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# Prediction of charmed and bottom exotic pentaquarks


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The notion that baryons are made out of **three quarks** is an **oversimplification**. Sometimes it works, sometimes not. Examples where it **does not work**:

1) "spin crisis": only **1/3** of the nucleon spin is carried by three valence quarks

2) "mass crisis": only **1/4** of the nucleon ♦ term is carried by three valence quarks:

$$\sigma_N = \frac{m_u + m_d}{2} < N \,|\, \bar{u}u + \bar{d}d \,|\, N >= 67 \pm 6\,\mathrm{MeV}$$

$$\frac{4\,\mathrm{MeV} + 7\,\mathrm{MeV}}{2} \times \ (\leq 3) \quad \leq \quad 17.5\,\mathrm{MeV}$$

Both paradoxes are explained by the presence of additional $\bar{Q}Q$ pairs in baryons.

To account for inevitable $\bar{Q}Q$ pairs, one needs a **relativistic quantum field theory**!

Great simplification but preserving relativistic field-theoretic features: use the **large-Nc limit**! (Nc is the number of quark colours, equal three, but can be treated as a free parameter)

At large Nc physics simplifies. If a clear picture of baryons is developed at large Nc, its imprint at Nc = 3 will be visible in the real world, in particular in the baryon spectrum.

Compute 1/Nc corrections. Put Nc=3 in the end.

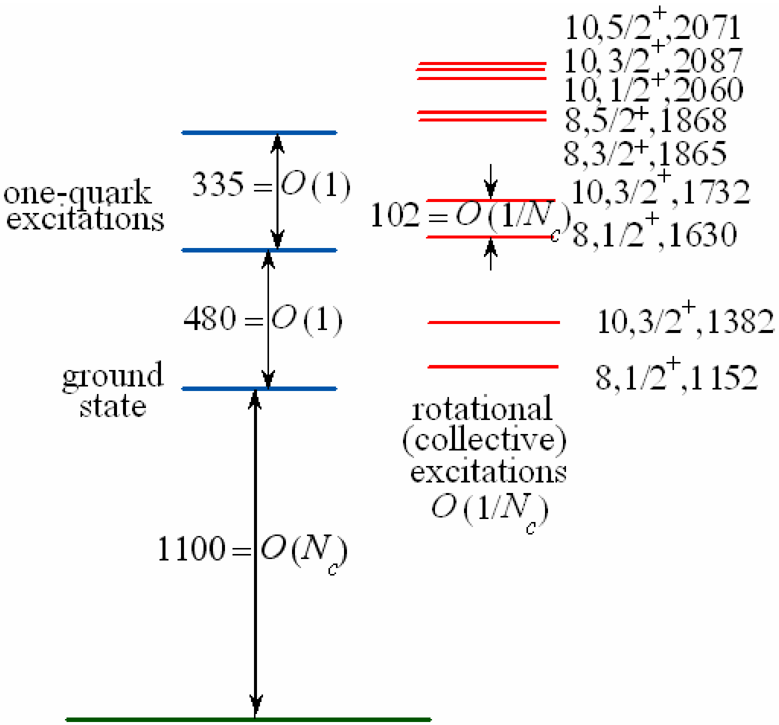
## How does baryon spectrum look like at $N_c \to \infty$ ?

(imagine number of colours is not 3 but 1003)

Witten (1979): Nc quarks in a baryon can be considered in a mean field (like electrons in a large-Z atom or nucleons in a large-A nucleus).

Colour field fluctuates strongly and cannot serve as a mean field, but colour interactions can be Fierz-transformed into quarks interacting with mesonic fields (possibly non-locally), whose quantum fluctuations are suppressed as $O(1/N_c)$.

***Examples***: instanton-induced interactions, NJL model, bag model…




The mean field is classical

Baryons are heavy objects, with mass $O(N_c)$

One-particle excitations in the mean field have energy $O(1)$

Collective excitations of a baryon as a whole have energy $O(1/N_c)$

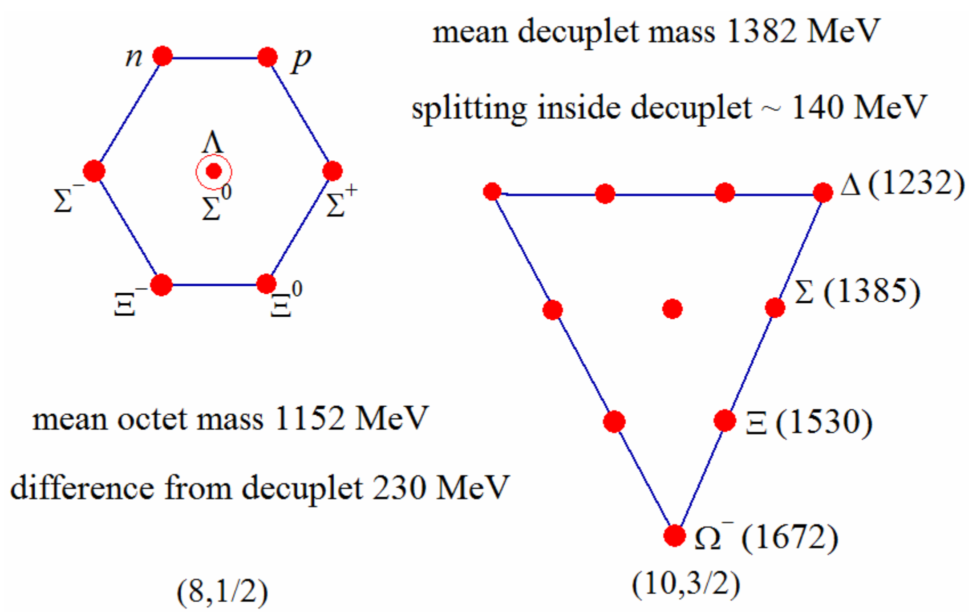
Important  Q.: if $N_c \to \infty$ what is smaller, $\frac{m_s}{\Lambda}$ *or* $\frac{1}{N_c}$?

the answer:

splitting inside SU(3) multiplets is $\sim m_s N_c$, numerically ~140 MeV

splitting between the centers of multiplets is $\sim \Lambda / N_c$, numerically ~ 230 MeV.

Hence, $m_s \leq \Lambda / N_c^2$ meaning that one can first put $m_s = 0$, obtain the degenerate SU(3) multiplets, and only at the final stage account for nonzero $m_s$, leading to splitting inside multiplets, and mixing of SU(3) multiplets.



$$H = \gamma^0(-i\partial_i\gamma^i + S + iP\gamma^5 + V_\mu\gamma^\mu + A_\mu\gamma^\mu\gamma^5 + T_{\mu\nu}\frac{i}{2}[\gamma^\mu\gamma^\nu])$$

equal-time Green function

[ Petrov, Polyakov (2004) ]

$$\text{nucleon mass} = N_c(E_{val} + E_{sea}) - (\text{no field})$$

its minimum determines the mean field.

**Baryon resonances** may be formed not only from quark excitations as in the customary non-relativistic quark models, but also **from particle-hole excitations** and ``Gamov--Teller'' transitions.

## What is the symmetry of the mean field?

Variant I (maximal symmetry): the mean field is SU(3)-flavor- and SO(3)-rotation-symmetric, as in the old constituent quark model (Feynman, Isgur, Karl,…) *A priori* nothing wrong about it, but $g_{\pi NN} \approx 13$ means the pion field in baryons is strong, and at large Nc it must be classical. However, there is no way to write the classical pion field in an SU(3) symmetric way!

There is no general rule but we know that most of the heavy nuclei (large *A*) are not spherically-symmetric. Having a dynamical theory one has to show which symmetry leads to lower ground-state energy.

Variant II (partly broken symmetry) : the mean field for the ground state breaks spontaneously SU(3) x SO(3) symmetry down to SU(2) symmetry of simultaneous space and isospin rotations, like in the `hedgehog' *Ansatz*

$$\pi^a = n^a P_0(r), \quad n^a = \frac{x^a}{r}, a = 1,2,3; \quad \pi^{4,5,6,7,8} = 0.$$

breaks SU(3) and SO(3) separately but supports SU(2) symmetry of simultaneous spin and isospin rotations !

Since SU(3) symmetry is broken, the mean fields for ***u,d*** quarks, and for ***s*** quark are **completely different** – like in large-A nuclei the mean field for Z protons is different from the mean field for A-Z neutrons.

Full symmetry is restored when one SU(3)xSO(3) rotates the ground and one-particle excited states $\Longrightarrow$ there will be "rotational bands" of SU(3) multiplets with various spin and parity.

In the `hedgehog' mean field with $SU(2)_{\text{iso+space}}$ symmetry:

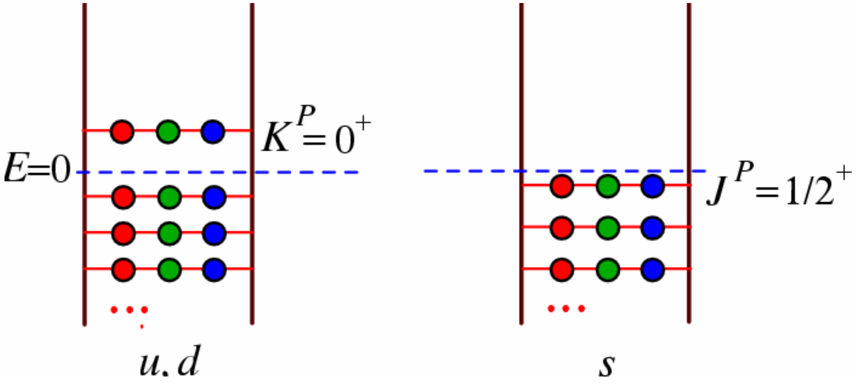
One-particle levels for ***s*** quarks are characterized by $J^P$ where **J** = **L** + **S**.

One-particle levels for ***u,d*** quarks are characterized by $K^P$ where **K** = **T** + **J**.

According to the Dirac theory, all negative-energy levels, both for s and u,d quarks,have to be fully occupied, corresponding to the vacuum.

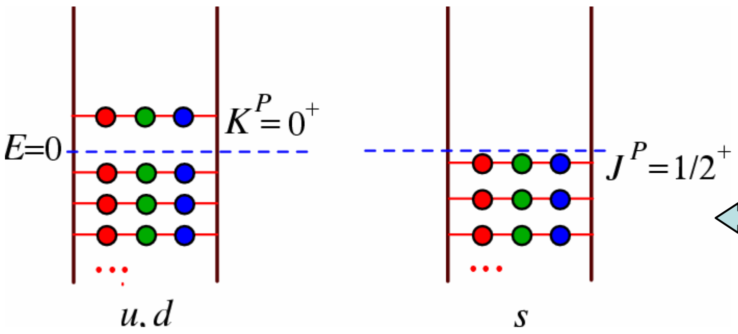
Exactly Nc quarks in antisymmetric state in colour occupy each of the 2J+1 (or 2K+1) degenerate levels; they form closed shells.

Filling in the lowest level with E>0 by Nc quarks makes a baryon :



## Ground-state baryon and lowest resonances

We assume confinement (*e.g.* $S \sim r$) meaning that the ***u,d*** and ***s*** spectra are discrete.



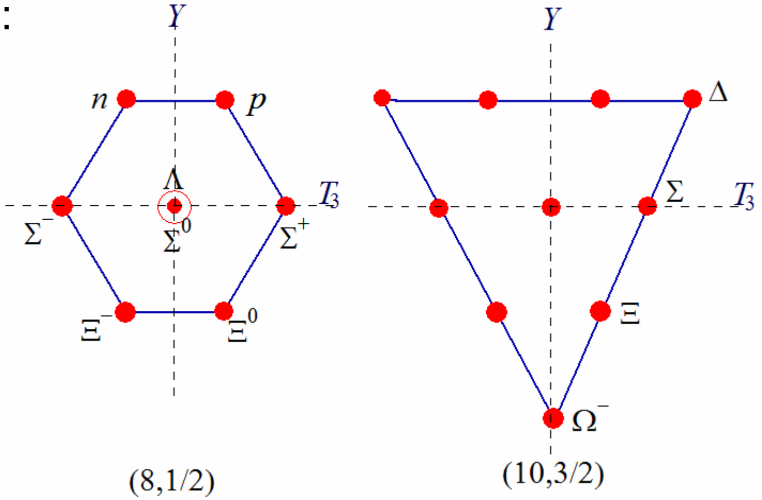

One has to fill in **all negative-energy levels** for ***u,d*** and separately for ***s*** quarks, and the **lowest positive-energy level** for ***u,d***.

This is how the ground-state baryon looks like.

This filling scheme breaks SU(3) symmetry (u,d and s quarks are treated differently), and rotational SO(3) symmetry. Both are restored when one considers SU(3) and SO(3) rotations of this filling scheme. Rotations are quantized and result in a `rotational band', in this case octet, spin ½, and decuplet, spin 3/2:

The lowest baryon multiplets:

1152(**8**, 1/2+) and 1382(**10**, 3/2+)



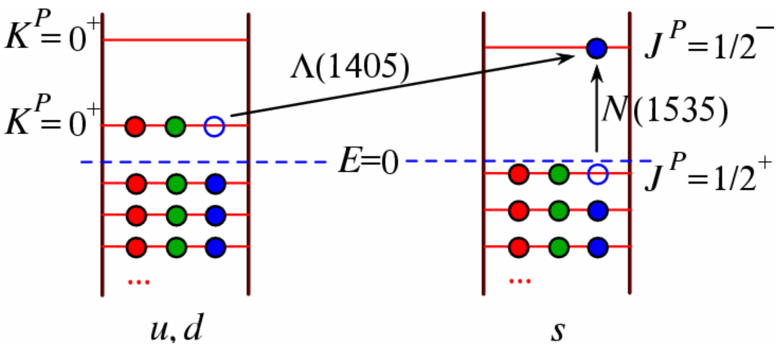
## The lowest resonances beyond the rotational band

[Diakonov, Nucl. Phys.A (2009)]

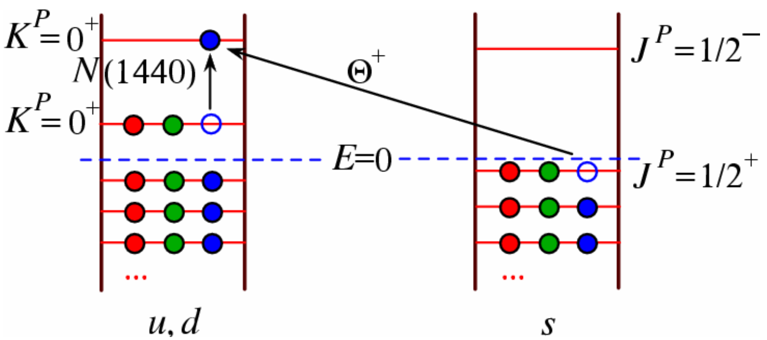
are **Λ(1405, ½-), N(1440, ½+)** and **N(1535, ½-).** They are one-particle excitations:
*uds*

**Λ(1405, ½-)** and **N(1535, ½-)** are two different ways to excite an ***s*** quark level. **N(1535, ½-)** is in fact a **pentaquark** $uud d\bar{s}$ [B.-S. Zou (2008)]

$N(1535) \to N\eta$ 45-60%




*important conclusion: s-quark level is about 130 MeV lower than u,d-quark level.*




**N(1440, ½+)** (*uud*) and $\Theta^+$**(½+)** ($uudd\bar{s}$) are two different excitations of the same level of ***u,d*** quarks. $\Theta^+$ is an analog of the **Gamov-Teller excitation** in nuclei! [when a proton is excited to the neutron's level or *vice versa*.]

Sum rule:

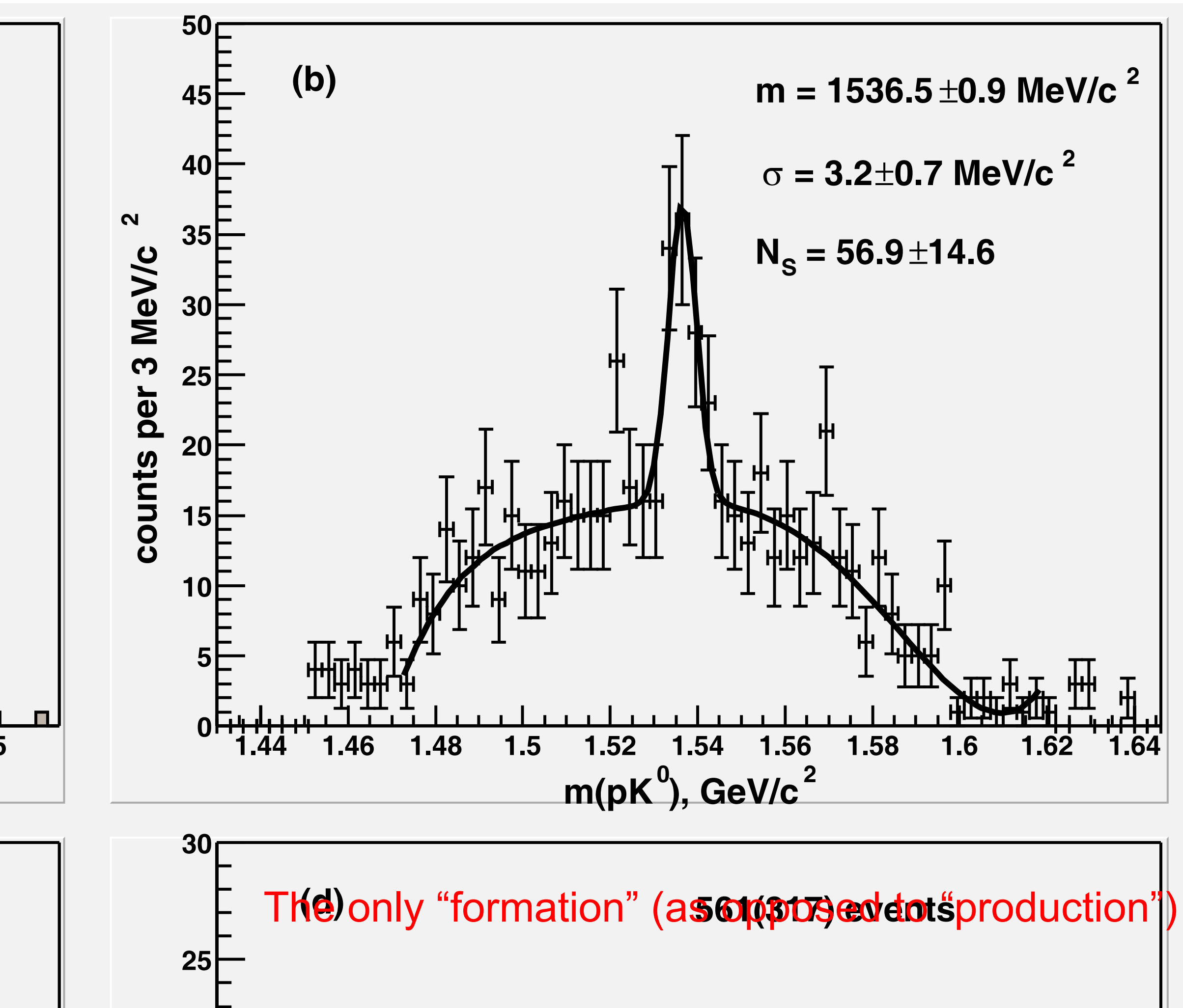
$$m_\Theta \approx 1440 + 1535 - 1405 \approx 1570\,\text{MeV} \qquad \text{(from PDG)}$$

$$m_\Theta \approx 1365 + 1510 - 1405 \approx 1470\,\text{MeV} \qquad \text{(from pole positions)}$$

$$m_\Theta = 1520 \pm 50\,\text{MeV}$$

# Experiments after 2005

1. A. Dolgolenko et al. (ITEP) have nearly doubled the statistics of the $K^{+}\mathrm{Xe} \to K^{0}p + \ldots$ events. The observed spectrum of $m(K^{0}p)$ :




$$\left.\frac{S}{\sqrt{S+B}}\right|_{S=60,B=68} = 5.3$$

$$m = 1537 \pm 2\,\mathrm{MeV}$$

$$\Gamma = 0.36 \pm 0.11\,\mathrm{MeV}$$

The only "formation" (as opposed to "production") experiment to date!

Bow and arrows can be more precise than a gun

2. A. Aleev *et al.* [SVD-2, MSU] studied $pA \to K^0 p + \ldots$ @ 70 GeV.

A strong signal seen in two independent samples:

**Fig. 2.** Sample I: The $(pK_s^0)$ invariant mass spectrum for the events with $N_{charged} < 8$. The dashed line stands for the peak extracted from the fit.

**Fig. 5.** Sample II: a) The $(K^+K^-)$ invariant mass spectrum. b) The $(K^-p)$ invariant mass spectrum.

**Fig. 7.** The $(\Lambda\pi^+)$ invariant mass spectrum with the additional $p_\Lambda < 6\ GeV/c$ cut.

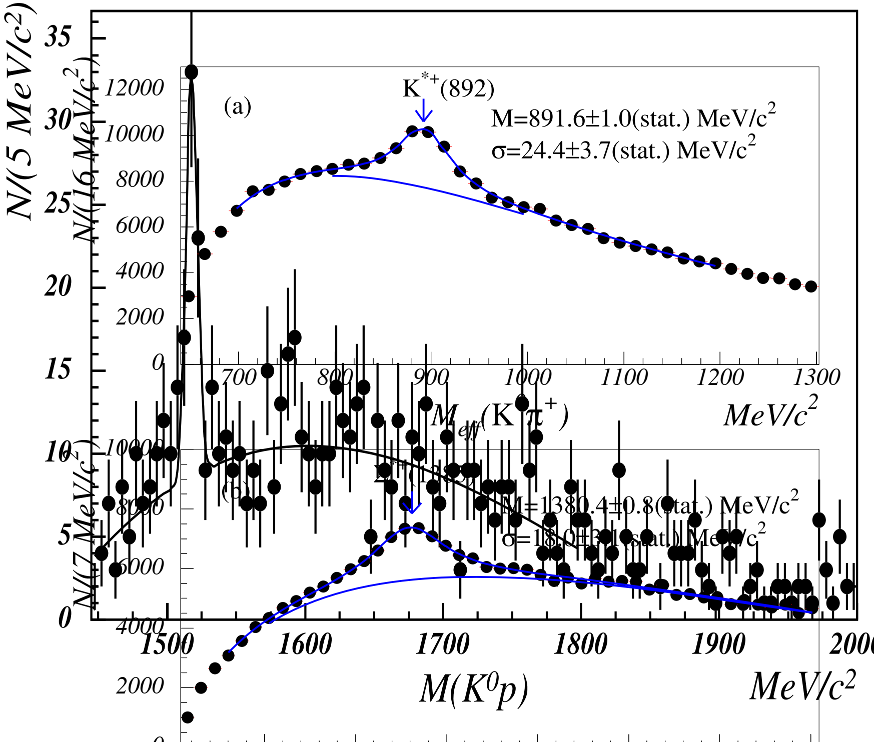


**Fig. 3.** Sample I: The $(pK_s^0)$ invariant mass spectrum for $K_s^0$ decaying inside the vertex detector with additional quality cuts explained in text.

**Fig. 6.** Sample II: a) The $(\pi^+K_s^0)$ invariant mass spectrum. b) $(\Lambda\pi^+)$ invariant mass spectrum.

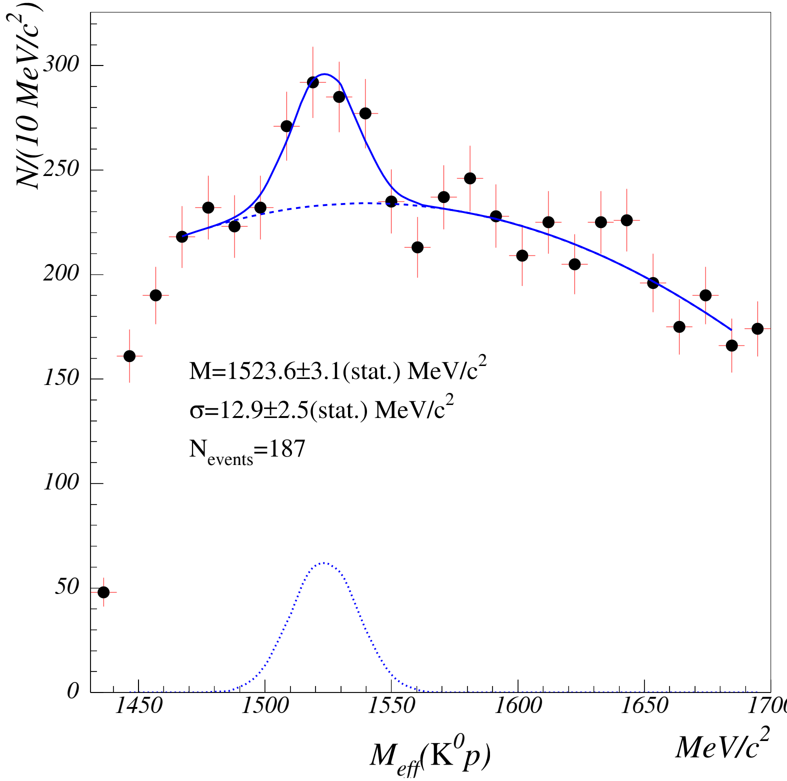


**Fig. 8.** Sample II: The $(pK_s^0)$ invariant mass spectrum with the cuts explained in text. The dotted line in the bottom stands for the peak extracted from the fit.

$$m = 1522 \pm 2 \pm 3\,\text{MeV}, \qquad \left.\frac{S}{\sqrt{S+B}}\right|_{S=392,\,B=1990} = 8.0$$

To estimate the natural width of the observed peak we selected events with the best reconstruction accuracy, applying the track quality cuts:

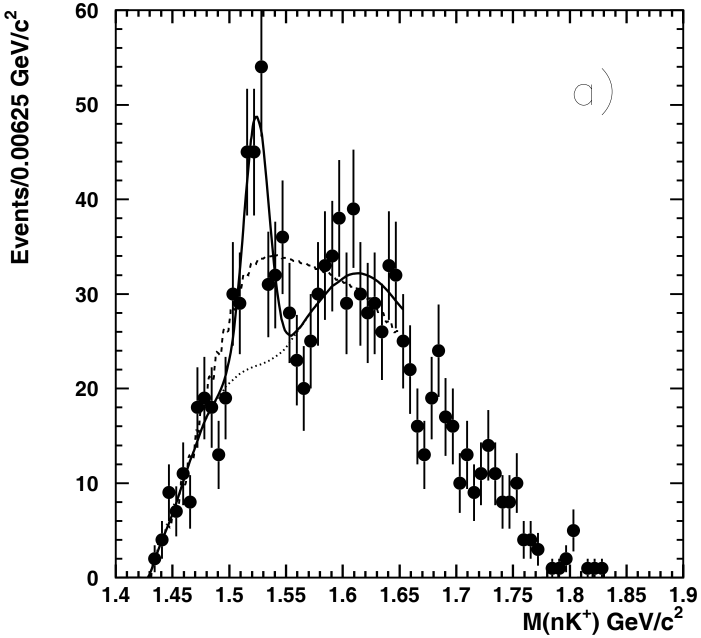
Effective mass of the $pK_s^0$ system is plotted in Fig.8. A peak is seen at the mass $M = 1523.6 \pm 3.1\ MeV/c^2$ with

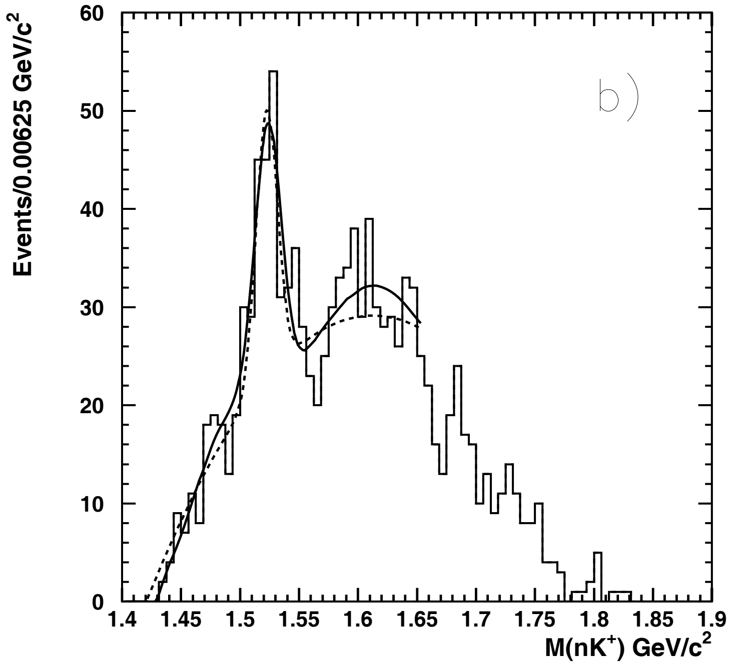
b=940 background events. The statistical significance for the peak is s/

Two different models were tried to describe the background. The first was taken from RQMD Monte Carlo

3. LEPS collaboration (SPring-8, Osaka), T. Nakano et al. (2008):

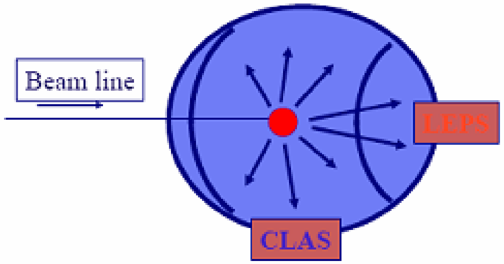
$$\gamma d \rightarrow K^- p K^+ n$$




$$m_\Theta = 1524 \pm 2 \pm 3\,\text{MeV}$$

Remarkably, LEPS does see the resonance in the same reaction and at the same energy where CLAS does <u>not</u> see a signal. However, LEPS detector registers particles in the forward direction, while CLAS registers everything except in the forward direction:



This scheme, with two levels for ***u,d*** quarks, and two levels for ***s*** quarks, seems to explain nicely all baryon resonances up to 2 GeV!

***A check:*** splitting between parity-plus and parity-minus multiplets, as due to rotation of a baryon as a whole:

$$(\mathbf{10}, 3/2^-, 1850) - (\mathbf{8}, 1/2^-, 1615) = 235\,\mathrm{MeV} = \frac{3}{2I_1}$$

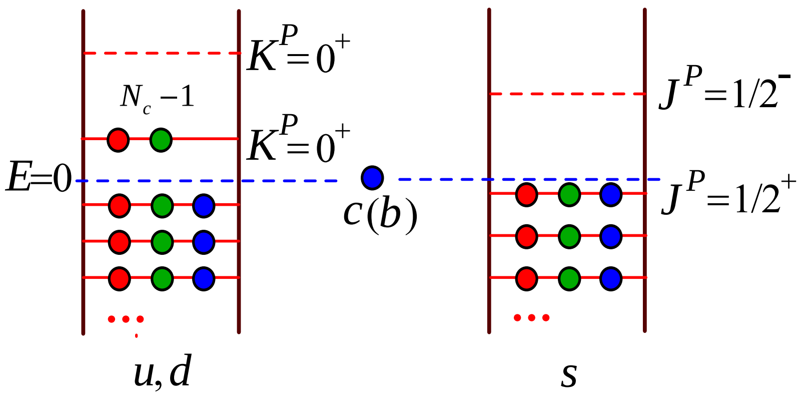
$$(\mathbf{10}, 3/2^+, 1382) - (\mathbf{8}, 1/2^+, 1152) = 230\,\mathrm{MeV} = \frac{3}{2I_1}$$

**The moments of inertia are the same !**

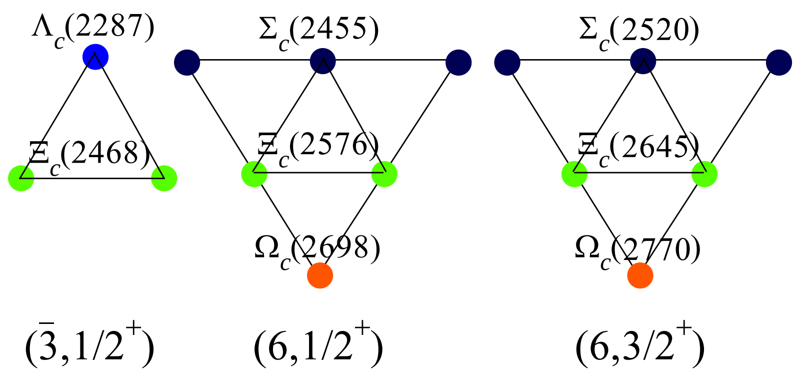
**Meaning that the large-Nc logic works well !**

# Charmed and bottom baryons from the large-Nc perspective

If one of the Nc ***u,d*** quarks is replaced by ***c*** or ***b*** quark, the mean field is still the same, and all the levels are the same! Therefore, charmed baryons can be ***predicted*** from ordinary ones!




standard charmed baryons



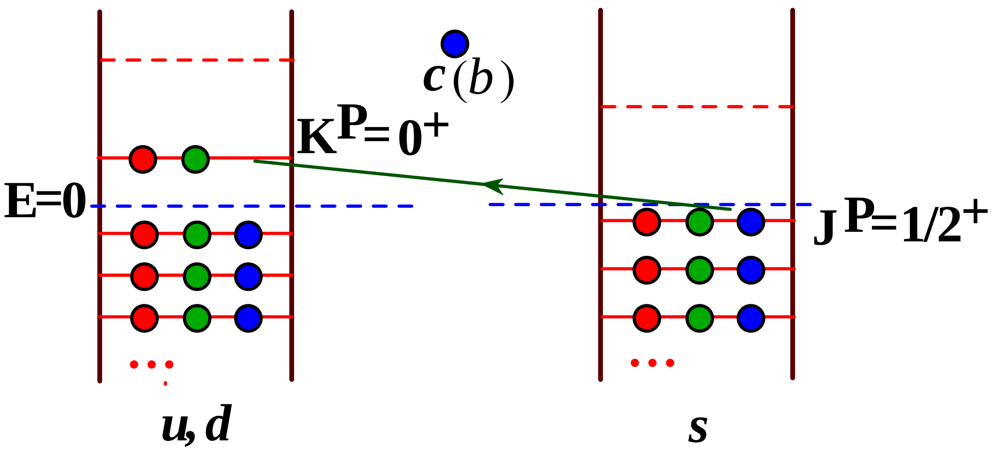

mean masses: $2408$ $\frac{2536+2603}{2}=2570$

**degenerate** up to $67\,\mathrm{MeV} \sim 1/N_c^2$

The difference 2570 – 2408 = **162 MeV** = $\frac{1}{I_1}$ . On the other hand, $\frac{1}{I_1}$ can be found from the octet-decuplet splitting $\frac{1}{I_1}$ = **153 MeV**. Only a **6%** deviation from large-Nc prediction.

It is a check that the mean field and the position of levels **do not change much** from light to charmed baryons!

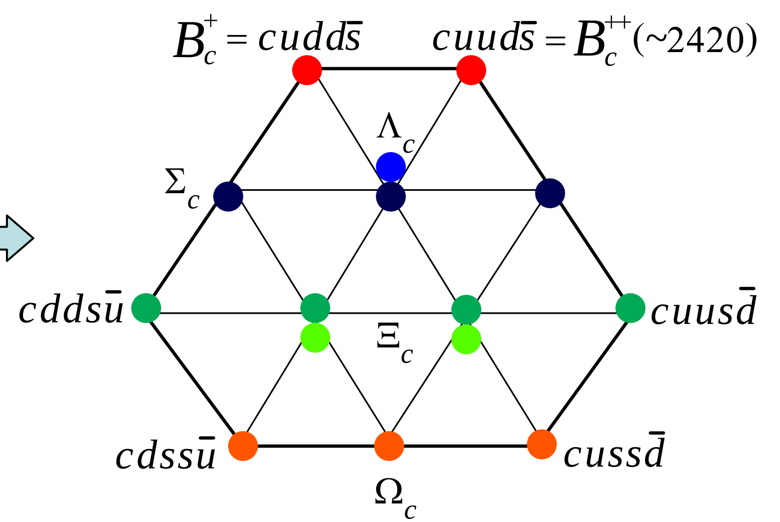
There is also a Gamov-Teller-type transition, resulting in pentaquarks $cuud\bar{s}, cudd\bar{s}$ :




***excitation energy is only 130 MeV!***

meaning charmed pentaquarks are only 130 MeV heavier than the lightest charmed baryon $\Lambda_c(2287)$

exotic 5-quark charmed baryons




$(\overline{15}, 1/2^+)$

**anti-decapenta-plet**

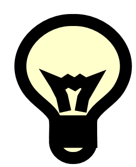
Exotic 5-quark charmed baryons $B_c^{++}, B_c^+$ are light (**~2420 MeV**) and can decay only weakly:

$$B_c^{++} \rightarrow p\pi^+, K^+K^0p, \ldots$$

**clear signature, especially in a vertex detector.**

**Life time** $10^{-13}$ $s$

strong decay threshold $m(\Lambda_c K) = 2780\,\text{MeV}$



$B_c =$ **"Beta-sub-c"**

***NB*:** $\Theta_c = uudd\bar{c}$ is another pentaquark, hypothetized by Stancu, and Lipkin and Karliner; in our approach it must be ~500 MeV heavier!

Big question: What is the production rate of $B_c^{++,+}(\sim 2420) = cuud\bar{s}, cudd\bar{s}$ ?

Expected production rate at LHC [Yu. Shabelsky + D.D.] :

$$\left.\begin{array}{ll} \bar{d}: & \dfrac{dN}{dy} \sim 10^{-4} \\ c\text{ baryons}: & \dfrac{dN}{dy} \sim 10^{-3} \end{array}\right\} \Rightarrow \quad B_c: \quad \frac{dN}{dy} \sim 10^{-7} \ ?$$

Decays:

$$B_c^{++} \to \left\{ \begin{array}{c} p\pi^+ \\ pK^+\bar{K}_0 \\ p\phi\pi^+ \to pK^+K^-\pi^+ \\ \ldots \end{array} \right. \qquad B_c^{+} \to \left\{ \begin{array}{c} p\pi^0 \\ p\pi^+\pi^- \\ p\phi \to pK^+K^- \\ \ldots \end{array} \right.$$

typical $Br \sim 10^{-2}$

LHCb: $10^{15}$ particles/ year $\times$ $10^{-9}$ $\sim$ $10^{6}$ $B_c^{++,+}$ / year

Somewhat less number but still a considerable amount of $B_b^{+,0}(\sim 5750) = buud\bar{s}, budd\bar{s}$ events expected at LHC ! Should decay mainly as $B_b \to B_c + \text{anything}$

# Summary

1. **Hierarchy of scales**:

baryon mass ~ Nc
one-quark excitations ~ 1
splitting between multiplets ~ 1/Nc
mixing, and splitting inside multiplets ~ m_s Nc < 1/Nc

2. **The key issue is the symmetry of the mean field** : the number of states, degeneracies follow from it. I have argued that the mean field in baryons is not maximal but next-to-maximal symmetric, $SU(3)\times SO(3)\to SU(2)$ . Then the number of multiplets and their (non) degeneracy is approximately right.

3. This scheme confirms the existence of $\left(\overline{\mathbf{10}},\frac{1}{2}^{+}\right)$ as a "Gamov – Teller" excitation, in particular, $m_{\Theta}=1520\pm 50\,\mathrm{MeV}.$

**4.** An extension of the same idea, based on large Nc, to charmed (bottom) baryons leads to a prediction of **anti-decapenta-plets of pentaquarks**. The lightest $B_c^{++,+}(\sim 2420)=cuu(d)d\bar{s}$ and $B_b^{+,0}(\sim 5750)=buu(d)d\bar{s}$ are exotic and **stable under strong decays**, and **should be looked for!**

## Additional conclusions

1. "Baryons are made of three quarks" contradicts the uncertainty principle. In fact, already at low resolution ~65% of nucleons are made of 3 quarks, ~25% of 5 quarks, and ~10% of more than 5.

2. The 5-quark component of baryons is rather well understood, and should be measured directly

3. Pentaquarks (whose lowest Fock component has 5 quarks) are not too "exotic" – just Gamov-Teller excitations. In addition to the narrow $\Theta^+ = uudd\bar{s}$ there is a new prediction of charmed (and bottom) pentaquarks $B_c^{++,+} = cuu(d)\bar{s}, B_b^{+,0} = buu(d)\bar{s}$ which decay only weakly.