Observation of a $\Theta^+\text{-Baryon}$ decay to $pK^0_S$ in $K^+$ and neutrino interactions with nuclei

DIANA collaboration of ITEP, Moscow & Frascati:
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and

re-analysis of data of Big Bubble Chamber Neutrino Collaboration

by A. Asratyan, A. Dolgolenko, M. Kubantsev
Observation of $\Theta^+$ in the DIANA bubble chamber

Separated beam of $K^+$ mesons with momentum of 750 MeV/c from ITEP 10 GeV proton accelerator irradiates DIANA chamber filled with liquid Xenon: density: 2.2 g/cm$^3$ Rad. length: 3.7 cm Volume: 700 liters Viewed with 4 cameras No magnetic field

The DIANA chamber under preparation

M. Kubantsev, ITEP/NWU

Pentaquark Workshop 2003, Nov 6-8, Jlab
Observation of $\Theta^+$ in the DIANA bubble chamber

Charged particles: identified by ionization; momentum measured by range. Interaction energy is determined by range of the kaon before interaction:

$$K^+ + N \rightarrow \Theta^+ \rightarrow P + K^0$$

( +1 strangeness!)

Protons are identified by range. $K^0_S$ are fitted to the vertex. About 25000 events with visible $K^0$ decays: $K^0_S \rightarrow \pi^+\pi^-$ and $K^0_S \rightarrow \pi^0\pi^0$ have been found.
Observation of $\Theta^+$ in the DIANA bubble chamber

$K^+$ range distributions:

(1) all incoming $K^+$: peak at 945 mm corresponds to decays of stopping kaons;

(2) $K^+$ decays (mostly in rest); all kaon decays are uniquely identified (+branching ratios are verified);

(3) charge exchange reaction events: $K^+Xe \rightarrow K^0 X$. 

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$K^+$ with range more than 550 mm are selected:

$K^+$ momentum distribution has a peak at 470 MeV/c for events of reaction:

$K^+\text{Xe} \rightarrow K^0 pX$

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Estimation of $K^0\, p$ effective mass reconstruction accuracy was made with observed decays $\Lambda^0 \rightarrow p\,\pi^-$.

- Observed value of mass ($p\,\pi^-$):
  \[ 1116 \pm 1 \text{ MeV/c}^2 \]

- Instrumental width:
  \[ \sigma = 3.3 \pm 1.0 \text{ MeV/c}^2 \]

(in similar momentum range as in $K^0\, p$ reaction !)

Observation of $\Theta^+$ in the DIANA bubble chamber
**Effective mass of $K^0p$ system fitted by linear combination of Monte-Carlo simulated and random star background distributions.**

Qualitatively, there is a narrow enhancement at $M \sim 1530-1540$ MeV/$c^2$ of 107 events over background of 84 (significance of 2.6 $\sigma$)

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To remove events affected by re-scattering of reaction products topological cuts are applied:

$\theta_K < 100^\circ$ and $\theta_P < 100^\circ$

(p and $K^0$ are selected mostly forward in laboratory frame)

and

$\cos \Phi_{pK} < 0$

(p and $K^0$ are emitted back-to-back)
Observation of $\Theta^+$ in the DIANA bubble chamber

After above cuts the peak near 1540 MeV/c$^2$ of total 73 events has estimated background of 44 events, resulting in statistical significance of 4.4 $\sigma$

Gaussian fit of the peak yields:

$M = 1539 \pm 2$ MeV/c$^2$

$\Gamma < 9$ MeV/c$^2$

(compatible with instrumental resolution)
Observation of $\Theta^+$ in the DIANA bubble chamber

Above we presented direct approach to search for $\Theta^+$ analyzing effective mass of $K^0p$ system.

Another approach is to measure cross sections for formation of $K^0p$, $K^+n$ and $K^+p$ final states as function of $\sqrt{s}$:

```
K^+  Theta^+  K
  |      |  |
N   N
```

Work on the $K^+$ Xe cross section data continues.
Observation of $\Theta^+$ in the DIANA bubble chamber

PDG 2002 tables show very scarce cross section data in region of $K^+$ momenta below 600 MeV/c.

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Observation of $\Theta^+$ in the DIANA bubble chamber

Later K+A data from 1990’s also shows some hints at $K^+$ momenta range of 400 –500 MeV/c: there is no good agreement with theory.

B. Sechi-Zorn et al (ibid)
Observation $\Theta^+ \rightarrow P^+ K^0_S$ in (Anti)Neutrino Interactions (strangeness is unidentified)

re-analysis of data of the Big Bubble Chamber Neutrino Collaboration are analysed by A. Asratyan, A. Dolgolenko and M. Kubantsev (ITEP, Moscow)
Observation of $\Theta^+$ in neutrino interactions

Two big bubble chambers: Fermilab 15’ and CERN BEBC, were close to each other in geometry, fiducial volume and operation conditions. Data were collected and processed using very similar techniques and algorithms.

Neutrino interactions were recorded in wide band neutrino beams of Fermilab 400 GeV accelerator (E180) and 800 GeV Tevatron (E632) with Neon-Hydrogen fill of 15’ BC and CERN 450 GeV accelerator with Hydrogen (WA21), Deuterium (WA25) and Neon (WA59) fills of BEBC.
Observation of $\Theta^+$ in neutrino interactions

These experimental data compiled by A. Asratyan (ITEP) comprise some 120000 (Anti)Neutrino charge current (CC) events*:

$$\nu_\mu (\bar{\nu}_\mu) + A \rightarrow \mu^- (\mu^+) + X.$$  

Neutral current events: $\bar{\nu}_\mu (\nu_\mu) + A \rightarrow \bar{\nu}_\mu (\nu_\mu) + X$ are not included (not measured systematically).

Even after several decades the bubble chamber neutrino data are still unrivaled in quality and completeness of physics information. We analysed CC events with the hadron system (X) containing protons (identified) + $K^0_S \rightarrow \pi^+\pi^-$ (fitted) + $X'$.

*Unfortunately E53 data are not included (61800 CC $\nu_\mu$ Ne events)
# Observation of $\Theta^+$ in neutrino interactions

<table>
<thead>
<tr>
<th>Experiment</th>
<th>WA21</th>
<th>WA25</th>
<th>WA59</th>
<th>E180</th>
<th>E632</th>
<th>Total</th>
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<td>15' B.C.</td>
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## Neutrinos:

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<tr>
<td>Mean, GeV</td>
<td>48.8</td>
<td>51.8</td>
<td>56.8</td>
<td>52.2</td>
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<td>Mean momentum of detected K0S, GeV/c</td>
<td>5.7</td>
<td>5.7</td>
<td>4.5</td>
<td>3.4</td>
<td>7.7</td>
<td>5.8</td>
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<td>All measured CC events</td>
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<td>26323</td>
<td>9753</td>
<td>882</td>
<td>5621</td>
<td>61325</td>
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<td>CC events with K0S</td>
<td>1050</td>
<td>1279</td>
<td>561</td>
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<td>587</td>
<td>3498</td>
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<td>CC events with K0S and identified protons (900&gt;P&gt;300 MeV/c)</td>
<td>78</td>
<td>128</td>
<td>193</td>
<td>8</td>
<td>157</td>
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## Antineutrinos:

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<td>Mean, GeV</td>
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<td>Mean momentum of detected K, GeV/c</td>
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<td>CC events with K0S</td>
<td>702</td>
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<td>123</td>
<td>2448</td>
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<tr>
<td>CC events with K0S and identified protons (900&gt;P&gt;300 MeV/c)</td>
<td>43</td>
<td>57</td>
<td>185</td>
<td>54</td>
<td>28</td>
<td>367</td>
</tr>
</tbody>
</table>
Observation of $\Theta^+$ in neutrino interactions

Identified protons emitted in momentum range of $300<P<900$ MeV/c in association with $K^0_S$ in $\nu_\mu$ CC and $\bar{\nu}_\mu$ CC collisions with Hydrogen, Deuterium, and Neon are used in the analysis.
Observation of $\Theta^+$ in neutrino interactions

$$\nu_\mu (\bar{\nu}_\mu) + A \rightarrow \mu^- (\mu^+) + P + K^0_S + X'$$

Hydrogen Neutrinos

Hydrogen Antineutrinos

Deuterium Neutrinos

Deuterium Antineutrinos

Neon Neutrinos

Neon Antineutrinos
Observation of $\Theta^+$ in neutrino interactions

$K^0_S p$ (identified) invariant mass distributions for $\nu_\mu CC + \bar{\nu}_\mu CC$ events: random star background is shown by dots; open histogram is for Neon events with one identified proton only.

Note: no events enter in the peak region twice.
Observation of $\Theta^+$ in neutrino interactions

$K^0_S p$ (identified) invariant mass for $\nu_\mu CC$ and $\bar{\nu}_\mu CC$ events combined with the random star background:

27 events with $\sim 8$ events of the background;

significance of $6.7\,\sigma$.

The same distribution with bins shifted by 5MeV is fitted to get mass and width of the peak.

Width of the peak is compatible with instrumental resolution.

Mass = $1533 \pm 5\,\text{MeV}/c^2$

Width < 20 MeV/c^2
Observation of $\Theta^+$ in neutrino interactions

Peak events mean values of

- neutrino energy of $E_\nu$ $(57\pm10 \text{ GeV})$ and transverse 4-momentum $Q^2(12.5\pm3.3 \text{ GeV}^2)$
- are consistent with those for all events with $K^0_S$.

No strangeness determined! – But there are no known $\Sigma^+$ states in this region. We interpret the peak at 1533 MeV/c$^2$ a signal of formation of the $\Theta^+$.

Further observations:

1. $\Theta^+$ production cross section by neutrinos appears to increase with atomic number of the target nucleus;
2. Relative $\nu$ and $\bar{\nu}$ yields of $\Theta^+$ are close;
3. Associated production of neutral strange particles is not different from other events with $K^0_S$ (specially no excess of $\Lambda^0$).
Comparison of $\Theta^+$ and $\Sigma^+(1385) \rightarrow \Lambda^0 + \pi^+$ in (anti)neutrino interactions

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Comparison of $\Theta^+$ and $\Sigma^+(1385)$ in (anti)neutrino interactions

Qualitatively we see most of $\Theta^+$ signal on Ne and small one on H$_2$ and D$_2$ with roughly the same luminosity. At the same conditions $\Sigma^+(1385)$ signal is seen on H$_2$ and D$_2$ and it is not seen on neon.

Observed $\nu$ and $\bar{\nu}$ yields of $\Theta^+$ are about the same.

$\Sigma^+(1385)$ is mostly produced in $\nu$, not $\bar{\nu}$ beam.

Observed $\Theta^+$ are produced slow moving in lab system: may speculate that it is produced by re-scattering of secondary kaons(?) in nuclei.

$\Sigma^+(1385)$ are produced at higher momenta and charge of interacting quark (+2/3 for $\nu$ and −1/3 for $\bar{\nu}$) is important. Re-interactions in nuclei apparently destroy $\Sigma^+(1385)$ peak.
Conclusions

A signal of $\Theta^+ \rightarrow pK^0_S$ is observed on level of $4.4\,\sigma$ in $K^+ Xe$ and $6.7\,\sigma$ in neutrino interactions with Neon and Deuterium.

Mass values and widths are found:

- $M = 1539\pm 2\,\text{MeV}/c^2$ and $\Gamma(\text{observed}) < 9\,\text{MeV}/c^2(K^+Xe)$
- $M = 1533\pm 5\,\text{MeV}/c^2$ and $\Gamma(\text{observed}) < 20\,\text{MeV}/c^2(\nu\text{Ne} + \nu\text{D}_2)$

Low energy $K^+$ cross sections with nucleons and nuclei are not well known, there are some hints of cross section enhancement at $\sqrt{s} \sim 1530-1540\,\text{MeV}$ from old and not so old data.

Work on the $K^+ Xe$ cross section data continues.

The cross section of $\Theta^+$ production by neutrinos appears to increase with atomic number of the target nucleus.