Evidence for formation of a narrow $K_{SP}^0$ resonance with mass near 1533 MeV in neutrino interactions

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Submitted to Yad. Fiz. (Phys. At. Nucl.)

Abstract

A narrow baryon resonance is observed in invariant mass of the $K_{SP}^0$ system formed in neutrino and antineutrino collisions with nuclei. The mass of the resonance is estimated as 1533 ± 5 MeV. The observed width is less than 20 MeV, and is compatible with being entirely due to experimental resolution. The statistical significance of the signal is near 6.7 standard deviations. The analysis is based on the data obtained in past neutrino experiments with big bubble chambers: WA21, WA25, WA59, E180, and E632.

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A narrow baryon resonance with mass near 1540 MeV and unnatural (positive) strangeness has been recently detected in the $K^+ n$ system formed in the reaction $\gamma n \rightarrow K^+ K^- n$ on Carbon [1] and in the $K^0 p$ system from the charge-exchange reaction $K^+ n \rightarrow K^0 p$ in low-energy $K^+ \text{Xe}$ collisions [2]. Similar observations have since been reported by two other photoproduction experiments [3, 4]. This object, referred as the $\Theta^+(1540)$, is tentatively interpreted as the lightest member of an antidecuplet of pentaquark baryons, as predicted some time ago in the framework of the chiral soliton model [5]. This paper reports on a search for formation of the $\Theta^+$ baryon in neutrino and antineutrino collisions with protons, deuterons, and Neon nuclei.

We analyze the data collected by several neutrino experiments with big bubble chambers—BEBC at CERN and the 15-foot chamber at Fermilab. These two bubble chambers were close to each other in geometry, fiducial volume, and operating conditions, and their data were collected and processed using very similar techniques and algorithms. In the past, this already allowed to combine the neutrino data collected with BEBC and the 15-foot bubble chamber for a number of physics analyses [6]. A database compiled by one of us (A.A.) comprises some 120 000 $\nu_\mu$- and $\bar{\nu}_\mu$-induced charged-current events, and embraces the bulk of neutrino data collected with BEBC (expts. WA21, WA25, and WA59) and a significant fraction of data collected with the 15-foot bubble chamber\(^1\) (expts. E180 and E632). Though obtained several decades ago, the neutrino data from big bubble chambers are still unrivaled in quality and completeness of physics information.

In the BEBC experiments WA21 (hydrogen fill), WA25 (deuterium fill), and WA59 (neon-hydrogen mix), the data were collected using essentially the same wide-band horn-focused beam, with mean energies of $\nu_\mu$CC and $\bar{\nu}_\mu$CC events near 50 and 40 GeV, respectively. The experiment E180 used the 15-foot bubble chamber filled with a Ne–H\(_2\) mix and exposed to a wide-band antineutrino beam under conditions very similar to WA59. In the last bubble-chamber experiment, E632 at Fermilab, the 15-foot chamber was filled with a (lighter) Ne–H\(_2\) mix and exposed to a neutrino beam with quadrupole-triplet focusing from the Tevatron. In E632, mean energies of neutrino and antineutrino events reached

\(^1\)Unfortunately, our database does not include the biggest neutrino sample from the 15-foot bubble chamber—that collected by the $\nu$Ne experiment E53 [7].
some 140 and 110 GeV, respectively. Neutral-current interactions are not systematically included in the database\(^2\), and therefore our analysis is restricted to charged-current events with \(p_\mu > 4\) GeV. Total numbers and mean energies of \(\nu_\mu\)CC and \(\bar{\nu}_\mu\)CC events collected by the aforementioned experiments are summarized in Table 1. Further details on these neutrino experiments can be found in [8].

Unlike charged kaons that are virtually indistinguishable from pions, neutral kaons are identified in a bubble chamber by reconstructing the decays \(K^0_S \rightarrow \pi^+\pi^-\). On average, the \(K^0(\bar{K}^0)\) detection efficiency is near 25%. At the same time, protons with momenta below \(\sim 1\) GeV can be identified by the stopping signature, bubble density, and variation of track curvature in magnetic field. Therefore, the \(K^0p\) channel seems mandatory when searching for formation of the \(\Theta^+\) in a bubble chamber. The numbers of events featuring either reconstructed \(K^0_S \rightarrow \pi^+\pi^-\) decays and identified protons with \(p_p < 900\) MeV, that are used in this analysis, are quoted in Table 1 for each (anti)neutrino sample considered. The momenta of protons identified in hydrogen, deuterium, and neon are plotted in Fig. 1. In deuterium, the enhancement at proton momenta below some 200 MeV is due to spectator protons. For neon events with reconstructed \(K^0_S\) mesons and identified protons, mean proton multiplicity is \(\simeq 1.4\).

For either fill, the \(m(K^0_Sp)\) distributions of \(\nu_\mu\)CC and \(\bar{\nu}_\mu\)CC events are separately plotted in Fig. 2 and combined—in Fig. 3. Protons are selected in the momentum interval of \(300 < p_p < 900\) MeV. The combined \(\nu + \bar{\nu}\) distribution for neon shows a distinct enhancement at \(m(K^0_Sp) \simeq 1530\) MeV. No neutrino events contribute twice or more to the peak region. The peak survives dropping the events that feature two or more identified protons with \(300 < p_p < 900\) MeV, see the lower (open) histogram in the bottom panel of Fig. 3. The combined \(\nu + \bar{\nu}\) distribution for deuterium is also slightly enhanced in the same mass region. The background in the peak region is estimated by pairing a \(K^0_S\) from one event and a proton—from another event randomly selected in the same \(\nu/\bar{\nu}\) subsample. Thus obtained ”random-star” distribution is then normalized to the \(K^0_Sp\) mass spectrum by the number of entries in the nonresonant region of \(m(K^0_Sp) > 2\) GeV (see the dotted histograms in Fig. 3). It is noteworthy that, apart from the peak

\(^2\)In WA59, the bulk of NC events were rejected at scanning stage.
near 1530 MeV in the $m(K^0_S p)$ distribution for neon, the random-star background fails to reproduce a broad enhancement in the mass region $1650 < m(K^0_S p) < 1850$ MeV of the same spectrum. The latter enhancement may be due to $\bar{K}^0 p$ decays of a number of excited $\Sigma^{*+}$ states that populate this mass region [9].

Figure 4 shows the $m(K^0_S p)$ distribution for the Neon and Deuterium data combined. In two 10-MeV bins between 1520 and 1540 MeV, we have 27 events with a background of $\sim 8$ events as estimated from random $K^0_S p$ pairs (see the dotted histogram). The statistical significance of the peak is thus near 6.7 standard deviations. It makes no sense to fit a signal restricted to just two bins as in the top panel of Fig. 4 so in the bottom panel we plot the same $m(K^0_S p)$ distribution with bins shifted by 5 MeV. A fit of the latter histogram to a Gaussian on top of linear background returns $M = 1533 \pm 5$ MeV and $\sigma = 8.4 \pm 2.0$ MeV for the position and r.m.s. width of the resonance, respectively. The r.m.s. width is found to be consistent with experimental resolution on $m(K^0_S p)$ estimated from live events in the peak ($\simeq 8.5$ MeV).

For neutrino and antineutrino events that contribute to the peak region of $1510 < m(K^0_S p) < 1550$ MeV, mean values of $E_\nu (57 \pm 10$ GeV) and $Q^2 (12.5 \pm 3.3$ GeV$^2$) are consistent with those for all CC events with detected $K^0_S$ mesons. Mean momentum of the $K^0_S p$ system for peak events, $\langle p(K^0_S p) \rangle = 1.08 \pm 0.06$ GeV, is much less than that of all detected $K^0_S$ mesons (see Table 1).

Unfortunately, neutrino data do not allow to determine the strangeness of the observed resonant state with mass near 1533 MeV, as was done in [1, 2, 3, 4]. On the other hand, there are no known $\Sigma^{*+}$ states in this mass region. Therefore, we interpret the enhancement near 1533 MeV observed in the $m(K^0_S p)$ distribution as a signal from formation of the $\Theta^+$ baryon in neutrino and antineutrino collisions with nuclei. The mass and width of this state are estimated as $M = 1533 \pm 5$ MeV and $\Gamma < 20$ MeV, respectively. The cross section of $\Theta^+$ production by neutrinos appears to increase with atomic number of the target nucleus.

The excellent neutrino data analyzed in this paper are a result of painstaking and ingenious work of the WA21, WA25, WA59, E180, and E638 experimental teams over many years, and their efforts are gratefully acknowledged. We wish to thank Prof.
M.V. Danilov, Prof. L.B. Okun, Dr. V.S. Borisov, and Dr. V.S. Verebryusov for useful comments and suggestions.

References

[1] T. Nakano et al. (LEPS Coll.), Phys. Rev. Lett. 91, 012002 (2003); hep-ex/0301020

[2] V.V. Barmin et al. (DIANA Coll.), Yad. Fiz. 66, 1763 (2003) [Phys. At. Nucl. 66, 1715 (2003)]; hep-ex/0304040

[3] S. Stepanyan et al. (CLAS Coll.), hep-ex/0307018

[4] J. Barth et al. (SAPHIR Coll.), hep-ex/0307083

[5] D. Diakonov, V. Petrov, and M. Polyakov, Z. Phys. A359, 305 (1977).

[6] A.E. Asratyan et al., Phys. Lett. 257B, 525 (1991);
   A.E. Asratyan et al. (Big Bubble Chamber Neutrino Coll.), Z. Phys. C58, 55 (1993);
   V.A. Korotkov et al. (Big Bubble Chamber Neutrino Coll.), Z. Phys. C60, 37 (1993);
   V.G. Zaetz et al. (Big Bubble Chamber Neutrino Coll.), Z. Phys. C66, 583 (1995).

[7] N.J. Baker et al. (E53 Coll.), Phys. Rev. D34, 1251 (1986).

[8] G.T. Jones et al. (WA21 Coll.), Z. Phys. C51, 11 (1991);
   D. Allasia et al. (WA25 Coll.), Z. Phys. C37, 527 (1988);
   S. Willocq et al. (WA59 Coll.), Z. Phys. C53, 207 (1992);
   V.V. Ammosov et al. (E180 Coll.), Nucl. Phys. B177, 365 (1981);
   D. DeProspo et al. (E632 Coll.), Phys. Rev. D50, 6691 (1994).

[9] K. Hagiwara et al. (Particle Data Group), Phys. Rev. D66, 010001 (2002).
| Experiment Chamber | WA21 | WA25 | WA59 | E180 | E632 |
|--------------------|------|------|------|------|------|
| Fill               | BEBC | BEBC | BEBC | 15’ B.C. | 15’ B.C. |

**Neutrinos:**

| Mean $E_{\nu}$, GeV | 48.8 | 51.8 | 56.8 | 52.2 | 136.8 |
| Mean momentum of detected $K_S^0$, GeV | 5.7 | 5.7 | 4.5 | 3.4 | 7.7 |
| All measured CC events | 18746 | 26323 | 9753 | 882 | 5621 |
| CC events with $K_S^0$ | 1050 | 1279 | 561 | 21 | 587 |
| CC events with $K_S^0$ and identified protons | 82 (78) | 307 (128) | 193 (193) | 9 (8) | 229 (157) |

**Antineutrinos:**

| Mean $E_{\bar{\nu}}$, GeV | 37.5 | 37.9 | 39.5 | 33.8 | 110.0 |
| Mean momentum of detected $K_S^0$, GeV | 4.2 | 4.2 | 3.5 | 3.4 | 7.6 |
| All measured CC events | 13155 | 16314 | 15693 | 5927 | 1190 |
| CC events with $K_S^0$ | 702 | 761 | 631 | 231 | 123 |
| CC events with $K_S^0$ and identified protons | 45 (43) | 116 (57) | 185 (185) | 56 (54) | 49 (28) |

Table 1: For the five neutrino experiments considered, mean energies of $\nu_\mu$- and $\bar{\nu}_\mu$-induced CC events, mean momenta of $K_S^0$ mesons reconstructed by $K_S^0 \rightarrow \pi^+\pi^-$ decays, and the numbers of all measured CC events, of those with detected $K_S^0$ mesons, and of those featuring either $K_S^0$ mesons and identified protons with momentum $p_p < 900$ MeV. The numbers in parentheses are for the additional selection of $p_p > 300$ MeV. Note that in the experiment E632, all neutrino events were measured on part of exposed film, and only those that showed $K_S^0 \rightarrow \pi^+\pi^-$ and $\Lambda^0 \rightarrow p\pi^+$ candidates were measured on another part of the film.
Figure 1: Momenta of identified protons emitted in association with $K^0_S$ mesons in $\nu_\mu$CC and $\bar{\nu}_\mu$CC collisions with Hydrogen, Deuterium, and Neon (top, middle, and bottom panels, respectively).
Figure 2: Invariant mass of the $K_S^0 p$ system formed in $\nu_\mu\text{CC}$ (on the left) and $\bar{\nu}_\mu\text{CC}$ (on the right) collisions with Hydrogen, Deuterium, and Neon (top, middle, and bottom panels, respectively).
Figure 3: Invariant mass of the $K^0_S p$ system for the $\nu_\mu$CC and $\bar{\nu}_\mu$CC events combined. The top, middle, and bottom panels are for the Hydrogen, Deuterium, and Neon data, respectively. The "random-star" background obtained by pairing a $K^0_S$ from one event and a proton from another event in depicted by dots. Dropping the events in Neon that feature two or more identified protons with $300 < p_p < 900$ MeV results in the lower (open) histogram in the bottom panel.
Figure 4: Invariant mass of the $K_S^0p$ system for the Neon and Deuterium data combined (top panel). The dots depict the random-star background. A fit of the same $m(K_S^0p)$ distribution but plotted with shifted bins is shown in the bottom panel.