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Θ^+(1540) AND ASSOCIATED EXOTIC STATES*

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Given the existing empirical evidence for an exotic Θ^+ baryon, we analyze possible properties of its SU(3)$_F$-partners, paying special attention to the nonstrange member of the antidecuplet N^*. A modified πN partial-wave analysis results in 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 Θ^+ nonstrange partner. We also briefly discuss recent negative results regarding the Θ-baryon and the possibility of higher exotic multiplets.

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The problem of observing multiquark (exotic and/or "cryptoexotic") states is as old as quarks themselves. The first experimental results on searches for exotics [1] were published soon after the invention of quarks [2].

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The initial straightforward motivation of "Why not?" was later supported by duality considerations [3] (duality was understood in those times as a correspondence between the sum over resonances and the sum over reggeons). However, several years of experimental uncertainty generated the question: "Why are there no strongly bound exotic states, such as those of two quarks and two antiquarks or four quarks and one antiquark?" [4].

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 [5]. Now, more than 10 publications support the existence of the Θ^+, with decays to both K^+n and K_Sp. Additional evidence for the Θ^+ (or some other exotic baryon(s) with $S = +1$) has been demonstrated recently [6] in properties of K^+-nuclear interactions. Direct width determinations have been hindered by the limitations of experimental resolution, resulting in upper bounds of order 10 MeV [5]. The quantum numbers of this state remain unknown, though the prediction of $J^P = 1/2^+$ was obtained in the work [7] that provided motivation for the original search.

Additional information related to the assignment of unitary partners is due to a more recent experimental result [8] giving evidence for one further explicitly exotic particle $\Xi^{--}_{3/2}$, with the mass 1862 ± 2 MeV and width less than 18 MeV (*i.e.*, less than resolution). Such a particle had been expected to exist as a member of an antidecuplet, together with the Θ^+, though, originally, at different mass [7]. However, the soliton calculation of mass differences within the antidecuplet requires some assumptions. In particular, it depends on the value of the σ-term, which is the subject of controversy. Its value, taken according to the latest πN data analysis [9], leads to an antidecuplet mass difference of about 110 MeV, instead of the originally predicted 180 MeV [10]. If the states $\Xi_{3/2}$ [8] and Θ 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 experimentally equal $(M_{\Xi_{3/2}} - M_\Theta)/3 \approx 107$ MeV, which corresponds very well to the GW SAID σ-term result [9]. This change also affects the masses of other unitary partners of the Θ^+: nucleon-like and Σ-like. The supposed antidecuplet, with Σ- and N-masses determined by the Gell-Mann–Okubo rule, looks today as shown on Fig. 1.

Due to $\mathrm{SU}(3)_F$-violating mixing with lower-lying nucleon-like octet states, M_{N^*} may shift upward, and reach about 1680 MeV [10]. 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 [11] as a 3 star resonance and used as input in the Θ^+ prediction [7], is not seen in the latest analysis of pion-nucleon elastic scattering data (see Table I). Studies which have claimed to see this state have given widely

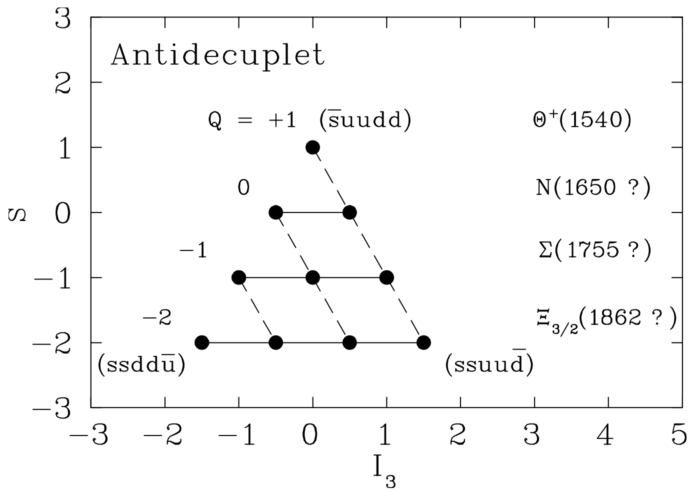

Fig. 1. Tentative unitary anti-decuplet with Θ^+. Isotopic multiplet (constant values of the charge) shown by solid (dashed) lines.

varying estimates of its mass and width (from ~ 1680 MeV to ~ 1740 MeV for the mass and from ~ 90 MeV to ~ 500 MeV for the total 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 ± 1% for $N\eta$). In any case, the PDG width of $N(1710)$ seems to be too large for the partner of the narrow Θ^+. It would be more natural for members of the same unitary multiplet to have comparable widths.

As has been emphasized recently (see Refs. [15,16]), any standard PWA by itself tends to miss narrow resonances due to a very small πN branching ratio or small total width $\Gamma < 30$ MeV. For this reason, we have considered [15] a modified PWA, assuming the existence of a narrow resonance,

TABLE I

Comparison of $N(1710)$ properties.

Collaboration	Mass (MeV)	Width (MeV)	Ref.
DPP	1710 (input)	< 40	[7]
KH	1723 ± 9	120 ± 15	[12]
CMU	1700 ± 50	90 ± 30	[13]
KSU	1717 ± 28	480 ± 230	[14]
GWU	~ 1700	not seen	[9]

and comparing the quality of fits with and without such a structure (a more detailed description is given in Ref. [16]). Such an approach was used initially to look for light nucleon resonances [15].

This method, applied to studies of the $\Theta^+(1540)$ [17], places a tight limit on its width, in full agreement with the results of other approaches [18]. We have used this method [16] to search πN scattering data for a narrow nucleon-like state assumed to be a member of the antidecuplet, accompanying the $\Theta^+(1540)$. The two candidate states, with masses 1680 MeV and 1730 MeV, would necessarily be quite inelastic with $\Gamma_{\rm el} < 0.5$ MeV and 0.3 MeV, respectively. Some support for a narrow structure in this mass region has recently been obtained in preliminary data based on direct measurements by the STAR [19] and GRAAL [20] Collaborations. Thus, the modified PWA seems to be a useful instrument in the search for narrow resonances.

Not all searches have yielded positive results. Some collaborations have not (yet) found the Θ^+ in their data. Of these negative results, some have been formally published (see, *e.g.*, Refs. [21–31]), while others exist mainly as rumors, or as conference slides. Nevertheless, all of these cast doubt on the existence of the Θ^+. Note that the negative results mainly correspond to energies higher than positive ones, and could be determined by different mechanisms. A new set of dedicated experiments, performed by several independent groups, are rather soon expected to provide more clear conclusions on the existence of this and other exotic hadrons.

More detailed analysis of the existing data shows that, though the present non-observation data require exotic production to be small as compared to conventional hadrons, they can not entirely exclude the existence of the Θ^+ and/or its companions/analogs. For example, analysis of the BES data [21], presented in Ref. [32], demonstrates some suppression of the Θ-production. However, given the present experimental accuracy, this suppression is not severe, an essentially stronger suppression of the exotic production could still have a natural explanation. Similar conclusions apply also to other data sets (see, *e.g.*, Ref. [25]). For this reason, we will assume the Θ^+ (as well as other multi-quark hadrons) to exist, and will discuss the consequences.

There is also a statement that the observed peak of Θ^+ could be due to a kinematical reflection of some of known resonances. A particular consideration has been suggested by Dzierba *et al.* [33] addressed to the CLAS analysis [34]. The specific model used by Dzierba *et al.* has, however, been criticized [35, 36], and may not be a serious concern for the CLAS results.

We should emphasize here that if the present evidence for the Θ turns out to be incorrect, we would have to answer another, but also difficult, question: why do we *not* see exotic hadrons? Here we take the position that the Θ does exist, but its production may be governed by different mechanisms than the production of conventional hadrons. Though we essentially agree with suggestions of Karliner and Lipkin [37] for ways to clarify the problem, we think that, first of all, it is important to reliably confirm the existence of the Θ in the processes where it has been reported. New data are being collected for this purpose, by several collaborations, and one could hope for a definitive answer within a year.

That is why, at the moment, we assume that the Θ^+ (as well as other multi-quark hadrons) exist, and discuss some consequences of this assumption (for details, see Ref. [16]).

Given our current knowledge of the Θ^+, the state commonly known as the $N(1710)$ is not the appropriate candidate to be a member of the antidecuplet together with the Θ^+. Instead, we suggest candidates with nearby masses, $N(1680)$ (more promising) and/or $N(1730)$ (less promising, but not excluded). Our analysis [16] 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 be quite narrow as well.

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.

Furthermore, we use the mixing angle ϕ, taken from Ref. [7], which was actually determined through formulas containing the σ-term (just as the mass difference in the antidecuplet). If we use parameters corresponding to more recent information, for both the σ-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 $N^* \to \pi\Delta$, 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 ~ 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. [7] assume linearization with respect to $\mathrm{SU}(3)_F$-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.*, πN collision or photoproduction). We expect the largest effect in the $\pi\pi N$ final state (mainly through $\pi\Delta$, though it is forbidden by $\mathrm{SU}(3)_F$). The final states ηN and

$K\Lambda$ may also be interesting and useful, especially the ratio of ηN and πN 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 photo-excitation amplitudes for neutral and charged states of this resonance, the point being that the antidecuplet contribution to the photo-excitation of the charged N^* is strongly suppressed (see details in Ref. [38]).

On the other hand, such a relatively simple picture of mixing cannot reproduce our small value(s) of $\Gamma_{\rm el}$. We assumed in our analysis that this could result from more complicated mixing with several other multiplets [16]. Such a possibility was recently confirmed [39].

For $\Xi_{3/2}$, attempts to measure the total width are necessary, though it could possibly be even smaller than Γ_{Θ^+}. Branching ratios for $\overline{K}\Sigma$ 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.

Extending our modified PWA technique, we applied it to KN and πN scattering [40] to search for higher exotic multiplets. Conventional and modified partial-wave analyses provide several sets of candidates for correlated pairs (Θ_1, Δ), each of which could label a related 27-plet [40]. Properties of the pairs (masses, mass orderings, spin-parity quantum numbers) do not quite correspond to the current theoretical expectations. Decay widths of the candidates are either wider or narrower than expected.

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