Present status of the nonstrange and other flavor partners of the exotic $\Theta^+$ baryon

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Abstract. Given the existing empirical information about the exotic $\Theta^+$ baryon, we analyze possible properties of its $SU(3)_F$-partners, paying special attention to the nonstrange member of the antidecuplet $N^*$. The modified $\pi N$ partial-wave analysis presents two candidate masses, 1680 MeV and 1730 MeV. In both cases, the $N^*$ should be rather narrow and highly inelastic. Our results suggest several directions for experimental studies that may clarify properties of the antidecuplet baryons, and structure of their mixing with other baryons. Recent experimental evidence from the GRAAL and STAR Collaborations could be interpreted as observations of a candidate for the $\Theta^+$ nonstrange partner.

Results from a wide range of recent experiments are consistent with the existence of an exotic $S=+1$ resonance, the $\Theta^+(1540)$ with a narrow width and a mass near 1540 MeV [1]. Direct width determinations have been hindered by the limitations of experimental resolution, resulting in upper bounds of order 10 MeV. The quantum numbers of this state remain unknown, though a prediction of $J^P = 1/2^+$ was obtained in the work [2] that provided motivation for the original search.

Additional information related to the assignment of unitary partners is due to a recent experimental result [3] giving evidence for one further explicitly exotic particle $\Xi_{3/2}^-$, with a mass $1862 \pm 2$ MeV and width $< 18$ MeV (i.e. less than resolution). Such a particle had been expected to exist as a member of an antidecuplet, together with the $\Theta^+$. However, the soliton calculation of the mass difference requires some assumptions. In particular, it depends on the value of the $\sigma$-term, which is the subject of controversy. Its value, taken according to the latest $\pi N$ data analysis [4], leads to an antidecuplet mass difference of about 110 MeV, instead of the originally predicted 180 MeV [5]. So, if the states $\Xi_{3/2}^-$ [3] and $\Theta$ are indeed members of the same antidecuplet, then, according to the Gell-Mann-Okubo rule, the mass difference of any two neighboring isospin multiplets in the antidecuplet should be constant and equal $(M_{\Xi_{3/2}^-} - M_{\Theta})/3 \approx 107$ MeV, which fits the GW SAID $\sigma$-term result very well [4]. This shift also effects the masses of other unitary partners of the $\Theta^+$: nucleon-like and $\Sigma$-like. The supposed antidecuplet, with $\Sigma$- and $N$-masses determined by the Gell-Mann–Okubo rule, looks today as shown on Fig. [4].
Due to $SU(3)_F$-violating mixing with lower-lying nucleon-like octet states, $M_{N^*}$ may shift upward, and reach about $1680$ MeV [5]. Mixing with higher-lying nucleon-like members of exotic 27- and 35-plets may also play a role.

The state $N(1710)$, though listed in the PDG Baryon Summary Table [6] as a 3-star resonance and used as input in the $\Theta^+$ prediction [2], is not seen in the latest analysis of pion-nucleon elastic scattering data (see Table 1). Studies which have claimed to see this state have given widely varying estimates of its mass and width (from $\sim 1680$ MeV to $\sim 1740$ MeV for the mass and from $\sim 90$ MeV to $\sim 500$ MeV for the width). Branching ratios have also been given with large uncertainties (10–20% for $N\pi$, 40–90% for $N\pi\pi$, and so on), apart from one which has been presented with much greater precision ($6\pm 1$% for $N\eta$). In any case, the PDG width of $N(1710)$ seems to be too large for the partner of the narrow $\Theta^+$. It would be more natural for members of the same unitary multiplet to have comparable widths.

As has been suggested recently (see Refs. [10, 11]), any standard PWA by itself tends to miss narrow resonances. For this reason, we considered [10] a modified PWA, assuming the existence of a narrow resonance, and compared the quality of fit with and without such structures (more detailed description of formulas see in Ref. [11]). Such an approach was used initially to look for light nucleon resonances [10].

This method, applied to studies of the $\Theta^+(1540)$ [12], though unable to determine the $\Theta^+$ quantum numbers, placed a tight limit on the width, in full agreement with the results of other approaches. We subsequently used this method [11] to search $\pi N$ scattering data for a narrow nucleon-like state assumed to be a member of the antidecuplet, accompanying the $\Theta^+(1540)$. The two candidate masses, $M_R = 1680$ MeV and $1730$ MeV, would necessary be quite inelastic with $\Gamma_{el} < 0.5$ MeV and 0.3 MeV, respectively. Some support for a narrow structure in this mass region has recently been obtained in a preliminary report based on direct measurements by the STAR [13] and GRAAL [14] Collaborations.

It should be noted that there have been other publications finding no evidence for the existence of the $\Theta^+$. These findings need more detailed consideration. Though the present non-observation data require some suppression of exotic production, as compared to conventional hadrons, they do not definitively exclude the existence of the $\Theta^+$ and/or its companions/analogs. For example, analysis of the BES data [15] in Ref. [16] shows that indeed there is some suppression of $\Theta$-production. However, suppression of the exotics at this level could have a quite natural explanation.

There is also a statement that the observed peak of $\Theta^+$ could be due to a kinematical reflection of some of known resonances. A particular consideration has been suggested by Dzierba et al. [17] addressed to the CLAS analysis [18]. The specific model used by Dzierba et al. has, however, been criticized [19], and may not be a serious concern for the CLAS results.

We should emphasize here that if the present evidence for the $\Theta$ turns out to be incorrect, we would have to answer a different, but also difficult, question: why do we not see exotic hadrons? We take here, for the sake of argument, the position that the $\Theta$ does exist, but its production is governed by different mechanisms. Though we essentially agree with suggestions of Karliner and Lipkin [20] about how to clarify the problem, we think that, first of all, it is especially important to reliably confirm the existence of the $\Theta$ in the processes where it has been reported. New data are being collected for this purpose, by several collaborations, and one would hope for a definitive answer within a year.

That is why, at the moment, we will assume the $\Theta^+$ (as well as other multi-quark hadrons) being existent, and will discuss some consequences of this fact (for details, see Ref. [11]).

To summarize, given our current knowledge of the $\Theta^+$, the state commonly known as the $N(1710)$ is not the appropriate candidate to be a member of the antidecuplet together with the $\Theta^+$. Instead, we suggest candidates with nearby masses, $N(1680)$ (more promising) and/or $N(1730)$ (less promising, but not excluded). Our analysis suggests that the appropriate state
should be rather narrow and very inelastic. Similar considerations have been applied to the \( \Xi_{3/2} (1862) \), assumed to be also a member of the same antidecuplet. It should also be quite narrow.

How reliable are our theoretical predictions? They have, indeed, essential theoretical uncertainties. We have yet to establish the existence of the (narrow) state originally associated with the \( N(1710) \). Moreover, we have assumed the presence of only one state with \( J^P = 1/2^+ \), either \( N(1680) \) or \( N(1730) \). If both exist with the same spin and parity, our conclusions should be reconsidered.

Futhermore, we use the mixing angle \( \phi \), taken from Ref. [2], which was actually determined through formulas containing the \( \sigma \)-term (just as the mass difference in the antidecuplet). If we use parameters corresponding to more recent information, for both the \( \sigma \)-term and the mass difference, we obtain larger mixing, up to \( \sin \phi \approx 0.15 \). With our formulas, this would most strongly influence the partial width \( N^* \rightarrow \pi \Delta \), increasing it to about 15 MeV. Other partial widths of \( N^* \) change not so dramatically, and the total width appears to remain not higher than \( \sim 30 \) MeV. Such a width could well be measured, but not in elastic scattering, because of an expected very small elastic branching ratio. Note, however, that the above large value for \( \sin \phi \) may appear problematic, since the formulas of Ref. [2] assume linearisation with respect to \( SU(3)_F \)-violation, and need to be reconsidered if the violation appears to be large.

Nevertheless, even having in mind all theoretical uncertainties, we can suggest several directions for experimental studies. First of all, one should search for possible new narrow nucleon state(s) in the mass region near 1700 MeV. Searches may use various initial states, (e.g., \( \pi N \) collision or photoproduction). We expect the largest effect in the \( \pi \pi N \) final state (mainly through \( \pi \Delta \), though it is forbidden by \( SU(3)_F \)). The final states \( \eta N \) and \( K \Lambda \) may also be interesting and useful, especially the ratio of \( \eta N \) and \( \pi N \) partial widths, as the latter is very sensitive to the structure of the octet–antidecuplet mixing. Another interesting possibility to separate antidecuplet and octet components of \( N^* \) is provided by comparison of photoexcitation amplitudes for neutral and charged isocomponents of this resonance, the point being that the antidecuplet component contribution to the photoexcitation of the charged \( N^* \) is strongly suppressed (see details in Ref. [21]).

On the other hand, such a relatively simple picture of mixing can not reproduce our small value(s) of \( \Gamma_{el} \). We assumed in our analysis that this could result from more complicated mixing with several other multiplets [11]. Such a possibility was recently confirmed [22].

For \( \Xi_{3/2} \), attempts to measure the total width are necessary, though it could possibly be even smaller than \( \Gamma_{\Theta^+} \). Branching ratios for \( \Sigma \Xi \) and \( \pi \Xi (1530) \), in relation to \( \pi \Xi \), are very interesting. These may give important information on the mixing of antidecuplet baryons with octets and higher \( SU(3)_F \)-multiplets.

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1. References
[1] See for example, Nakano T 2004, Plenary talk at NSTAR 2004, Grenoble, March 2004
[2] Diakonov D, Petrov V and Polyakov M 1997 Z. Phys. A359 305
[3] Alt C et al. 2004 Phys. Rev. Lett. 92 042003
[4] Arndt R, Briscoe W J, Strakovsky I I, Workman R L, and Pavan M M 2004 Phys. Rev. C 69 035213
[5] Diakonov D and Petrov V, 2004 Phys. Rev. D 69 094011
[6] Eidelman S et al. 2004 Phys. Lett. B 592 1
[7] Koch R 1985 Z. Phys. C 29, 597; Höhler G 1983 Pion–Nucleon Scattering, Landoldt–Börnstein Vol. I/9b2, edited by Schopper H (Springer Verlag).
Figure 1. Tentative unitary anti-decuplet with $\Theta^+$. Isotopic multiplet (constant values of the charge) shown by solid (dashed) lines.

Table 1. Comparison of N(1710) properties.

| Collaboration | Mass (MeV) | Width (MeV) | Ref |
|---------------|------------|-------------|-----|
| DPP           | 1710 (input) | <40          | [2] |
| KH            | 1723±9     | 120±15       | [7] |
| CMU           | 1700±50    | 90±30        | [8] |
| KSU           | 1717±28    | 480±230      | [9] |
| GWU           | 1710       | no state !   | [4] |