EXOTIC CHALLENGES*

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We list and discuss theoretical consequences of recent discovery of $\Theta^+$. 

1. Has $\Theta^+$ been really found?

Let us start with a word of warning. No evidence of $\Theta^+$ has been found in HERA-B\textsuperscript{1}, RHIC\textsuperscript{2}, BES\textsuperscript{3}, LEP\textsuperscript{4} and Fermilab\textsuperscript{5}. The reasons maybe either of experimental nature or a peculiar production mechanism\textsuperscript{6,7}.

In contrast to the low energy almost fully exclusive experiments that reported $\Theta^+$, experiments which do not see exotics are mostly high energy inclusive ones\textsuperscript{8}. It is difficult to produce exotic states in the high energy experiments which are dominated by the Pomeron exchanges\textsuperscript{9,10}. Note that experiments which do not see $\Theta^+$ put in fact an upper bound on the (yet unknown) production mechanism, rather than exclude its existence.

Another piece of negative evidence comes from the old $KN$ scattering data that have been recently reanalyzed\textsuperscript{11,12}. Here one can accommodate at most one resonance near 1545 MeV with very small width $\Gamma_{\Theta^+} < 2$ MeV. $K^+d$ cross-section including the hypothesis of a narrow resonance recalculated in the Jülich meson exchange model\textsuperscript{13} yields $\Gamma_{\Theta^+} < 1$ MeV. However, "non-standard" analysis of the phase shifts allows for more exotics\textsuperscript{14,15}.

All these facts call for a new high precision $KN$ experiment in the interesting energy range.

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2. How many $\Theta$’s?

Since the first report on $\Theta^+$ by LEPS 16, many other experiments confirmed its existence 17. Reported masses are shown in Fig. 1. Some of these results were reported at this Workshop 18 together with new results from LEPS 19. In principle data in Fig. 1 should represent one state. However, if taken literary, ZEUS and CLAS data for example are not compatible.

![Figure 1. Mass of $\Theta^+$ as reported by various experiments. Statistical and systematic errors have been added in quadrature. Squares refer to $K^+\Lambda$ final state and circles to $K^0\Lambda$.](image)

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It is therefore legitimate to ask: do all these experiments see the same state? Before this issue is decided experimentally let us examine predictions of different models. Chiral models predict a tower of exotic rotational states starting with $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, etc. The lowest excitation of $\Theta^+$ is an isospin triplet of spin $\frac{3}{2}$ belonging to flavor 27. The mass $\Theta_{27}$ is only slightly larger than the mass of $\Theta^+$ and depends weakly on the value of pion nucleon $\Sigma_{\pi N}$ term (see Fig. 2). Note that theoretical uncertainty of the model 20 is approximately $\pm 30$ MeV.

In the correlated quark models additional states are also unavoidable. In the diquark model 21 the spin-orbit interaction splits spin $\frac{1}{2}$ and $\frac{3}{2}$ states by a tiny amount of a $\Delta E \sim 35 \div 65$ MeV 22. Similarly in the diquark-triquark scenario 23, the mass splitting would be of the order of 40 MeV. Hence a nearby isosinglet $\Theta^*$ state of spin $\frac{3}{2}$ is expected in these
Figure 2. The spectra of $\Omega_{1/2}$ baryons (solid lines) together with the masses of the $\Theta_1$ and $\Xi_{3/2}$ in the $2\Sigma_3/2$ (dashed lines) as functions of $\Sigma_{\pi N}$, using parameters fitted from the masses of the $\Theta^+$ and non-exotic states.

models. This is a distinguishing feature, since the soliton models do not accommodate spin $3/2$ antidecuplet.

Although there are no more exotics in the minimal diquark model, the tensor diquarks in 6 of SU(3) flavor are almost unavoidable. They lead to further exotics like 27 which in the schematic model of Shuryak and Zahed is even lighter than $\Omega_0$.

We see therefore the importance of experimental searches both for the isospin partners of $\Theta^+$ and for another peak in the $\Theta^+$ channel. Preliminary CLAS results indicate two states at 1523 and 1573 MeV, similarly bubble chamber experiment analyzed by the Yerevan group reports 3 states at 1545, 1612 and 1821 MeV. Finally, there is also report of a number of exotic resonances from Dubna and from the "non-standard" phase shift analysis. So far the searches for $\Theta^{++}$ provided no evidence, although some structures in $K^+p$ channel have been seen by CLAS and STAR. There is no evidence for $\Theta^{++}$ in the old $K^+p$ scattering data.

3. Spin and parity of $\Theta^+$

Spin and parity of $\Theta^+$ are at present unknown. While almost all theorists agree that spin should be 1/2 the parity distinguishes between different models. Chiral models predict positive parity, similarly quark models with flavor dependent forces and correlated quark models predict $P = +$. In uncorrelated quark models and sum rules $P = -$. 
Unlike model calculations lattice simulations (summarized at this Workshop by S. Sasaki) should give clean theoretical answer whether pentaquarks exists and what their quantum numbers are. However, since pentaquarks are excited QCD states, lattice simulations are difficult and give ambiguous message: either there is no bound $\Theta^+$ state, or there is one but with negative parity. One simulation indicates $P = +$.

Let us stress that, unlike in the case of $\Omega^-$ whose spin and parity are not measured but assumed after the quark model, the parity of $\Theta^+$ is of utmost importance to discriminate between various models and to understand how QCD binds quarks.

4. The width of $\Theta^+$

A key prediction of the seminal paper by Diakonov, Petrov and Polyakov (DPP) was the observation that (in contrast to the naive expectations) in the chiral quark soliton model antidecuplet states should be very narrow. The decay width for $B \to B' + \phi$ is given by:

$$\Gamma_{B \to B' + \phi} = \frac{G_R^2}{8\pi} \frac{p^3}{M M'} C(B', B, \phi).$$

(1)

Here $M$ and $M'$ are baryon masses, $p$ is meson momentum in the $B$ rest frame, $C$ denotes pertinent SU(3) Clebsch-Gordan coefficient and $G_R$ stands for a coupling constant for baryon $B$ in the SU(3) representation $R$. It has been observed that $G_{T\Omega} \equiv 0$ in the nonrelativistic limit of the soliton model which is very useful as a first approximation. This was a clear indication that $T\Omega$ baryons would be narrow. How narrow is of course a question of reliability of approximations employed to derive (1) and the phenomenological input used to determine $G_{T\Omega}$. DPP made a conservative estimate that $\Gamma_{\Theta^+} < 15$ MeV. In a more recent analysis they have argued that $\Gamma_{\Theta^+} \sim 3.6 \div 11.2$ MeV.

In the diquark models $\Theta^+$ decay proceeds via diquark breakup and is therefore believed to be small. Recently it was shown that the narrowness of $\Theta^+$ in the quark model with flavor-spin interactions follows from the group-theoretical structure of the wave function.

Further suppression comes from the SU(3) breaking corrections due the mixing with other representations for $m_s \neq 0$. Therefore moderate admixtures of other representations for which the relevant couplings are not suppressed may substantially modify the decay width. In the case of $\Theta^+ \to KN$ the admixtures of $T\Omega$ and 27 in the wave function of the final nucleon affect the decay width. In the quark-soliton model they further
suppress $\Gamma_{\Theta^+}$ by a factor of 0.2. In Fig. 3 we show modification factor $R^{(\text{mix})}$ for the width of $\Theta^+$ and for two partial widths of $\Xi_{\pi\Sigma}$ coming from representation mixing in the chiral quark-soliton model as functions of the pion-nucleon $\Sigma_{\pi N}$ term. To conclude: the decay widths within the antidecuplet may substantially differ from the SU(3) symmetry values.

On experimental side the results for $\Theta^+$ width are unclear. Most experiments quote upper limits, however there are a few which claim to have measured $\Gamma_{\Theta^+}$ and quote error bars. ZEUS gives $\Gamma_{\Theta^+} = 6.1 \pm 1.6 \pm 0.6$ MeV. This result is consistent with the upper limit from DIANA ($K^+ + Xe$): $\Gamma_{\Theta^+} < 9$ MeV. Results from a $C_3 H_8$ bubble chamber in Dubna by Yerevan group $\Gamma_{\Theta^+} = 16.3 \pm 3.6$ MeV, from COSY $\Gamma_{\Theta^+} = 18 \pm 4$ MeV and Hermes $\Gamma_{\Theta^+} = 19 \pm 5$ (stat) $\pm 2$ (syst) MeV are two times larger. As discussed in Sect. 1 old $K$ scattering data put the lowest limit $\Gamma_{\Theta^+} < 1/2$ MeV.

In almost all theoretical models mechanisms were found which suppress $\Theta^+$ decay width. The question is now: how much? Therefore the measurement of the $\Theta^+$ width is of utmost importance and will provide constraints on various theoretical scenarios.

![Figure 3. Correction coefficients $R^{(\text{mix})}$ for $\Theta^+$ and $\Xi_{\pi\Sigma}$ decays as functions of $\Sigma_{\pi N}$. Large supression of $\Theta^+$ together with a moderate enhancement of $\Xi_{\pi\Sigma}$ leads to strong SU(3) violation for the decay widths.](image)

5. Exotic cascades

So far only one experiment reported the states which form the "base" of $\Theta^0$, namely $I = 3/2$ $\Xi_{\Omega\Omega}$ and $\Xi_{10}$ at 1862 MeV. This result needs confirmation, so far reports from other groups are negative.
In the original paper DPP predicted the mass of the exotic $\Xi_{\pi \pi}$ states above 2 GeV. This prediction, however, depends on the residual freedom of the model which is conveniently parameterized in terms $\Sigma_{\pi N}$. They used $\Sigma_{\pi N} = 45$ MeV, while present estimates indicate a larger value of approximately 70 MeV. As seen from Fig. 2 larger values of $\Sigma_{\pi N}$ are compatible with the NA49 result.

Original prediction of the diquark model was 1750 MeV. Pure SU(3) arguments indicate that for ideal mixing scenario employed by Jaffe and Wilczek it is difficult accommodate exotic cascades at 1862 MeV without invoking new nucleon-like narrow resonances. Similar conclusion has been reached for arbitrary mixing.

Similarly to $\Theta^+$, the decay widths of exotic cascades will be modified by additional mixing, as depicted in Fig. 3.

6. Cryptoexotic states and mixing

If $\Theta^+$ mass is 1539 MeV and $\Xi_{\pi \pi}$ 1862 MeV then equal spacing within the antidecuplet requires additional cryptoexotic nucleon-like and $\Sigma$-like states with masses 1648 MeV and 1757 MeV respectively. These states should be in principle narrow with the decay widths related to $\Gamma_{\Theta^+}$ by the SU(3) symmetry. However, as discussed above, mixing will modify these relations. The nucleon-like and $\Sigma$-like states can mix with known (and unknown) resonances of the same parity and spin. Most of analysis in this direction was done for two nucleon-like states $|S_{1,2}\rangle$ assuming $J^P = 1/2^+$ for antidecuplet. Here three possible scenarios are discussed: 1) both states $|S_{1,2}\rangle$ correspond to known resonances, 2) one state corresponds to the yet undiscovered resonance and 3) both have to be discovered.

Mixing has been also discussed by Weigel within the framework of the Skyrme model (with the dilaton field). In this approach, apart from rotations, another mode, namely the "breathing" mode of the soliton, was quantized and a subsequent mixing with other states was investigated. Radially excited octet states were identified with known $N^*$ resonances (Roper or $N^*(1710)$, etc.), so that no novel states were predicted. Unfortunately little can be said about the decay widths within this approach.

Cohen made an important remark that not only masses but also decay widths are affected by mixing and any phenomenological analysis should discuss both simultaneously. He excluded ideal mixing scenario, unless new cryptoexotic nucleon-like resonances exist.

The analysis of masses and decay widths of the $N^*$ states under the as-
assumption that they correspond to the Roper and \(N^*(1710)\) indicates \(^{45}\) that it is impossible to match the mass splittings with the observed branching ratios even for arbitrary mixing. It is shown that the mixing required for the decay \(N^*(1710) \rightarrow \Delta \pi\) is not compatible with the mixing deduced from the masses. A possibility based on the nonideal mixing scenario advocated by Diakonov and Petrov \(^{44}\) is that there should be a new \(N^*\) resonance in the mass range of 1650 \(\div\) 1680 MeV.

Similar conclusion has been reached in the quark soliton model \(^{47}\). Here already the ordinary nucleon state has a non-negligible admixture of \(\Theta^0\) which leads to the suppression of the decay width. Further decrease may be achieved by adding a mixing to another nucleon-like state as Roper and/or \(N^*(1710)\) and by the admixture of \(^{37}^{38}\).

The same authors \(^{47}\) claim that the improved phase shift analysis admits two candidates for the narrow nucleon-like resonances at 1680 and 1730 MeV and with widths smaller than 0.5 and 0.3 MeV, respectively.

To conclude this Section let us note that physics of \(N^*\) and \(\Sigma^*\) states will be most probably dominated by extensive mixing between different nearby states which will affect both masses and decay widths. New, narrow resonances are theoretically expected. Experimental searches for such states have been recently performed with positive preliminary evidence \(^{29,48}\).

7. Summary

A convincing experiment confirming \(\Theta^+\) is in our opinion still missing. If \(\Theta^+\) exists we have to understand why some experiments do not see it while the others do. Although yet unknown production mechanism might provide an explanation, it is really hard to understand why similar experiments like ZEUS and H1 give contradictory results.

There is a common agreement that spin of \(\Theta^+\) is 1/2. However, there is no such consensus as far as parity is concerned. Measuring the parity will discriminate between different models. Even more importantly it will either strengthen our confidence in lattice QCD simulations or pinpoint some yet unknown weaknesses of this approach.

Certainly the measurement of the width is badly needed. An intuitive explanation why \(\Theta^+\) is so narrow is still missing although in various models formal arguments have been given. Since the leading decay mode \(\Theta^0 \rightarrow 8 + 8\) (where the second 8 refers to the outgoing meson) is very small even moderate admixtures of other SU(3) representations in the final state or in the initial state for cryptoexotic members of \(\Theta^0\) are going to modify
substantially the decay widths. Warning: SU(3) relations between different
decay widths will not hold!

Mixing will be very important for cryptoexotic nucleon-like and Σ-like
states. Most probably, new narrow resonances are required for consistent
theoretical picture. Also the confirmation of Ξ_{10}(1862) is badly needed.

Somewhat unexpectedly the discovery of Θ^+ and possibly of Ξ_{10}
has shaken our understanding of the QCD bound state. Simple quark model
pictures must be modified and very likely soliton models might contain
necessary ingredients to explain new exotics.

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