Analysis of Λ_c baryons

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Outline

- Diquark
- Mass loaded flux tube model
- Classification of Λ_c baryons
- Conclusions and discussions

Diquark qq

Quarks/antiquarks in hadron containing more than 3 quarks may have complicated correlations and form different clusters

Diquarks were first mentioned by Gell-Mann

M. Gell-Mann, Phys. Lett. **8**, 214 (1964)

♠ Two quark correlation

Two quarks will attract each other and make up a diquark when the two quarks are in an antisymmetric color representation

Point particle?

Wave function

$$|hadron\rangle = |color\rangle \times |spin\rangle \times |flavor\rangle \times |spatial\rangle$$

Baryons: antisymmetric

The symmetry of the spatial part: parity

$$|diquark\rangle = |color\rangle \times |spin\rangle \times |flavor\rangle$$

Diquark: antisymmetric, color antisymmetric

- Color

$|color\rangle$: $\bar{3}_c$, antisymmetric

- Spin

$|spin\rangle$: $\bar{1}_s$, antisymmetric, $S = 0$

$|spin\rangle$: 3_s, symmetric, $S = 1$

- Flavor

$|flavor\rangle$: $\bar{3}_f$, antisymmetric, $I = 0$

$|flavor\rangle$: 6_f, symmetric, $I = 1$

- $SU(6)_{cs}$

  c: color

  s: spin

♠ Good diquark

Good diquark $[qq]$: antisymmetric, $|\bar{3}_c, \bar{1}_s, \bar{3}_f\rangle$, scalar

Bad diquark (qq): antisymmetric, $|\bar{3}_c, 3_s, 6_f\rangle$, vector

♠ Baryons

quark $+$ diquark

Mass loaded flux tube model

♠ Idea

Alexander Selem and Frank Wilczek, hep-ph/0602128, Ringberg 2005, New trends in HERA physics, 337-356

Two masses m_1 and m_2 are connected by a flux tube or relativistic string with constant tension T rotaing with angular momentum L. The flux tube or string is responsible for the color confinement

Meson: quark m_1 and anti-quark m_2

Baryon: quark m_1 and diquark m_2

The energy of the system

$$E = m_1\gamma_1 + m_2\gamma_2 + \frac{T}{\omega}\int_0^{\omega r_1}\frac{1}{\sqrt{1-u^2}}du + \frac{T}{\omega}\int_0^{\omega r_2}\frac{1}{\sqrt{1-u^2}}du$$

The angular momentum of the system

$$\begin{aligned} L &= m_1\omega r_1^2\gamma_1 + m_2\omega r_2^2\gamma_2 \\ &\quad + \frac{T}{\omega^2}\int_0^{\omega r_1}\frac{u^2}{\sqrt{1-u^2}}du + \frac{T}{\omega^2}\int_0^{\omega r_2}\frac{u^2}{\sqrt{1-u^2}}du \end{aligned}$$

ω, r_i and γ_i are parameters in the model

The energy of the heavy-light systems

$$E = M + \sqrt{\frac{\sigma L}{2}} + 2^{\frac{1}{4}} \kappa L^{-\frac{1}{4}} m^{\frac{3}{2}}, \tag{1}$$

with $\kappa = \frac{2}{3} \frac{\pi^{\frac{1}{2}}}{\sigma^{\frac{1}{4}}}$

M: heavy quark mass; m: light quark/diquark mass

Their results on Λ_c baryons

L	J^P(theory)	J^P(PDG)	Mass(expt.)
1	$\frac{1}{2}^-$	$\frac{1}{2}^-$	$\Lambda_c(2595)^+$
1	$\frac{3}{2}^-$	$\frac{3}{2}^-$	$\Lambda_c(2625)^+$
2	$\frac{5}{2}^+$	$\frac{5}{2}^+$	$\Lambda_c(2880)^+$

Tab. 1: Parameters: $m_c = 1.6$ GeV, $m_{qq} = 0.18$ MeV, $\sigma = 0.974$ GeV^2.

Spin-orbit forces were ignored!

Contributions of spin-orbit interactions are large!

Energy splitting resulting from spin-orbit interactions is comparable to the energy gap resulting from different orbit

Hong-Yun Shan and Ailin Zhang, D and D_s in mass loaded flux tube, arXiv: 0805.4764 [hep-ph]

$$E = M + \sqrt{\frac{\sigma L}{2}} + 2^{\frac{1}{4}} \kappa L^{-\frac{1}{4}} m^{\frac{3}{2}} + a \vec{L} \cdot \vec{S} \tag{2}$$

Classification of Λ_c baryons

Baryons made from u, d, s, and c quarks belong to $SU(4)$ multiplets

$SU(4)$ multiplets: $4 \times 4 \times 4 = 20 + 20'_1 + 20'_2 + \bar{4}$

Λ_c: $I = 0$

Λ_c baryons picture: u and d quark is in [ud](good diquark) configuration, the good diquark and the c quark locate at the ends of the flux tube

The lightest Λ_c^+: $J^P = \frac{1}{2}^+$, $m = 2286.46 \pm 0.14$ MeV. The spin J has not actually been measured

Spectrum of excited Λ_c baryons(MeV):

L	J^P(theory)	J^P(PDG)	Mass(theory)	Mass(expt.)
1	$\frac{1}{2}^-$	$\frac{1}{2}^-$	2584	$\Lambda_c(2595)^+$
1	$\frac{3}{2}^-$	$\frac{3}{2}^-$	2644	$\Lambda_c(2625)^+$
2	$\frac{3}{2}^+$	$?^?$	2772	$\Lambda_c(2765)^+$
2	$\frac{5}{2}^+$	$\frac{5}{2}^+$	2872	$\Lambda_c(2880)^+$
3	$\frac{5}{2}^-$	$?^?$	2935	$\Lambda_c(2940)^+$
3	$\frac{7}{2}^-$	$?^?$	3076	**?**

Tab. 2: Parameters: $m_c = 1.39$ GeV, $m_{qq} = 0.521$ MeV, $\sigma = 0.999$ GeV^2 and $a = 40$ MeV.

PDG: Amsler C, *et al.*. (Particle Data Group), Phys. Lett. **B667**, 1 (2008).

The minimum of mean square error of the mass of the Λ_c: $\Lambda_c(2595)^+$, $\Lambda_c(2625)^+$, $\Lambda_c(2880)^+$, $\Lambda_c(2940)^+$

Parameters:

$m_c = 1.39$ GeV,

$m_{qq} = 0.521$ MeV: comparable with other predictions

$\sigma = 0.999$ GeV^2:

$a = 40$ MeV

Few of the J^P quantum numbers given in PDG have been measured

Classification:

♠ $\Lambda_c(2765)^+$

$\Lambda_c(2765)$ or $\Sigma_c(2765)$?

If $\Lambda_c(2765)$, its J^P: $\frac{3}{2}^+$
If $\Sigma_c(2765)$, another Λ_c with $J^P = \frac{3}{2}^+$ and mass ≈ 2770 MeV

♠ $\Lambda_c(2940)^+$

Its J^P: $\frac{5}{2}^-$

Prediction:

♠ $\Lambda_c(3076)^+$?

The mass difference among different orbits(with spin-orbit interactions ignored)

$$E(L=2)-E(L=1)=209 \quad MeV,$$
$$E(L=3)-E(L=2)=182 \quad MeV,$$
$$E(L=4)-E(L=3)=162 \quad MeV$$

The mass splitting resulting from the spin-orbit interactions in the same orbit

$$E(L=1;\frac{3}{2}^-)-E(L=1;\frac{1}{2}^-)=30 \quad MeV,$$
$$E(L=2;\frac{5}{2}^+)-E(L=2;\frac{3}{2}^+)=115 \quad MeV,$$
$$E(L=3;\frac{7}{2}^-)-E(L=3;\frac{5}{2}^-)=141 \quad MeV$$

Spin-orbit interactions are large for higher excited Λ_c

They should be taken into account!

Conclusions and discussions

- Diquark is a good approximation for Λ_c baryons!
- The dynamics of Λ_c baryons is well described by the mass loaded flux tube!
- J^P of some Λ_c baryons are assigned!
- Theoretical and Experimental explorations required!

Thank you!