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Hadron spectroscopy from strangeness to charm and beauty

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Abstract

Quarks of different flavors have different masses, which will cause breaking of flavor symmetries of QCD. Flavor symmetries and their breaking in hadron spectroscopy play important role for understanding the internal structures of hadrons. Hadron spectroscopy with strangeness reveals the importance of unquenched quark dynamics. Systematic study of hadron spectroscopy with strange, charm and beauty quarks would be very revealing and essential for understanding the internal structure of hadrons and its underlying quark dynamics.

Keywords: Hadron spectroscopy; Multi-quark states

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1. Hadron spectroscopy with strangeness

In classical constituent quark models, baryons are ascribed as three-quark (qqq) states and mesons are ascribed as quark–antiquark ($q\bar{q}$) states. This picture is very successful in explaining properties of the spatial ground states of the flavor SU(3) vector meson nonet, baryon octet and

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decuplet. Its predicted $\Omega(sss)$ baryon with mass around 1670 MeV was discovered by later experiments. However even for the lowest spatial excited states, this picture failed badly in both meson and baryon sectors.

In the meson sector, the lowest spatial excited SU(3) nonet is the scalar nonet composed of $f_0(500)$, $\kappa(600\text{–}800)$, $a_0(980)$ and $f_0(980)$. In the classical constituent quark models, these scalars should be $q\bar{q}(L=1)$ states with $f_0(500)$ as $(u\bar{u}+d\bar{d})/\sqrt{2}$ state, $a_0^0(980)$ as $(u\bar{u}-d\bar{d})/\sqrt{2}$ state and $f_0(980)$ as mainly $s\bar{s}$ state. Then in this picture, it cannot explain why the mass of $a_0(980)$ is degenerate with $f_0(980)$ instead of close to $f_0(500)$ as in the ρ–ω case in the vector nonet. This made R.J. Jaffe [1] proposing these scalars are $q^2\bar{q}^2$ states instead of $q\bar{q}$ states. In the new picture, the $f_0(500)$ is ascribed as $[ud]\overline{[ud]}$ state, $a_0^0(980)$ as $([us]\overline{[us]}-[ds]\overline{[ds]})/\sqrt{2}$ state and $f_0(980)$ as $([us]\overline{[us]}+[ds]\overline{[ds]})/\sqrt{2}$ state. This gives a natural explanation of the degeneracy of $a_0(980)$ and $f_0(980)$. Here $[q_1q_2]$ means a good diquark with configuration of flavor representation $\bar{\mathbf{3}}$, spin 0 and color $\bar{3}$. Alternatively, these scalars are also proposed to be meson–meson dynamically generated states [2,3].

In the baryon sector, the similar thing seems also happening [4]. In the classical quark models, the excited baryon states are described as excitation of individual constituent quarks, similar to the cases for atomic and nuclear excitations. The lowest spatial excited baryon is expected to be a (uud) N^* state with one quark in orbital angular momentum $L=1$ state, and spin-parity $1/2^-$. However, experimentally, the lowest negative parity N^* resonance is found to be $N^*(1535)$, which is heavier than two other spatial excited baryons: $\Lambda^*(1405)$ and $N^*(1440)$. This is the long-standing mass reverse problem for the lowest spatial excited baryons.

In the simple 3q constituent quark models, it is also difficult to understand the strange decay properties of the $N^*(1535)$, which seems to couple strongly to the final states with strangeness. Besides a large coupling to $N\eta$, a large value of $g_{N^*(1535)K\Lambda}$ is deduced [5,6] by a simultaneous fit to BES data on $J/\psi\to\bar{p}p\eta$, $pK^-\bar{\Lambda}+\text{c.c.}$, and COSY data on $pp\to pK^+\Lambda$. There is also evidence for large $g_{N^*(1535)N\eta'}$ coupling from $\gamma p\to p\eta'$ reaction at CLAS [7] and $pp\to pp\eta'$ reaction [8], and large $g_{N^*(1535)N\phi}$ coupling from $\pi^-p\to n\phi$, $pp\to pp\phi$ and $pn\to d\phi$ reactions [9–11].

The third difficulty is the strange decay pattern of another member of the $1/2^-$-nonet, $\Lambda^*(1670)$, which has its coupling to $\Lambda\eta$ much larger than NK and $\Sigma\pi$ according to its branching ratios listed in PDG [12].

All these difficulties can be easily understood by considering large 5-quark components in them [4,5,13,14]. The $N^*(1535)$ could be the lowest $L=1$ orbital excited $|uud\rangle$ state with a large admixture of $|[ud][us]\bar{s}\rangle$ penta-quark component having $[ud]$, $[us]$ and $\bar{s}$ in the ground state. The $N^*(1440)$ could be the lowest radial excited $|uud\rangle$ state with a large admixture of $|[ud][ud]\bar{d}\rangle$ penta-quark component having two $[ud]$ 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 $|[ud][us]\bar{s}\rangle$ penta-quark component has a higher mass than $|[ud][ud]\bar{d}\rangle$ penta-quark component. The lighter $\Lambda^*(1405)1/2^-$ is also understandable in this picture. Its main 5-quark configuration is $|[ud][qs]\bar{q}\rangle$ which is lighter than the corresponding 5-quark configuration $|[ud][us]\bar{s}\rangle$ in the $N^*(1535)1/2^-$. The large mixture of the $|[ud][us]\bar{s}\rangle$ penta-quark component in the $N^*(1535)$ naturally results in its large couplings to the $N\eta$, $N\eta'$, $N\phi$ and $K\Lambda$. The main 5-quark configuration for the $\Lambda^*(1670)$ is $|[us][ds]\bar{s}\rangle$ which makes it heavier than other $1/2^-$ states and larger coupling to $\Lambda\eta$.

Besides the penta-quark configurations with the diquark correlation, the penta-quark system may also be in the form of meson–baryon states. The $N^*(1535)$, $\Lambda^*(1405)$ and some other baryon resonances are proposed to be meson–baryon dynamically generated states [3,15–20].