PROCEEDINGS OF SCIENCE

The hidden-charm multiquark states

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Since 2003 many charmonium-like states were observed experimentally. Especially those charged charmonium-like Z_c states and bottomonium-like Z_b states cannot be accommodated within the naive quark model, which are good candidates of either the hidden-charm tetraquark states or molecules composed of a pair of charmed mesons. In 2015, the LHCb Collaboration discovered two hidden-charm pentaquark states, which are also beyond the quark model. In this talk, we review the current experimental progress and investigate various theoretical interpretations of these candidates of the multiquark states. We list the puzzles and theoretical challenges of these models when confronted with the experimental data. We also discuss possible future measurements which may distinguish the theoretical schemes on the underlying structures of the hidden-charm multiquark states.

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PoS(INPC2016)374

1. Motivation

We all know the motion and interaction of hadrons differ from those of nuclei and quark or gluons. Hadron physics is the bridge between nuclear physics and particle physics. The famous Higgs mechanism contributes around 20 MeV to the nucleon mass through the current quark mass. Nearly all the mass of the nucleon and visible matter in our universe comes from the nonperturbative QCD interaction. The study of hadron spectrum explores the mechanism of confinement and chiral symmetry breaking (χSB).

According to the number (N) of the valence quarks, we have the glueballs (N=0), mesons (N=2), baryons (N=3), tetraquarks (N=4), pentaquarks (N=4), deuteron (N=6), nuclei, neutron stars. At present, the tetraquarks and pentaquarks are still missing.

It's interesting to compare QCD and QED. In fact, the QED analogues of the baryon, glueball and hybrid meson do NOT exist. However, there are common features between the QED and QCD spectrum. For the positronium, we have the pion which is composed of $q\bar{q}$. For the hydrogen atom, we have the heavy meson and baryon where the light quarks circle around the heavy quark. For the positronium molecule, one may expect the light scalar tetraquark candidates such as the sigma and kappa mesons. For the hydrogen molecule, one may expect the hidden-charm tetraquark states. For the polarized atoms or molecules, we have the deuteron. We may also expect other hadronic molecules composed of heavy hadrons.

The organizers of the conference asked me to tell the audience why the XYZ states are interesting to nuclear physicists. First of all, some XYZ state may be shallow deuteron-like states. The chiral dynamics (or the pion-exchange force) and coupled channel effects are important. We can use the same nuclear physics techniques to study some of the XYZ states. In my talk I will mainly focus on the XYZ states which the audience may have interest in. Interested readers may also consult the extensive review on the hidden-charm multiquark states [1].

2. Experimental status

Since 2003, many charmonium-like states were observed. Their production mechanisms include the initial state radiation, double charmonium production, two-photon fusion, B meson decay and excited charmonium decays etc. Their discovery modes include both the hidden-charm and open-charm modes.

Up to now, the lattice QCD simulation reproduces the charmonium spectrum below the $D\bar{D}$ threshold very well. On the other hand, many new states above the $D\bar{D}$ threshold were discovered experimentally since 2003. Some are even charged. They are good candidates of the exotic mesons.

In the very beginning, I want to emphasize that many XYZ states lie very close to the open-charm threshold. It's quite possible that some states are not real resonances. They could be fake signals arising from

- - Kinematical effect
- - Opening of new threshold
- - Cusp effect

- - Final state interaction
- - Interference between continuum and well-known charmonium states
- - Triangle singularity due to the special kinematics
- - $\cdots$

3. Theory

Many XYZ states do not fit into quark model spectrum easily. There are some popular theoretical speculations.

- Hadronic molecules are loosely bound states composed of a pair of heavy hadrons. The long-range pion exchange force may play an important role in the formation of the loosely bound hadronic molecules. The molecular states may be quite sensitive to the isospin configurations.
- Tetraquarks are speculated to be tightly bound objects of four quarks. They are bound by the colored-force between quarks. They may decay through rearrangement. Since the dominant part of the color confining force are flavor independent, the tetraquarks shall always be accompanied by partner states. In general, there are many states within the same multiplet. Some are even charged or carry strangeness, which provides a powerful handle in the experimental search of these states. The color-magnetic interaction is responsible for the mass splitting between these states. If one member of the multiplet exists, all the other members should also exist.
- Hybrid charmonium are bound states composed of a pair of quarks and one or more gluons.
- Last but not the least, these XYZ states could also be the conventional charmonium. One should be very cautious that the quark model spectrum could be distorted by the coupled-channel effects.

4. Selected examples: $P_c, X(3872), Z_b/Z_c, Y(4260)$

The multiquark states were first proposed by Gell-Mann in 1964 in his pioneering paper [2]. However, no convincing states were discovered in the past several decades. In 2003, LEPS collaboration reported the Θ pentaquark [3]. Now this signal disappeared.

4.1 P_c states

In 2015, the LHCb collaboration reported two hidden-charm pentaquark states [4]. In the decay process $\Lambda_b \to J/\psi PK$, LHCb observed two resonances in the $J/\psi P$ final state. The lower state is broad. Its mass is 4380 MeV and width is around 205 MeV. The higher state lies around 4450 MeV. It's quite narrow. From the best fit, their spin-parity quantum numbers are $\frac{3}{2}^-$ and $\frac{5}{2}^+$ respectively.

According to the color configurations, there are two possible binding mechanisms: tightly bound or weakly bound. The idea of the loosely bound molecular states is not new in nuclear physics since Yukawa proposed the pion in 1935. The deuteron is a very loosely bound molecular state composed of a proton and neutron arising from the color-singlet meson exchange.

We adopted the same one-meson-exchange formalism to discuss the possible molecular states composed of a pair of heavy hadrons. The charmed meson and baryon are the same as the proton and neutron in the formation of the loosely bound molecular states. Several years ago, we studied the hidden-charm molecular baryons composed of anti-charmed meson and charmed baryon [5]. The lower state $P_c(4380)$ could be explained the $\bar{D}^{(*)}\Sigma_c^{(*)}$ molecule [5, 6].

Through the S-wave charmed meson and baryon scattering, the hidden-charm baryons with negative parity can also be generated dynamically [7]. The total widths of the hidden-charm baryons were less than 60 MeV, quite narrow. The charm-less decay modes are important within this formalism.

The two P_c states were also explained as the tightly bound states [8, 9]. For example, the authors of Ref. [8] assumed quarks and diquarks are fundamental building blocks in the diquark model. The mass difference between $P_c(4380)$ and $P_c(4450)$ is about 70 MeV, which is - partly due to the orbital excitation around 280 MeV and partly due to the mass difference between the scalar and axial-vector diquarks around 200 MeV.

The other possible interpretations of these P_c states can be found in the review [1].

4.2 X(3872)

In 2003, Belle collaboration observed X(3872) in the $J/\psi\pi\pi$ mode [10], which was the first XYZ state. The J^{PC} quantum numbers of X(3872) are 1^{++}. Its production rate at the hadron colliders (Tetraron and LHC) is similar to that of ψ'. The quark model prediction for the χ'_{c1} mass is roughly 100 MeV higher, where the χ'_{c1} is the radial excitation of the axial vector charmonium.

X(3872) lies very close to the $\bar{D}D^*$ threshold with a mass difference less than 0.2 MeV. This state is very narrow. Its total width is less than 1 MeV. The discovery mode $X(3872) \to J/\psi\rho \to J/\psi\pi\pi$ violates isospin symmetry, but its decay width is comparable to the decay width of $X(3872) \to J/\psi\omega \to J/\psi\pi\pi\pi$ decay mode. One may wonder whether X(3872) is an axial-vector charmonium or molecular state.

Within the meson exchange model, we considered (1) the S-D wave mixing which plays an important role in forming the loosely bound deuteron; (2) the mass difference between the neutral and charged D/D^* mesons, and (3) the coupling of $\bar{D}D^*$ to $\bar{D}^*D^*$ channel [11, 12, 13]. We notice that X(3872) is a good candidate of the loosely bound molecular state. In fact, if we replace the proton and neutron inside the deuteron by the $\bar{D}$ and D^* mesons, we reproduce the X(3872). Within the molecular scheme, the large isospin violation can be explained naturally [11].

However, the E1 decay pattern suggests that X(3872) is a good candidate of the axial vector charmonium [14, 15]. If X(3872) is a radial excitation of χ_{c1}, both the radial wave functions of χ'_{c1} and $\psi(2S)$ contain one node. Their overlapping is large. χ'_{c1} will decay into $\psi(2S)\gamma$ more easily. In fact, the experimental E1 decay rate of X(3872) is consistent with the quark model prediction for the χ'_{c1}.

Based on the measurement of the E1 decay ratio, LHCb concludes: "The measured value agrees with expectations for a pure charmonium interpretation of X(3872) and a molecular-charmonium mixture interpretations" [15]. Moreover, the large production cross section of X(3872) at LHC with very large P_T is comparable with that of $\psi(2S)$, which requires a significant $c\bar{c}$ component. On the other hand, the isospin violating dipion decay of X(3872) requires the molecular component. The current experimental information strongly suggests that X(3872) should probably be a mixture of χ'_{c1} and $\bar{D}D^*$ molecule [16].

The recent dynamical lattice QCD simulation used many operators including $c\bar{c}$, two-meson and diquark-antidiquark ones [17]. They found a lattice candidate for the X(3872) with $J^{PC} = 1^{++}$ and I = 0 only if both the $c\bar{c}$ and $\bar{D}D^*$ operators are included. This candidate cannot be found without the $c\bar{c}$ component. This lattice QCD simulation strongly supports X(3872) as a mixture of $c\bar{c}$ and molecule.

It's interesting to compare three candidates of the exotic states: $\Lambda(1405)$, $D_{sj}(2317)$ and X(3872). $\Lambda(1405)$ is lower than the quark model prediction for the P-wave uds state and lies very close to the $\bar{K}N$ threshold. $D_{sj}(2317)$ is lower than the quark model prediction for the P-wave charm strange meson and lies very close to the DK threshold. X(3872) is lower than the quark model prediction for the P-wave $c\bar{c}$ state χ'_{c1} and lies very close to the $\bar{D}D^*$ threshold.

In the above three cases, we observe the common feature: the couple channel effects play a very important role and lower the bare quark model level significantly. The S-wave continuum couples to the bare quark model state strongly. The quark model spectrum is distorted dramatically. For comparison, the bottomonium analogue X_b was not found since χ'_{b1} is not close to the $\bar{B}B^*$ threshold.

4.3 The charged Z_b and Z_c states

Let's move on to the charged states. In 2011, Belle collaboration observed two charged Z_b states [18]. They are very close to the $\bar{B}B^*$ and $\bar{B}^*B^*$ threshold with $J^P = 1^+$. Their open-bottom decay modes are dominant. Later, BESIII [19] and Belle [20] collaborations observed a similar state $Z_c(3900)$ in the $J/\psi\pi$ mode, which is close to the $\bar{D}D^*$ threshold with $J^P = 1^+$. This state was also observed in the $\bar{D}D^*$ mode. Compared with the traditional charmonium, the open-charm decay mode of $Z_c(3900)$ is strongly suppressed. The decay dynamics might be different. These Z_b and Z_c states are very similar.

One may wonder whether Z_b and Z_c are tetraquark states. If they are tetraquarks, they shall fall apart into the open-charm modes easily. The s-wave $\bar{D}D^*$ mode should dominate the $\bar{D}^*D^*$ mode for the higher state $Z_c(4025)$ because of the huge phase space difference. However, BESIII didn't observe $\bar{D}D^*$ mode for $Z_c(4025)$ up to now while Belle didn't observe $\bar{B}B^*$ mode for the higher Z_b state.

Let's turn back to the above dynamical lattice QCD simulation, which used many operators. They didn't find any exotic candidates in the isovector channel. This lattice QCD simulation strongly disfavors either the diquark-antidiquark or tetraquark interpretations of the X(3872) and $Z_c(3900)$ [17].

If the Z_b states are real resonances, they could be the S-wave $\bar{B}^{(*)}B^*$ molecular states [21, 12, 13]. In fact, within the meson exchange model, both Z_b states can be explained as the $\bar{B}B^*$ and $\bar{B}^*B^*$ molecules. Besides the isovector Z_b states, there are also several loosely bound isoscalar molecular states. However, within the same model, the Z_c states seem unbound with a "reasonable" cutoff parameter [22, 23]. The potential is roughly the same for the Z_b and Z_c systems. But the kinetic energy of the Z_c systems is larger since the D meson mass is smaller than the B meson mass. The hidden-charm/bottom molecules were discussed extensively in literature [22, 23, 24, 25, 26].

The Z_c states lie above the open-charm thresholds. Their measured mass and width seem channel dependent. Could they be non-resonant signals arising from open-charm/bottom thresholds, final state interactions such as $\bar{D}D^*$ rescattering or triangle singularity etc? Some of these non-resonant mechanisms could explain the current experimental data.

4.4 Y(4260)

In PDG, there are three well-established vector charmonium above 4 GeV: $3S/\psi(4040)$, $2D/\psi(4160)$, $4S/\psi(4415)$. In the quark model, one expects at most five vector charmonium states between 4 and 4.7 GeV: $3S/\psi(4040)$, $2D/\psi(4160)$, $4S/\psi(4415)$, $3D$, $5S$. But seven states were observed experimentally: $\psi(4008)$, $\psi(4040)$, $\psi(4160)$, $\psi(4260)$, $\psi(4360)$, $\psi(4415)$, $\psi(4660)$. What are these additional Y states? The situation is very confusing now.

Y(4260) was first discovered in the $J/\psi\pi\pi$ mode with the ISR technique by Babar collaboration [27] while Y(4360) was observed in the $\psi(2S)\pi\pi$ channel with the same technique [28]. But these two states were not observed in the R-value scan and open-charm process. In the R-value scan, all the well-established vector charmonium appear as a peak. But Y(4260) and Y(4360) show up as a dip.

Y(4260) may be accommodated as the $\psi(4S)$ charmonium state with the screened linear potential [29]. Y(4260) also seems a very good candidate of the charmonium hybrid [30, 31, 32]. According to lattice QCD simulation [33, 34], the vector hybrid charmonium lie around 4.26 GeV. Because of the gluon, the 1^{--} hybrid charmonium does not couple to the virtual photon very strongly, which explains the dip in the R-value scan. One of the favorable decay mode of hybrid states is the p-wave + s-wave meson pair, which explains the non-observation in the $D^{(*)}\bar{D}^{(*)}$ modes. The $c\bar{c}$ pair within the vector charmonium is a spin-singlet while the gluon is color-magnetic, which is favorable to the spin-singlet hidden-charm decay mode.

5. Summary

Now let me summarize. The excited Upsilon states act as a molecule factory. Because $M[\Upsilon(5S)] = 10.860$ GeV, $M[BB^* + \pi] = 10.604 + 0.140 = 10.744$ GeV, and $M[B^*B^* + \pi] = 10.650 + 0.140 = 10.790$ GeV, the phase space of the decay $\Upsilon(5S) \to \bar{B}^{(*)}B^*\pi$ is tiny. The relative motion between the $\bar{B}^{(*)}B^*$ pair is very slow, which is favorable to the formation of the $\bar{B}^{(*)}B^*$ molecular states. $\Upsilon(5S)$ or $\Upsilon(6S)$ is the ideal place to study either the molecular states or the $\bar{B}^{(*)}B^*$ interaction. Similar signals will be produced abundantly at Belle2 in the coming years!

The vector charmonium spectrum is very puzzling at present. The excited charmonium decay is ideal in the search of the Z_c signals. The γ, 1π, 2π, 3π and other light degree of freedom will act as a quantum number filter of these states. X(3872), χ'_{c1}, and Y(4260) are the key states in revealing the underlying structure of the charmonium-like XYZ states. Through the decay pattern and possible partner states, we can test the various theoretical picture. The experimental measurement of the various pionic and electromagnetic transitions are crucial.

PoS(INPC2016)374

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PoS(INPC2016)374