Does the $\Sigma(1580)_{3/2}^-$ resonance exist?

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Precise new data for the reaction $K^− p \to π^0 \Lambda$ are presented in the c.m. energy range 1565 to 1600 MeV. Our analysis of these data sheds new light on claims for the $\Sigma(1580)_{3/2}^-$ resonance, which (if it exists with the specified quantum numbers) must be an exotic baryon because of its very low mass. Our results show no evidence for this state.

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The $\Sigma(1580)_{3/2}^-$ resonance was first reported in 1973 as a narrow $I = 1$ structure in a preliminary analysis of high statistics measurements of $K^− p$ and $K^− d$ total cross sections. It was subsequently observed in $K^− p \to π^0 \Lambda$ by Litchfield who identified it as a $J^P = 3/2^-$ state with mass $1582 \pm 4$ MeV, width $11 \pm 4$ MeV, and amplitude at resonance $0.10 \pm 0.02$.

For his analysis, Litchfield used the only experimental data then available in the c.m. energy range 1560 to 1600 MeV, which were the bubble-chamber measurements of Armenteros et al. Some details of his analysis will be presented below. The final analysis of the total $K^-$-nucleon total cross sections yielded mass $1583 \pm 4$ MeV, width $15$ MeV, and $(J + 1/2) x = 0.06$, where $x$ is the $KN$ branching fraction.

The $\Sigma(1580)_{3/2}^-$ resonance, if confirmed, would be of strong theoretical interest because it cannot be accommodated as an ordinary $q^3$ state due to its very low mass. More specifically, this state would necessarily be the lowest $\Sigma^*$ with $J^P = 3/2^-$. One expects such a state to be the octet partner of the $N(1520)_{1/2}^-$. However, that partner is well established as the $\Sigma(1670)_{1/2}^-$, in good agreement with quark-model predictions. The next $\Sigma^*$ with the right quantum numbers is expected to lie about 100 MeV higher than the $\Sigma(1670)_{1/2}^-$. Two bubble-chamber experiments that studied the analog reaction $K^− p \to π^+ \Lambda$ were performed subsequent to Litchfield’s analysis. The results of these two experiments did not require the $\Sigma(1580)_{3/2}^-$ but neither was it ruled out. In this Letter, we present precise new experimental results of the $K^− p \to π^0 \Lambda$ reaction in the c.m. energy range 1565 to 1600 MeV.

Our measurements of the $K^− p \to π^0 \Lambda$ reaction were conducted at Brookhaven National Laboratory (BNL) with the Crystal Ball (CB) multiphoton spectrometer, which was installed in the C6 beam line of the Alternating Gradient Synchrotron. The experiment was performed with a momentum-analyzed $K^−$ beam incident on a 10-cm-long liquid hydrogen target located in the center of the CB. While measurements were performed at eight different beam momenta, this Letter reports only on the lowest three momenta: 514, 560, and 581 MeV/c. We plan a more extensive report on the full data set at a later date.

The Crystal Ball consists of 672 optically isolated NaI(Tl) crystals, shaped like truncated triangular pyramids and arranged in two hemispheres that cover 93% of 4\pi steradians. The event trigger was a coincidence of the beam trigger and a CB signal that required the total energy deposited in the crystals to exceed some threshold. Our trigger for neutral events required, in addition, that there was no corresponding signal from the system of scintillation counters surrounding the target. We achieved a typical energy resolution for electromagnetic...
showers in the CB of $\Delta E/E = 0.020/[\text{GeV}]^{0.36}$. Shower directions were measured with a resolution in $\theta$, the polar angle with respect to the beam axis, of $\sigma_\theta = 2^\circ - 3^\circ$ for photon energies in the range 50 to 500 MeV, assuming that the photons were produced in the hydrogen target. The resolution in $\phi$ was $2^\circ / \sin \theta$. Our resolution for the momentum determination of individual beam particles was about 0.6%, whereas the uncertainty of the mean momentum of the beam on target was about 0.3%. The momentum divergence of the kaon beam on target was about 2%. To illustrate the CB mass resolution, we show in Figs. 1a-c the invariant mass spectra for the experimental events that were selected by kinematic fit to three hypotheses: $K^- p \rightarrow \pi^0 \pi^0 \Lambda$, $K^- p \rightarrow \gamma \gamma \Lambda$, and $K^- p \rightarrow \pi^0 \gamma \Lambda$. The $\Lambda$ hyperon was identified by its decay into $\pi^0 n$. The spectra shown were obtained for a beam momentum of 750 MeV/c, which is above the threshold for $K^- p \rightarrow \eta \Lambda$. The invariant mass of the $3\pi^0$ peak from $\eta$ decays has a root-mean-square width $\sigma_m(3\pi^0) \approx 5$ MeV in comparison with $\sigma_m(2\gamma) \approx 6$ MeV for $\eta \rightarrow \gamma \gamma$. Since the constraint on the $\Lambda$ hyperon mass was used in the kinematic fit for the secondary vertex determination, we cannot illustrate the $\Lambda$ mass resolution. Instead, we show in Fig. 1c the $\gamma \Lambda$ peak from $\Sigma^0$ decays, which has $\sigma_m(\gamma \Lambda) \approx 6$ MeV. More details on the CB apparatus, trigger conditions, and the absolute cross-section determination can be found in Refs. [2][3][4].

To select candidates for the reaction

$$K^- p \rightarrow \pi^0 \Lambda \rightarrow \pi^0 \pi^0 n \rightarrow 4\gamma n ,$$  \hspace{1cm} (1)

we used the neutral 4- and 5-cluster events. A “cluster” is a group of neighboring crystals in which energy is deposited from a single-photon electromagnetic shower. The neutral clusters have a 20-MeV threshold in software deposited from a single-photon electromagnetic shower. The hypothesis of reaction (1) was tested by a kinematic fit included five constraints on the masses of the two $\pi^0$'s and the $\Lambda$, in addition to the four main constraints of the kinematic fit (energy and 3-momentum conservation), the total number of constraints in the hypothesis of reaction (1) is seven. The effective number of constraints is this total less the number of free parameters of the fit; it results in 2-C and 4-C fits for 4- and 5-cluster events, respectively. In the case of 4-cluster events, we have three possible pairing combinations to yield the two $\pi^0$'s; this becomes six combinations when we further allow the choice of each $\pi^0$ to be from the $\Lambda$ decay. For 5-cluster events, the number of pairing combinations is five times larger, as the neutron is also involved in the cluster permutations.

Those events in which at least one pairing combination satisfied our hypothesis at the 5% C.L. (i.e., with probability $> 5\%$) were accepted for further analysis. The pairing combination with the largest confidence level was used to reconstruct the kinematics of the reaction. Additional selection criteria (on the primary vertex, the decay length of the $\Lambda$, and confidence level of other possible hypotheses) were also applied for better suppression of background processes. The largest background turned out to be from processes that were not kaon beam interactions in the liquid hydrogen target. The major part of these background events were $K^-$ decays in the beam. Such events were analyzed with “empty-target” samples and then were subtracted from the experimental distributions. These events did not survive the kinematic fit C.L. plus other selection criteria. The fraction of this background subtracted from the selected events of reaction (1) comprises 6–9%.

Another significant background could arise from the misidentification of $K^- p \rightarrow K_0^0 \gamma n \rightarrow \pi^0 \pi^0 n \rightarrow 4\gamma n$ events as our $K^- p \rightarrow \pi^0 \Lambda$ reaction. To suppress this background, we fitted our events to both the $K^- p \rightarrow \pi^0 \Lambda$ and $K^- p \rightarrow K_0^0 \gamma n$ hypotheses and applied the following selection criterion on the largest probabilities of the kinematic fits: $P(K^- p \rightarrow \pi^0 \Lambda) > 2 \times P(K^- p \rightarrow K_0^0 \gamma n)$. This enabled us to decrease the $K_0^0 \gamma n$ background to a level less than 4%. Background from $K^- p \rightarrow \pi^0 \Sigma^0 \rightarrow \pi^0 \gamma \Lambda \rightarrow 5\gamma n$ events was found to be less than 2%. For one momentum, we simulated large statistics for the $\pi^0 \Sigma^0$ and $K_0^0 \gamma n$ backgrounds according to their differential cross sections. The subtraction of these backgrounds with their small weights did not change the shape of the $K^- p \rightarrow \pi^0 \Lambda$ differential cross sections, it was just made smaller by the percent of the events subtracted; consequently, for the other momenta, the $K^- p \rightarrow \pi^0 \Lambda$ differential cross sections were just corrected by the fraction of $\pi^0 \Sigma^0$ and $K_0^0 \gamma n$ backgrounds, without the direct subtraction as was done for the empty-target background.

The experimental number of the selected events was 3539, 6741, and 10046 for beam momenta of 514, 560, and 581 MeV/c, respectively. About 20% of these events were reconstructed from the 5-cluster sample (i.e., with the neutron detected in the CB). The combinatorial background in our $K^- p \rightarrow \pi^0 \Lambda$ events was estimated to be not larger than 1–2%. Reconstructed $\pi^0 \Lambda$ events comprised about 0.2% of all neutral-trigger events collected.
in the given momentum range.

Acceptance corrections were based on a Monte Carlo simulation of the $K^- p \to \pi^0 \Lambda$ reaction for each momentum, which was performed according to phase space by using the experimental beam-trigger events as input for kaon beam distributions. Specifically, the phase-space Monte Carlo simulation produced the $\pi \Lambda$ state with an isotropic angular distribution with respect to the beam direction; further, the decay of the $\Lambda$ in its rest frame was also assumed to be isotropic. The CB neutral trigger and resolution conditions for data sets of each beam momentum were properly reproduced by the Monte Carlo simulations. The simulated and experimental distributions for the $\Lambda$ decay length were in good agreement, and comparable to those shown in Fig. 12 of Ref. 8, which shows the $\Lambda$ decay-distance distributions for $K^- p \to \eta \Lambda$. Our Monte Carlo simulations used the PDG decay length $\sigma = 7.89$ cm. From our simulation of $K^- p \to \pi^0 \Lambda$ events, we determined that the primary vertex resolution was $\sigma_z = 1.9$ cm, the $\Lambda$ decay length resolution was $\sigma_{\text{decay}} = 3.0$ cm, and the c.m. $\theta$ resolution for outgoing neutral pions was $\sigma_\theta \approx 0.06$ rad (or $\approx 3.4^\circ$). Our mean detection efficiency for the $K^- p \to \pi^0 \Lambda \to \pi^0 \pi^0 n$ events was about 28%. The typical CB acceptance for the $\cos \theta$ distribution is shown in Fig. 1d. For the calculation of the cross sections, we used the PDG branching ratio for the $\Lambda \to \pi^0 n$ decay of 0.358$\pm$0.005 12. The effective proton density in the target times the effective target length was $(4.05 \pm 0.08) \times 10^{-4}$ mb$^{-1}$. An additional systematic uncertainty in the obtained cross sections, which comes mostly from the calculation of the kaon beam monitor number and from the evaluation of the fraction of useful events lost due to pile-up in the CB, was estimated to be less than 7%. This contribution was not included in the quoted final uncertainty. The pile-up events (clusters) were easily removed using the measured TDC information.

The polarization of the $\Lambda$ was measured via its decay asymmetry:

$$P(\cos \theta) = 3 \left( \sum_{i=1}^{N(\theta)} \cos \xi_i \right) / (\alpha \Lambda N(\theta)).$$

Here $\theta$ refers to the direction of the outgoing $\pi^0$ (not from $\Lambda$ decay) with respect to the incident $K^-$ meson in the c.m. system. $N(\theta)$ is the total number of $K^- p \to \pi^0 \Lambda$ events in the $\cos \theta$ bin, and $\alpha \Lambda = +0.65$ is the $\Lambda$ decay asymmetry parameter. The angle $\xi$ was defined for the $i$-th event in the $\cos \theta$ bin by $\cos \xi = \vec{N} \cdot \vec{n}$, where $\vec{n}$ is a unit vector in the direction of the decay neutron (in the $\Lambda$ rest frame) and $\vec{N}$ is a unit vector normal to the production plane: $\vec{N} = (\vec{K}^- \times \vec{\pi}^0)/|\vec{K}^- \times \vec{\pi}^0|$. Finally, the vectors $\vec{K}^-$ and $\vec{\pi}^0$ are unit vectors in the direction of the incident $K^-$ and the outgoing $\pi^0$ meson, respectively.

Our Monte Carlo simulations for $K^- p \to \pi^0 \Lambda$ were generated with no polarization for the produced $\Lambda$; however, simulations with a nonzero $\Sigma^0$ polarization were performed for the reaction $K^- p \to \pi^0 \Sigma^0$ to investigate possible acceptance effects in the $\Sigma^0$ polarization. These studies suggest a possible acceptance effect of about 10-15% of the polarization value. It is notable that our polarization measurements are in good agreement with the bubble-chamber results of Armenteros et al. 6, where both experiments have enough statistics (e.g., at 750 MeV/c) to make a sensible comparison. One expects acceptance effects to be very small in bubble-chamber experiments. For the results discussed in this Letter, statistical uncertainties were the main contributions to the total uncertainties in our $\Lambda$ polarization measurements.

For the comparisons required in this work, it was necessary to rebin our data into smaller momentum intervals. This was made possible because we measured the deviation from the nominal beam momentum for each event. The size of these bins was limited by the precision of the relative $K^-$ momentum determination, which was $\pm 2$ MeV/c. Data at the beam momentum 514 MeV/c were rebinned into two intervals with mean momenta of 506 and 523 MeV/c. Data at 560 MeV/c were rebinned into three intervals (544, 560, and 576 MeV/c), and data at 581 MeV/c were rebinned into two intervals (571 and 591 MeV/c). Figure 2 shows our representative data for $d\sigma/d\Omega$ and the $\Lambda$ polarization in $K^- p \to \pi^0 \Lambda$ at 560 and 591 MeV/c. Our measurements are in good agreement with older measurements 3, although our results are of much higher statistical precision. In particular, our results for the $\Lambda$ polarization are a dramatic improvement over older measurements 3. Additional illustrations of the good agreement of our results with older measurements can be found in a CB internal report 3.

The differential and transversity cross sections ($\Lambda$ polarization times differential cross section) were expanded in terms of Legendre polynomials and associated Legendre functions, in the usual way:

$$
\frac{d\sigma}{d\Omega} = \chi^2 A_0 \sum_{L=0}^{N} (A_L/A_0) P_L(\cos \theta)
$$

and

$$
\frac{P d\sigma}{d\Omega} = \chi^2 A_0 \sum_{L=1}^{N} (B_L/A_0) P_L(\cos \theta).
$$

Coefficients with $L > 4$ were consistent with zero.

Figures 6 and 4 respectively, show experimentally determined values (open circles) of the $A_L/A_0$ and $B_L/A_0$ coefficients from the analysis of Litchfield 2. Our new results are shown by solid squares. Open squares denote the $R_L^0 p \to \pi^+ \Lambda$ measurements by Cameron et al. 7. Older $R_L^0 p \to \pi^+ \Lambda$ results by Engler et al. 6 are not shown since they have comparable precision to those from the Litchfield analysis and do little to resolve the issue. Table 4 gives our results for the fitting coefficients shown.
FIG. 1: The invariant mass distributions for the experimental events at $p_{K^-} = 750$ MeV/c that were selected by kinematic fit to the three hypotheses: (a) $K^- p \rightarrow \pi^0 \pi^0 \Lambda \rightarrow 4 \pi^0 n \rightarrow 8 \gamma n$, $\sigma_m(\eta \rightarrow 3 \pi^0) \approx 5$ MeV; (b) $K^- p \rightarrow \gamma \gamma \Lambda \rightarrow \gamma \pi^0 n \rightarrow 4 \gamma n$, $\sigma_m(\eta \rightarrow 2 \gamma) \approx 6$ MeV; (c) $K^- p \rightarrow \gamma \pi^0 \Lambda \rightarrow \gamma \pi^0 \pi^0 n \rightarrow 5 \gamma n$, $\sigma_m(\Sigma^0 \rightarrow \gamma \Lambda) \approx 6$ MeV; (d) Acceptance of $K^- p \rightarrow \pi^0 \Lambda$ for the $\cos \theta$ distribution at $p_{K^-} = 560$ MeV/c, where $\theta$ refers to the direction of the outgoing $\pi^0$ with respect to the incident $K^-$ meson in c.m. system.

FIG. 2: Top: Differential cross section (a) and the induced $\Lambda$ polarization (b) for $K^- p \rightarrow \pi^0 \Lambda$ at 560 MeV/c. Bottom: Differential cross section (c) and the induced $\Lambda$ polarization (d) at 591 MeV/c. Only statistical uncertainties are shown. The curves show the results of fitting our data by using the expansions in Eqs. (3) and (4) with terms up to $L = 4$, as described in the text.

Cameron et al. [7], find no evidence for the $\Sigma(1580)^3_{-2}$ state.

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TABLE I: Fitting coefficients for the low-momentum $d\sigma/d\Omega$ and $P \cdot d\sigma/d\Omega$ data. The incident momentum $P_{\text{lab}}$ and c.m. energy $E_{\text{CM}}$ are in MeV/c and MeV, respectively.

| $P_{\text{lab}}$ | $E_{\text{CM}}$ | $A_0$   | $A_1/A_0$ | $A_2/A_0$ | $A_3/A_0$ | $A_4/A_0$ | $B_1/A_0$ | $B_2/A_0$ | $B_3/A_0$ | $B_4/A_0$ |
|------------------|-----------------|---------|------------|------------|------------|------------|------------|------------|------------|------------|
| 506              | 1565            | 0.0535(22) | 1.15(11)   | 0.29(11)   | -0.00(16)  | 0.132(68)  | 0.078(66)  | 0.006(56)  | 0.017(39)  |
| 544              | 1573            | 0.0512(21) | 1.075(68)  | 0.73(11)   | -0.07(12)  | 0.168(70)  | 0.192(68)  | 0.074(56)  | 0.027(42)  |
| 560              | 1582            | 0.0584(30) | 0.885(89)  | 0.73(14)   | -0.01(14)  | 0.080(76)  | 0.175(74)  | 0.033(60)  | 0.022(48)  |
| 571              | 1594            | 0.0626(18) | 0.876(50)  | 0.76(8)    | -0.07(8)   | 0.103(45)  | 0.012(43)  | -0.025(37) | -0.029(28) |
| 591              | 1603            | 0.0618(18) | 0.684(54)  | 0.70(8)    | -0.10(8)   | 0.196(41)  | 0.101(39)  | 0.045(33)  | -0.005(26) |

FIG. 3: $A_L/A_0$ coefficients as a function of c.m. energy (see text).

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FIG. 4: $B_L/A_0$ coefficients as a function of c.m. energy (see text).