Lecture 2: PENTAQUARKS UPDATE

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Heavy Quark Physics

Dubna, June 6-16, 2005

- Historical note

- Review of the new wave of exotics Θ^+, Ξ^{--}, Ξ_c^0

- Latest experimental results

  - Trento Workshop February 2005, SPring-8, g10@JLAB

  - APS meeting, April 2005, g11@JLAB

- Theoretical approaches, short look

- Conclusions

References:
F.S. hep-ph/0504284

HISTORICAL NOTE

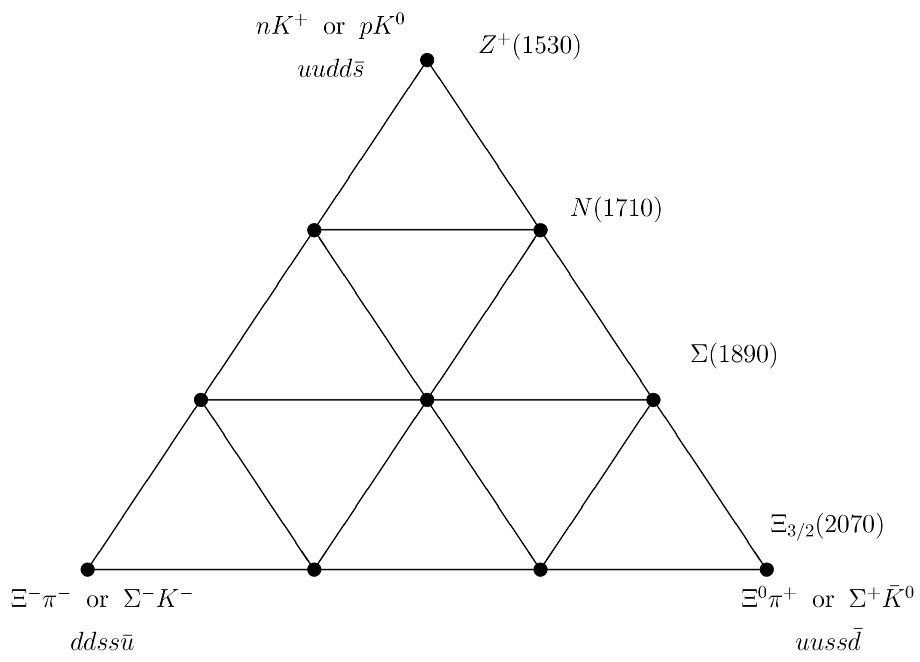
Light pentas: since 70' until 1984
Searches in the mass range 1.74 GeV to 2.16 GeV
Parity not important, in fact negative

Heavy pentas: Theory 1987 $\rightarrow$ E791 (Fermilab) 1998 inconclusive
Mass range below threshold
$N + D_s$ **= 2908 MeV or** $\Lambda + D$ **= 2982 MeV**
Parity: negative

Positive parity heavy pentas $uudd\bar{c}$**, F. S. PRD58(1998)**

NEW WAVE

D.Diakonov, V.Petrov, M.Polyakov, Z. Phys. A359(1997)305



Chiral soliton model: Θ^+ is a collective excitation of the mean chiral field → low mass and narrow width

PRESENT EXPERIMENTAL STATUS: LIGHT PENTAS

Θ^+ **M ≃1530 MeV, $\Gamma < 25$ MeV, I = 0**

*10 or more independent measurements report confirmation

*nearly as many report null evidence (HERA-B, PHENIX, BES)

*Deuterium results from SPring-8 (background estimate)
(T. Nakano → encouraging)

*High statistics experiments on hydrogen g11 and deuterium g10, CLAS detector

$\Xi_{3/2}^{--}$ M $\simeq$ 1862 MeV, $\Gamma \simeq$ 18 MeV

- observed and not seen at Na49 at CERN
  confirmed at Trento 2005

- not seen WA89 (Σ^--nucleus), CDF ($p\bar{p}$), BaBar (e^+e^-)

PRESENT EXPERIMENTAL STATUS: HEAVY PENTAS

Θ_c^0 **M $\simeq$ 3100 MeV, $\Gamma \simeq$ 12 MeV**

- **observed by H1 Collaboration (HERA) March 2004**
  confirmed at Trento 2005

- **null evidence from ZEUS ($e-p$ collisions), CDF ($p\bar{p}$) collisions, Belle ($B-meson$ decay)**

LEPS results presented by K. Hicks, Trento, February 2005

LEPS New LD2 and LH2 runs

- Data taken from Oct. 2002 to Jun. 2003.
- ~$2 \cdot 10^{12}$ photons on a 15cm-long LD2 target.
- LH2 data were taken in the same period with ~ $1.4 \cdot 10^{12}$ photons on the target.

# of photons: LH2:LD2 ≈ 2:3

# of events from a proton: LH2:LD2≈ 2:3
(e.g. KKp from ϕ production)

# of events from a nucleon: LH2:LD2≈ 1:3

Search for Pentaquarks at CLAS

- **g10**
  deuteron, $E_\gamma \sim$ 1.0 - 3.5 GeV , completed 2004

- **g11**
  proton, $E_\gamma \sim$ 1.6 - 3.8 GeV , completed 2004, see APS05

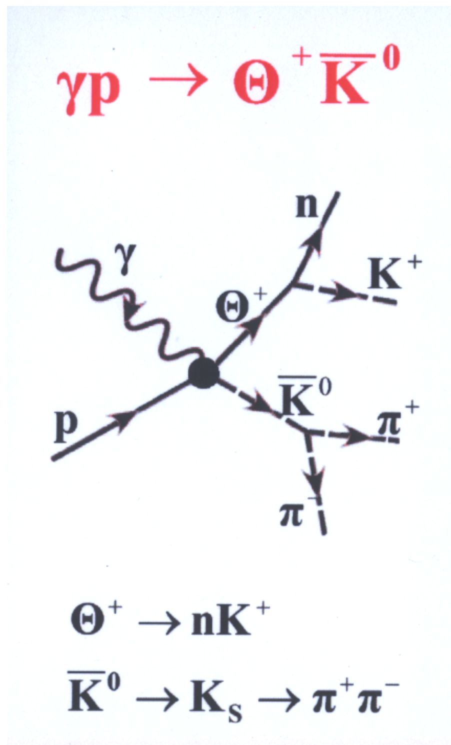
- **eg3**
  deuteron, $E_\gamma \sim$ 4.0 - 5.4 GeV , data taking completed 2005

- **Super-g**
  proton, $E_\gamma \sim$ 3.8 - 5.7 GeV , planned 2006

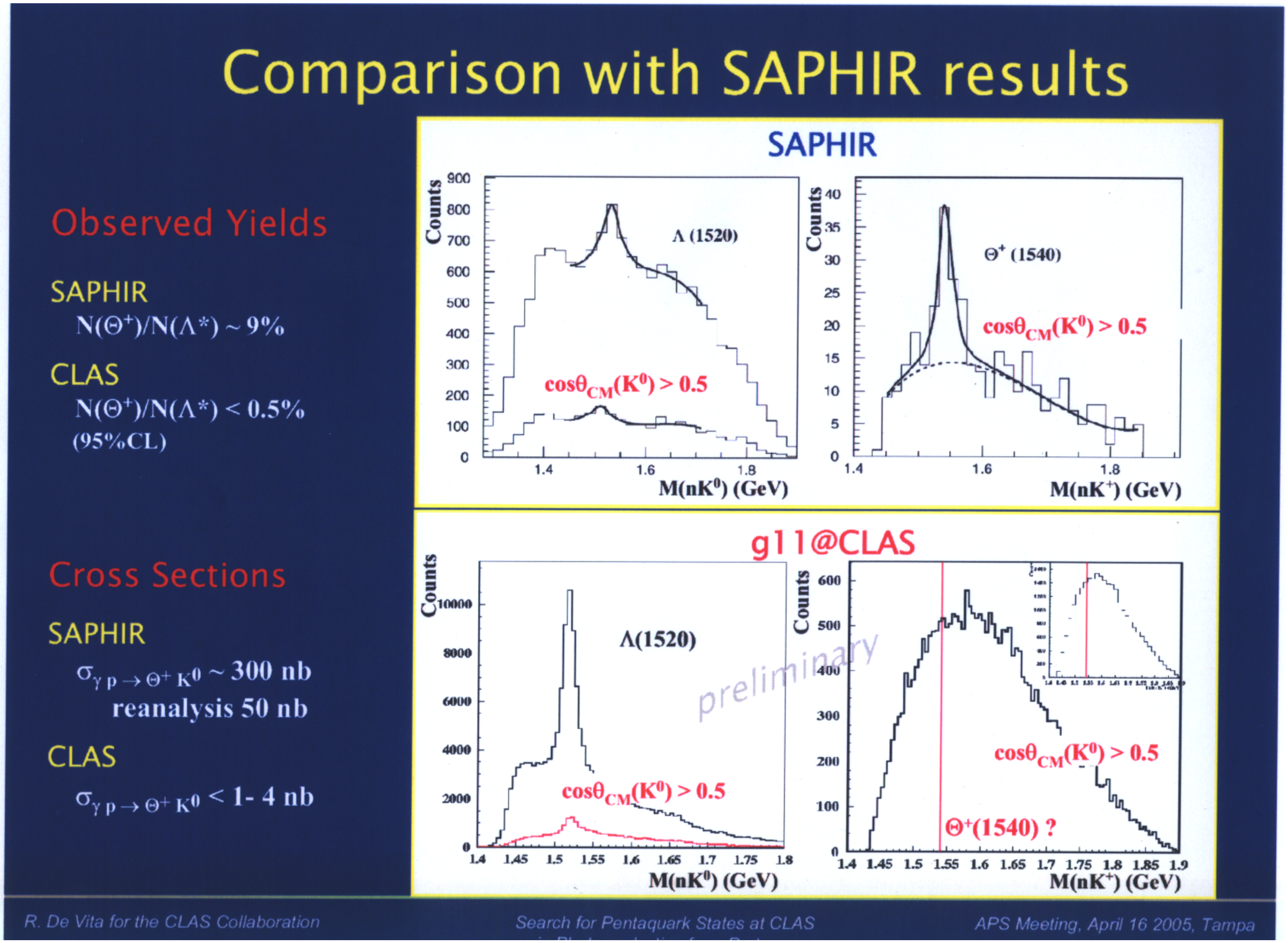
g11@JLAB

Collect more than 10 times the statistics of previous mesurements

Run in May - July 2004, preliminary at APS meeting, April 2005



g11@JLAB



Comparison with SAPHIR results
Observed Yields
SAPHIR
N(Θ+)/N(Λ*) ~ 9%
CLAS
N(Θ+)/N(Λ*) < 0.5%
(95%CL)
Cross Sections
SAPHIR
σγ p → Θ+ K0 ~ 300 nb
reanalysis 50 nb
CLAS
σγ p → Θ+ K0 < 1- 4 nb
SAPHIR
Λ (1520)
Θ+ (1540)
cosθCM(K0) > 0.5
Counts
M(nK0) (GeV)
M(nK+) (GeV)
g11@CLAS
Λ(1520)
preliminary
Θ+(1540) ?
R. De Vita for the CLAS Collaboration
Search for Pentaquark States at CLAS
APS Meeting, April 16 2005, Tampa

PRESENT APPROACHES to the ANTIDECUPLET

- Spin and parity of $\Theta^+ \rightarrow$ polarization experiments
- Consistency with partial wave analysis
- Photoproduction cross sections on proton, neutron
- Chiral soliton model revisited, masses & widths
- Constituent quark models, masses & widths
- Octet-antidecuplet or higher representation mixing
- Group theoretical classification of
$q \times q \times q \times q \times \bar{q}$ states $\rightarrow$ mass formulae
- Heptaquarks or $K\pi N$ molecular picture
- Skyrme model (bound state or rigid rotator)
- Description of pentas in the instanton model
- QCD sum rules
- Lattice calculations
- Magnetic moments of pentaquarks
- Θ^+ in relativistic heavy ion collisions

MAIN ISSUES

- **The mass of Θ^+**
- **The strong decay width**
- **Spin and Parity**
- **Splitting between isomultiplets**
- **SU(3)- flavour representation mixing**
- **Production mechanism**

Lattice QCD results

- Quenched approximation $\rightarrow$ dynamical effects are omitted, but correct picture for narrow states

- Action chirally symmetric at vanishing quark mass
$\rightarrow$ one can reach light quark masses

- Choice of operators is crucial to have the best overlap with Θ^+
$\rightarrow$ Kaon-Nucleon type or diquark-diquark-antiquark structure

- Difficult to distinguish the resonance from the continuum
$\rightarrow$ controversy about the existence of a resonant state

- Presently - consensus ? - lowest state has negative parity

QCD sum rules

Lowest state has negative parity, M $\sim$ 1.5 GeV

S. L. Zhu, PRL 91 (2003) [hep-ph/0307345]
Sugyama, Doi, Oka
Kwon, Hosaka, S. H. Lee, hep-ph/0505040
Wang, Yang, Wan, hep-ph/0501015

CONSTITUENT QUARK MODELS

TWO STANDARD MODELS

Colour-Spin (CS)

$$V_{CS} = -\sum_{i<j}^{5} C_{ij}^{CS} \lambda_i^c \cdot \lambda_j^c \vec{\sigma}_i \cdot \vec{\sigma}_j$$

Lowest resonant state has $J^P = 3/2^-$

Flavour-Spin (FS)

$$V_{FS} = -\sum_{i<j}^{4} C_{ij}^{FS} \lambda_i^F \cdot \lambda_j^F \vec{\sigma}_i \cdot \vec{\sigma}_j$$

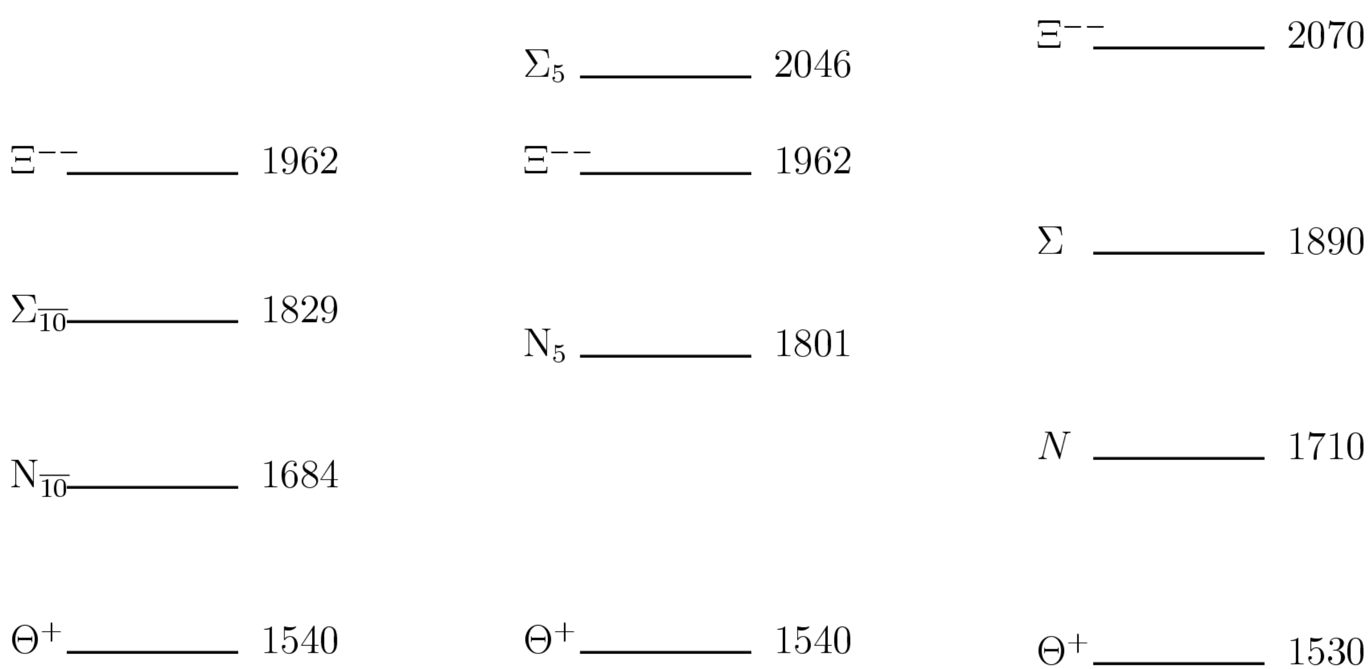
Lowest resonant state has $J^P = 1/2^+$

How important is spontaneous breaking of chiral symmetry ?

PENTAQUARK SPECTRUM in the FS MODEL

nearly ideal mixing

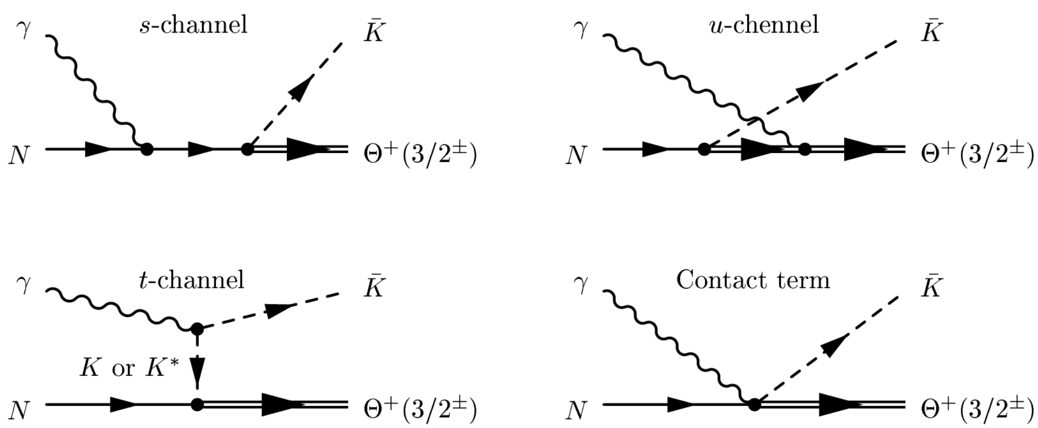
F. S. PLB595,269(2004);erratum PLBB598,295(2004).



a) pure antidecuplet   b) mixed with the octet   c) DPP 1997

Production mechanism on nucleon, $J^P = 1/2^+, 3/2^\pm$

Nam, Hosaka, Kim, hep-ph/0505134



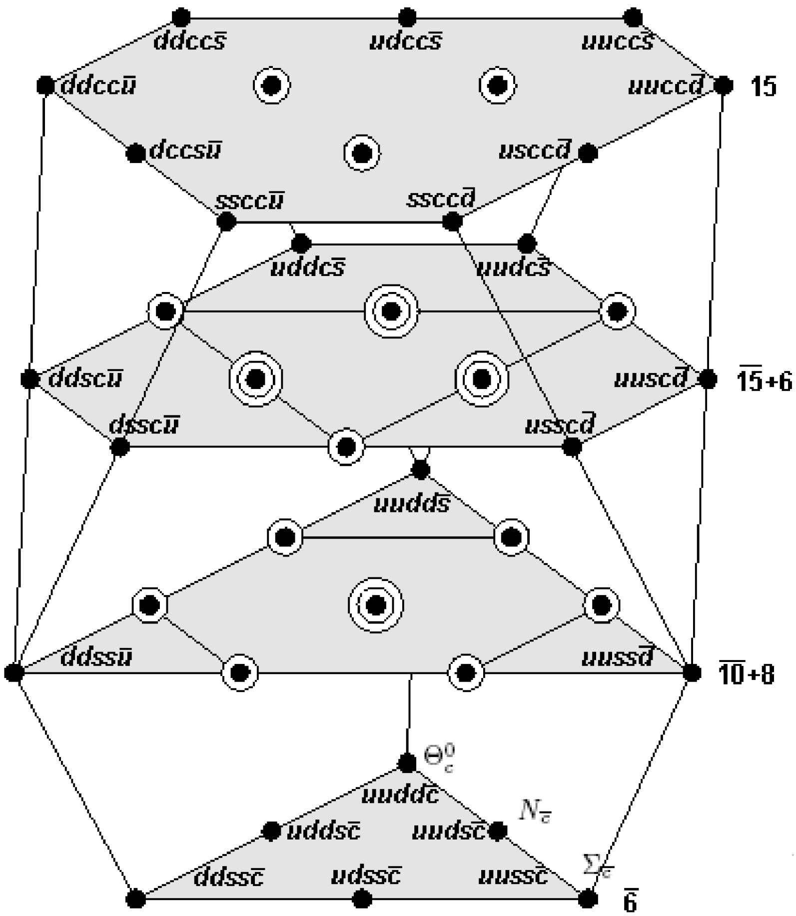
State dependent result

$J^P = 1/2^+$ $\sigma \sim 1$ nb for n and p

$J^P = 3/2^-$ **Proton** $\sigma \sim$ **4 nb**, **Neutron** $\sigma \sim$ **200 nb**

CHARMED PENTAQUARKS in the $\overline{60}$-plet of SU(4)

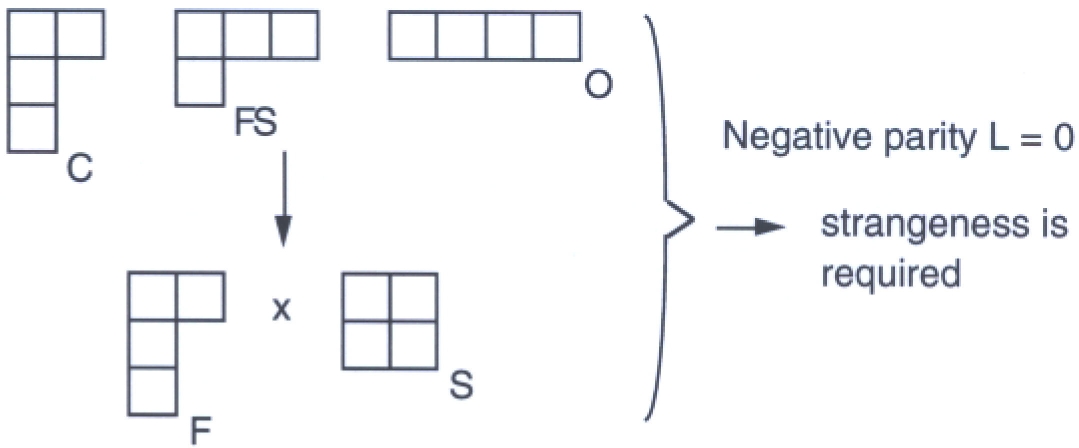
Bin Wu & Bo-Qiang Ma, hep-ph/0402244



Negative parity pentaquarks

C. Gignoux et al., PLB193(1987)323

H. J. Lipkin, PLB195(1987)484

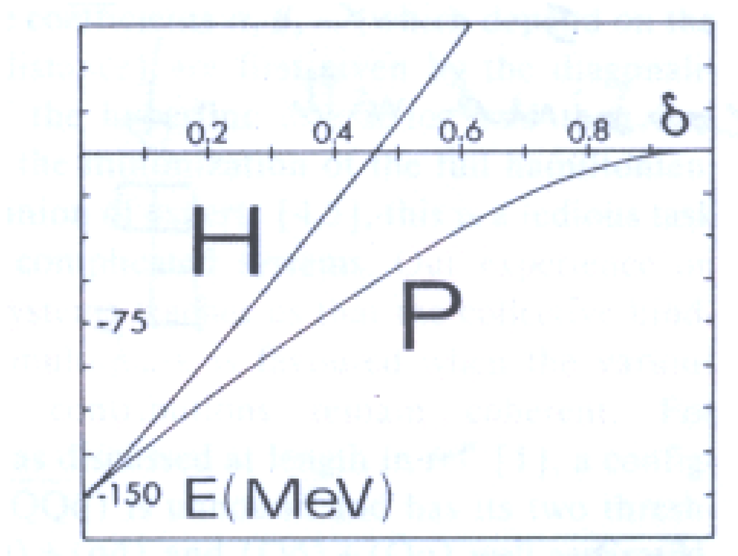


Negative parity pentaquarks

C. Gignoux et al., PLB193(1987)323

$$V_{CS} = -C_{CS} \sum_{i<j}^{5} \lambda_i^c \cdot \lambda_j^c \vec{\sigma}_i \cdot \vec{\sigma}_j$$

$$\Delta E = E(q^4\overline{Q}) - E(q^3) - E(q\overline{Q})$$



$\langle V_{CS}/C_{CS} \rangle$ = - 16; $\quad \delta = 1 - m_u/m_s$

Skyrme model (Callan-Klebanov version)

Riska & Scoccola, PLB299,338(1993)

1. strangeness is not required
2. the lowest states have positive parity ($\ell = 1$)

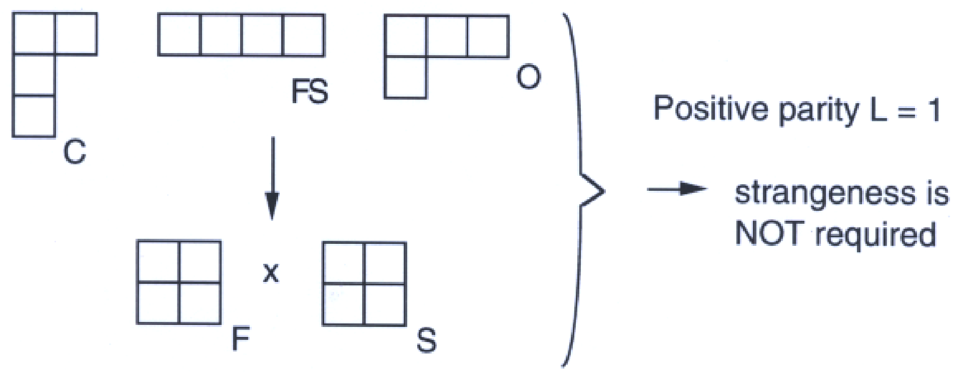
———— ($\ell = 2$)

———— ($\ell = 0$)

———— ($\ell = 1$) $M(q^4\bar{c}) \simeq 2.6$ - 2.7 GeV

Flavour-spin model

F. S. PRD58,111501(1998)



$$V_{FS} = -C_{FS} \sum_{i<j}^{4} \lambda_i^F \cdot \lambda_j^F \vec{\sigma}_i \cdot \vec{\sigma}_j$$

$P = +1$	V_{FS}/C_{FS}	$P = -1$	V_{FS}/C_{FS}
$[22]_F[22]_S[4]_{FS}$	- 28	$[211]_F[22]_S[31]_{FS}$	- 16
$[31]_F[31]_S[4]_{FS}$	- 64/3	$[211]_F[31]_S[31]_{FS}$	- 40/3

MASSES (MeV) of the antisextet charmed pentaquarks $P = +1$

Penta	I	Content	FS model FS 1998	$D - D - \bar{c}$ JW 2003	CS model KM2004
Θ_c^0	0	$u\ u\ d\ d\ \bar{c}$	2902	2710	2835 ± 30
N_c^0	1/2	$u\ u\ d\ s\ \bar{c}$	3161		
Ξ_c^0	1	$u\ u\ s\ s\ \bar{c}$	3403		

Predictions

FS 1988: F.S. PRD58(1998)111501

JW 2003: Jaffe & Wilczek PRL 91 (2003) 232003

Postdictions. K. Maltman, PLB604 (2004) 175

NB. $N + D = 2808$ MeV

CONCLUSIONS

- g11 results do not exclude the existence of pentaquarks. There are about 10 positive exp.

- Need of a deeper understanding of the production mechanism of Θ^+ and high statistics/resolution exp.

- New pentaquark meeting at JLAB autumn, 2005

WHY THE FS MODEL ?

- Good description of baryon spectra,

- Previous experience in heavy pentaquarks,
  F. S. PRD58(1998)111501

- Symmetry consistent with the large N_c limit of QCD
  $\rightarrow$ naturally small width for Θ^+
  (Jenkins & Manohar, hep-ph/0402024)
  N. B. The irreducible representations are referred to as Skyrme representations

- Support from lattice calculations,
  F. Lee, PENTAQUARK04, SPring-8

STABLE $\mathrm{uudd\bar{s}}$

F. S. & D. O. Riska, PLB575,242(2003)

1) qq **pairs**, schematic **Flavour-Spin** interaction

Glozman & Riska, PR268(1996)263

$$\mathbf{V}_\chi \; = \; - \, \mathbf{C}_\chi \; \sum_{\mathbf{i} \, < \, \mathbf{j}}^{\mathbf{4}} \lambda_{\mathbf{i}}^{\mathbf{F}} \cdot \lambda_{\mathbf{j}}^{\mathbf{F}} \; \tilde{\sigma}_{\mathbf{i}} \cdot \tilde{\sigma}_{\mathbf{j}}$$

$$C_\chi \sim 30 \text{ MeV} \quad (\Delta - N \; splitting)$$

enough if the antiquark is heavy

2) $q\bar{s}$ **pairs, schematic η-meson exchange**

Pion decay $D_s^* \to D_s \pi^0$ **requires** $\pi^0 - \eta$ **mixing**
$\to \eta$ **meson couples to** s **or** $\bar{s}$ **(Laehde and Riska, '02)**

$$\mathrm{V}_\eta = \mathrm{V}_\mathbf{0} \sum_{\mathbf{i}}^{\mathbf{4}} \tilde{\sigma}_\mathbf{i} \cdot \tilde{\sigma}_\mathbf{j}$$

$\mathrm{V}_\mathbf{0} = 2\mathrm{C}_\chi$ **lowers the binding energy by 350 MeV**

Conclusion: $\mathrm{V}_\chi + \mathrm{V}_\eta$ **makes** $\mathrm{uudd\bar{s}}$ **J^P=1/2$^+$, I=0, S=+1 stable**

REALISTIC FLAVOUR-SPIN HAMILTONIAN

Graz parametrization, Glozman, Papp & Plessas, PLB '96

$$H = \sum_i m_i + \sum_i \frac{\vec{p}_i^{\,2}}{2m_i} - \frac{\vec{P}^2}{2M} + \sum_{i<j} V_{conf}(r_{ij}) + \sum_{i<j} V_\chi(r_{ij})$$

$$V_{\text{conf}}(r_{ij}) = -\frac{3}{8}\lambda_i^c \cdot \lambda_j^c \, C \, r_{ij}$$

$$\begin{aligned} V_\chi(r_{ij}) \;&=\; \Bigg\{ \sum_{F=1}^{3} V_\pi(r_{ij}) \lambda_i^F \lambda_j^F \\ &+ \sum_{F=4}^{7} V_K(r_{ij}) \lambda_i^F \lambda_j^F + V_\eta(r_{ij}) \lambda_i^8 \lambda_j^8 + V_{\eta'}(r_{ij}) \lambda_i^0 \lambda_j^0 \Bigg\} \vec{\sigma}_i \cdot \vec{\sigma}_j \end{aligned}$$

N. B. **Parameters (m_i, meson masses, etc) fitted to baryon spectra**
$\rightarrow$ **good level order**

Internal Jacobi coordinates

$$\vec{x} = \vec{r}_1 - \vec{r}_2 \ ,$$
$$\vec{y} = (\vec{r}_1 + \vec{r}_2 - 2\vec{r}_3)/\sqrt{3}$$
$$\vec{z} = (\vec{r}_1 + \vec{r}_2 + \vec{r}_3 - 3\vec{r}_4)/\sqrt{6} \ ,$$
$$\vec{t} = (\vec{r}_1 + \vec{r}_2 + \vec{r}_3 + \vec{r}_4 - 4\vec{r}_5)/\sqrt{10}$$

Basis states of POSITIVE parity:

assume s^3p content for $[31]_O$

$$\psi_1 = \begin{array}{|c|c|c|}\hline 1 & 2 & 3 \\ \hline 4 \\ \cline{1-1} \end{array} = \langle \vec{x}\,|000\rangle\,\langle \vec{y}\,|000\rangle\,\langle \vec{z}\,|010\rangle$$

$$\psi_2 = \begin{array}{|c|c|c|}\hline 1 & 2 & 4 \\ \hline 3 \\ \cline{1-1} \end{array} = \langle \vec{x}\,|000\rangle\,\langle \vec{y}\,|010\rangle\,\langle \vec{z}\,|000\rangle$$

$$\psi_3 = \begin{array}{|c|c|c|}\hline 1 & 3 & 4 \\ \hline 2 \\ \cline{1-1} \end{array} = \langle \vec{x}\,|010\rangle\,\langle \vec{y}\,|000\rangle\,\langle \vec{z}\,|000\rangle$$

to be multiplied by $\langle \vec{t}\,|000\rangle$

Gaussian Ansatz

$$\psi_1^5 = \psi_0 \ z \ Y_{10} \ (\hat{z})$$

$$\psi_2^5 = \psi_0 \ y \ Y_{10} \ (\hat{y})$$

$$\psi_3^5 = \psi_0 \ x \ Y_{10} \ (\hat{x})$$

$$\psi_0 = [\frac{1}{48\pi^5\alpha\beta^3}]^{1/2} \mathrm{exp} \left[- \frac{1}{4\alpha^2} \left(x^2 + y^2 + z^2 \right) - \frac{1}{4\beta^2} t^2 \right]$$

Variational parameters α **,** β

Expectation values (MeV) and total energy

$$\mathbf{E} = \sum_{n=1}^{5} m_i + \langle T \rangle + \langle V_c \rangle + \langle V_\chi \rangle$$

$q^4\bar{q}$	$\sum_{n=1}^{5} m_i$	$\langle T \rangle$	$\langle V_c \rangle$	$\langle V_\chi \rangle$	E	M	α(fm)	β(fm)
$uudd\bar{d}$	1700	1864	442	-2044	1962	1452	0.42	0.92
$uudd\bar{s}$	1800	1848	461	-2059	2050	1540	0.42	1.01
$uuds\bar{d}$	1800	1535	461	-1563	2233	1732	0.45	0.92
$uuds\bar{s}$	1900	1634	440	-1663	2310	1800	0.44	0.87
$ddss\bar{u}$	1900	1418	464	-1310	2472	1962	0.46	0.92
$uuss\bar{s}$	2000	1410	452	-1310	2552	2042	0.46	0.87

The antidecuplet members with $Y = 1$ and $Y = 0$

$$M(N_{\overline{10}}) = \frac{1}{3}M(uudd\bar{d}) + \frac{2}{3}M(uuds\bar{s}),$$
$$M(\Sigma_{\overline{10}}) = \frac{2}{3}M(uuds\bar{d}) + \frac{1}{3}M(uuss\bar{s})$$

The octet members with $Y = 1$ and $Y = 0$

$$M(N_8) = \frac{2}{3}M(uudd\bar{d}) + \frac{1}{3}M(uuds\bar{s}) = 1568 \text{ MeV},$$
$$M(\Sigma_8) = \frac{1}{3}M(uuds\bar{d}) + \frac{2}{3}M(uuss\bar{s}) = 1936 \text{ MeV}.$$

THE ANTIDECUPLET MASS SPECTRUM (MeV) $P = +1$

Penta	$Y,\ I,\ I_3$	Present results	Carlson et al.
Θ^+	$2, 0, 0$	1540	1540
$N_{\overline{10}}$	$1, 1/2, 1/2$	1684	1665
$\Sigma_{\overline{10}}$	$0, 1, 1$	1829	1786
Ξ^{--}	$-1, 3/2, -3/2$	1962	1906

Carlson et al. PLB579(2004)52

NO kinetic energy, NO η'-meson exchange

NO symmetry breaking in η-meson exchange

NO orbital excitation in the radial matrix elements

$\rightarrow$ conflict with POSITIVE parity

N.B. Updated partial wave analysis gives 1680 MeV or 1730 MeV, Arndt et al., nucl-th/0312126

N.B. Smaller splitting in the CS model

V. Dmitrasinovic & F. S.

* Totally antisymmetric q^4 wave fct., NO $\bar{3}$ S=0, I=0 diquarks
* Full CS interaction
* Broken SU(3) by the quark masses

$M = M_0 - 58\ Y$

M_0 is fixed by the Θ^+ mass $\rightarrow$ $M(\Xi^{--}) \simeq 1710$ MeV

THE MIXING IN THE FLAVOUR-SPIN MODEL

$$\mathbf{V} = \begin{cases} \frac{2\sqrt{2}}{3}(\mathbf{m_s} - \mathbf{m_u}) + \frac{\sqrt{2}}{3}\,[\mathbf{S}(\mathbf{uuds\bar{s}}) - \mathbf{S}(\mathbf{uudd\bar{d}})] = \mathbf{166}\ \text{MeV} & \text{for N} \\ \frac{2\sqrt{2}}{3}(\mathbf{m_s} - \mathbf{m_u}) + \frac{\sqrt{2}}{3}\,[\mathbf{S}(\mathbf{uuss\bar{s}}) - \mathbf{S}(\mathbf{uuds\bar{d}})] = \mathbf{155}\ \text{MeV} & \text{for } \Sigma \end{cases}$$

$$\mathbf{S} = \langle \mathbf{T} \rangle + \langle \mathbf{V}_\chi \rangle$$

Physical states

$$|\mathbf{N}^*\rangle = |\mathbf{N_8}\rangle \cos\theta_\mathbf{N} - |\mathbf{N_{\overline{10}}}\rangle \sin\theta_\mathbf{N},$$
$$|\mathbf{N_5}\rangle = |\mathbf{N_8}\rangle \sin\theta_\mathbf{N} + |\mathbf{N_{\overline{10}}}\rangle \cos\theta_\mathbf{N}$$

$\theta_N = 35.34^0 \rightarrow$ **M(N$_5$) = 1801 MeV is 67 % antidecuplet**

$\theta_\Sigma = -35.48^0 \rightarrow$ **M(Σ_5) = 2046 MeV is 67 % antidec.**

N. B. Ideal mixing $\theta_N = 35.26^0$, $\theta_\Sigma = -35.26^0$

M(N*) = 1451 MeV is 67 % pentaquark octet

Also a q^3 state N(1440) = 1495 MeV $\rightarrow$

TWO resonances in the Roper region (**P. Morsch et al. PRL '99**)

M(Σ^*) = 1719 MeV is 67 % pentaquark octet

SOME RECENT CONSTITUENT QUARK MODEL RESULTS

Takeuchi & Shimizu, hep-ph/0411016

FS model - semirelativistic version - Graz

The lowest state is $J^P = 1/2^+$

CS model - nonrelativistic one gluon exchange

1)The lowest resonant state is $J^P = 3/2^-$

2)The $J^P = 1/2^-$ **states is lower, but in the continuum**

CONSTITUENT QUARK MODELS

* One can accommodate Θ^+ and partners
* absolute mass is not determined

* Ξ^{--} - Θ^+ mass difference is model dependent
* Coupling $\overline{\mathbf{10}}_\mathbf{F}$ & $\mathbf{8}_\mathbf{F}$ due to SU$_F$(3) breaking $\rightarrow$ IDEAL mixing

* 2 states: q^3 and $q^4\bar{q}$ in the Roper mass region $\rightarrow$ higher Fock components for baryon q^3 states

* small width: $\langle\Theta|KN\rangle$ flavour-spin or orbital space
* spin-orbit partners