The narrow pentaquark

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Abstract

The experimental status of the pentaquark searches is briefly reviewed. Recent null results by the CLAS collaboration are commented, and new strong evidence of a very narrow Θ^+ resonance by the DIANA collaboration is presented. On the theory side, I revisit the argument against the existence of the pentaquark – that of Callan and Klebanov – and show that actually a strong resonance is predicted in that approach, however its width is grossly overestimated. A recent calculation gives 2 MeV for the pentaquark width, and this number is probably still an upper bound.

1 Experimental status

The original claim for the discovery of a narrow exotic baryon resonance in two independent experiments by T. Nakano *et al.* [1] and A. Dolgolenko *et al.* [2], announced in the end of 2002 [1], were followed in 2003-04 by a dozen experiments confirming the resonance and about the same amount of non-sighting experiments. In 2005 the results of the two CLAS high-statistics experiments were announced [4, 5], which didn't see a statistically significant signal of the Θ^+ resonance in the γd and γp reactions and gave upper bounds for its production cross sections. Although those upper bounds didn't contradict the theoretical estimates (see below) many people in the community jumped to the conclusion that "pentaquarks do not exist".

Meanwhile, in 2005-06 new results became available [6, 7] partly based on new data, confirming seeing the Θ^+.

Usually, if one suspects a resonance in a system A+B, the best thing is to study the *formation* of the resonance in AB scattering, in this case in the K^+n (or K^0p) scattering. Unfortunately, mankind has lost K^+ and K^0 beams at the appropriate (low) energies, therefore most of the processes studied so far are of the *production* type. We do not have much experience with pentaquarks, which does not make it easy to estimate the production cross sections to be able to judge that this or that non-observation of a resonance "kills" it.

A *quasi*-formation experiment where a quasi-free K^+ scattered off a quasi-free neutron inside a deuteron in γd reaction was performed at SPring-8, near Osaka; the results were reported by T. Nakano with many details at a number of conferences [6]: there is a clear resonance signal, see Fig. 1.

[1] They were totally independent as both groups didn't know about the work of one another and made a tedious re-analysis of data taken long before, however both searches were triggered off by the authors of Ref. [3] where the resonance at $\sim 1530\,\text{MeV}$ and width less than $15\,\text{MeV}$ had been predicted.

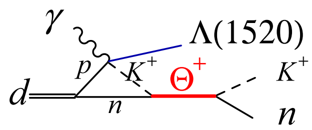
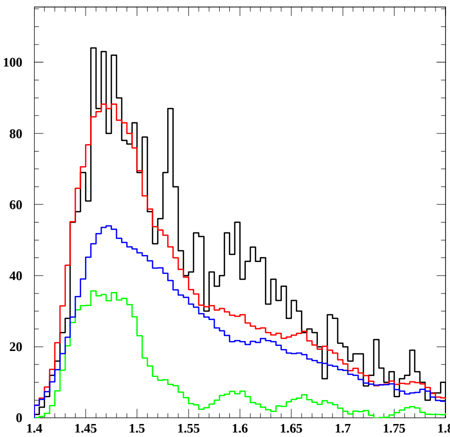


Fig. 1a,b. Above: reaction studied by LEF
Right: the spectrum of mass of the K^+n sy
tem [6]. The red histogram shows the estimat
background. One observes a narrow peak
1.54 GeV.



Why LEPS collaboration at SPring-8 sees the Θ^+ peak whereas CLAS collaboration at the Jefferson Lab does not? In both cases it is the same γd reaction at comparable energies, however the kinematics and the detector acceptance are different. Having a model for the reaction it is possible to compute the K^+n mass spectrum adjusted to the kinematical cuts imposed by the two collaborations and their apparatuses. This has been done in Ref. [8], see Fig. 2.

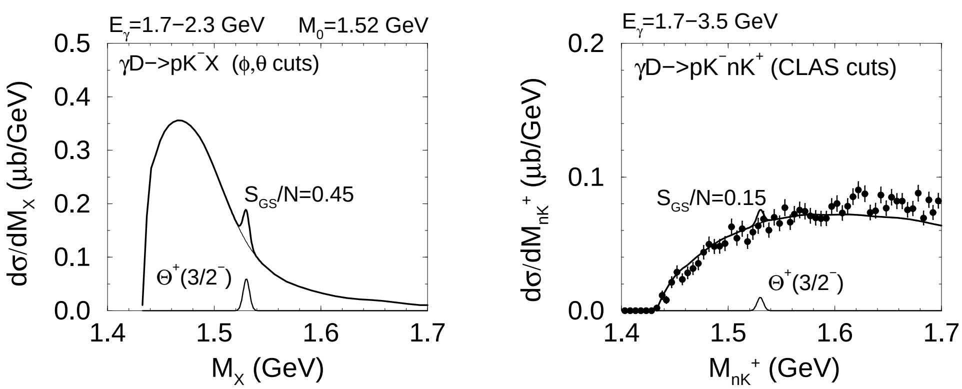


Fig. 2 a,b (from Ref. [8]. Θ^+ should be mildly visible in the LEPS setup (left) but buried under the background in the CLAS setup (right). With most CLAS data points lying on the calculated solid curve, the authors of Ref. [8] demonstrate a fair control of the background. Spin-parity $3/2^-$ has been assumed for the Θ^+; were it $1/2^+$ the signal-to-background would be worse.

A similar conclusion has been recently drawn by V. Guzey [9] from evaluating the cross section of the process $\gamma d \to \Lambda K^+ n$ also studied by the CLAS collaboration with no statistically significant resonance structure observed. The claim is that in the CLAS setup [10] the Θ^+ signal would be almost completely washed out through interference with non-resonant processes.

CLAS collaboration studied also the Θ^+ production in the $\gamma p \to \bar{K}^0(K^+n)$ (and K^0p) reaction [5], again with a null result. It should be noted that it is different from the $\gamma p \to \pi^+K^-K^+n$ reaction where a 7σ signal of the Θ^+ has been previously reported by the same collaboration [11]. The reaction $\gamma p \to \bar{K}^0\Theta^+$ is a simple 2-body one, and its cross section can be estimated more or less reliably from the (reggeized) vector K^* exchange. The vector K^* coupling to the $p\Theta$ transition vanishes in the $SU(3)$ limit, so it couples through the magnetic moment vertex, $\sigma_{\mu\nu}q_\nu$, but even this coupling is expected to be an order of magnitude less than for the octet-octet and octet-decuplet magnetic transitions [12]. The estimate of the $\gamma p \to \bar{K}\Theta$ yield has been made in Ref. [13] prior to the CLAS experiment, with the result of about 0.2 nb. The CLAS experimental upper limit of ~ 0.7 nb for the Θ production [5] is, therefore, not too restrictive. One can hardly conclude from these numbers that "Θ^+ does not exist". However, the impressive amount of data collected by CLAS allows one to hope that a clever analysis combined with reliable theoretical estimates may really bury (or reveal) the Θ^+.

I do not discuss here the numerous non-sighting experiments at high energies: the exotic baryon production cross sections are not known there. It can be argued, however, that the Θ^+ production at high energies is at least an order of magnitude less than that of the ϕ meson and two orders of magnitude less than of the Λ hyperon [14]. However those ratios may vary depending on the concrete experimental setup.

Finally, let me draw attention to the *direct formation* experiment [7] which, in my mind, gives to date the most strong evidence in favour of a very narrow Θ^+. It is the DIANA experiment at ITEP, Moscow, – actually the update of their first analysis of the $K^+n(\mathrm{Xe}) \to K^0p$ data [2] but now with approximately double statistics. Previously, there were about 30 events above the estimated background, now there about 60, as it should be if the signal is real. Also, more thorough analysis has been performed to understand better the kinematics of the reaction and the background processes, see Fig. 3. The resonance peak is seen already in the raw data (white histogram) but is strongly enhanced by a mild kinematical cut suppressing re-scattering (grey histogram).

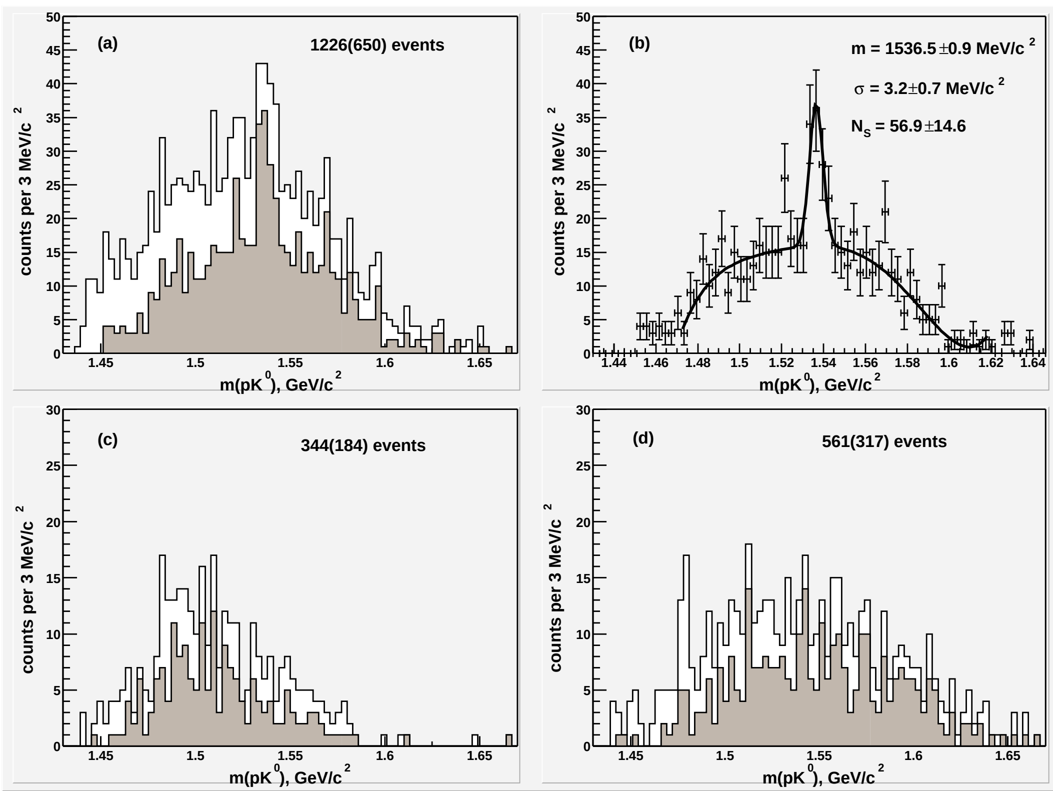


Fig. 3 (from Ref. [7]). K^0p mass distribution in the range of the incident K^+ momenta where the Θ^+ resonance *can be* formed due to neutron's Fermi motion (**a**,**b**), and where it *cannot be* formed: K^+ momenta are either too low (**c**) or too high (**d**). In **c**,**d** the invariant mass spectrum is filled owing partly to re-scattering of final particles in the Xe nucleus, cf. [15].

If this is not a resonance, what is it? The authors find its statistical significance to be 7.3σ, 5.3σ, 4.3σ, depending on whether one estimates it as $S/\sqrt{B}$, $S/\sqrt{S+B}$ or $S/\sqrt{S+2B}$. The mass is found to be $M_\Theta = 1537 \pm 2\,\mathrm{MeV}$ and the width $\Gamma_\Theta = 0.36 \pm 0.11\,\mathrm{MeV}$ (!) (plus possible systematic uncertainties). This is the only experiment where the direct estimate of the width is possible since the formation cross section averaged over the resonance range is proportional to the width. The only other available formation experiment with the secondary kaon beam at

BELLE sets an upper limit of Γ_Θ beyond the above value [16].

We have to keep in mind that there are numerous and so far uncontested observations of a KN resonance at 1.53 GeV in neutrino- [17], photon- [18] and proton- [19] induced reactions. The analysis of old K^+d data by Gibbs calls for the exotic resonance with the width $0.9 \pm 0.3\,\mathrm{MeV}$. An anomaly in K^+ scattering off nuclei needs an "additional reactivity" as compared to the usual optical potential scattering [21]. Last but not least, the GRAAL collaboration reports a possible narrow $N^*(1675)$ resonance in the $\gamma n \to \eta n$ reaction (but not in the $\gamma p \to \eta p$) [22] which is consistent with the resonance being the antidecuplet partner of the Θ^+.

Given a small $KN\Theta$ coupling constant (since the width is very small) and a small $K^*N\Theta$ coupling (since the transition magnetic moment is small), it is difficult to arrange for a sizable production of the Θ^+. Maybe a good chance of seing it is via an interference with some process with large amplitude – then at least the cross section is proportional to the small coupling but not its square. However, if Θ^+ is produced through interference, it becomes hostage of the specific conditions of a reaction: the resonance may appear as a peak or a dip or an oscillation, depending on the relative phase of the amplitudes. One may be lucky in one setup and less lucky in another, as Guzey's example [9] has shown.

The direct formation experiment [7] reveals Θ^+ and the quasi-formation experiment [6] sees it, too. The high-statistics CLAS γd and γp experiments impose upper limits on the production cross sections, which seem so far to be beyond the danger zone for the Θ^+. The high energy probes also impose certain limits on the production, but at present it is not easy to translate them into physical meaning.

Future progress can be obtained along the following lines: a) by performing a high-flux KN formation experiment (planned at J-PARC), b) by learning to make reliable estimates for the production cross sections, such that the comparison with the data becomes meaningful, and c) by inventing clever new methods of searching Θ^+ taking into account that all its couplings to normal hadrons are small.

2 Theoretical surprise

Probably the only theoretical argument against the existence of exotic baryons is due to Callan and Klebanov [23] [2]. It relies on the academic limit of large number of colours N_c when baryons can be considered in the mean field approximation with quarks bound by the self-consistent pion field, the "soliton" (*à la* large-Z Thomas–Fermi atom or the large-A shell model for nuclei). The Skyrme model is a popular realization of this idea, although not a too realistic one [25].

In this approach, octet and decuplet baryons are all rotational excitations – in ordinary and flavour spaces – of the same object, the large 'classical' baryon. At large N_c, however, baryons with minimal strangeness (like the nucleon, the Δ, the Θ...) correspond to rotational states which are more like a precession along a high latitude around the "North pole" [24, 26]. Such a rotation can be as well considered as a small oscillation about the pole. Therefore, at large N_c the existence or non-existence of the Θ^+ can be studied by considering small oscillations of the kaon field about the 'classical' nucleon, which I shall generically call the 'Skyrmion'. In other words, it is sufficient to look into the kaon scattering off a Skyrmion, and that is what Callan and Klebanov did. After the discovery of the Θ^+, the study has been repeated in more detail in Ref. [27]. One has to solve a Schrödinger-Klein-Fock equation [3] but with a Wess–Zumino–

[2] T. Cohen gave an additional argument [24] why the Callan–Klebanov approach to the exotic baryon must be correct at large number of colours.

[3] Historical survey by Jackson and Okun [28] disclosed that the relativistic wave equation for spin 0 particle has been first written down and published in *Zeitschrift für Physik* in 1926 practically simultaneously by E. Schrödinger, O. Klein and V. Fock. Moreover, Fock's is *the* paper where gauge invariance in quantum theory was first introduced (he called it the gradient invariance). Gordon's paper on the application of the already known equation came later. Therefore, I do not see reasons to prolong historical injustice, and call the relativistic wave equation by its proper name.

Witten term linear in the time derivative, and find the scattering phases for given quantum numbers. The resulting phase in the strangeness +1, spin $1/2^+$ channel is plotted in Fig. 4a.

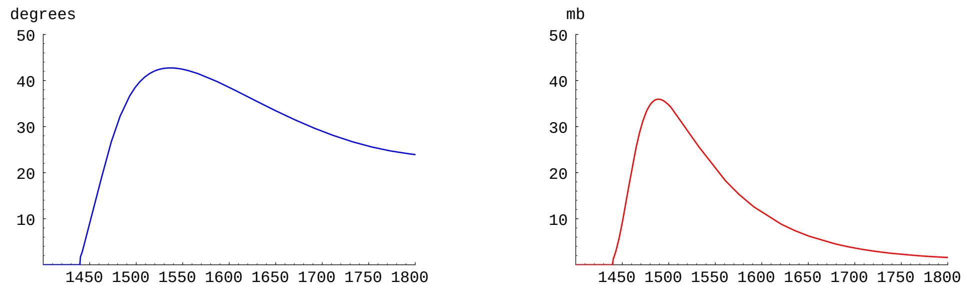


Fig. 4a,b. The K^+n scattering phase [27] (left) and the ensuing K^+n scattering cross section (right) as function of the invariant K^+n mass in the Skyrme model. Note that at the maximum the cross section is as large as 35 mb ! Courtesy V. Petrov.

The point made in Refs. [23, 27] is that the K^+n phase shift in Fig. 4a does not pass through 90^o as it should be for an isolated Breit–Wigner resonance, and therefore there is no exotic resonance, at least in the large-N_c limit. However, if there is both a resonance *and* a potential scattering, the phase shift needs not go through $\pi/2$.

To see what is going on, it is instructive to solve the Callan–Klebanov K^+n scattering equation in the complex energy plane, simultaneously varying the coefficient in front of the Wess–Zumino–Witten term [29]. When it is zero, there is exact zero-energy solution corresponding to the rotation of the soliton as a whole in the flavour space. It was on the base of the quantization of this rotation that the light and narrow Θ^+ was predicted [3]. As one increases the coefficient of the Wess–Zumino–Witten term towards its physical value, the would-be zero energy level moves up but obtains an imaginary part. With the standard Skyrme model parameters used by Klebanov *et al.*, the pole position of the Θ^+ resonance is at $E_\Theta = 1510 - \frac{i}{2}\cdot 120\,\mathrm{MeV}$. Indeed, had Klebanov *et al.* [27] plotted the K^+n cross section from their phase shift according to the well-known formula $\sigma = (4\pi/k^2)(2j+1)\sin^2\delta$, they would get a very strong resonance, see Fig. 4b.

Thus, the prediction of the Skyrme model is not that there is no exotic resonance but just the opposite: **there is a very strong resonance**, at least when the number of colours is taken to infinity! Therefore, a theorist must be worried not by the existence of an exotic resonance but rather by its absence: why a very general theoretical prediction – a broad exotic resonance – is not observed in nature [4].

The answer is that the Callan–Klebanov large-N_c logic in general and the concrete Skyrme model in particular grossly overestimate the resonance width. In reality it becomes very narrow, and that is why it is so difficult to observe it. We first deal with the large-N_c limit and check if it is a good approximation for the Θ^+ resonance. A general argument has been presented in Ref. [26] that it is not but here we give a more direct argument.

Let us recall the equation for the Θ^+ width [3] [5]:

$$\Gamma_\Theta = \frac{3|\mathbf{p}|^3}{2\pi(M_N+M_\Theta)^2}\cdot\frac{1}{5}\cdot\left(G_0 - G_1 - \frac{1}{2}G_2\right)^2 \tag{1}$$

where $\mathbf{p}$ is the 3-momentum of the kaon and $G_{0,1,2}$ are axial couplings appearing as constants in front of different $SU(3)$ structures. Eq.(1) is written for the real world, $N_c = 3$, however

[4]Varying the parameters of the Skyrme model [27, 30] or modifying it [31] can make the exotic resonance narrower or broader but one cannot get rid of it. The reason is very general: energy levels do not disappear as one varies the parameters but move into the complex plane.

[5]The kinematical factor in eq.(1) is written in the non-relativistic limit for simplicity; its precise form is irrelevant for the present discussion.

Michal Praszalowicz has generalized it to the world with arbitrary N_c [32]:

$$\Gamma_\Theta = \frac{3|\mathbf{p}|^3}{2\pi(M_N+M_\Theta)^2}\cdot\frac{3(N_c+1)}{(N_c+3)(N_c+7)}\cdot\left(G_0-\frac{N_c+1}{4}G_1-\frac{1}{2}G_2\right)^2. \tag{2}$$

To join the Callan–Klebanov logic, one has first to take the limit $N_c\to\infty$ (because only in this limit one can replace large-angle rotation in the flavour space by small oscillations of the kaon field) but then put $N_c=3$ in the final result in order to compare it with eq.(1) written at $N_c=3$ from the start. One should mind that $G_0=\mathcal{O}(N_c^{\frac{3}{2}})$, $G_{1,2}=\mathcal{O}(N_c^{\frac{1}{2}})$, $M_N=\mathcal{O}(N_c)=M_\Theta$, $|\mathbf{p}|=\mathcal{O}(1)$, $\Gamma_\Theta=\mathcal{O}(1)$. This operation leads to

$$\Gamma_\Theta^{\rm CK} = \frac{3|\mathbf{p}|^3}{2\pi(M_N+M_\Theta)^2}\cdot 1\cdot\left(G_0-\frac{3}{4}G_1\right)^2. \tag{3}$$

This width is expected to correspond to the imaginary part of the pole position in the Callan–Klebanov scattering problem. Comparing eqs.(1,3) one clearly sees what happens when the limit $N_c\to\infty$ is used: the width is first increased by a factor of 5 (!) and then may be further increased by a more shallow cancelation of the constants $G_{0,1,2}$. These constants as well as the masses have also $1/N_c$ corrections but those are expected to be additionally suppressed by powers of $1/2\pi$, see below.

The conclusion is that the exotic resonance is theoretically inevitable but that its small width cannot be obtained in the large-N_c limit. Had N_c been 300 instead of 3, Θ^+ could be as broad as any other well-established baryon resonance. It would have been produced in abundance in hadron collisions.

3 Estimate of the Θ^+ width

Forbidding ourselves to use large N_c as a theoretical tool we get in trouble. However, one can still use the Relativistic Mean Field Approximation (RMFA) [26] (alias the Chiral Quark Soliton Model [25]). Being a relativistic field-theoretic model, it allows to account for quark pair creation and annihilation in a consistent way, and that is what we need here.

The RMFA is generally justified when N_c is large. At a closer look, however, one can see that there are two types of $1/N_c$ corrections to the mean-field results. One type comes from high-frequency fluctuations; these are in fact meson loop corrections that bring in additional powers of $1/2\pi$. These corrections go in powers of $1/(2\pi N_c)\approx 6\%$ and will be ignored at the present level of accuracy. I remind that in QED the actual expansion parameter from radiative corrections is not $\alpha=1/137$ but rather $\alpha/2\pi\sim 10^{-3}$. The success of Wilson's ϵ-expansion in computing anomalous dimensions for critical phenomena is due to the fact that the actual expansion parameter is not $\epsilon=1$ but rather $\epsilon/2\pi$.

Other type of corrections to the mean field arise from low frequencies and are all related to zero modes, *viz.* translations and rotations of the "soliton" as a whole. These corrections are $\mathcal{O}(1/N_c)$ but are not accompanied by additional small factors $1/2\pi$. An example of such correction is presented by the Clebsch–Gordan coefficient in eq.(2):

$$\frac{3(N_c+1)}{(N_c+3)(N_c+7)} = \frac{3}{N_c}\left(1-\frac{9}{N_c}+\frac{69}{N_c^2}-\frac{501}{N_c^3}+\ldots\right) \tag{4}$$

Apparently one cannot trust the result of the leading order when $N_c=3$. Such corrections must be summed up exactly, which is equivalent to treating the rotations exactly at the physical value $N_c=3$.

In the mean field approximation *all* quark wave functions inside *all* baryons belonging to the octet, decuplet and exotic antidecuplet are known for *all* their Fock, i.e. $3Q$, $5Q$, $7Q$,...

components [26]. The leading component in the ordinary octet and decuplet baryons is naturally the $3Q$ one (judging from its normalization) but there is a sizable ($\sim$30%) addition of the $5Q$ component. For some baryon observables the $5Q$ component gives a mild correction (and that is why the primitive $3Q$ constituent quark models are not so bad as one would naively expect) but in some other observables higher components are critical to obtain agreement with the experiment, *e.g.* to explain the "spin crisis" or the large value of the nucleon σ-term. About 30% of the time nucleons are pentaquarks!

As to the exotic Θ^+ and other members of the antidecuplet, their *lowest* Fock component is the $5Q$ one, nothing terrible. The spatial wave function of 5 quarks in Θ^+ is very similar to that of the $5Q$ component of the nucleon, only the spin-flavour part of the wave function is somewhat different. The extra $Q\bar{Q}$ pair in the Θ^+ is a (known [26]) mixture of $0^+, 0^-, 1^-$ and 1^+ waves corresponding to scalar, pseudoscalar, vector and axial mesons. However, they do not form 'molecules' as the 'mesons' are deep inside the '$3Q$ baryons' in pentaquarks.

To evaluate the width of the $\Theta^+ \to K^+ n$ decay one has to compute the transition matrix element of the strange axial current, $<\Theta^+|\bar{s}\gamma_\mu\gamma_5 u|n>$. The important point is that there are, generally, two contributions to this matrix element: the "fall apart" process (Fig. 5, A) and the "5-to-5" process where Θ^+ decays into the $5Q$ component of the nucleon (Fig. 5, B). I stress that one does not exist without the other: if there is a "fall apart" process it means that there is a non-zero coupling of quarks to pseudoscalar (and other) mesons, meaning that there is a transition term in the Hamiltonian between $3Q$ and $5Q$ states (Fig. 5, C). Hence the eigenstates of the Hamiltonian must be a mixture of $3Q, 5Q, ...$ Fock components. Therefore, assuming there is process A, we have to admit that there is process B as well.

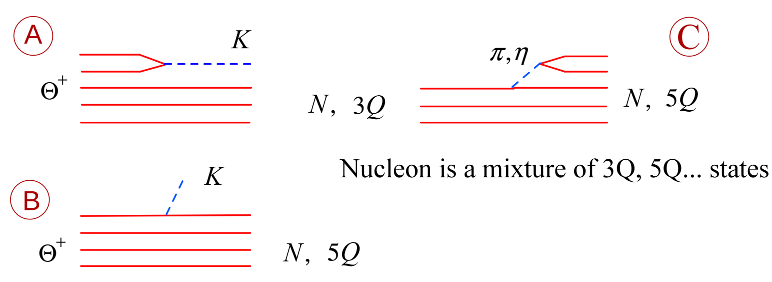


Fig. 5. Contributions A and B to the $\Theta^+ \to K^+ n$ decay.

Moreover, each of the amplitudes A and B are not Lorentz-invariant, only their sum is. Evaluating the "fall-apart" amplitude and forgetting about the "5-to-5" one makes no sense. For example, in the lab frame there is a tendency for the two amplitudes to cancel each other (A. Hosaka, private communication). A convenient way to evaluate the sum of two graphs, A and B, is to go to the infinite momentum frame (IMF) where only the process B survives, as axial (and vector) currents with a finite momentum transfer do not create or annihilate quarks with infinite momenta. The baryon matrix elements are thus non-zero only between Fock components with *equal number* of quarks and antiquarks. We note that in the RMFA, moving from one frame to another just requires a Lorentz transformation of the mean field and of the corresponding vector and spinor fields without changing the form of the mean field. This is seen, *e.g.*, from comparing two different ways of calculating nucleon parton distributions in the RMFA, leading to the same results [33].

The transition matrix element of the strange axial charge, $<\Theta^+|\bar{s}\gamma_0\gamma_5 u|n>$ was evaluated in the IMF in Ref. [26] with the resulting width $\Gamma_\Theta = 2\,\text{to}\,4\,\text{MeV}$. The uncertainty was mainly due to the uncalculated quark-exchange contributions and relativistic corrections. These were subsequently computed by Cédric Lorcé [34] with the result

$$\Gamma_\Theta \approx 2\,\text{MeV}. \tag{5}$$

It should be noted that the calculation of the above matrix element was performed assuming the chiral limit for the kaon and zero momentum transfer. In fact the momentum transfer in the $\Theta^+ \to K^+ n$ decay is several hundred MeV, therefore one must expect a further formfactor-type suppression of the estimate (5) such that Γ_Θ may well end up at the sub-MeV level which is where the current value of the width is [7].

The physical reason why the axial constant for the $\Theta \to N$ transition $g_{\Theta NK} \approx 0.14$ appears to be an order of magnitude less than the nucleon constant $g_N = 1.26$ (resulting in the suppression of the Θ width by two orders of magnitude as compared to the normal 100 MeV width for strongly decaying baryons) is clearly seen from the calculations [26, 34]. The large value of the axial constant in normal baryons in mainly due to their $3Q$ component, the $5Q$ component contributing much less. However, it is the latter contribution that is comparable to the axial constant $g_{\Theta NK}$ as it is a $5Q$ effect, too. It is suppressed to the same extent as is the $5Q$ component in ordinary baryons. As stressed in our first publication [3], in the imaginary non-relativistic limit when ordinary baryons are made of three quarks with no admixture of $Q\bar{Q}$ pairs the Θ^+ width tends to zero strictly.

To summarize: The very small width of Θ^+ is natural; the present estimate (5) will probably go down when formfactor suppression is included. We have revisited the theoretical argument of Callan and Klebanov against the exotics and found that actually it is the opposite: the Skyrme model at large N_c predicts a too strong resonance. We have shown, however, that a broad width is a very-large-N_c artifact. On the experimental side, there is new strong evidence of an extremely narrow Θ^+ from DIANA, a very significant new evidence from LEPS, and other older evidence which is difficult to brush aside. The null results from the new round of CLAS experiments are compatible with what one should expect based on the estimates of production cross sections.

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