Search for formation of isospin-3/2 Ξ states by neutrinos

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Abstract

A narrow peak near 1870 MeV is observed in the combined invariant-mass spectrum of the systems ΛK\(_0\)\(\pi^-\), ΛK\(_0\)\(\pi^+\), ΛK\(^-\)\(\pi^-\), and ΛK\(^-\)\(\pi^+\) formed in \(\nu_\mu\)- and \(\bar{\nu}_\mu\)-induced charged-current collisions with free protons, deuterons, and Neon nuclei. Observed width of the resonance is consistent with being entirely due to apparatus smearing. A possible interpretation of the peak is formation and three-body ΛK\(\pi\) decay of an exotic baryon with \(I = 3/2\) and \(S = -2\).

A narrow peak near 1862 MeV has been observed in invariant masses of the Ξ\(^-\)\(\pi^-\) and Ξ\(^-\)\(\pi^+\) systems formed in \(pp\) collisions [1], tentatively interpreted as a baryon state with \(S = -2\) and \(I = 3/2\) that is part of the (hypothesized) antidecuplet of pentaquark baryons [2]. Here, I report on a search for formation of this exotic baryon in neutrino and antineutrino collisions with free protons, deuterons, and neon nuclei. Instead of Ξ\(^-\)\(\pi^-\), I analyze the system ΛK\(\pi\) which may provide access to all four charge states of the Ξ\(_{10}\): Ξ\(^+\)\(_{10}\) → Λ\(\bar{K}^0\)\(\pi^+\), Ξ\(^0\)\(_{10}\) → ΛK\(^-\)\(\pi^+\), Ξ\(^-\)\(_{10}\) → Λ\(\bar{K}^0\)\(\pi^-\), and Ξ\(^-\)\(_{10}\) → ΛK\(^-\)\(\pi^-\). The system ΛK\(\pi\) has a higher mass threshold than Ξ\(\pi\), but on the other hand the smallness of observed Ξ\(_{10}\) width indicates that the kinematically favored decay Ξ\(_{10}\) → Ξ\(\pi\) is subject to some dynamic suppression which may render the three-body ΛK\(\pi\) channel competitive.

As in the previous search for formation of the Θ\(^+\)(1540) baryon [3], I analyze the data collected by several neutrino experiments with big bubble chambers—BEBC at CERN and the 15-foot chamber at Fermilab. Though logged several decades ago,
Table 1: Relevant characteristics of the bubble-chamber neutrino data analyzed in this paper. For E632, I show either the actual number of measured CC events (in the parentheses) and the “equivalent” number that includes all CC events analyzed for \(V^0\) emission.

| Experiment Chamber Fill | WA21 BEBC Hydrogen | WA25 BEBC Deuterium | WA59 BEBC Neon–H\(_2\) | E180 15' B.C. Neon–H\(_2\) | E632 15' B.C. Neon–H\(_2\) | Total |
|-------------------------|---------------------|---------------------|------------------------|------------------------|------------------------|-------|
| Neutrinos:              |                     |                     |                        |                        |                        |       |
| Mean \(E_{\nu}\), GeV  | 48.8                | 51.8                | 56.8                   | 52.2                   | 136.8                  | 56.7  |
| Mean \(K^0_S(\Lambda)\) momentum, GeV | 5.7(3.5)            | 5.7(3.4)            | 4.5(2.8)               | 3.4(1.9)               | 7.7(5.1)               | 5.3(3.3) |
| All CC events           | 18746               | 26323               | 9753                   | 882                    | 8550(5621)             | 64250 |
| CC events with \(K^0_S\) | 1050                | 1279                | 561                    | 21                     | 587                    | 3498  |
| CC events with \(\Lambda\) | 442                | 644                | 378                    | 19                     | 352                    | 1835  |
| CC events with \(\Lambda\) and \(K^0_S\) | 41             | 76                | 46                     | 0                     | 52                     | 215  |
| Antineutrinos:          |                     |                     |                        |                        |                        |       |
| Mean \(E_{\bar{\nu}}\), GeV | 37.5                | 37.9                | 39.5                   | 33.8                   | 110.0                  | 38.9  |
| Mean \(K^0_S(\Lambda)\) momentum, GeV | 4.2(2.5)            | 4.2(2.0)            | 3.5(2.1)               | 3.4(1.4)               | 7.6(2.9)               | 4.0(2.1) |
| All CC events           | 13155               | 16314               | 15693                  | 5927                   | 1810(1190)             | 52900 |
| CC events with \(K^0_S\) | 702                 | 761                 | 631                    | 231                    | 123                    | 2448  |
| CC events with \(\Lambda\) | 427                | 459                | 587                    | 165                    | 62                     | 1700  |
| CC events with \(\Lambda\) and \(K^0_S\) | 56             | 62                | 58                     | 17                     | 6                      | 199   |

bubble-chamber neutrino data are still unrivaled in quality and completeness. I rely on a database that comprises some 120 000 \(\nu_\mu\)- and \(\bar{\nu}_\mu\)-induced charged-current (CC) events on hydrogen, deuterium, and neon targets. In the past, these combined bubble-chamber neutrino data were employed in a number of physics analyses [4]. The database embraces the bulk of neutrino data obtained with BEBC (experiments WA21, WA25, and WA59) and a significant fraction of those collected with the 15-foot bubble chamber (experiments E180 and E632). Total numbers and mean energies of \(\nu_\mu\)CC and \(\bar{\nu}_\mu\)CC events detected and reconstructed by the aforementioned experiments [5] are summarized in Table I. Also shown are the statistics of CC events with reconstructed \(K^0_S\) mesons and \(\Lambda\) hyperons in the final state.

The bubble chamber is a good spectrometer, but provides virtually no identification for charged kaons. (Still, a few are identified by bubble density, range consistent with track curvature, and decay signature at endpoint.) Therefore, kaon mass is combinatorially assigned to any negative hadron for which the \(K^-\) hypothesis was not ruled out at the stage of kinematic reconstruction. I reject those \(\Lambda K^-\) subsystems that fall in the \(\Sigma^-\) (1385)
mass region as soon as the pion hypothesis is selected: \(1355 < m(\Lambda\pi^-) < 1415\) MeV. The masses of all selected \(\Lambda K^-\pi^\pm\) systems are plotted in Fig. 1. (Here and in what follows, I combine the neutrino and antineutrino data and those for all targets.) Despite the proximity of the \(\Lambda K\pi\) mass threshold, including “assigned” \(K^-\) mesons is seen to result in a high level of combinatorial background. So I cut on an angle appropriate for 3-body decays, \(\theta_{\text{norm}}\). In the \(\Lambda K\pi\) frame, the 3-momenta of the three daughters lie in the same decay plane, and \(\theta_{\text{norm}}\) is defined as the angle between the normal to this plane and the \(\Lambda K\pi\) boost direction from lab. (Note that \(\cos \theta_{\text{norm}} = \pm 1\) corresponds to exactly transverse position of the decay plane with respect to the \(\Lambda K\pi\) direction of motion.) Given an unpolarized parent, the signal should be uniformly distributed in \(|\cos \theta_{\text{norm}}|\). On the other hand, the mean value of \(|\cos \theta_{\text{norm}}|\) does not exceed 0.29 for all selected \(\Lambda K^-\pi^\pm\) systems, since inclusive hadrons are largely emitted with small transverse momenta to the hadron jet. The effects of the selections \(|\cos \theta_{\text{norm}}| > 0.5\) and \(|\cos \theta_{\text{norm}}| > 0.7\) on the \(\Lambda K^-\pi^\pm\) mass spectrum are shown in Fig. 1. Note that in a narrow region near 1870 MeV, the mass spectrum is less depleted by cutting on \(|\cos \theta_{\text{norm}}|\) than in the upstream and downstream regions. Since \(K^0\) mesons are reliably identified by \(K^0_S \to \pi^+\pi^-\) decays, no \(|\cos \theta_{\text{norm}}|\) selection is applied to the \(\Lambda K^0_S\pi^-\) and \(\Lambda K^0_S\pi^+\) systems.

![Figure 1](image_url)

Figure 1: Invariant mass of the \(\Lambda K^-\pi^-\) and \(\Lambda K^-\pi^+\) systems combined. The light- and dark-shaded histograms result from the selections \(|\cos \theta_{\text{norm}}| > 0.5\) and \(|\cos \theta_{\text{norm}}| > 0.7\), respectively.
Invariant masses of selected $\Lambda K_S^0\pi^-$, $\Lambda K_S^0\pi^+$, $\Lambda K^-\pi^-$ ($|\cos \theta_{\text{norm}}| > 0.5$), and $\Lambda K^-\pi^+$ ($|\cos \theta_{\text{norm}}| > 0.5$) systems are separately plotted in Fig. 2. All four show small enhancements near 1870 MeV. And finally, in Figs. 3 ($|\cos \theta_{\text{norm}}| > 0.5$) and 4 ($|\cos \theta_{\text{norm}}| > 0.7$) I add up the mass spectra for all selected $\Lambda K_S^0\pi^\pm$ and $\Lambda K^-\pi^\pm$ systems, neglecting possible mass differences between the states of different charges. A distinct narrow enhancement is seen at $m(\Lambda K\pi) \simeq 1870$ MeV. The “grand-total” $m(\Lambda K\pi)$ spectrum is then fitted to a Gaussian on top of a third-order polynomial, see the middle panels of Figs. 3 and 4. Either fit returns a central mass value slightly in excess of 1870 MeV and an rms width of $\sigma \simeq 4 \pm 1$ MeV. The observed width is consistent with being entirely due to apparatus smearing of $m(\Lambda K\pi)$, estimated as $\sim 5$ MeV using individual errors for live events in the peak region. Statistical significance of the putative signal, (optimistically) estimated as $S/\sqrt{B}$ over the mass region of $\pm 2\sigma$ around the peak position, is over 8 standard deviations.

Figure 2: The $\Lambda K_S^0\pi^-$, $\Lambda K_S^0\pi^+$, $\Lambda K^-\pi^-$ ($|\cos \theta_{\text{norm}}| > 0.5$) and $\Lambda K^-\pi^+$ ($|\cos \theta_{\text{norm}}| > 0.5$) mass distributions. Dark-shaded histograms are for identified charged kaons.
Two events in the peak have $K_S^0$ mesons among the secondaries emitted in association with the $\Lambda K\pi$ system, and yet another one — an associated charged kaon which is a $K^+$ identified in neon, see Fig. 3. Had two $s\bar{s}$ pairs been produced per (anti)neutrino collision, one would expect $\sim 6 \pm 3$ events with associated $K_S^0$ mesons from fragmentation of the two $s\bar{s}$ quarks. Note however that two $s$ quarks may also result from a strangeness-changing transition $u \rightarrow s$ accompanied by creation of a single $s\bar{s}$ pair.

In summary, a narrow peak near 1870 MeV is observed in the combined invariant-mass spectrum of the systems $\Lambda K_S^0\pi^-$, $\Lambda K_S^0\pi^+$, $\Lambda K^-\pi^-$, and $\Lambda K^-\pi^+$ formed in $\nu_\mu$- and $\bar{\nu}_\mu$-induced CC collisions with free protons, deuterons, and Neon nuclei. Observed width of

![Graph](https://via.placeholder.com/150)

Figure 3: The $\Lambda K_S^0\pi^-$, $\Lambda K_S^0\pi^+$, $\Lambda K^-\pi^-$ ($|\cos\theta_{\text{norm}}| > 0.5$), and $\Lambda K^-\pi^+$ ($|\cos\theta_{\text{norm}}| > 0.5$) mass spectra added up for all Ne+H$_2$+D$_2$ data (top panel). The light- and dark-shaded areas are the contributions from events with additional $K_S^0$ mesons and identified charged kaons, respectively. Shown in the middle panel is a Gaussian fit of the combined $m(\Lambda K\pi)$ spectrum. The effect of an additional selection $Q^2 > 5$ GeV$^2$ is illustrated in the bottom panel.
the putative ΛKπ resonance is consistent with being entirely due to apparatus resolution. A possible interpretation of the peak is formation and ΛKπ decay of an exotic baryon with \( I = \frac{3}{2} \) and \( S = -2 \). Our results may support the earlier observation of a \( \Xi^-\pi^\pm \) resonance near 1862 MeV in \( pp \) collisions [1], provided that the discrepancy of \(~10\) MeV between the masses of the two resonances can be explained by systematic effects.

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Figure 4: Similar data as in Fig. 3 but with a tighter selection \(|\cos \theta_{\text{norm}}| > 0.7\) for the \( \Lambda K^-\pi^- \) and \( \Lambda K^-\pi^+ \) systems.
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