $\pi^0\pi^0\Sigma^0$ Dalitz plots (column 3); the Dalitz plot projections (columns 4 and 5); the cos θ^* spectra in units of mb/sr (column 6). The dashed curves in the $m^2(\pi^0\Sigma^0)$ and $m^2(\pi^0\pi^0)$ spectra are the $\pi^0\pi^0\Sigma^0$ phase-space distributions normalized to the data. The arrow in the $m^2(\pi^0\Sigma^0)$ spectra pointing up marks the $\Lambda(1405)$ mass, and the arrow pointing down marks the $\Lambda(1520)$ mass.

second column, we show the same distributions obtained for the MC events of reaction (1). One can see that there is also a small combinatorial background from the reaction itself. The experimental $\pi^0\pi^0\Sigma^0$ Dalitz plots, which are obtained after background subtraction and acceptance correction, are shown in the third column of the figure. Note that every event has two entries in the Dalitz plot, since the $m(\pi^0\Sigma^0)$ invariant mass is calculated for each of the two outgoing π^0's. The $m^2(\pi^0\Sigma^0)$ and $m^2(\pi^0\pi^0)$ projections of the acceptance-corrected Dalitz plots are shown in the fourth and fifth columns, respectively. These spectra are compared to the corresponding phase-space distributions (shown by the dashed curves) normalized to the data. The vertical axis of the cos θ^* spectrum of the dipion production angle (shown in the sixth column) is in units of mb/sr, so this distribution can be interpreted as the differential cross section for reaction (1).

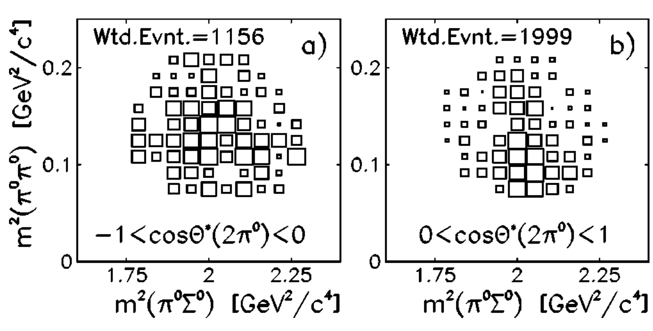

FIG. 2. Comparison of the $\pi^0\pi^0\Sigma^0$ Dalitz plots (background subtracted and acceptance corrected) obtained at $p_{K^-}=687$ MeV/c for backward (a) and forward (b) dipion production angles θ^*.

The presence of the $\Lambda(1405)$ produced in process (2) is clearly seen in the $m^2(\pi^0\Sigma^0)$ spectra, in which the Breit-Wigner mass of the $\Lambda(1405)$ state is marked by the arrow pointing up. The mass and width of our $\Lambda(1405)$ peak is in agreement with the known parameters for this hyperon [13]. The changes in the $\Lambda(1405)$ shape for different momenta can be explained by the fact that for every $\pi^0\Sigma^0$ system produced from $\Lambda(1405)$ decay, there is the second $\pi^0\Sigma^0$ system, the invariant mass of which smears the resonance signal in the spectra. The data at our highest beam momentum show a rising signal from the $\Lambda(1520)$ state produced in process (3). The $\Lambda(1520)$ mass is marked in the $m^2(\pi^0\Sigma^0)$ spectra by the arrow pointing down. Note that the spike at low $m^2(\pi^0\Sigma^0)$ is a reflection of the $\Lambda(1520)$ signal on the symmetry line (defined in Ref. [4]) of the Dalitz plot. The $m^2(\pi^0\pi^0)$ spectra of $K^-p \to \pi^0\pi^0\Sigma^0$ show an enhancement in the low mass region; this is opposite to the $K^-p \to \pi^0\pi^0\Lambda$ and $\pi^-p \to \pi^0\pi^0 n$ reactions. A visual examination of the Dalitz plots and their projections is sufficient to see that the $f_0(600)$-meson contribution is insignificant.

Another interesting feature of the $\pi^0\pi^0\Sigma^0$ events becomes apparent when the data are divided into subsets of different cos θ^* (see Figure 2). A strong dependence of the Dalitz plot density on the dipion production angle is observed. The same feature was also observed in the $K^-p \to \pi^0\pi^0\Lambda$ and $\pi^-p \to \pi^0\pi^0 n$ reactions.

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 [13]. The systematic uncertainty in our total cross sections is

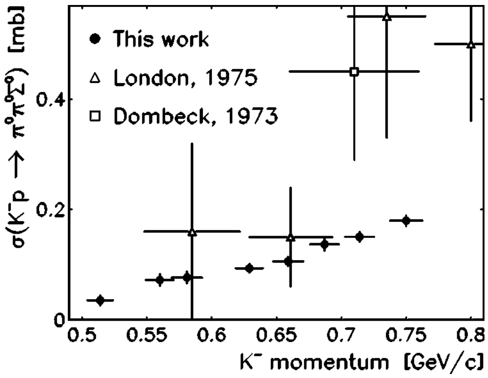

FIG. 3. Total cross section $\sigma_t(K^-p \to \pi^0\pi^0\Sigma^0)$ as a function of the beam momentum. Our results are compared to the old measurements of this channel (Ref. [6,7]).

estimated to be less than 10%. The major contributors 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. Our results for $\sigma_t(K^-p \to \pi^0\pi^0\Sigma^0)$ as a function of the beam momentum are shown in Fig. 3. The energy dependence of $\sigma_t(K^-p \to \pi^0\pi^0\Sigma^0)$ is consistent with the expectation of the dominant role of the $\Sigma(1660)1/2^+$ and/or $\Sigma(1670)3/2^-$ resonances in this energy range. In the same figure, we also show the results of the old measurements [6,7] of reaction (1). It illustrates that our measurement has dramatically improved the quality of the data on this reaction.

In summary, a measurement of $K^-p \to \pi^0\pi^0\Sigma^0$ has been performed at eight incident momenta between 514 and 750 MeV/c. The experimental Dalitz plots and invariant mass spectra show that $\pi^0\pi^0\Sigma^0$ production is dominated by the $\pi^0\Lambda(1405)$ intermediate state with a rising contribution from $\pi^0\Lambda(1520)$ at the three highest beam momenta. The density distribution in the Dalitz plots strongly depends on the dipion (or the Σ^0) production angle. The total cross section $\sigma_t(K^-p \to \pi^0\pi^0\Sigma^0)$ gradually rises from 35 to 180 μb; this behavior is consistent with the expectation of the dominant role of the $\Sigma(1660)1/2^+$ and/or $\Sigma(1670)3/2^-$ resonances in this energy range. Flavor symmetry implies that $\pi^0\pi^0$ production via the $f_0(600)$ meson should lead to similar features of the $\pi^0\pi^0\Sigma^0$, $\pi^0\pi^0\Lambda$, and $\pi^0\pi^0 n$ final states. On the other hand, when the $\pi^0\pi^0$ production is dominated by baryonic-resonance intermediate states, only the $\pi^0\pi^0\Lambda$ and $\pi^0\pi^0 n$ features are expected to be similar (as they are; see Refs. [4,5]). Our data on $\pi^0\pi^0$ production imply that the $f_0(600)$ contribution to $\pi^0\pi^0\Sigma^0$ production is insignificant. Further discussions of the features of $\pi^0\pi^0$ production by π^- and K^- are presented in Ref. [14].

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