# The narrow pentaquark $\Theta^+$

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**The statements:**

**1**. Skyrme model with conventional parameters predicts a **strong** $\Theta^+$ **resonance** which is a continuous deformation of the $SU(3)$ rotational mode of a Skyrmion

**2**. Determination of the $\Theta^+$ width from the Skyrme model is possible but the result is irrelevant

**3**. Determination of the $\Theta^+$ width from nonrelativistic models is nonsense

**4**. To determine the $\Theta^+$ width one needs a model
- that is relativistic
- where one can compute the 5-quark wave function of the **nucleon**
- where one can compute the 5-quark wave function of the $\Theta^+$

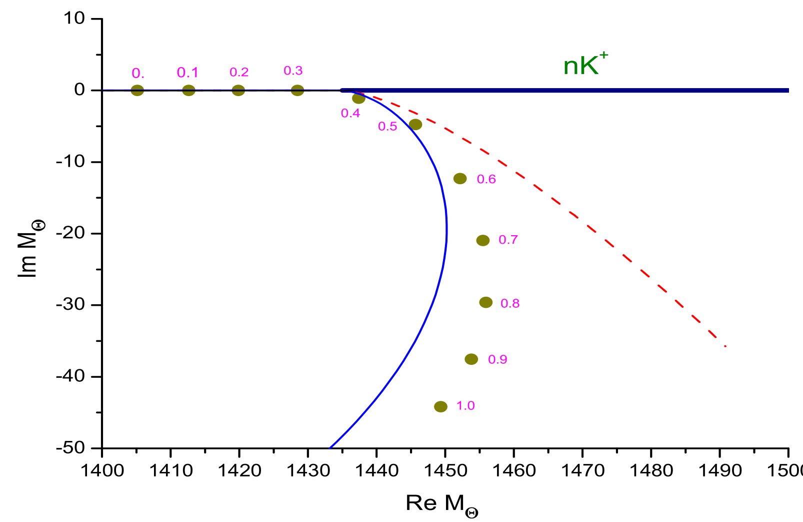
**5**. The only reasonable estimate available today gives $\Gamma_\Theta \sim 1$ MeV

**1**. At large $N_c$, it is justifiable to study the exotic $\Theta^+$ from kaon scattering off a Skyrmion, whatever is its dynamical realization. Specifically in the Skyrme model it leads to the Callan–Klebanov equation for the kaon wave:

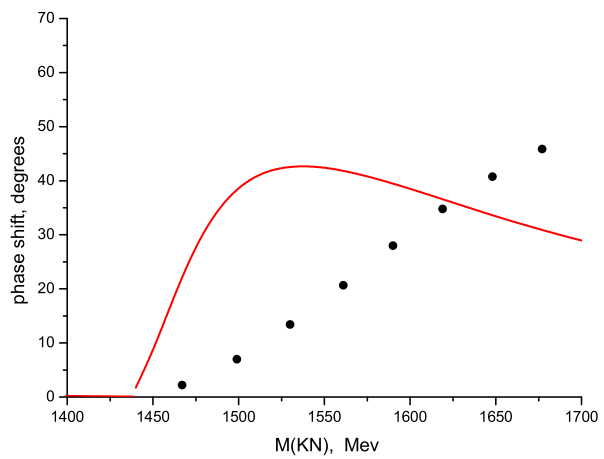
$$\left\{\omega^2 A(r) - 2\omega\gamma B(r) + \left[C(r)\frac{d^2}{dr^2} + D(r)\frac{d}{dr} - V(r)\right]\right\} K(r) = 0,$$

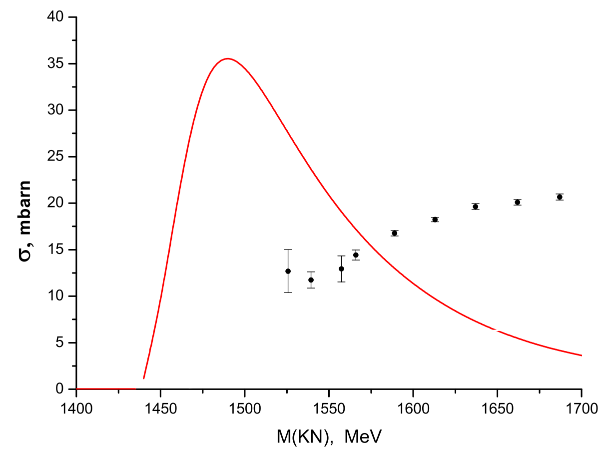
$$\text{rotational mode} \quad [ \quad \ldots \quad ] \sin\frac{P(r)}{2} = 0.$$

A resonance cannot disappear as one varies parameters but move in the complex plane; is is a continuous deformation from the rotational mode: **Fig.:** pole position as function of $\gamma$. For "realistic" parameters $\sqrt{s}_{\text{pole}} = 1449 - i\,\frac{88}{2}\,\text{MeV}$ [D.D. and V. Petrov (2008)]




One can also find phase shifts [Klebanov *et al.* (2003)] and the cross section in $P_{01}$ wave:




strong $\Theta^+$ resonance predicted by the Skyrme model

An exotic $\Theta^+$ is a robust prediction of any chiral model at large $N_c$.

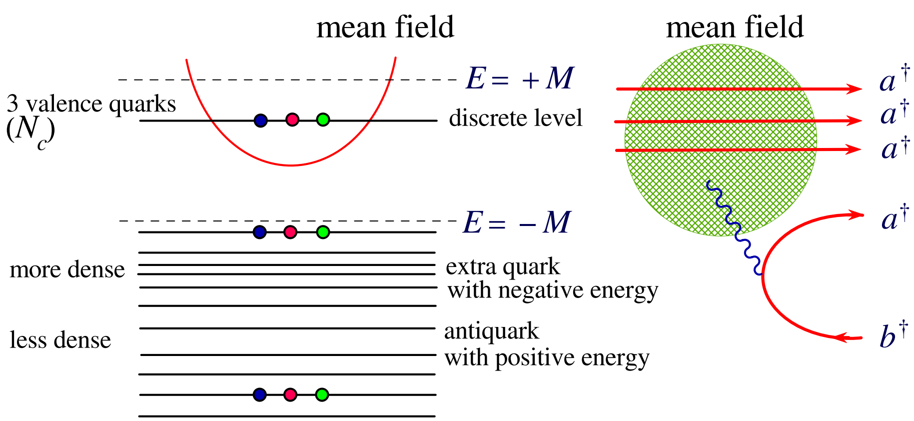
**2.** However concretely the Skyrme model grossly overestimates the width because i) it is "ultrarelativistic", ii) $N_c = 3$.

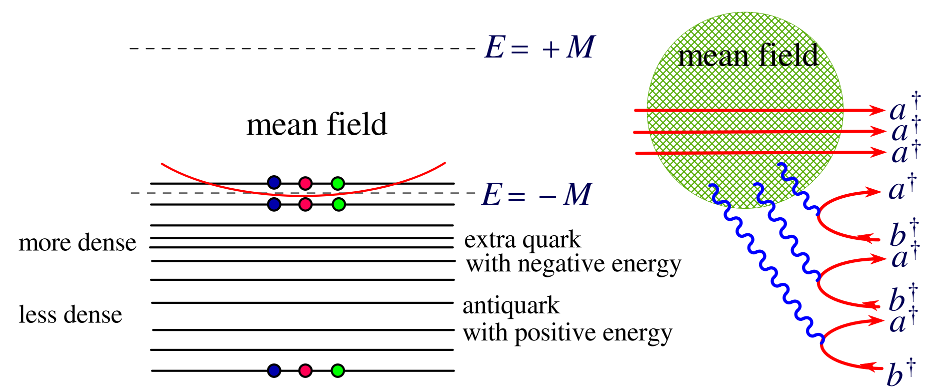
At large $N_c$ in the Skyrme model

- the nucleon is made of $N_c$ quarks, *plus* $(\epsilon N_c)$ $Q\bar{Q}$ pairs, where $\epsilon \sim 1$
- the $\Theta^+$ is made of $N_c$ quarks, *plus* $(\epsilon N_c + 1)$ $Q\bar{Q}$ pairs

$\Longrightarrow$ no smallness in the $\Theta^+/N$ overlap $\Longrightarrow$ $\Theta^+$ broad!

Valence quarks and polarized Dirac sea in the mean chiral field, also shown as the $Q\bar{Q}$ component of the Fock wave function of a baryon:



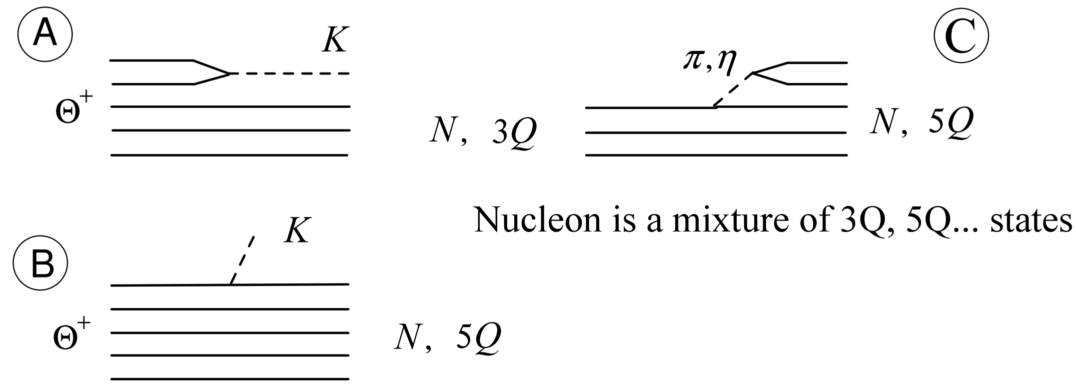

**normal:**
3Q + few $Q\bar{Q}$ pairs, $\epsilon \ll 1$,
non-relativistic case

**Skyrme model limit:**
3Q + many $Q\bar{Q}$ pairs, $\epsilon \approx 1$,
ultra-relativistic case

In reality, the nucleon is a $3Q$ state, plus a small $(\sim 30\%)$ admixture of $Q\bar{Q}$ pairs. The Skyrme model implies that the nucleon has $\mathcal{O}(N_c)$ i.e. many $Q\bar{Q}$ pairs.

## **3.** How to compute the $\Theta^+$ width?

"Fall-apart" (A) and "5-to-5" (B) contributions to the $\Theta^+ \to K^+ n$ decay:



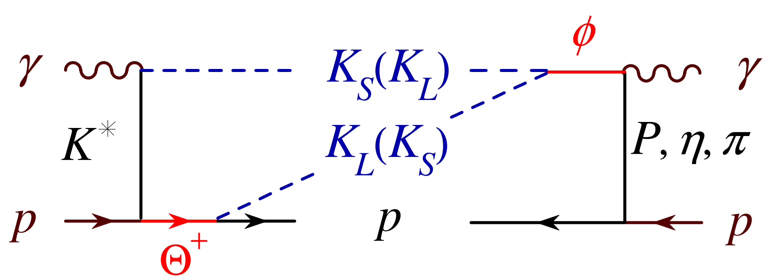

only the sum $A + B$ is Lorentz-invariant and meaningful.

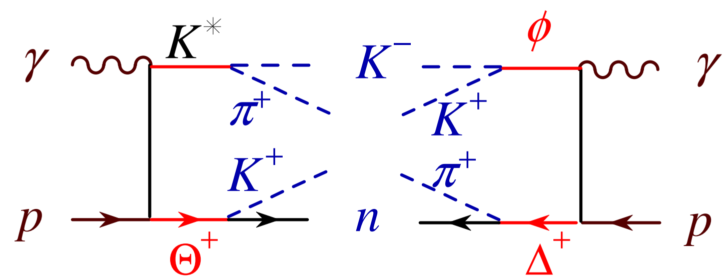
To estimate the width $\Gamma_\Theta$, one needs
(i) a relativistic model, as pair creation and annihilation is a relativistic effect
(ii) a model where the $5Q$ component of the neutron can be found
(iii) and the $5Q$ component of the $\Theta^+$

The Chiral Quark Soliton Model does all that, and a parameter-free estimate gives $\Gamma_\Theta \sim 1\,\mathrm{MeV}$ !!

**4.** How to observe $\Theta^+$ when all couplings to ordinary baryons are small?

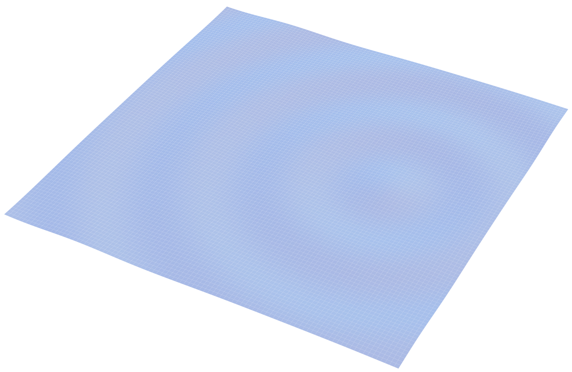
Look for the $\Theta^+$ production in **interference** with a known resonance yielding the same final state but having a high production rate [Amarian, D.D., Polyakov (2008)]. For example,

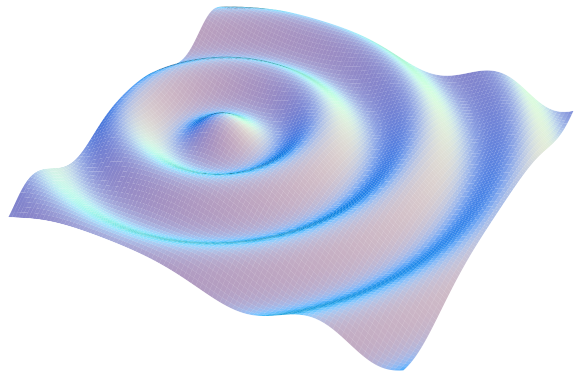


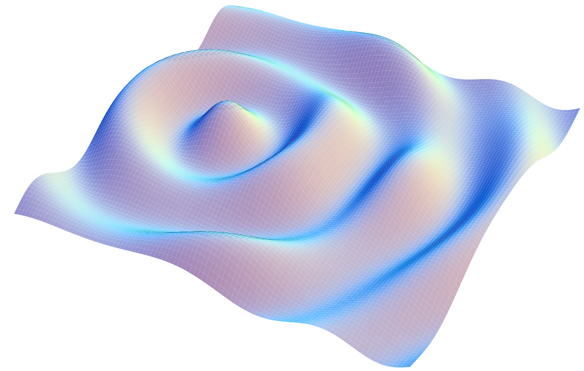




The interference production cross section is **linear** in the $\Theta^+$ couplings whereas the non-interference cross section is quadratic. That gives an obvious gain if the couplings are small.

If you cannot see waves from a small stone thrown in a pond, throw next to it a big stone, and check the presence of a small one from the **interference** picture:







quadratic effect

linear effect