Prospects for Pentaquark Searches in e^+e^- Annihilations and $\gamma\gamma$ Collisions

S. Armstrong, B. Mellado, Sau Lan Wu

Department of Physics University of Wisconsin - Madison Madison, Wisconsin 53706 USA

Abstract

Recent strong experimental evidence of a narrow exotic S=+1 baryon resonance, Θ^+ , suggests the existence of other exotic baryons. We discuss the prospects of confirming earlier experimental evidence of Θ^+ and the observation of additional hypothetical exotic baryons in e^+e^- annihilations and $\gamma\gamma$ collisions at LEP and B Factories.

1 Introduction

Recent strong experimental evidence of a narrow exotic baryon resonance with strangeness S = +1, Θ^+ , may open a new chapter in the development of hadron spectroscopy. A narrow resonance peak near $1540 \,\mathrm{MeV}/c^2$ was observed in pK_s^0 and nK^+ invariant mass spectra in a number of different reactions [1, 2, 3, 4, 5, 6, 7]. However, it has been argued recently that the excess of events observed in the K^+n invariant mass spectrum may be caused by kinematic reflections from the decay of mesons such as $f_2(1275)$, $a_2(1320)$, and $\rho_3(1690)$ [8].

The quark model based on quark-antiquark mesons and three-quark baryons has been greatly successful in understanding a wealth of hadron spectroscopy. However, there is nothing in Quantum Chromodynamics (QCD) that prevents pentaquark bound states or resonances to appear in Nature. If fully confirmed, this exotic baryon would be most naturally explained as a pentaquark state of four quarks and an antiquark $(udud\overline{s})$.

According to the Standard Model (SM), baryons are arranged in octects with spin- $\frac{1}{2}$ and decuplets with spin- $\frac{3}{2}$. In the mid 1980s, the existence of anti-decuplet was hypothesized within the framework of the chiral soliton model [9, 10, 11, 12, 13]. In 1987, Praszalowicz presented the first estimate of the mass of what is today Θ^+ (viewed as the lightest member of the hypothesized anti-decuplet), a value around 1530 MeV/ c^2 , in striking agreement with the measurement [14, 15]. In 1997, Diakonov, Petrov and Polyakov calculated the mass and the width of the lightest member of the anti-decuplet operating under the assumption that the known nucleon resonance $N(1710, \frac{1}{2}^+)$ is a member of the hypothesized antidecuplet [16]. They predicted Θ^+ to have a mass around 1530 MeV/ c^2 and a width less than 15 MeV/ c^2 . Predictions were made for the mass, width and the branching ratios of other members of the suggested anti-decuplet (i.e., N, Σ , and Ξ baryons) [16, 18].

No accurate prediction of the Θ^+ mass and width was ever made within the constituent quark model. The direct determination of the Θ^+ mass jointly with upper limits on the decay width may be used as input to models based on the constituent quark model. An incresing number of models are apprearing, which consider the mass, width, spin, isospin and parity of Θ^+ and make predictions concerning the existence of additional baryons (for a recent collection of references see [19]). The mass and the quantum numbers of the Θ^+ may be calculated using lattice QCD, which is known to reproduce mass ratios of stable hadrons. Quenched lattice QCD computations of Θ^+ mass agree very well with the experimental value [20, 21].

Recently, the NA49 Collaboration reported evidence (roughly 4 standard deviations) of a narrow resonance in the $\Xi^-\pi^-$ invariant mass spectrum observed in proton-proton collisions at $\sqrt{s}=17.2\,\mathrm{GeV}$ [22]. A less prominent excess of events were reported in the $\Xi^-\pi^+$, $\Xi^+\pi^-$ and $\Xi^+\pi^+$ invariant mass spectra. These hint, nevertheless, to the

¹The authors used initially the notation Z^+ . The later was renamed by the authors to Θ [17].

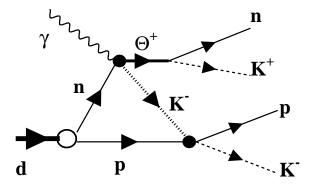


Figure 1: A re-scattering diagram in γd collisions that could contribute to the exclusive reaction mechanism leading to $\Theta^+ \to K^+ n$ and an energetic proton. The exotic baryon is produced via interactions in the final state (after the CLAS Collaboration).

existence of a isospin quartet, as predicted by the anti-decuplet idea. Jaffe and Wilczek have interpreted the results of the NA49 Collaboration as an evidence of an octet cascade nearly degenerate with the resonance observed in the $\Xi^-\pi^-$ system [23].

The existence of heavier exotic baryons, where the anti-strange quark, \overline{s} , is replaced by anti-charm or anti-beauty, now seems to be a natural consequence of the observation of Θ^+ . The masses of the lightest members of higher exotic multiples (Θ^0_c and Θ^+_b) have been recently conjectured by a number of authors based on the constituent quark model [24, 25, 26, 27]. These models suggest that Θ^0_c and Θ^+_b will appear as relatively narrow resonances. This is in contradiction with a recent calculation performed with quenched lattice QCD, which predicts that the Θ^0_c mass is 640 MeV/ c^2 above the DN (D-meson and N-baryon) threshold [21].

In the present discussion, we present the prospects of confirming earlier experimental evidence of Θ^+ and the observation of additional hypothetical exotic baryons in e^+e^+ collisions provided by LEP and B Factories. The potential of observing exotic baryons in $\gamma\gamma$ collisions and e^+e^- annihilations is discussed.

2 Pentaquark Production

Little is known about the production mechanism giving rise to exotic baryon states in collisions involving hadrons. One can make educated guesses given the fact that Θ^+ has been observed in a number of different reactions.

Collisions involving photons are attractive for $\Theta^+ \to KN$ searches thanks to the relatively high content of strange quarks in photons. Most of the reactions in which Θ^+ baryons have been observed involve photon collisions with hadrons.

At low energies in the exclusive reaction $\gamma d \to K^+K^-pn$ where $\Theta^+ \to K^+n$, one could

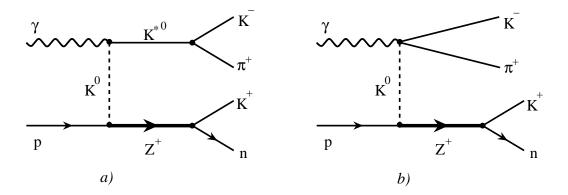


Figure 2: Feynman diagrams for $\gamma p \to \pi^+ K^+ K^- n$ (after V. Kubarovsky and S. Stepanian, for the CLAS Collaboration).

draw a re-scattering diagram, as depicted in Figure 1. Thanks to the re-scattering process in the final state, the proton, which acts as an spectator, acquires enough momentum that it may be detected [3].

Figure 2 depicts possible Feynman diagrams for the reaction $\gamma p \to \pi^+ K^+ K^- n$. These diagrams correspond to a t-channel exchange mechanism. Hence, one would expect that the $\cos \theta^*$ distribution, where θ^* is the angle between the $\pi^+ K^-$ momentum and the photon beam in the center of mass system, peaks in the forward region. This feature has been verified experimentally [28].

Figure 3 depicts possible diagrams for the production of pentaquarks in $\gamma\gamma$ collisions. The diagrams on the left and right in Figure 3 correspond to the exclusive double and single pentaquark production. Blobs are depicted in both diagrams; these imply the presence of non-perturbative probability amplitudes.

Cross sections for the exclusive production $\gamma\gamma \to p\overline{p}$, $\Sigma^0\overline{\Sigma}^0$, $\Lambda^0\overline{\Lambda}^0$ collisions have been reported by a number of experiments: CLEO [29], VENUS [30], OPAL [31], L3 [32, 33], and BELLE [34]. The agreement between the various experiments is not excellent. Nevertheless, the cross section of $\gamma\gamma \to p\overline{p}$ for $\gamma - \gamma$ center-of-mass energy, $W_{\gamma\gamma} \approx 2M_p$, where M_p corresponds to the proton mass, is of the order of 4 to 8 nb.² Thanks to the high luminosity regime, experiments at B Factories are in an excellent position to collect large statistics of di-baryon events in exclusive $\gamma\gamma$ reactions.³ Given the cross sections for di-baryon production being of the order of few nb, di-pentaquark production could be

²Cross sections of $\gamma\gamma \to \Lambda^0\overline{\Lambda}^0$ at $W_{\gamma\gamma} \gtrsim 2M_{\Lambda^0}$ reported by CLEO and L3 differ by an order of magnitude.

³Belle has collected approximately $2 \times 10^4 \ p\overline{p}$ candidates and roughly $6 \times 10^3 \ \Sigma^0 \overline{\Sigma}^0$, $\Lambda^0 \overline{\Lambda}^0$ pairs with approximately $89 \ \text{fb}^{-1}$ of integrated luminosity [34].

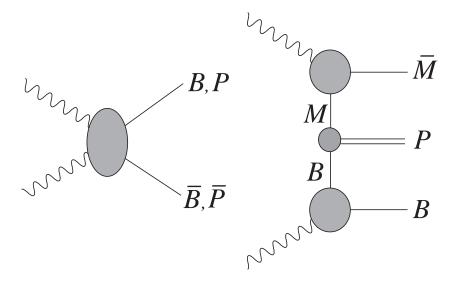


Figure 3: The diagrams on the left and right correspond to single and double Θ^+ production in a $\gamma\gamma$ collision. The blobs imply non-perturbative probability amplitudes. $B(\overline{B})$, $M(\overline{M})$ and $P(\overline{P})$ denote baryon, meson and pentaquark, respectively.

observed at the B Factories provided that the reaction $\gamma\gamma \to \Theta^+\overline{\Theta}^-$ is suppressed with respect to $\gamma\gamma \to p\overline{p}$ by less than three orders of magnitude.

The exclusive production of di-baryons in $\gamma\gamma$ collision may be viewed within the framework of the hard scattering picture (HSP), according to which the scattering amplitude may be expressed in terms of a convolution of a process-dependent (calculable in perturbation theory) piece with a process-independent amplitude for finding the corresponding hadron in the final state [35, 36]. Experimental results seem to be reasonably well described by this approach [37, 38]. These models operate under the assumption that baryons can be expressed in terms of quark structures (quark-di-quark bound states). A number of groups are able to interpret the pentaquarks in terms of bound states of quark structures: Jaffe and Wilczek view the pentaquark as a bound state of diquark-diquark-antiquark [24]; Karliner and Lipkin advocate a diquark-triquark configuration [25]. In principle, the formalism developed within the HSP may be extended to accommodate exclusive di-pentaquark production in $\gamma\gamma$ collisions [39].

Single pentaquark production may be viewed as a collision of non-resonant ⁴ di-baryon and a di-meson pairs (see Figure 3). One of the incoming photons fluctuates into two mesons with strangeness. One of them collides with the hadronic system produced by the other incoming photon. Non-resonant exclusive production of $p\bar{p}\pi^+\pi^-$ was observed by the TPC/Two-Gamma Collaboration in $\gamma\gamma$ collisions at PEP [40].⁵ The $W_{\gamma\gamma}$ dependence

⁴By non-resonant it is implied that the baryons and mesons are not produced as a result of the decay of a heavier baryons.

 $^{^5}$ In [40] it was reported that no $\Delta^0\overline{\Delta}^0$ production was observed and only a small fraction of the events

of the cross section was parameterized with a power-law functional form including a threshold effect [40]

$$\sigma\left(\gamma\gamma \to p\overline{p}\pi^{+}\pi^{-}\right) \propto W_{\gamma\gamma}^{-b} \left[1 - 4\frac{\left(M_{p} + M_{\pi}\right)^{2}}{W_{\gamma\gamma}^{2}}\right]^{\frac{1}{2}},\tag{1}$$

where M_{π} is the mass of the π meson and b is a free parameter. A fit to the data yielded $b \approx 5$.

It is relevant to note that no significant $\rho^0 \to \pi^+\pi^-$ contribution was found in $p\overline{p}\pi^+\pi^-$ events. We will assume that the contribution from $p\overline{p}\phi$ in $p\overline{p}KK$ events is also negligible. Furthermore, one can assume that the exclusive non-resonant cross sections $\sigma\left(\gamma\gamma\to p\overline{p}K^0\overline{K}^0\right)\approx\sigma\left(\gamma\gamma\to p\overline{p}K^+K^-\right)$. By using factorization of vertexes in the right diagram in Figure 3 and Expression 1, one can verify:

$$\sigma\left(\gamma\gamma\to p\overline{p}K^+K^-\right)\approx\sigma\left(\gamma\gamma\to p\overline{p}\pi^+\pi^-\right)\frac{\sigma\left(\gamma\gamma\to\pi^+\pi^-K^+K^-\right)}{\sigma\left(\gamma\gamma\to\pi^+\pi^-\pi^+\pi^-\right)}\left(\frac{M_p+M_\pi}{M_p+M_K}\right)^5,\quad(2)$$

where $\sigma(\gamma\gamma \to p\overline{p}K^+K^-)$ and $\sigma(\gamma\gamma \to p\overline{p}\pi^+\pi^-)$ are evaluated for $W_{\gamma\gamma}$ close the corresponding production threshold. Here, M_K is the mass of the K meson.

Results of four-prong final states (including $\pi^+\pi^-\pi^+\pi^-$ and $\pi^+\pi^-K^+K^-$) in $\gamma\gamma$ were observed in collisions [41, 42, 43, 44, 45]. The $\gamma\gamma\to\pi^+\pi^-\pi^+\pi^-$ is dominated by the $\gamma\gamma\to\rho^0\rho^0$ for $W_{\gamma\gamma}$ close to the production threshold but it is negligible for $W_{\gamma\gamma}>2$ GeV. The contribution to $\gamma\gamma\to\pi^+\pi^-K^+K^-$ from $\gamma\gamma\to\pi^+\pi^-K^+K^-$ from $\gamma\gamma\to\pi^+\pi^-\phi$ is very small as it is concentrated at the production threshold. The amplitude squared of the matrix elements in the reactions $\gamma\gamma\to\pi^+\pi^-\pi^+\pi^-$ and $\gamma\gamma\to\pi^+\pi^-K^+K^-$ were extracted from the cross sections by dividing by the phase space and the photon flux factors. The energy dependence of both matrix elements is similar for $W_{\gamma\gamma}>2$ GeV, suggesting similar production mechanisms. The ratio $\frac{\sigma(\gamma\gamma\to\pi^+\pi^-K^+K^-)}{\sigma(\gamma\gamma\to\pi^+\pi^-\pi^+\pi^-)}\approx 0.25$ to 0.3 for $W_{\gamma\gamma}>2$ GeV [41, 42, 43, 44, 45]. Using Expression 2 we obtain $\sigma(\gamma\gamma\to p\overline{p}K^+K^-)\approx 0.1$ nb for $W_{\gamma\gamma}\gtrsim 2$ (M_p+M_K). The experiments at B Factories could be able to reconstruct on the order of hundreds of $p\overline{p}$ - $K^0\overline{K}^0$ pairs in $\gamma\gamma$ collisions.

One might believe that exotic baryons, such as Θ^+ and other members of the hypothetical anti-decuplet, may only be observed in reactions involving γ 's and hadrons ($\gamma\gamma$, NN, γN , πN , KN). However, a narrow resonance consistent with Θ^+ has been also observed in the K_s^0p spectrum in charge current neutrino experiments ($\nu_\mu CC$ and $\overline{\nu}_\mu CC$) [6]. In this reaction, Θ^+ is most probably produced in the hadronization process. According to [6], the appearance of most of Θ^+ candidates occurred in the reaction $\nu_\mu Ne \to K_s^0 pX$. Very few candidates were observed in the similar reaction on Hydrogen and Deuterium, despite the fact that the number of charged-current interactions used in their analysis was a factor of 2.5 larger than that available for charged-current interaction with Neon.

were consistent with
$$\gamma \gamma \to \Delta^{++} \overline{\Delta}^{--}$$
, $\Delta^{++} \overline{p} \pi^{-}$, or $\overline{\Delta}^{--} p \pi^{+}$.

The observation of $\Theta^+ \to K^+ p$ in neutrino-induced charged-current interactions gives hope that exotic baryons may be observed in hadronic Z decays with LEP data at $e^+ e^-$ center-of-mass energies near 91 GeV. Generally speaking, inclusive pentaquak searches may be performed on $e^+ e^- \to q \overline{q}$ at LEP and B Factories. Additionally, it has been recently argued that Θ^+ and exotic charmed baryons may be observed in B meson decays [46].

Together with the observation of $\Theta^+ \to KN$, three experiments have reported the production of $\Lambda^0(1520) \to KN$ [3, 5, 7]. Similar production rates have been reported for Θ^+ and $\Lambda^0(1520)$. This is understandable due the presence of strangeness and their proximity in mass.⁶ Unfortunately, the production rate of $\Lambda^0(1520) \to K^-p$ was not reported in the neutrino-induced charged-current reactions [6].

Pair or single production of heavier pentaquarks, such as Θ_c^0 and Θ_b^+ , may be difficult to produce in $\gamma\gamma$ collisions due to the relatively small content of heavy quarks in the photon. On the contrary, inclusive searches may be performed because continuum e^+e^- annihilations and hadronic Z decays include decays into heavy quarks (i.e., $c\overline{c}$, $b\overline{b}$) (see Section 4).

Exclusive production of pentaquarks in e^+e^+ annihilations is expected to drop very rapidly with the center-of-mass energy [48]. In order to observe exclusive pentaquark production in e^+e^+ annihilations, the center-of-mass energy should be somewhat above twice the pentaquark mass (see Section 4).

3 e^+e^- Collisions at LEP and B Factories

From 1989 to 1995, LEP accelerated e^+ and e^- beams to an energy 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 detector experiment (ALEPH, DELPHI, L3, and OPAL). In these data, each experiment recorded more than 3 million hadronic Z decays yielding in excess of 5×10^5 reconstructed K_S^0 mesons and $10^4 \Lambda^0$ baryons.

The second phase of LEP (LEP2) involved increasing the center-of-mass energy to nearly 210 GeV in consecutive annual upgrades between 1995 and 2000. In November of 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⁻¹ was delivered during LEP2 to each experiment.

The CESR accelerator at Cornell collided e^+e^- with a center-of-mass energy at or just below the $\Upsilon(4S)$ mass (10.58 GeV). By 1999 the CLEOII [49] detector had collected

 $^{^6\}Theta^+(1540)$ displays $S=+1, I(J^P)=0(\frac{1}{2}^+)$ (the spin and parity have not been established experimentally yet), whereas $\Lambda^0(1520)$ complies with $S=-1, I(J^P)=0(\frac{3}{2}^+)$ with a full width of 15.6 MeV/ c^2 [47].

over 9.1 fb⁻¹ on resonance and 4.4 fb⁻¹ just below the resonance.⁷ During 2001-2003 the CESR accelerator delivered to CLEOIII [50] several fb⁻¹ at center-of-mass close to all Υ resonances. In 2003 the CESR-c program started by running at $\psi(3770)$ [51].

The PEP-II accelerator at SLAC is a high-luminosity asymmetric e^+e^- collider with a center-of-mass energy near that $\Upsilon(4S)$ peak with electron and positron beam energies of 9 GeV and 3.1 GeV, respectively. Thus far, data-taking of the BaBar experiment [52] consists of three runs: 91.6 fb⁻¹ of data were collected in Runs 1 and 2; a further 33.8 fb⁻¹ were collected in Run 3.

Like PEP-II, KEKB is a dedicated high-luminosity asymmetric e^+e^- collider with a center-of-mass energy near the $\Upsilon(4S)$ peak with electron and positron beam energies of 8 GeV and 3.5 GeV, respectively [53]. Between October 1999 and December 2003, the Belle [54] experiment at KEKB received an integrated luminosity of 177.2 fb⁻¹.

LEP and B Factories offer the possibility of investigating $\gamma\gamma$ collisions in the process $e^+e^- \to e^+e^- X$, where the flux factor of γ radiated of the incoming e^+e^- are well known functions [55, 56]. The outgoing leptons carry most of the energy of the incoming beams and their transverse momenta are usually very small, thus they scape through the beam-pipe undetected. Hence, the photon virtuality is small enough so that the colliding photons in untagged events may be treated as quasi-real.

Due to baryon number conservation, baryons need to be pair produced in a $\gamma\gamma$ collision. We will be particularly interested in observing the exclusive reaction $e^+e^- \to e^+e^- B\overline{B}M\overline{M}$ (see Section 2). In order to observe Θ^+ and $\Xi_{\frac{3}{2}}$ exotic baryons, $W_{\gamma\gamma} \gtrsim 3$ to 4 GeV, which is kinematically accessible at LEP and B Factories.

The potential of the B factories is also discussed in [46].

4 Prospective Searches

In this Section, we compile a list of final states that need to be looked into with data collected at LEP and B Factories. The scope of this exercise is

- Confirming the discovery of Θ^+ reported by other experiments. Make a measurement of the mass and width of this exotic baryon;
- Searching for heavier partners of Θ^+ , in which \overline{s} is replaced by \overline{c} and \overline{b} (Θ_c^+ and Θ_b^+ , respectively);
- Searching for a isospin quartet $\Xi_{\frac{3}{2}}$ members of the hypothetical anti-decuplet, which existence has been hinted by NA49 [22];

⁷In 1995 CLEOII was upgraded to CLEOII.V.

| Channel | Mass Range (MeV/c^2) | $e^+e^- \to q\overline{q}$ | $\gamma\gamma$ |
|---|-------------------------------|----------------------------|----------------|
| $\Theta^+ \to K_s^0 p \to p \pi^+ \pi^-$ | 1530-1540 | OK | OK |
| $\Theta^{*+} \to K_s^0 p \to p \pi^+ \pi^-$ | 1540-1680 | OK | OK |
| $\Theta_c^0 \to D^- p$ | 2700-3000 | OK | ? |
| $\Theta_c^0 \to \Theta^+\pi^- \to p\pi^+\pi^-\pi^-$ | 2700-3000 | OK | ? |
| $\Theta_b^+ 	o B^0 p$ | 6000-6400 | OK | ? |
| $\Theta_b^+ 	o \Theta_c^0 \pi^+$ | 6000-6400 | OK | ? |
| $\Xi_{\frac{3}{2}} \to \Xi(\to \Lambda^0 \pi) \pi \to p \pi \pi \pi$ | ≈ 1860 | OK | ОК |
| $\Xi_{\frac{3}{2}}^{\pm} \to \Xi^0 (\to \Lambda^0 \pi^0) \pi^{\pm} \to p \pi^- \pi^0 \pi^{\pm}$ | ≈ 1860 | OK | OK |
| $\Xi_{\frac{3}{2}}^{\pm} \to \Sigma^{0} (\to p\pi^{0}) K^{\pm} \to p\pi^{-}\pi^{0} K^{\pm}$ | ≈ 1860 | OK | OK |
| $\Xi_{\frac{3}{2}}^+ \to \Sigma^+(\to p\pi^0)K_S^0 \to p\pi^0\pi^+\pi^-$ | ≈ 1860 | OK | OK |
| $\Xi_{\frac{3}{2}}^{0} \to \Sigma^{+}K^{-} \to p\pi^{0}K^{-}$ | ≈ 1860 | OK | OK |
| $\overline{\Xi}_{\frac{3}{2}}^{+++} \to \Sigma^+ K^+ \to p\pi^0 K^+$ | ≈ 1860 | OK | ОК |

Table 1: List of prospective channels for exotic Baryon searches. It is assumed that the LEP and B Factories experiments cannot reconstruct neutrons with good efficiency.

• Pursuing a more general, model-independent, search for resonances in baryon-meson invariant mass spectra.

There are no theoretical predictions of the production rate of exotic baryons in e^+e^- annihilations and $\gamma\gamma$ collisions. However, the observation of Θ^+ may serve as a "calibration" process: exotic baryons with strangeness may be produced copiously enough in e^+e^- annihilations and $\gamma\gamma$ collisions at LEP and the B Factories. The production rate of the known baryon resonance $\Lambda^0(1520) \to KN, \Sigma\pi$ may also give a feeling for the expected production rate of Θ^+ .

Table 1 displays a list of prospective final states for exotic baryon searches. It is assumed that the experiments at LEP and B Factories are incapable of reconstructing neutrons with good efficiency; hence these channels are excluded from the discussion.

The first row in Table 1 implies that the known exotic baryon Θ^+ may be searched for in both e^+e^- annihilations and $\gamma\gamma$ collisions. The second row in Table 1 corresponds to an orbital excitation of Θ^+ , Θ^{*+} with $J^P=\frac{3}{2}^+$ (as opposed to $\frac{3}{2}^+$ for Θ^+) predicted by [57]. The third and fourth rows in Table 1 correspond to lightest members of hypothetical higher multiplets.

Rows 3 through 6 correspond to heavy pentaquark decay modes. The mass predictions given in [24, 25, 26] are used. Rows 4 and 6 correspond to heavy pentaquark weak decays, as conjectured in [27].

B Factories are also charm factories, since $c\overline{c}$ pairs are produced as copiously as $b\overline{b}$. Large statistics of D mesons have been reconstructed at B Factories [58, 59, 60, 61], turning them into attractive scenarios for Θ^0_c searches. As pointed out in [46], charmed pentaquarks may be produced in B decays. Additionally, the branching ratio of $B^0 \to D^*(2010)^{\pm}p\overline{p}\pi^{\mp}$ is $6.5\text{x}10^{-4}$ [47], allowing the final state $D^*(2010)^{\pm}p\overline{p}$ to be produced in B decays copiously enough at B Factories. Unfortunately, because of the limited center-of-mass energies provided by B Factories, the production of Θ^+_b there is not kinematically accessible. LEP experiments are suited for heavy exotic baryon searches in e^+e^- annihilations.⁸ A question mark is placed under $\gamma\gamma$ collisions, since the $c\overline{c}$ and $b\overline{b}$ content of the photons is significantly smaller than that of lighter quarks.

The following rows in Table 1 correspond to prospective searches of the isospin quartet $\Xi_{\frac{3}{2}}$. In the seventh row the charge of $\Xi_{\frac{3}{2}}$ is not specified. Here, $\Xi_{\frac{3}{2}}^{--}$, $\Xi_{\frac{3}{2}}^{0}$ and their antiparticles are implied. It is worth noting that the CESR accelerator has recently started delivering e^+e^- collisions at a center-of-mass close to the mass of $\psi(3770)$, which is just above the threshold for double $\Xi_{\frac{3}{2}}$ production.

The prospective final states given in Table 1 are motivated by theoretical expectations, which are more or less model-dependent. From an experimentalist's point of view, a more general search for baryon-meson resonances may be pursued. We suggest that BM invariant mass spectra be investigated extensively, where B is a baryon (e.g., p, Λ , Σ , Ξ , Ω , with charged particles and $\gamma\gamma$ in the final state) and M is a meson (e.g., π , η , ω , ϕ , K, D, J/ψ , B, Υ , with charged particles and $\gamma\gamma$ in the final state).

Fortunately, the detectors at LEP and B Factories are suited for these searches. For instance, due to high combinatoric background, stringent selection criteria involving particle identification may be required, testing for (in)consistency with the p, K^{\pm} , and π^{\pm} hypotheses. Measurements of dE/dx, for example, in CLEOII [49] and ALEPH [65] offer excellent separation, although admittedly over a limited soft-momentum spectrum for adequate $K^{\pm}-p$ separation. One of the most notable improvements implemented in CLEOIII [50] with respect to CLEOII is the addition of a Cherenkov detector, which is the primary particle identification device for high momentum hadrons. The BaBar detector provides high performance particle identification, especially over 91% of 4π via analysis of Cherenkov radiation in its DIRC detector [52]. Belle possesses particle identification capabilities utilizing dE/dx measurements and Time-of-Flight scintillation counters for the low-momentum regime and Cerenkov aerogel detectors for the high momentum regime [54]. The reconstruction of the various species of mesons as described in from the extensive experience in other analyses performed in the past by the experiments at LEP and B Factories.

⁸For instance, the ALEPH Collaboration reported on the observation of excited charm and beauty states [62, 63, 64]. These analyses may be trivially turned into pentaquark searches.

5 Conclusions

Strong experimental evidence for a narrow exotic baryon resonance with strangeness S = +1, Θ^+ , has created a great deal of excitement. The observation of the exotic baryon Θ^+ could have a number of exciting implications. The idea the anti-decuplet may be finally realized: The hint of $\Xi_{\frac{3}{2}}$ observed by NA49 seems to support this interpretation. Furthermore, heavier partners of Θ^+ may exist in nature, Θ_c^0 and Θ_b^+ , where \overline{s} is replaced by \overline{c} and \overline{b} , respectively.

The exotic baryons Θ^+ and $\Xi_{\frac{3}{2}}$ may be observed in $\gamma\gamma$ collisions at LEP and B Factories thanks to the relatively high content of strange quarks in the photon. The observation of these exotic baryons in e^+e^- annihilations may be possible provided that these are produced copiously enough in hadronization of quarks produced in Z decays. This hypothesis seems to be supported by the observation of Θ^+ in neutrino-induced charged-current interactions.

The observation of Θ^+ (whether in e^+e^- annihilations or in $\gamma\gamma$ collisions) seems to be a cornerstone for observing further exotic baryon resonances at LEP and B Factories. If Θ^+ is observed at LEP and B Factories, a new rich window of opportunity will open. Additionally, we suggest that a more general search in baryon-meson invariant mass spectra be performed.

6 Acknowledgments

We would like to thank A. Böhrer, D. Diakonov, Y. Gao, M. Karliner, J.L. Rosner, W. Schweiger and T.T. Wu for most useful discussions. We would also like to thank K. Cranmer, S. Paganis, W. Wiedenmann and H. Zobernig for their comments and suggestions to the text. This work was supported in part by the United States Department of Energy through Grant No. DE-FG0295-ER40896.

References

- [1] V.V. Barmin et al. (DIANA Collaboration), Phys. Atom. Nucl. 66 (2003) 1715
- [2] T. Nakano et al. (LEPS Collaboration), Phys. Rev. Lett. 91 (2003) 012002
- [3] S. Stepanyan et al. (CLAS Collaboration), hep-ex/0307018
- [4] V. Kubarovsky et al. (CLAS Collaboration), hep-ex/0311046
- [5] J. Barth et al. (SAPHIR Collaboration), submitted to Phys. Lett. **B**, hep-ex/0307083
- [6] A.E. Asratyan, A.G. Dolgolenko and M.A. Kubantsev, submitted to Yad. Fiz. (Phys. At. Nucl.), hep-ex/0309042
- [7] A. Airapetian et al. (HERMES Collaboration), hep-ex/0312044
- [8] A.R. Dzierba *et al.*, hep-ph/0311125
- [9] D. Diakonov and V. Petrov, preprint LNPI-967 (1984), published in Elementary Particles, Moscow, Energoatomizdat (1985) Vol. 2., 50 (in Russian)
- [10] M. Chemtob, Nucl. Phys. **B256** (1984) 600
- [11] M. Praszalowicz, Skyrmions and Anomalies, World Scientific (1987) 112
- [12] H. Walliser, Baryon as Skyrme Soliton, World Scientific (1992) 247
- [13] H. Walliser, Nucl. Phys. A548 (1984) 649
- [14] M. Praszalowicz, talk at workshop on Skyrmions and Anomalies, M. Jezabek and M. Praszalowicz editors, World Scientific 1987, 112
- [15] M. Praszalowicz, hep-ph/0308114
- [16] D. Diakonov, V. Petrov and M.V. Polyakov, Z. Phys. A359 (1997) 305
- [17] D. Diakonov, private communication
- [18] D. Diakonov and V. Petrov, hep-ph/0310212
- $[19]\,$ C.E. Carlson, C.D. Carone, H.J. Kwee and V. Nazaryan, hep-ph/0312325
- [20] F. Csikor, Z. Fodor, S.D.Katz and T.G. Kovacs, JHEP 0311 (2003) 070
- [21]S. Sasaki, hep-lat/0310014
- [22] C. Alt $et\ al.$ (NA49 Collaboration), hep-ex/0310014

- [23] R.L. Jaffe and F. Wilczek, hep-ph/0312369
- [24] R.L. Jaffe and F. Wilczek, hep-ph/0307341
- [25] M. Karliner and H.J. Lipkin, hep-ph/0307343
- [26] K. Cheung, hep-ph/0308176
- [27] A.K. Leibovich *et al.*, hep-ph/0312319
- [28] V. Kubarovsky and S. Stepanyan (for the CLAS Collaboration), hep-ex/0307088
- [29] M. Artuso et al. (CLEO Collaboration), Phys. Rev. **D50** (1994) 5484
- [30] H. Hamasaki et al. (VENUS Collaboration), Phys. Lett. **B407** (1997) 185
- [31] G. Abbiendi et al. (OPAL Collaboration), Eur. Phys. J. C28 (2003) 45
- [32] M. Achard *et al.* (L3 Collaboration), Phys. Lett. **B536** (2002) 24
- [33] M. Achard et al. (L3 Collaboration), Phys. Lett. **B571** (2003) 11
- [34] C.C. Kuo *et al.* (for the Belle Collaboration), in proceedings of PHOTON 2003, Frascati, Italy, eds. F. Anulli *et al.*, to appear in Nucl. Phys. Proc. Suppl.
- [35] G.P. Lepage and S.J. Brodsky, Phys. Rev. **D22** (1980) 2157
- [36] G.P. Lepage and S.J. Brodsky, Exclusice Processes in Quantum Chromodynamics, in Perturbative Quantum Chromodynamics, World Scientific, Singapore 1989, 93
- [37] C.F. Berger and W. Schweiger, Eur. Phys. J. C28 (2003) 249
- [38] C.F. Berger and W. Schweiger, hep-ph/0309095
- [39] W. Schweiger, private communication
- [40] H. Aihara et al. (TPC/Two-Gamma Collaboration), Phys. Rev. **D40** (1989) 2772
- 41 H. Aihara et al. (TPC/Two-Gamma Collaboration), Phys. Rev. **D37** (1988) 28
- [42] W. Braunschweig et al. (TASSO Collaboration), Z. Phys. C41 (1988) 353
- [43] C. Berger *et al.* (PLUTO Collaboration), Z. Phys. **C38** (1988) 521
- [44] H. Albrecht et al. (ARGUS Collaboration), Phys. Lett. **B198** (1987) 255
- [45] M. Althoff et al. (TASSO Collaboration), Z. Phys. C32 (1986) 11
- [46] J.L. Rosner, hep-ph/0312269

- [47] K. Hagiwara et al. (The Particle Data Group), Phys. Rev. **D66** (2003) 010001
- [48] S.J Brodsky, hep-ph/0311355
- [49] Y. Kuboda et al. (CLEO Collaboration), Nucl. Instrum. Methods A320 (1992) 66
- [50] S.E. Kopp (for the CLEO Collaboration), Nucl. Instrum. Methods A384 (1996) 61
- [51] R.A. Briere et al. (CLEO-c Collaboration), CLNS-01-1742 (2001)
- [52] BaBar Collaboration, BaBar Technical Design Report, SLAC-R-95-457 (1995)
- [53] KEKB, B Factory Design Report, KEK Report 95-1 (1995), unpublished
- [54] A. Abashian et al. (Belle Collaboration), Nucl. Instrum. Methods A479 (2002) 117
- [55] V.N. Gribov et al., Sov. Phys. JETP 14 (1962) 1308
- [56] V.M. Budnev, I.F. Ginzburg, G.V. Meledin and V. G. Serbo, Phys. Rev. C15 (1975) 181
- [57] J.J. Dudek and F.E. Close, Submitted to Elsevier Science, hep-ph/0311258
- [58] H. Muramatsu et al. (CLEO Collaboration), Phys. Rev. Lett. 89 (2002) 251802
- [59] K. Abe et al. (Belle Collaboration), hep-ex/0308034
- [60] B. Aubert et al. (BaBar Collaboration), Phys. Rev. Lett. **91** (2003) 012002
- [61] B. Aubert et al. (BaBar Collaboration), Phys. Rev. **D65** (2002) 091104
- [62] D. Buskolic et al. (ALPEH Collaboration), Z. Phys. C69 (1996) 393
- [63] D. Buskolic et al. (ALPEH Collaboration), Z. Phys. C73 (1997) 601
- [64] A. Heister et al. (ALPEH Collaboration), Phys. Lett. **B526** (2002) 34
- [65] ALEPH Collaboration, Nucl. Instrum. Methods A294 (1990) 121.