Pentaquark Searches in Electron-Positron Annihilations and Two-Photon Collisions at LEP

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Evidence for the production of exotic hadron states composed of five quarks (pentaquarks) has been searched for in data collected by the ALEPH, DELPHI, and L3 experiments at LEP. No significant signal is observed. Several 95% C.L. upper limits are set on the production rates of such particles.

1. Introduction

The past 18 months have seen extraordinary developments in the field of hadron spectroscopy. Several experiments have reported strong experimental evidence of narrow exotic baryon resonances with quantum numbers indicative of the existence of bound states beyond the canonical constituent-quark model view with two or three (anti-)quark bound states. Permitted within the framework of Quantum Chromodynamics, these states have been previously unobserved.

Numerous experimental excesses have been reported in pK₀S and nK⁺ invariant mass spectra consistent with a resonance of mass near 1535 MeV/c² and width less than 10 MeV/c² carrying strangeness S = +1. Furthermore, evidence of a narrow resonance in Ξ⁻π⁺ invariant mass spectra has also been observed consistent with a resonance of mass near 1860 MeV/c² and width less than 18 MeV/c². Finally, the heavy flavor sector is not immune from the appearance of these new states: an excess is observed in pD*⁻ invariant mass spectra consistent with a resonance of mass near 3100 MeV/c² and width less than 15 MeV/c².

These experimental results have generated at least an order-of-magnitude more papers concerning the interpretation and phenomenology of these new resonances is that of a pentaquark bound state consisting of four quarks and an anti-quark (e.g., uduS, dsdπ, uduπ); these states are also described within and may enhance the validity of chiral soliton models.

Searches for pentaquark states in e⁺e⁻ annihilations and γγ collisions have been proposed. Results from these searches may be compared directly to the observation of known non-exotic states which decay into relevant and similar final states (e.g., Λ(1520) → pK⁻, Ξ(1530)⁰ → Ξ⁻π⁺, D⁺(2010)→D⁰π⁺). Negative results may help illuminate the as yet poorly understood pentaquark production process.

2. The Experiments and Data Sets

From 1989 to 1995, LEP accelerated and collided counter-rotating beams of electrons and positrons to energies of roughly 45 GeV, allowing collisions with center-of-mass energies at or near the Z peak. This first phase of LEP (LEP1) delivered a total of 200 pb⁻¹ to each of four large general-purpose detector experiments (ALEPH, DELPHI, L3, and OPAL). In these data, each experiment recorded more than 3 million hadronic Z decays yielding in excess of 5×10⁵ reconstructed K₀S mesons and 10⁴ Λ baryons.

The second phase of LEP (LEP2) involved increasing the center-of-mass energies to nearly 210 GeV in consecutive annual upgrades between 1995 and 2000. Starting in Novem-

[1]Here, and throughout this paper, charge conjugation is assumed.
number 1995, LEP attained center-of-mass energies between 130 and 136 GeV. Subsequent years yielded energies of 161 and 172 GeV (1996), 183 GeV (1997), 189 GeV (1998), between 192 and 196 GeV (1999), and between 200 and 209 GeV (2000). An integrated luminosity of about 500 pb\textsuperscript{-1} was delivered during LEP2 to each experiment.

Thus far, ALEPH, DELPHI, and L3 have analyzed various data samples searching for evidence of pentaquark production. These detectors are described in detail elsewhere \cite{7,8,9}.

### 3. Searches for Pentaquark Production

The event selection strategies across the three LEP experiments which have conducted pentaquark searches are similar. ALEPH \cite{10} and DELPHI \cite{11} searched for evidence of pentaquark production from the fragmentation of quarks from roughly four million hadronic Z decays (e\textsuperscript{+}e\textsuperscript{-} \rightarrow Z \rightarrow q\bar{q} \rightarrow \Theta(1535)^{+}X) within data taken at or near center-of-mass energies of 91.2 GeV. L3 \cite{12} searched for evidence of pentaquark production from two-photon interactions (e\textsuperscript{+}e\textsuperscript{-} \rightarrow e\textsuperscript{+}e\textsuperscript{-}\gamma\gamma \rightarrow e\textsuperscript{+}e\textsuperscript{-}\Theta^{+}X) in data taken between center-of-mass energies of 189 and 209 GeV, with a luminosity-weighted average value of 198 GeV; the data sample corresponds to 610 pb\textsuperscript{-1}.

All of the experiments make quality cuts to select good events as well as exploiting the relevant particle identification capabilities of subdetectors. All of the experiments rely upon specific energy loss by ionization (dE/dx) of charged particles traversing the fiducial volume of various tracking chambers to discriminate between charged particle species (\pi\textsuperscript{\pm}, K\textsuperscript{\pm}, p/\bar{p}, or e\textsuperscript{\pm}). DELPHI complements such information with data from a Barrel Ring Imaging Cherenkov Counter (BRICH).

Selection of K\textsuperscript{0}\textsubscript{S} \rightarrow \pi^{+}\pi^{-} candidates makes use of decay length criteria relative to the primary vertex of oppositely-charged pairs of identified pions as well as cuts on the quality of reconstructed secondary vertices. Similarly, ALEPH selects \Lambda \rightarrow p\pi^{-} candidates by associating oppositely-charged identified pion and proton tracks. Furthermore, \Lambda candidates are paired with pion tracks which yield a displaced secondary vertex to yield a sample of \Xi^{-} candidates. Finally, samples of D\textsuperscript{0}, D\textsuperscript{+}, and D\textsuperscript{++} mesons were obtained using techniques described in detail in Ref. \cite{13} with the addition of harder momenta criteria (p(D\textsuperscript{0}) > 7 GeV/c and p(D\textsuperscript{+}) > 14 GeV/c).

#### 3.1. Searches in \(pK\) channels

As a benchmark and cross-check, ALEPH performed a search for doubly-charged (pK\textsuperscript{+}) and neutral (pK\textsuperscript{-}) combinations. No resonant structure is observed in the invariant mass distribution of doubly-charged pK combinations, shown in Figure 1(a). A smooth deviation of the data from Monte Carlo expectation is observed in both neutral and doubly-charged combinations due to imperfect simulation of the detector response. The observed data-to-simulation ratio from doubly-charged combinations is used to correct the simulation of neutral pK combinations, shown in Figure 1(b). The neutral pK combinations show clear resonant activity in the mass range from 1460 to 1800 MeV/c\textsuperscript{2}; this is due to the production of known \Lambda and \Sigma\textsuperscript{+} resonances. As illustrated in Figure 1(c), non-resonant simulation is subtracted from the data, and the resulting invariant mass distribution is fit to the amplitude of eight NK resonances, most prominently the \Lambda(1520) followed by broader contributions from \Sigma(1480), \Sigma(1560), \Sigma(1580), \Sigma(1620), \Sigma(1660), \Sigma(1670), and \Sigma(1750). This results in a yield from the \Lambda(1520) of 2874±320 (stat.)±270 (syst.) combinations. When considered with the selection efficiency of 9.7±0.9\% and Br(\Lambda(1520) \rightarrow pK\textsuperscript{-}) =22.5\%, this yields a production rate per hadronic Z decay of \(N_{\Lambda(1520)} = 0.033 ± 0.004 ± 0.003\), in agreement with other measurements of this quantity \cite{14}.

ALEPH then searched for resonant activity in invariant mass distribution of pK\textsuperscript{0}\textsubscript{S} combinations. Figure 2 shows the distribution from 480 000 combinations with a pK\textsuperscript{0}\textsubscript{S} purity of 50\% compared to the Monte Carlo simulation containing only known octet and decuplet baryon ground states. No evidence for the production of \Theta(1535)^{+} or its antiparticle is seen. When considered with the selection efficiency of 6.3±0.2\% and an assumed
Figure 1. ALEPH invariant mass spectra for (a) doubly-charged pK$^+$ combinations, (b) neutral pK$^-$ combinations, (c) neutral pK$^-$ combinations after background subtractions with locations of known $\Lambda(1520)$ and $\Sigma^*$ baryon resonances indicated. Data are denoted by the points with error bars. In (a) and (b), the solid line denotes Monte Carlo simulation including known decuplet and octet baryons; in (c), the solid line represents a fit which includes the known $\Lambda(1520)$ and $\Sigma^*$ resonances.

Figure 2. ALEPH invariant mass spectrum for pK$^0_S$ combinations. A search region indicated by the long horizontal area was examined for evidence of the $\Theta(1535)^+$. Br($\Theta(1535)^+ \rightarrow pK^0_S$)=25% yields a 95% C.L. upper limit on the production rate of $\Theta(1535)^+$ and its antiparticle per hadronic Z decay is found to be $N_{\Theta(1535)^+} < 0.0025$.

DELPHI have also examined invariant mass spectra of pK$^-$, pK$^+$, and pK$^0_S$ combinations from hadronic Z decays which are shown in Figures 3(a), 3(b), and 3(c) respectively. From a fit to the pK$^-$ spectrum, an excess in the $\Lambda(1520)$ region of $306 \pm 55$ events is observed consistent with the mass and width of the $\Lambda(1520)$ as well as with previous measurements of the production rate per hadronic Z decay [14]. No excess is seen in the invariant mass spectrum for pK$^+$ combinations; this is interpreted as an 95% C.L. upper limit for the average multiplicity of the production of a doubly-charged pentaquark, $\Theta^{++}$, of $< N_{\Theta^{++}} > < 0.006$ for the mass region between 1.5 GeV/c$^2$ and 1.75 GeV/c$^2$. Furthermore, no excess is seen in the invariant mass spectrum for pK$^0_S$ and yields a 95% C.L. upper limit...
for the average multiplicity of $\Theta^+$ production of $<N_{\Theta^+}> < 0.015$ for the mass range between 1.52 GeV/$c^2$ and 1.56 GeV/$c^2$.

L3 examined the invariant mass of $pK^0_S$ combinations in two-photon interactions; this invariant mass spectrum is shown in Figure 4. No excess is observed in the data, with 1176 events observed and 1253 ± 44 events expected from a background fit. An 95% C.L. upper limit for the inclusive production reaction $e^+e^- \rightarrow e^+e^- \Theta^+X$ cross section of about 20 pb is obtained, to be compared to the inclusive $\Lambda$ production cross section of 197.8 ± 13.8 pb.

3.2. Searches in $\Xi^{\pm}\pi^{\pm}$ channels

ALEPH examined the invariant mass spectra of $\Xi^-\pi^-$ and $\Xi^-\pi^+$ combinations; these distributions are shown in Figure 5. In the $\Xi^-\pi^+$ distribution, a clear peak corresponding to the production of the well-established $\Xi(1530)^0$ resonance is observed and corresponds to a production rate per hadronic $Z$ decay of $N_{\Xi(1530)^0} = (77 \pm 8 \pm 6) \times 10^{-4}$ in good agreement with ALEPH and OPAL results [15]. No evidence is seen for the production of a doubly-charged or neutral $\Xi(1862)$ state, and 95% C.L. upper limits are set at

$$N_{\Xi(1862)^-\Xi(1862)^0} \rightarrow \Xi^0 \pi^- < 4.5 \times 10^{-4},$$

$$N_{\Xi(1862)^0} \rightarrow \Xi^- \pi^+ < 8.9 \times 10^{-4}.$$

3.3. Searches in $D^{(*)\pm}p$ channels

ALEPH examined invariant mass spectra for $D\pi$ combinations (Figure 6) and $D^{*\pm}p$ combinations for evidence of charm pentaquark $\Theta(3100)$ production. No evidence was found. Upper limits at 95% C.L. were set on the production rates

$$N_{\Theta_c(3100)^0} \rightarrow \Theta_c(3100)^0 \rightarrow D^* p < 6.3 \times 10^{-4},$$

$$N_{\Theta_c(3100)^0} \rightarrow \Theta_c(3100)^0 \rightarrow D^- p < 31 \times 10^{-4}.$$

4. Summary

No evidence for the production of pentaquarks in LEP data has been observed by the ALEPH, DELPHI, and L3 experiments. Production scenarios involving fragmentation of quarks from

Figure 3. DELPHI invariant mass spectra for (a) $pK^-$, (b) $pK^+$, and (c) $pK^0_S$ combinations. Data are denoted by crosses while a polynomial fit is indicated by the solid line. The peak in (a) corresponds to the known $\Lambda(1520)$ resonance.
Figure 4. L3 invariant mass spectrum for pK$_S^0$ combinations.

Figure 5. ALEPH invariant mass spectra for (a)\(\Xi^-\pi^-\) and (b)\(\Xi^-\pi^+\) combinations for the data (dots with error bars) and Monte Carlo simulation (histogram).

Figure 6. ALEPH invariant mass spectra of Dp combinations for the data (dots with error bars) and the Monte Carlo simulation (histogram).

Figure 7. ALEPH invariant mass spectra of D$^{*\pm}$p combinations for the data (dots with error bars) and the Monte Carlo simulation (histogram).
hadronic Z decays as well as inclusive production in two-photon interactions are considered. Upper limits at 95% C.L. have been set on relevant production rates.

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