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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:

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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-anti-quark ($q\bar{q}$) 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 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 $f_0(500)$, $\kappa(600 \sim 800)$, $a_0(980)$ 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 $J/\psi \to \bar{p}p\eta$, $pK^-\bar{\Lambda}$ + *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, 10, 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 $\bar{N}K$ 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 $|uud>$ state with a large admixture of $|[ud][us]\bar{s}>$ pentaquark component having $[ud]$, $[us]$ and $\bar{s}$ in the ground state. The $N^*(1440)$ could be the lowest radial excited $|uud>$ state with a large admixture of $|[ud][ud]\bar{d}>$ pentaquark component having two $[ud]$ diquarks in the relative P-wave. While the lowest $L = 1$ orbital excited $|uud>$ state should have a mass lower than the lowest radial excited $|uud>$ state, the $|[ud][us]\bar{s}>$ pentaquark component has a higher mass than $|[ud][ud]\bar{d}>$ pentaquark component. The lighter $\Lambda^*(1405)1/2^-$ is also understandable in this picture. Its main 5-quark configuration is $|[ud][qs]\bar{q}>$ which is lighter than the corresponding 5-quark configuration $|[ud][us]\bar{s}>$ in the $N^*(1535)1/2^-$. The large mixture of the $|[ud][us]\bar{s}>$ pentaquark 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 $|[us][ds]\bar{s}>$ 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, 16, 17, 18, 19, 20]. However, a challenge for this meson-baryon dynamical picture is to explain the mass and decay pattern of the $\Lambda^*(1670)$.

From above facts and discussion for both meson and baryon sectors, one can see that unlike atomic and nuclear excitations where the number of constituent particles are fixed, the favorable hadronic excitation mechanism for the lowest spatial excited states in light quark sector seems to be dragging out a light $q\bar{q}$ pair from gluon field rather than to excite a constituent quark to be $L = 1$ state. A breathing mode of $qqq \leftrightarrow qqqq\bar{q}$ is proposed [21, 22] for the lowest $1/2^-$ baryon nonet. Each baryon is a mixture of the three-quark and five-quark components.

While the new picture gives a nice account of properties of scalar meson nonet and well-established members of the lowest $1/2^-$ baryon nonet, it is necessary to check its distinguishable predictions of other members in the $1/2^-$ baryon nonet. While the classical quenched quark models [23] predict the $1/2^-$ Σ^* and Ξ^* to be around 1650 MeV and 1760 MeV, respectively, the unquenched quark models [13, 14, 22] expect them to be around 1400 MeV and 1550 MeV, respectively, and meson-baryon dynamical models [24, 25, 26] predict them to be around 1450 MeV and 1620 MeV, respectively.

For Σ resonance with $J^P = \frac{1}{2}^-$, the PDG [12] lists a two-star $\Sigma(1620)$ resonance, which seems to support the quenched quark models. However, only four references listed in PDG show weak evidence for its existence. In Ref. [27], the total cross sections for K^-p and K^-n are analyzed, which indicates some Σ resonance around 1600 MeV without J^P quantum number. Refs. [28, 29] are based on multichannel analysis of the $\overline{K}N$ reactions. Both claim evidence for a $\Sigma\ \frac{1}{2}^-$ resonance with mass around 1620 MeV but give contradicted coupling properties to $\pi\Lambda$ and to $\pi\Sigma$. Other later multichannel analyses of the $\overline{K}N$ reactions support the existence of an $\Sigma(1660)\frac{1}{2}^+$ [12]. Ref. [30] analyzes the reaction $K^-n \to \pi^-\Lambda$ and gives two comparable solutions with and without $\Sigma(1620)\frac{1}{2}^-$.

On the other hand, there are also some supports of the unquenched 5-quark models with $\Sigma^*(\frac{1}{2}^-)$ of much lower masses. The re-analysis of old data on $K^-p \to \Lambda\pi^+\pi^-$ finds hidden $\Sigma^*(\frac{1}{2}^-)$ with mass around 1380 MeV under the $\Sigma(1385)\frac{3}{2}^+$ peak [31]. From an analysis of the recent LEPS data on $\gamma n \to K^+\Sigma^{*-}(1385)$ [32], there is also a possibility for the existence of such low mass $\Sigma^*(\frac{1}{2}^-)$ [33]. An analysis of CEBAF data on $\gamma p \to K^+\pi\Sigma$ also suggests a possible $\Sigma^*(\frac{1}{2}^-)$ around 1400 MeV [34].

To clarify the situation for Σ resonances, recently, a combined fit for the new CB data [35] on $K^-p \to \pi^0\Lambda$ together with the old data [30] on $K^-n \to \pi^-\Lambda$ for the energies from 1569 to 1676 MeV was performed [36]. The $\overline{K}N \to \pi\Lambda$ reaction is the best channel available for the study of the Σ resonances because the $\pi\Lambda$ is a pure isospin 1 channel. The high precision Crystal Ball Λ polarization data [35] are crucial for discriminating $\Sigma(1620)\frac{1}{2}^-$ from $\Sigma(1635)\frac{1}{2}^+$. It shows that the $\Sigma(1660)\frac{1}{2}^+$ is definitely needed, while $\Sigma(1620)\frac{1}{2}^-$ is not needed at all. Although $\Sigma(1380)\frac{1}{2}^-$ is not demanded in this analysis, it cannot be excluded. Therefore, no evidence to support the classical quenched quark models at all from the $1/2^-$ baryons. Additional $\Sigma(1542)\frac{3}{2}^-$, $\Sigma(1840)\frac{3}{2}^+$ and $\Sigma(1610)\frac{1}{2}^+$ may exist.

The $\Sigma(1542)\frac{3}{2}^-$ is consistent with the resonance structure $\Sigma(1560)$ or $\Sigma(1580)\frac{3}{2}^-$ in PDG [12] and seems a good isospin partner of $\Lambda(1520)\frac{3}{2}^-$. Recently a very interesting narrow $\Lambda(1670)\frac{3}{2}^-$ with a width about 1.5 MeV was claimed from an analysis of $K^-p \to \eta\Lambda$ data [37]. Together with $N^*(1520)\frac{3}{2}^-$ and either $\Xi(1620)$ or $\Xi(1690)$, they fit in a nice $3/2^-$ baryon nonet with large penta-quark configuration, *i.e.*, $N^*(1520)$ as $|[ud]\{uq\}\bar{q}>$ state, $\Lambda(1520)$ as $|[ud]\{sq\}\bar{q}>$ state, $\Lambda(1670)$ as $|[ud]\{ss\}\bar{s}>$ state, and $\Xi(16xx)$ as $|[ud]\{ss\}\bar{q}>$ state. Here $\{q_1q_2\}$ means a diquark with configuration of flavor representation **6**, spin 1 and color $\bar{3}$. The $\Lambda(1670)$ as $|[ud]\{ss\}\bar{s}>$ state gives a natural explanation for its dominant $\eta\Lambda$ decay mode with a very narrow width due to its very small phase space meanwhile a D-wave decay.

The available information on the hadron spectroscopy with strangeness strongly indicates that $qqqq\bar{q}$ in S-state is more favorable than qqq state with $L = 1$ and $q^2\bar{q}^2$ in S-state is more favorable than $q\bar{q}$ state with $L = 1$. The multi-quark components are very substantial and important for hadronic excited states. Even $q^6\bar{q}$ configuration may play dominant role for some baryon resonances [38, 39].

To further establish the multi-quark picture for hadronic excited states, it is very important to complete the low-lying hyperon spectrum, especially the $1/2^-$ and $3/2^-$ Σ^*, Ξ^* and Ω^*. Here the Ω^* spectrum has a unique advantage that the favorable $q\bar{q}$ excitations from quark sea have different flavor from the valence strange quarks [40]. Kaon beam experiment at JPARC and hyperon production from charmonium decays at BESIII may play very important role in this aspect. It is also important to check the cases with s quarks replaced by c or b quarks.

2. From strangeness to charm and beauty

Various pictures and dynamics for the spectroscopy with strangeness can be extended to and checked by its charm and beauty partners. For example, if $f_0(980)$ is a $K\bar{K}$ molecule mainly due to light vector meson exchange force [41], then with the same mechanism there should also exist DK, $B\bar{K}$, $D\bar{D}$ and $\bar{B}B$ molecules [42, 43]. The newly established $D^*_{s0}(2317)$ is regarded as a DK molecule or tetra-quark state by many people [44]. The $f_1(1420)$ was proposed to be a $K^*\bar{K}$ molecule [45]; now the newly established $X(3872)$ is regarded as its $D^*\bar{D}$ partner [46, 47]. The $\Lambda_c(2595)1/2^-$ was proposed [48] to be DN molecule as the charm partner of $\Lambda(1405)$.

Although many hadron resonances were proposed to be hadron-hadron dynamically generated states or multi-quark states, most of them cannot be clearly distinguished from classical quark model states due to tunable ingredients and possible large mixing of various configurations in these models. Even in 2010, the PDG [49] still claimed that "The clean Λ_c spectrum has in fact been taken to settle the decades-long discussion about the nature of the $\Lambda(1405)$ – true 3-quark state or mere $\bar{K}N$ threshold effect? – unambiguously in favor of the first interpretation." A possible solution to this problem is to extend the penta-quark study to the hidden charm and hidden beauty sectors. If the $N^*(1535)$ is the $\bar{K}\Sigma$ quasi-bound state with hidden strangeness, then naturally by replacing $s\bar{s}$ by $c\bar{c}$ or $b\bar{b}$ one would expect super-heavy N^* states with hidden charm and hidden beauty just below $\bar{D}\Sigma_c$ and $B\Sigma_b$ thresholds, respectively.

Following the Valencia approach of Ref.[50] and extending it to the hidden charm sector, the interaction between various charmed mesons and charmed baryons were studied with the local hidden gauge formalism in Refs.[51, 52]. Several meson-baryon dynamically generated narrow N^* and Λ^* resonances with hidden charm are predicted with mass around 4.3 GeV and width smaller than 100 MeV. The S-wave $\Sigma_c\bar{D}$ and $\Lambda_c\bar{D}$ states with isospin I=1/2 and spin S=1/2 were also investigated by various other approaches [53, 54, 55]. They confirm that the interaction between Σ_c and $\bar{D}$ is attractive and results in a $\Sigma_c\bar{D}$ bound state not far below threshold. The low-lying energy spectra of five quark systems $uudc\bar{c}$ (I=1/2, S=0) and $udsc\bar{c}$ (I=0, S=−1) are also investigated with three kinds of schematic interactions: the chromomagnetic interaction, the flavor-spin dependent interaction and the instanton-induced interaction [56]. In all the three models, the lowest five quark state ($uudc\bar{c}$ or $udsc\bar{c}$) has an orbital angular momentum $L = 0$ and the spin-parity $J^P = 1/2^-$; the mass of the lowest $udsc\bar{c}$ state is heavier than the lowest $uudc\bar{c}$ state, which is different from the prediction of meson-baryon dynamical model [51, 52]. The predicted new resonances definitely cannot be accommodated by quark models with three constituent quarks. Because these predicted states have masses above η_cN and $\eta_c\Lambda$ thresholds, they can be looked for at the forthcoming PANDA/FAIR and JLab 12-GeV upgrade experiments. This is an advantage for their experimental searches, compared with those baryons with hidden charms below the η_cN threshold proposed by other earlier approaches [57, 58].

The same meson-baryon coupled channel unitary approach with the local hidden gauge formalism was extended to the hidden beauty sector in Ref.[59]. Two $N^*_{b\bar{b}}$ states and four $\Lambda^*_{b\bar{b}}$ states were predicted to be dynamically generated. Because of the hidden $b\bar{b}$ components involved in these states, the masses of these states are all above 11 GeV while their widths are of only a few MeV, which should form part of the heaviest island for the quite stable N^* and Λ^* baryons. For the Valencia approach, the static limit is assumed for the t-channel exchange of light vector mesons by neglecting momentum dependent terms. In order to investigate the possible influence of the momentum dependent terms, the conventional Schrodinger Equation approach was also used to study possible bound states for the $B\Sigma_b$ channel by keeping the momentum dependent terms in the t-channel meson exchange potential. It was found that within the reasonable model parameter range the two approaches give consistent predictions about possible bound states. This gives some justification of the simple Valencia approach although there could be an uncertainty of 10 - 20 MeV for the binding energies.

Production cross sections of the predicted $N^*_{b\bar{b}}$ resonances in pp and ep collisions were estimated as a guide for the possible experimental search at relevant facilities in the future. For the $pp \to pp\eta_b$ reaction, the best center-of-mass energy for observing the predicted $N^*_{b\bar{b}}$ is 13 ∼ 25 GeV, where the production cross section is about 0.01 nb. For the $e^- p \to e^- p\Upsilon$ reaction, when the center-of-mass energy is larger than 14 GeV, the production cross section should be larger than 0.1 nb. Nowadays, the luminosity for pp or ep collisions can reach $10^{33} cm^{-2} s^{-1}$, this will produce more than 1000 events per day for the $N^*_{b\bar{b}}$ production. It is expected that future facilities, such as proposed electron-ion collider (EIC), may discover these very interesting super-heavy N^* and Λ^* with hidden beauty.

Very recently, the observation of the iso-vector meson partners of the predicted $N^*_{b\bar{b}}$, $Z_b(10610)$ and $Z_b(10650)$, were reported by Belle Collaboration [60]. This gives us stronger confidence on the existence of the super-heavy island for the $N^*_{b\bar{b}}$ and $\Lambda^*_{b\bar{b}}$ resonances.

3. Conclusions

Available information on hadron spectroscopy with strangeness and charm reveals unquenched quark picture. Dragging out a $q\bar{q}$ from gluon field is a very important excitation mechanism for hadrons. To correctly describe the hadron spectrum, it is necessary to go beyond the classical quenched quark models which assuming a fixed number of constituent quarks. Distinguishable prediction for hyperon spectroscopy from the new picture is yelling for experimental confirmation. Kaon beam experiments at JPARC and hyperon production data from charmonium decays at BESIII can play very important role here. Super-heavy narrow N^* and Λ^* resonances are predicted by various models to exist around 4.3 GeV and 11 GeV for hidden charm and beauty, respectively. Their iso-vector meson partners $Z_b(10610)$ and $Z_b(10650)$ have recently been observed. Experimental confirmation of them will unambiguously establish multi-quark dynamics. They can be looked for at CEBAF-12GeV-upgrade at Jlab and PANDA at FAIR, maybe also at JPARC, super-B, RHIC , EIC.

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