Vol. 35 (2004) ACTA PHYSICA POLONICA B No 12

PENTAQUARKS*

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(Received October 4, 2004)

I discuss the recent experimental and theoretical developments following the discovery of the Θ^+ pentaquark — an exotic $uudd\bar{s}$ baryon resonance observed in the KN channel by several experiments, and an exotic Ξ^{*--} ($ddss\bar{u}$) reported by NA49 at CERN. I focus on the theoretical interpretation of the data, both in terms of quark and chiral degrees of freedom, on the predictions for related exotic states, and on several unresolved questions raised by the experimental data, such why some experiments observe the pentaquarks and other do not, the apparently extremely narrow width of the Θ^+ and the determination of its parity. I also describe the likely properties of the proposed heavy-quark pentaquarks — an anticharmed exotic baryon Θ_c ($uudd\bar{c}$) and Θ_b^+, ($uudd\bar{b}$), which are expected to be extremely narrow or even stable against strong decays. H1 recently reported observation of a possible Θ_c candidate in $D^{*-}p$ channel. Pentaquarks are also being searched for in e^+e^- annihilation and $\gamma\gamma$ collisions in the LEP data and at B-factories.

PACS numbers: 12.38.–t, 12.39.–x, 12.39.Mk

1. Introduction

In the course of the last year we have witnessed a remarkable renaissance of QCD spectroscopy, with several new surprising experimental results: two new extremely narrow mesons containing c and $\bar{s}$ quarks (BaBar, CLEO, Belle); a new very narrow resonance precisely at at $D^{0*}D^0$ threshold (Belle, CDF, D0); enhancements near $\bar{p}p$ thresholds (BES, Belle); a $\Lambda_c\,\bar{p}$ resonance (Belle), and exotic 5-quark resonances: Θ^+ ($uudd\bar{s}$), Ξ^{*--} ($ddss\bar{u}$),

* Presented at the XLIV Cracow School of Theoretical Physics, Zakopane, Poland, May 28–June 6, 2004.

Θ_c ($uudd\bar{c}$). The existence of these states provides a serious challenge to the traditional picture of hadrons made either of three quarks or a quark and an antiquark. Clearly, QCD bound-state dynamics is still an open problem. In this brief review I will focus on the pentaquarks.

2. The experimental status of the Θ^+ pentaquark

By now there is a large number of experimental reports on observing the Θ^+ pentaquark [1] as either K^+n or K_sp resonance, as shown in Fig. 1. One experiment (ZEUS) reported also observing the anti particle, $\bar{\Theta}^-$. All experiments report relatively narrow widths, but so far these are all consistent with the experimental resolution. The true width is likely to be much more narrow $\lesssim$ 1–4 MeV, as suggested by several indirect but quite robust arguments. Such a narrow width of a resonance at 100 MeV above threshold is a puzzle in itself.

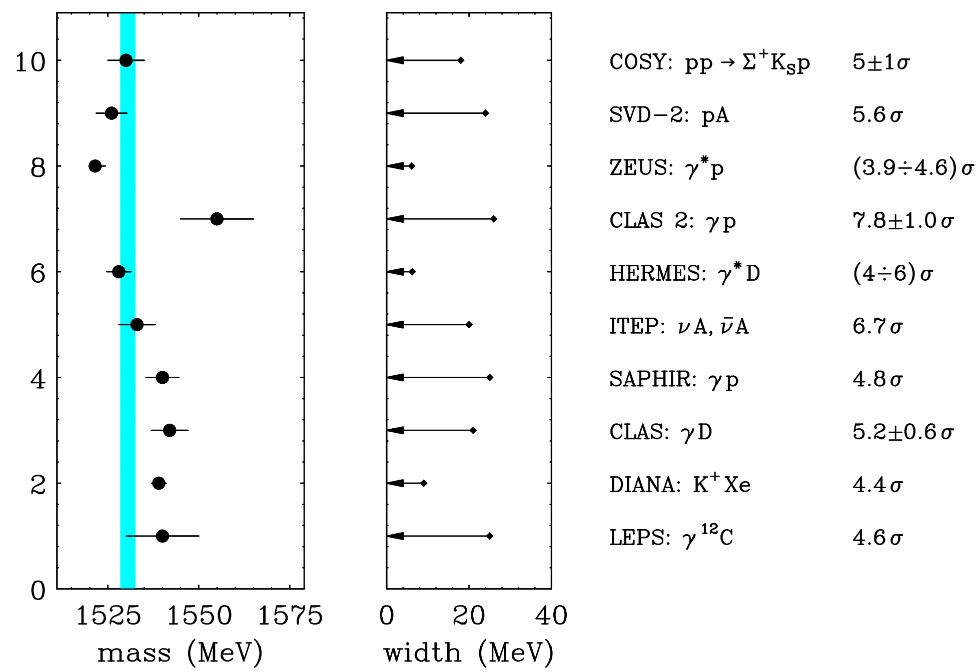

Fig. 1. Summary of experiments which reported Θ^+ observation.

Despite a large number of experiments reporting observation of the Θ^+, the experimental situation is not clear for several reasons.

First, there is a substantial scatter of the Θ^+ mass values, indicating possible systematic effects, or presence of additional resonances.

Second, the relevant cross sections are very small, probably on the order of μb, while the non-exotic processes are $\sim mb$. Therefore, in order to extract the signal from the background, sophisticated cuts are needed, depending on the specific experimental setup. The systematic effects introduced by these cuts continue to be studied.

Third, several experiments (HERA-B, PHENIX, DELPHI and ALEPH) looked for the Θ^+ and did not see it. At present, it is an open question why some experiments see the Θ^+ and others do not. Two of these are LEP experiments which see a lot of protons, but no deuterons. H1 reports $\bar{d}/\bar{p} \approx 5.0^{-4}$, so it is puzzling why the LEP experiments do not see antideuterons. This has to be resolved before we know if we should worry that they do not see the Θ^+.

One possible resolution [20] of the contradiction between the various experiments is that a specific production mechanism is present in the experiments that see the Θ^+ and is absent in those that do not see it. The CLAS data on $\gamma p \to \pi^+ K^- K^+ n$, and in particular the $(K^+ K^- n)$ mass distribution which shows a peak at the mass of 2.4 GeV suggest that there might be a cryptoexotic N^* resonance with hidden strangeness.

Searches for such baryon resonances with hidden strangeness have indicated possible candidates but these searches did not go up to 2.4 GeV.

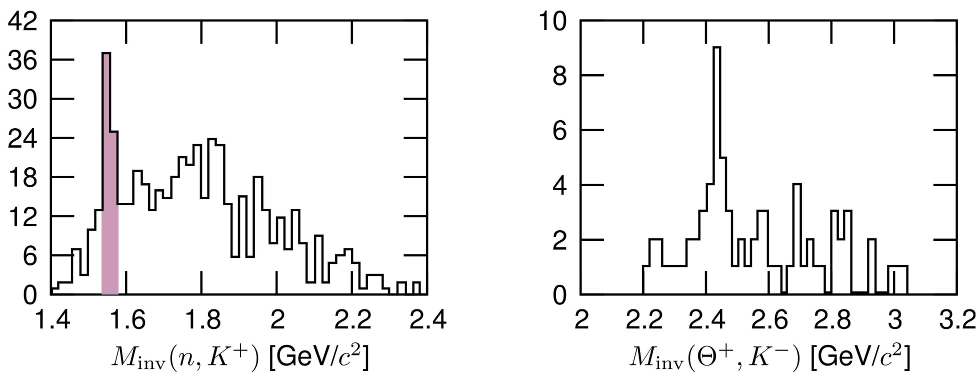

Fig. 2. Left panel: $(K^+ n)$ invariant mass distribution in CLAS $\gamma p \to \pi^+ K^- K^+ n$ experiment, `hep-ex/0311046`. Right panel: $(K^+ K^- n)$ invariant mass distribution corresponding to the data under the Θ^+ peak in the left panel.

3. Development of the pentaquark theory

The possible existence of pentaquarks was suggested as early as 1977 by Jaffe. In the early 1980's a negative-parity $\bar{c}suud$ pentaquark was considered by Lipkin, but the specific story of the Θ^+ really began with the revival of the Skyrme model at the end of 1983. The Skyrme model is a low-energy approximation to large N_c QCD, which in turn shares many features of real-world QCD. The fundamental degrees of freedom in the Skyrme model are nonlinearly coupled quasi-Goldstone $\mathrm{SU}(3)_f$ pseudoscalars and the baryons emerge as solitons. A somewhat more general class of similar models is collectively referred to as chiral soliton models (χSM). When properly quantized, the ground state soliton is a $J^P = \frac{1}{2}^+ \mathrm{SU}(3)_f$ octet. The first excited state is a $J^P = \frac{3}{2}^+ \mathrm{SU}(3)_f$ decuplet. The next one is a $J^P = \frac{1}{2}^+ \mathrm{SU}(3)_f$ antidecuplet which cannot be constructed out of 3 quarks. This was realized early on and several research groups estimated the mass of the lightest member of the $\overline{\mathbf{10}}$ at around 1540 MeV. But most people viewed this as a problem for the model, since it was well known and documented by the Review of Particle Properties that such states did not exist [4]. Then in 1997 Diakonov, Petrov and Polyakov (DPP) did two things [5]: (a) they took the prediction seriously, effectively declaring that $\overline{\mathbf{10}}$ is not a bug, but a feature (b) they estimated that the state is less than 15 MeV wide, which made its detection seem feasible. Later on it turned out that certain results in their paper needed to be revised, including the specific values of the width and the predictions for masses of other states in $\overline{\mathbf{10}}$. In particular, they predicted $M(\Xi^{--}) = 2070$ MeV, *versus* the NA49 result [6] 1862 MeV (more on this below). But the paper triggered the first experiment in Japan and this really got the ball rolling.

Recently we re-analyzed [11] the predictions of chiral-soliton models for the masses and decay widths of baryons in the $\overline{\mathbf{10}}$. We found 1430 MeV $< M(\Theta^+) <$ 1660 MeV and 1790 MeV $< M(\Xi^{--}) <$ 1970 MeV. These are consistent with the masses reported recently, but more precise predictions rely on ambiguous identifications of non-exotic baryon resonances. The overshoot in the original DPP prediction for $M(\Xi^{--})$ is mainly due to an outdated value of the πN Σ-term. Parametrically $\Gamma(\overline{\mathbf{10}}) \sim \mathcal{O}(1/N_c^2)$, but with realistic couplings it is hard to get $\Gamma(\overline{\mathbf{10}}) < 10$ MeV. A key prediction is a light $\mathbf{27}$ with $J^P = \frac{3}{2}^+$, *i.e.* a Θ-like $I = 1$ state within 100 MeV above $\Theta^+(I = 0)$.

One remarkable prediction of the χSM is that the SU(3) breaking in $\overline{\mathbf{10}}$ is linear in hypercharge. This is similar to the baryon decuplet, where it amounts to counting the number of strange quarks. But for $\overline{\mathbf{10}}$, it is seemingly counterintuitive, as it implies that Θ^+ with one antistrange quark is *lighter* than the nonstrange $N^* \in \overline{\mathbf{10}}$. To understand where this comes from, it is best to rederive the result in the quark language, by carefully constructing the $\overline{\mathbf{10}}$ quark wave functions.

Starting from $|\Theta^+\rangle = |uudd\bar{s}\rangle$, we can generate the other states in $\overline{\mathbf{10}}$ by repeatedly applying a U-spin lowering operator which replaces d by s: $U_-|d\rangle = |s\rangle$, $U_-|\bar{s}\rangle = -|\bar{d}\rangle$. Thus:

$$|p^*\rangle = U_-|uudd\bar{s}\rangle = -\sqrt{\frac{1}{3}}\,|uud\,d\bar{d}\rangle + \sqrt{\frac{2}{3}}\,|uud\,s\bar{s}\rangle\,. \tag{1}$$

So p^* is heavier than Θ^+ because one of the components in its wave function contains *two* heavier quarks in the form of an $\bar{s}s$ pair. It has no net strangeness and is *cryptoexotic*. The leading SU(3) breaking effect is proportional to the total number of strange *plus* antistrange quarks, $\langle \#s + \#\bar{s}\rangle_{p^*} = 2 \times (\sqrt{2/3})^2 = 4/3$, so $\Delta\langle \#s + \#\bar{s}\rangle = 1/3$ and $\Delta M \sim m_s/3$. There are also subleading effects, having to do with the color hyperfine interaction $\sim 1/m_q$, but these depend on the specific form of the wave function.

A definitive full QCD analysis of the pentaquarks will be eventually provided by lattice gauge theory (LGT). It will probably take a while, as dealing with unstable resonances in LGT is notoriously difficult. The main problem is the need to separate the resonance from scattering states with the same quantum numbers. In our case, one needs to make sure that the Θ^+ two-point function on the lattice is not contaminated by contributions from KN. This requires careful measurement of finite-volume effects and is extremely costly in computer time.

The quark model and the χSM provide complementary descriptions of the pentaquarks properties. If we want to "peek inside", the quark model is clearly the way to go.

4. Correlated quarks — diquarks and triquarks

Most quark model treatments of multiquark spectroscopy use the color-magnetic short-range hyperfine interaction as the dominant mechanism for possible binding. The hyperfine interaction between two quarks denoted by i and j is then written as

$$V_{\rm hyp} = -V(\vec{\lambda}_i \cdot \vec{\lambda}_j)(\vec{\sigma}_i \cdot \vec{\sigma}_j)\,, \tag{2}$$

where $\vec{\lambda}$ and $\vec{\sigma}$ denote the generators of $\mathrm{SU}(3)_c$ and the Pauli spin operators, respectively. The interaction is attractive in states symmetric in color $\times$ spin and repulsive in antisymmetric states. Because of Pauli principle the interaction is always repulsive between same-flavor quarks.

This flavor antisymmetry suggests that the bag or single-cluster models commonly used to treat normal hadrons may not be adequate for multiquark systems. In such a state, with identical pair correlations for all pairs in the system, all same-flavor quark pairs are necessarily in a higher-energy configuration, due to the repulsive nature of their hyperfine interaction. The $uudd\bar{s}$ pentaquark is really a complicated five-body system where the optimum wave function to give minimum color-magnetic energy can require flavor-dependent spatial pair correlations for different pairs in the system; *e.g.*, that keep the like-flavor uu and dd pairs apart, while minimizing the distance and optimizing the color couplings within the other pairs.

We consider here a possible model for a strange pentaquark that implements these ideas by dividing the system into two color non-singlet clusters which separate the pairs of identical flavor quarks. The two clusters, a ud diquark and a $ud\bar{s}$ triquark, are in a relative P-wave, are separated by a distance larger than the range of the color-magnetic force and are kept together by the color electric force. Therefore, the color hyperfine interaction operates only within each cluster, but is not felt between the clusters, as shown schematically in Fig. 3.

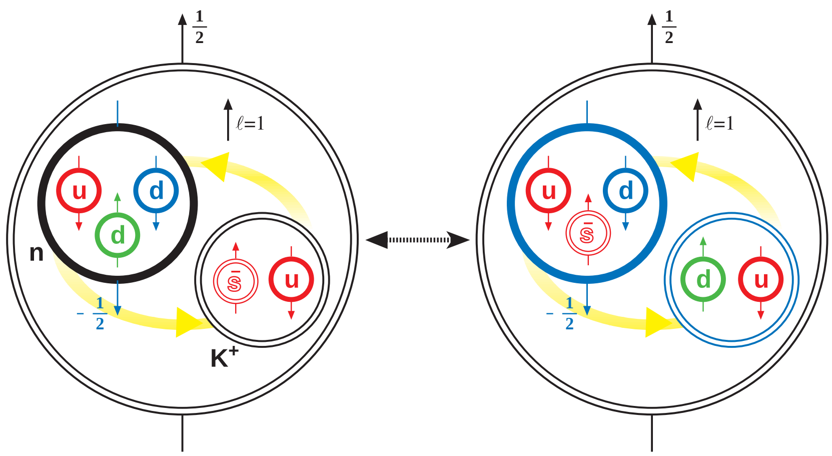

Fig. 3. K^+n and the diquark-triquark configuration of the $uudd\bar{s}$ pentaquark.

An unusual aspect of the $uudd\bar{s}$ pentaquark is that the S-wave has higher energy than the P-wave. This is because in the S-wave there is no angular momentum barrier to prevent repulsive interaction between same-flavor quarks. Therefore, this correlated quark picture predicts a positive parity pentaquark, in agreement with the χSM. It is extremely important to measure the parity in an experiment. If it turns out to be negative, you can throw away all my papers on the subject, together with most of the other theoretical papers!

Using the diquark–triquark configuration as the starting point, we can extract some specific properties of the Θ^+. The $|ud\, du\bar{s}\rangle$ configuration contains a ud diquark, which is an isosinglet, has $S = 0$ and is a color antitriplet. The $ud\bar{s}$ triquark contains another isosinglet ud pair, but this time with $S = 1$. The triquark has $S = \frac{1}{2}$ and is a color triplet. Since ud and $ud\bar{s}$ are in a relative P-wave, Θ^+ has $J^P = \frac{1}{2}^+$, $I = 0$ and is in $\overline{\mathbf{10}}$ of $\mathrm{SU}(3)_f$.

A very similar structure was proposed in Ref. [21], shortly after Ref. [9] appeared. The only difference is that the second ud pair is assumed to have $S=0$, rather than $S=1$. This means that there is no hyperfine interaction between $\bar{s}$ and the light quarks, and so the hyperfine binding is somewhat weaker than in Ref. [9]. In Ref. [7] it was pointed out that the ud–$ud\bar{s}$ and $(ud)^2$–$\bar{s}$ configurations mix strongly, so the true ground state has a somewhat lower energy that either of the two.

In the diquark–triquark configuration the hyperfine binding turns out [9, 10] to be about 50 MeV stronger than the total hyperfine interaction in the KN system. But this does not mean that the state is below KN threshold, because there is the additional cost of putting the $\{ud\}\{du\bar{s}\}$ system in a P-wave. The latter can be estimated by noticing that the cost of such excitations only depends on the reduced mass of the system. The reduced mass of the $\{ud\}\{du\bar{s}\}$ is quite close to that of $c\bar{s}$ in the D_s, where the P-wave excitation energy is about 200 MeV. Putting it all together, one obtains [9,10] an estimate $M(\Theta^+) \approx 1592 \pm 50$ MeV, reasonably close to the experimental value of 1530 ± 10 MeV.

This looks encouraging, but one must also deal with the other member of the $\overline{\mathbf{10}}$, the Ξ^{--} which was observed by NA49 at 1862 ± 2 MeV [6]. This is to be contrasted with a triquark–diquark configuration prediction of 1720 ± 50 MeV. This difference of roughly 100 MeV is generic for all correlated quark models [21]. One should note however, that Ξ^{--} is 400 MeV above the $\Xi\pi$ threshold, while Θ^+ is only 100 MeV above the KN threshold. This is an open challenge for the theory. Moreover, one can derive a variational mass inequality [13] relating the Ξ^{--} and Θ^+ masses: $M(\Xi^{--}) - M(\Theta^+) \lesssim 300$ MeV, *versus* the experimental value of 300 MeV. This puts strong constraints on models of 5-quark structure and indicates a urgent need for experimental confirmation of the NA49 results.

The existence of strongly mixed ud–$ud\bar{s}$ $(ud)^2$–$\bar{s}$ configurations for the Θ^+ provides a possible explanation of its narrow width [12]. It is a standard feature of quantum mechanics that in the case of an exact degeneracy the two configurations have equal weight in the mixed state, and the relative phase is such that the two decay amplitudes into KN destructively interfere, exactly cancelling each other and decoupling the mixed state from the KN decay channel. When the two configurations are almost degenerate, the two decay amplitudes almost cancel, yielding a very narrow width of the mixed state, on the order of a few MeV.

There is an associated new experimental prediction: the destructive interference mechanism suppresses only the coupling of the Θ^+ to KN, but not the coupling to K^*N. The latter channel is above threshold, so it cannot be seen in a decay, but the lack of suppression in $\Theta^+ K^* N$ coupling should be observable in the baryon-exchange $K^- p$ reactions where the kaon is observed going backward in the center-of-mass system:

$$K^- p \to \bar{K}^0 n\,, \quad K^- p \to \bar{K}^{*0} n\,, \quad K^- p \to \bar{K}^0 N^{*0}\,, \quad K^- p \to \bar{K}^{*0} N^{*0}\,, \quad (3)$$

where N^{*0} denotes any $I = 1/2$ electrically neutral baryon resonance.

These reactions shown in Fig. 4 can only proceed via the t-channel exchange of an exotic positive-strangeness baryon. But if the Θ^+ couples only weakly to KN, the $K^- \Theta^+ \to n$ and $p \to \bar{K}^0 \Theta^+$ vertices are also weak by crossing and the $K^- p \to \bar{K}^{*0} N^{*0}$ reaction should be much stronger than the other three which require a $\Theta^+ KN$ coupling [12].

The $\Theta^+ K \Delta$ coupling is forbidden by isospin if the Θ^+ is an isoscalar. Therefore, the presence of the Δ in these baryon exchange reactions is a test for the presence of exotic positive strangeness baryons with higher isospin.

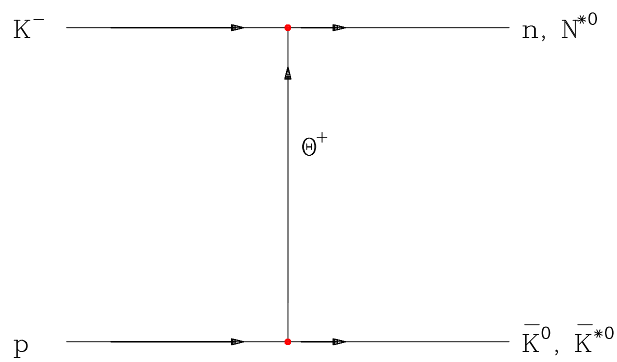

Fig. 4. Baryon-exchange diagram corresponding to the reactions (3).

5. Experimental challenges and future directions

In my opinion, the most pressing issues in pentaquark research at the moment are experimental. The most important among these is the confirmation of Θ^+ and Ξ^{*--}.

After that, it is essential to measure the parity. Several methods have been proposed. Most of them rely on identifying some measurable asymmetry which depends on the pentaquark parity. All these proposals are quite challenging. A detailed discussion of their relative merits is outside the scope of this talk, both because of space limitations and because of the limited competence of the speaker in such matters.

In parallel it is important to search for additional exotic states:

(a) those obtained by replacing $\bar{s} \to \bar{c}, \bar{b}$: Θ_c ($uudd\bar{c}$) and Θ_b^+ ($uudd\bar{b}$). More about these shortly.

(b) $\overline{\mathbf{10}}$ with $J = \frac{3}{2}$ [22]: assuming that Θ^+ and other members of the $\overline{\mathbf{10}}$ have $J = \frac{1}{2}$ which results from $S = \frac{1}{2}$ and $L = 1$, it is natural to look for partners with $J = \frac{3}{2}$. Current estimates [22] indicate that such states could be within $\lesssim 50$ MeV of their $J = \frac{1}{2}$ counterparts.

(c) exotics in higher representations: **27**, **35**, *etc.* There are indications from the χSM [11] that such states could be within $\lesssim 100$ MeV of the $\overline{\mathbf{10}}$.

Clearly, a whole new spectroscopy waits to be explored!

5.1. Predictions: Θ_c and Θ_b^+

If the existence of Θ^+ is confirmed, the case for the existence of its heavy cousins will be quite strong. The basic idea is quite simple [14]: assuming we have a reasonable approximate quark wave function for the Θ^+, replace $\bar{s}$ by $\bar{c}$ or $\bar{b}$ and compute the properties of the resulting state. At present we do not know how far this strategy can be pushed, because the strength of the color-magnetic hyperfine interaction is inversely proportional to the quark mass. So the configuration which is optimal for $\bar{s}$ might not be optimal for a heavy quark. Still, it is worthwhile to explore the consequences of this approach.

A rough prediction of this approach is that Θ_c has $J^P = \frac{1}{2}^+$, $I = 0$, mass of about 3000 ± 50 MeV and a width $(1 \div 2) \times 20$ MeV. Similarly, Θ_b^+ has $J^P = \frac{1}{2}^+$, $I = 0$, mass of about 6.4 GeV and a very narrow width, $(1 \div 2) \times 4$ MeV.

There are two basic methods in searching for such states:

(a) look for unexpectedly narrow peaks in DN, D^*N and BN B^*N, invariant mass distributions where the mesons contain a heavy antiquark;

(b) look for a proton coming out from a vertex which is known to carry anti-charm or anti-bottom flavor. This approach is particularly well suited to B factories where the flavor of a secondary vertex can easily be tagged.

Recently H1 published evidence for a narrow anticharmed baryon resonance [15] in the $D^{*-}p$ and $D^{*+}\bar{p}$ channels, *i.e.* $uudd\bar{c}$ and $\bar{u}\bar{u}\bar{d}\bar{d}c$, with a mass $3099 \pm 3 \pm 5$ MeV and width 12 ± 3 MeV, and estimated statistical significance of $5.4\,\sigma$, as shown in Fig. 5. This is of course very exciting, but

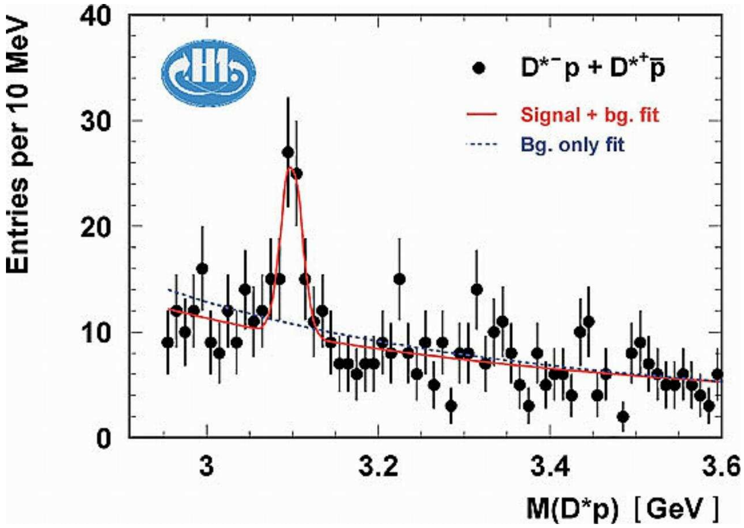

Fig. 5. H1 data for a resonance in $D^{*-}\,p$ and $D^{*+}\,\bar{p}$ invariant mass spectra.

the sister ZEUS experiment sees no sign of such a resonance in their data, despite a somewhat larger data sample. In addition, there are conference reports from FOCUS [17], ALEPH [18], CLEO, BaBar and CDF [19] who looked for this resonance in their data and did not see it. At present no one understands the reason for this disagreement between the various experiments. However, since H1 sees the resonance at the same mass in both $D^{*-}\,p$ and $D^{*+}\,\bar{p}$, one can safely rule out a statistical fluctuation.

Recently, with Bryan Webber we have estimated the probability of producing Θ_c in LEP and the Tevatron, taking the H1 data as input and assuming formation through D^*p coalescence [23]. In our model the cross section for Θ_c formation is proportional to the rate of production of pD^{*-} (or $\bar{p}D^{*+}$) pairs in close proximity both in momentum space and in coordinate space. The constant of proportionality is determined from the Θ_c cross section in deep inelastic scattering as reported by the H1. The HERWIG Monte Carlo is used to generate simulated DIS events and also to model the space–time structure of the final state, as shown in Fig. 6.

Requiring the proton and the D^* be within a 100 MeV mass window and separated by a spacelike distance of no more than 2 fm, we find that a "coalescence enhancement factor" $F_{\rm co} \sim 4$ is required to account for the H1 signal. The same approach is then applied in order to estimate the number of Θ_c events produced at LEP and the Tevatron.

For each of the four LEP experiments the model predicts between 25 and 40 H1-like Θ_c events. For the Tevatron a signal of many thousands of events would have been expected.

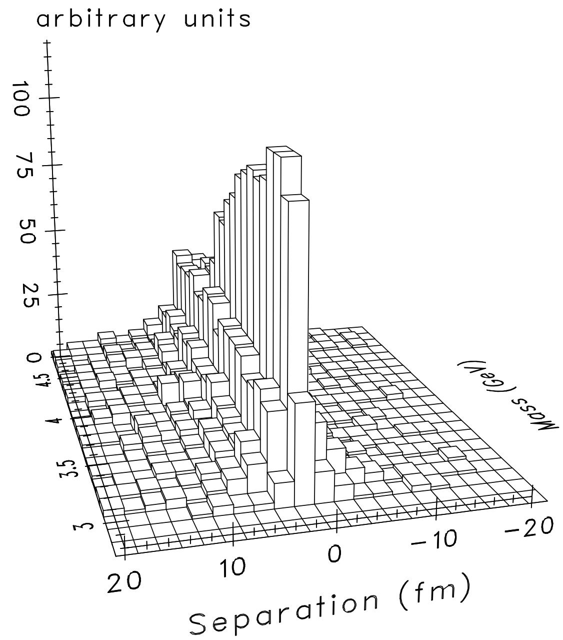

Fig. 6. Predicted pD^* joint mass-separation distribution in DIS.

Since both LEP and Tevatron experiments reported null results, our analysis implies that the either the H1 signal is spurious and due to an unknown systematic effect, or alternatively that it corresponds to a real resonance, whose production mechanism in DIS is substantially different from the production mechanism in e^+e^- and the Tevatron. Yet another possibility is that either the theoretical or experimental analysis is missing an essential ingredient.

5.2. Search for pentaquarks at B factories

In B factories one expects a reasonable branching ratio for $B \to$ baryon+ antibaryon, somewhere below 10^{-6}. Producing a pentaquark with an antibaryon requires production of an additional $\bar{q}q$ pair, as shown in Fig. 7. Making such an extra $\bar{q}q$ pair carries a penalty in the BR. It is hard to make a precise estimate of this penalty, but it is probably at least an order of magnitude. So with enough data the $B \to$ pentaquark + antibaryon decay should be attainable. This decay has a particularly striking signature. Since it is a two-body decay where the mass of the initial state is exactly known, energy and momentum conservation in the B CM frame ensure that unlike in the hadron reactions, there are no kinematical ambiguities. Moreover, for modes with $\Theta^+ \to K_s\, p$ decay, the K_s flavor is tagged by the antibaryon.

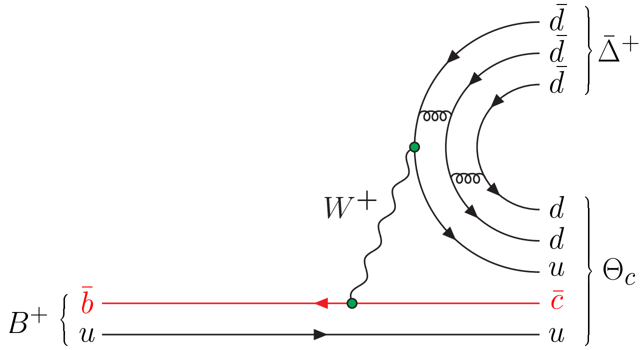

Fig. 7. Pentaquark production in B decays.

The original work described here was done in collaboration with Harry Lipkin, John Ellis and Michał Praszałowicz and Bryan Webber. This research was supported in part by a grant from the United States–Israel Binational Science Foundation (BSF), Jerusalem.

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