Justifying the exotic $\Theta^+$ pentaquark

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Abstract

The existence of a light $S = +1$ baryon resonance follows from Quantum Field Theory applied to baryons. This is illustrated in the Skyrme model (where $\Theta^+$ exists but is too strong) and in a new mean field approach where $\Theta^+$ arises as a consequence of three known resonances: $\Lambda(1405)$, $N(1440)$ and $N(1535)$.

Key words: baryon resonances, exotic resonances, Skyrme model, pentaquark

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After strong signals of the exotic $S = +1$ baryon have been announced in the Fall of 2002 from two independent searches [1,2] initiated by a theoretical prediction of a light and narrow exotic resonance [3], there has been much confusion in the field, both on the experimental and theoretical sides. The anomalously small width is the key to that confusion. If $\Gamma_\Theta \leq 1$ MeV [4] it means that the $(\Theta KN)$ coupling is an order of magnitude less than the typical pseudoscalar couplings of normal mainly $3Q$ baryons, and one expects that the vector coupling $(\Theta K^*N)$ is similarly strongly suppressed. The $\Theta^+$ production cross sections are then very small and it indeed becomes a challenge to reveal it experimentally.

Theoretically, both the light mass and a small width are uncomprehensible from the naïve point of view on hadrons, which assumes one adds up $\approx 350$ MeV per constituent quark, plus $150$ MeV for strangeness. With that arithmetics, one expects a pentaquark $uudds$ state at $\geq 1900$ MeV ($400$ MeV heavier than in reality!) and, of course, there is no way to avoid a large width from a fall-apart decay.

There have been strong warnings in the past that the constituent quark picture is an oversimplification, the “spin crisis” and the anomalously huge nucleon $\sigma$-term being examples of such warnings [5]. However it is the light and narrow $\Theta^+$ that is really a shock to the simplistic view. Not only is $\Theta^+$ exotic but its width is unprecedentedly small for a strongly decaying resonance.

Lacking in the traditional picture is Quantum Field Theory saying that all baryons are in fact quantum-mechanical superpositions of $3Q, 5Q, 7Q, \ldots$ states, and Spontaneous
Breaking of Chiral Symmetry, saying that constituent quarks have to interact strongly at least with the pseudoscalar meson fields. A very rough, very approximate model of baryons that accommodates, however, this physics is the Skyrme model. There is a prejudice that the Skyrme model is somehow opposite or perpendicular to quark models. In fact the Skyrme model is in accordance with quarks \[6\] but it is in one way better as it allows baryons to be made of \(N_c\) quarks, plus an indefinite number of \(Q\bar{Q}\) pairs.

The question whether \(\Theta^+\) exists in the Skyrme model has been studied, at large \(N_c\), in Ref. \[7\] in the Callan–Klebanov approach, with the conclusion that there are “no \(S=+1\) kaon bound states or resonances in the spectrum”. This is a misunderstanding: the \(KN\) cross section in the \(T=0, L=1\) wave, computed from the phase shifts in the Skyrme model \[7\] exhibits a strong resonance around 1500 MeV, see Fig. 1 (the existing data for the full cross section are also shown there). A more precise way to formulate it is that the \(KN\) scattering amplitude has a pole at \(m_{\text{res}} - i \Gamma/2 = 1449 - i\ 44\) MeV \[6\], for the standard parameters of the Skyrme model. Therefore, the Skyrme model does predict a strong exotic resonance, and there is no way to get rid of it as its origin is very general. However, as explained in detail in Ref. \[6\], the Skyrme model grossly overestimates the \(\Theta^+\) width. In realistic settings it becomes very narrow, and that is why it is so hard to detect it.

There is a nice way to understand \(\Theta^+\) in simple terms and see that it is unavoidable \[8\]. If the number of quark colors \(N_c = 3\) is considered to be a large number, the \(N_c\) quarks in a baryon can be viewed, according to Witten, as bound by a mean field. Any reasonable Ansatz for the mean field breaks symmetry between \(u, d\) quarks on the one hand and \(s\) quarks on the other. The (approximate) \(SU(3)\) symmetry is restored when one considers rotations of the mean field in flavor space: that produces \(SU(3)\) baryon multiplets. The splittings between multiplet centers are \(O(1/N_c)\), and the splittings inside multiplets are \(O(m_s)\). The ground-state baryon – the nucleon – is obtained by filling in all negative-energy one-particle states in the mean field, and adding one filled shell with positive energy for \(u, d\) quarks, see Fig. 2. The \(s\)-quark shells are characterized by \(J^P\) whereas the \(u, d\)-quark shells are characterized by \(K^P\) where \(K = J + T\). The highest shell filled by \(N_c\) quarks in antisymmetric state in color must have \(J^P = 1/2^+\) for \(s\) quarks, and \(K^P = 0^+\) for \(u, d\) quarks. The lowest baryon multiplets \((8, 1/2^+)\) and \((10, 3/2^+)\) are obtained from quantizing the rotations of this filling scheme in flavor and ordinary spaces.

The lowest baryon resonances that are not rotational excitations of the ground-state baryon are \(\Lambda(1405, 1/2^-)\) and \(N(1440, 1/2^+)\). They can be obtained as one-quark exci-
tations in the mean field: $\Lambda(1405)$ as the $1/2^−$ excitation of the $s$ quark (Fig. 3) and $N(1440)$ as a $0^+$ (or $1^+$) excitation of $u, d$ quarks (Fig. 4). The existence of the excited $1/2^−$ level for $s$ quarks implies that it can be also excited by $s$ quark from the highest filled $s$-quark shell: such particle-hole excitation can be identified with the $N(1535, 1/2^−)$ resonance, see Fig. 3. At $N_c = 3$ it is mainly a pentaquark baryon $u(d)udd\bar{s}$, which explains its large decay branching into $\eta N$, a long-time mystery.

The existence of the excited (Roper) $0^+$ level for $u, d$ quarks implies that it can be also excited from the $s$-quark shell, forming an exotic pentaquark $\Theta^+ = uudds$, see Fig. 4. Since the positions of all levels involved are already fixed from the masses of the three resonances, we estimate the $\Theta^+$ mass as $m_\Theta \approx 1440 + 1535 − 1405 = 1570$ MeV, with the uncertainty of few tens MeV as the resonance masses are not precisely known. Thus, in the mean field picture the exotic pentaquark is a consequence of the three well-known resonances and is light [8]. One should not expect a qualitative change in the levels as one goes from large $N_c$, where the mean field is exact, to the real-world $N_c = 3$.

In this interpretation, $\Theta^+$ is a Gamov–Teller-type resonance long known in nuclear physics, where a neutron from a filled shell can be put on an excited proton level. All four excitations shown in Figs. 3, 4 entail their own rotational bands of $SU(3)$ multiplets.

Finally, I would like to remark that with all couplings of $\Theta^+$ to ordinary baryons being small, a promising way of detecting it is in interference with the production of known resonances, since the interference cross sections are linear (and not quadratic) in the small coupling constants [9].

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