Multi-quark components in baryons

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A brief review on some recent progresses in our understanding of multi-quark components in baryons is presented. The multi-quark components in baryons seem to be mainly in colored quark cluster configurations rather than in “meson cloud” configurations or in the form of a sea of quark-antiquark pairs. The colored quark cluster multi-quark picture gives a natural explanation of empirical indications for a positive strangeness magnetic moment $\mu_s$ of the proton and the longstanding mass-reverse problem of $S_{11}(1535)$ and $P_{11}(1440)$ $N^*$ resonances. A model-prediction for the $\mu_s$ of the proton is given.

Keywords: Multi-quark components; baryon

1. Introduction

In the classical quark model invented 40 years ago, a baryon is composed of three quarks. The simple $3q$ constituent quark model has been very successful in explaining the static properties, such as mass and magnetic moment, of the ground states of the flavor SU(3) octet and decuplet baryons. However, with advent of the QCD in 1973 and later electron-proton deep inelastic scattering experiments, we know that besides the three valence quarks in the proton there are many other partons including quark-antiquark pairs and gluons.

Before 1990, in all global analyses of parton distribution in nucleons, a symmetric light-quark ($\bar{u}, \bar{d}$) sea was assumed, based on the usual assumption that the sea of quark-antiquark pairs is produced perturbatively from gluon splitting. However, a surprisingly large asymmetry between the $\bar{u}$ and $\bar{d}$ sea quark distributions in the proton has been observed in more recent deep inelastic scattering and Drell-Yan experiments.

There have been many theoretical attempts trying to find the origins for this asymmetry. It is believed that the asymmetry cannot be produced from perturbative QCD and mesonic degrees of freedom play an important role for the effect. In the popular meson-cloud model, the excess of $\bar{d}$ over $\bar{u}$ in the proton is explained by a mixture of $n\pi^+$ with the $\pi^+$ composed of $ud$. On the other hand, the excess of $\bar{d}$ over $\bar{u}$ can be also explained by a simple statistical model by taking proton as an ensemble of quark-gluon Fock states and using the principle of detailed balance for transitions between various Fock states through creation or annihilation of partons. The basic idea in Ref. is rather simple: while sea quark-antiquark pairs are produced flavor blindly by gluon splitting, $\bar{u}$ quarks have larger
probability to annihilate than $\bar{d}$ quarks due to the fact that there are more $u$ quarks than $d$ quarks in the proton, which hence causes the asymmetry.

To understand the multi-quark components of the nucleon, the strangeness in the proton is of particular interest, because it definitely comes from the multi-quark part. In the next section, we give a brief review of some recent progress on this aspect and a simple model-prediction for the strangeness magnetic moment $\mu_s$ of the proton. In section 3, we discuss how the inclusion of penta-quark components can explain the longstanding mass-reverse problem of $S_{11}(1535)$ and $P_{11}(1440) N^*$ resonances and some relevant properties. Finally we give conclusions in section 4.

2. Strangeness in the proton

Several measurements including the $\pi N \sigma$-term, neutrino-induced charm production and polarization effects in electron-nucleon deep-inelastic scattering indicate that there may be significant $s\bar{s}$ component in the proton. Recently four experiments on parity violation in electron-proton scattering suggest that the strangeness magnetic moment of the proton $\mu_s$ is positive. This is in contradiction with most theoretical calculations. The meson-cloud calculations with a fluctuation of the proton into a kaon and a strange hyperon lead to a negative value for the strangeness magnetic moment $\mu_s$. The statistical model gives a zero value for the $\mu_s$. Various lattice QCD calculations give various values for $\mu_s$:

$$-0.28 \pm 0.10^{17}, +0.05 \pm 0.06^{18}, -0.046 \pm 0.019 \mu_N^{19}$$

Very recently, a complete analysis of the relation between the $\mu_s$ and the possible configurations of the $uuds\bar{s}$ component of the proton concludes that for a positive $\mu_s$ value the $\bar{s}$ is in the ground state and the $uuds$ system in the $P$-state. The conventional $K^+ \Lambda$ configuration has the $\bar{s}$ mainly in $P$-state and hence leads to a negative $\mu_s$ value. The hidden strangeness analogues of recently proposed diquark cluster models for the $\theta^+$ pentaquark have $\bar{s}$ in the ground state and the $uuds$ system in the $P$-state, hence give a positive $\mu_s$ value. The analysis suggests that the $qqq\bar{q}$ components in baryons may be mainly in colored quark cluster configurations rather than in the conventional “meson cloud” configurations.

In order to explain the observed excess of $\bar{d}$ over $\bar{u}$ and the non-zero $s\bar{s}$ contributions, the minimal model-wave-function for the proton should be

$$|p> = N\{|uud\} + \epsilon_1|ud\bar{d}\} + \epsilon_2|ud\{us\bar{s}\}$$

(1)

where $N = 1/\sqrt{1+\epsilon_1^2+\epsilon_2^2}$, $|ud\}$ and $|us\}$ are scalar diquarks as in Jaffe-Wilczek diquark model. In order to reproduce the experimental measured values $\bar{d} - \bar{u} \approx 0.15^{15}$ and $2\bar{s}/(\bar{u} + \bar{d}) \approx 0.48^{20}$, we have $(N\epsilon_1)^2 \approx 0.12$ and $(N\epsilon_2)^2 \approx 0.03$. Note here $\epsilon_2^2/\epsilon_1^2 \approx 1/4$ which is smaller than the corresponding SU(3) symmetry value $1/9$ due to heavier $s$ quark mass than $u$, $d$ quarks. For this simple model-wave-function, the probability of the $s\bar{s}$ component is $P_{s\bar{s}} = (N\epsilon_2)^2 \approx 0.03$, and the corresponding strangeness magnetic moment $\mu_s$ can be calculated as

$$\mu_s/\mu_N = \frac{m_p}{3m_s}(1 + \frac{2m_s}{m_{ud} + m_{us}})P_{s\bar{s}}$$

(2)
where $m_{ud}$ and $m_{us}$ are diquark masses for $|ud|$ and $|us|$, respectively. Taking $m_u = m_d = 360\text{MeV}$, $m_s = 500\text{MeV}$, $m_{ud} = 720\text{MeV}$ and $m_{us} = 860\text{MeV}$ as in Ref.\[23\], we have a prediction $\mu_s = 0.043\mu_N$. Since we have assumed zero $uud\bar{u}\bar{u}$ component in the simple model-wave-function, the value should be regarded as the lower limit for the $\mu_s$. For $\mu^\text{exp}_s$ the result of the SAMPLE experiment\[15\] is $\mu_s = (0.37 \pm 0.34)\mu_N$.

More precise measurement of the $\mu_s$ are crucial for finally pinning down the multi-quark components in the proton.

3. Penta-quark components in $N^*$ resonances

From the study of the proton, we know that the probability of multi-quark components in the proton are larger than 15%. Then for the excited nucleon states, $N^*$ resonances, there should be more multi-quark components. To understand the properties of the $N^*$ resonances, it is absolutely necessary to consider these multi-quark components. A long-standing problem in conventional $3q$ constituent quark models is to explain the mass reverse of the $S_{11}(1535)$ and $P_{11}(1440)$ $N^*$ resonances.

Recently from BES results on $J/\psi \to \bar{p}p\eta$\[25\] and $\psi \to pK^+\Lambda$\[25\] the ratio between effective coupling constants of $S_{11}(1535)$ to $K\Lambda$ and $p\eta$ is deduced to be $g_{N^*(1535)K\Lambda}/g_{N^*(1535)p\eta} = 1.3 \pm 0.3$\[27\]. With previous known value of $g_{N^*(1535)p\eta}$, the obtained new value of $g_{N^*(1535)K\Lambda}$ is shown to reproduce recent $pp \to pK^+\Lambda$ near-threshold cross section data as well. Taking into account this large $N^*K\Lambda$ coupling in the coupled channel Breit-Wigner formula for the $S_{11}(1535)$, its Breit-Wigner mass is found to be around 1400 MeV, much smaller than previous value of about 1535 MeV obtained without including its coupling to $K\Lambda$.

The nearly degenerate mass for the $S_{11}(1535)$ and the $P_{11}(1440)$ $N^*$ resonances can be easily understood by considering multi-quark components in them. The $N^*(1535)1/2^-$ could be the lowest $L = 1$ orbital excited $|uud\rangle$ state with a large admixture of $||ud||us\rangle\bar{s} \rangle$ pentaquark component having $|ud\rangle$, $|us\rangle$ and $\bar{s}$ in the ground state. The $N^*(1440)$ could be the lowest radial excited $|uud\rangle$ state with a large admixture of $||ud||ud\rangle\bar{d} \rangle$ pentaquark component having two $|ud\rangle$ diquarks in the relative P-wave. While the lowest $L = 1$ orbital excited $|uud\rangle$ state should have a mass lower than the lowest radial excited $|uud\rangle$ state, the $||ud||us\rangle\bar{s} \rangle$ pentaquark component has a higher mass than $||ud||ud\rangle\bar{d} \rangle$ pentaquark component. The large mixture of the $||ud||us\rangle\bar{s} \rangle$ pentaquark component in the $N^*(1535)$ may also explain naturally its large coupling to the final states with strangeness.

4. Conclusions

The probability of multi-quark components in the proton is at least 15%. The empirical indications for a positive strangeness magnetic moment $\mu_s$ of the proton suggest the multi-quark components in baryons to be mainly in colored quark cluster configurations rather than in “meson cloud” configurations or in the form of a sea of quark-antiquark pairs. The $\mu_s$ of the proton is predicted to be no less than 4.3% of the total magnetic moment of the proton. The colored quark cluster multi-quark
picture gives a natural explanation of the longstanding mass-reverse problem of \( S_{11}(1535) \) and \( P_{11}(1440) \) \( N^* \) resonances, and the large coupling of the \( S_{11}(1535) \) to the channels with strangeness.

**Acknowledgements**

I thank B.C.Liu, D.O.Riska and Y.J.Zhang for collaboration on relevant issues. The work is partly supported by CAS Knowledge Innovation Project (KJCX2-SW-N02) and the National Natural Science Foundation of China.

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