Exotic New Hadrons

Atsushi Hosaka
Research Center for Nuclear Physics, Ibaraki 567-0047, Japan

Abstract

The research project, "Elucidation of New Hadrons with a variety of Flavors (New Hadrons)", supported by MEXT by has ended in the fiscal year 2013 [1]. This note reports important aspects of hadron physics which are reached by the research project, because many colleagues from RCNP committed to it.

1 Introduction

More than half century has past since Gell-Mann and Zweig proposed the particle *quarks* (Zweig called *ace*) [2, 3]. At that time, quarks were used as hypothetical particles to explain hadrons, but now it is widely accepted that they are the fundamental building blocks of the visible matter in the universe. The dynamics of quarks together with gluons is dictated by Quantum Chromodynamics (QCD), which is the part of the standard theory of elementary particles. QCD, however, is one of the most difficult problems in the subatomic physics, where much effort is devoted to explain the properties of hadrons and atomic nuclei, recently also by using the most powerful super computer today. In this situation, discoveries of the so-called *exotic hadrons* have been successively made, with which we expect to study clues to hadrons from QCD.

The standard quark model tells that there are two kinds of hadrons, baryons made of three quarks (qqq) and mesons made of a pair of quark and anti-quark ($\bar{q}q$), see Fig. 1. Quarks are colorful and can not be observed isolated, while the observed hadrons are colorless composite of quarks and gluons. Though qqq and $\bar{q}q$ are the simplest combinations to be colorless, it is also possible to make the ones from more quarks and anti-quarks. It is interesting to see that Gell-Mann in his original paper pointed out such possibilities [2]. However, the hadrons found till the end of the 20th century were all classified by the simplest combinations of qqq and $\bar{q}q$.

Figure 1: Mesons of $\bar{q}q$ and baryons of qqq.

2 Discoveries of new particles

The new era was opened by a Japanese group at KEK, the Belle group. Electron-positron accelerator at KEK is designed to produce bottom mesons B for the study of the Kobayashi-Maskawa theory and beyond. The B-meson is a heavy meson containing a bottom quark b and a light quark. At this energy not only B-mesons but also D-mesons which contains a charm quark, and charmonia containing $\bar{c}c$ are also produced abundantly. Thus the accelerator provides unique opportunities for the study of hadrons containing charm quarks.

Under this background, the first new particle was found, which is now called $X(3872)$ [4]. Among a number of reaction events, they were able to extract the process $B \to K + (J/\psi + \pi^+ + \pi^-)$ and find a peak structure in the invariant mass of $J/\psi + \pi^+ + \pi^-$, the evidence of the resonant state. The evidence of the particle was also confirmed by other facilities, and its properties have been studied in detail. The $X(3872)$ is the best established particle among the so far observed exotic hadrons.

What are exotic about $X(3872)$ are; (1) the mass is far away from the quark model prediction assuming a simple $\bar{c}c$ structure, (2) it can live longer than typical hadrons, and (3) its decays violate isospin symmetry largely. It turned out that these unexpected properties are explained if $X(3872)$ is assumed to be made by a pair of D-mesons, $\bar{D}D^*$. If so, $X(3872)$ is an object containing four quarks, a charm quark and antiquark pair and a light quark and antiquark pair.

Another discovery is the $Z^+(4430)$ through the process $B \to K + (\pi^\pm + \psi')$. Though this is the second, it is as important as the first one, because this particle is charged and *must* contain $\bar{q}q$ pair in addition to the $\bar{c}c$ pair. Thus it is a genuine four quark state. Recently, LHCb have analyzed a phase rotation in the amplitude which shows undoubtedly that the peak is associated with a resonance [6]. The third important finding was made for charged bottomonium like states, $Z_b^+(10610)$ and $Z_b^+(10650)$ [7]. Because of the charged nature again, they are also genuinely four quark states such as $\bar{b}b\bar{d}u$. The fact that their masses are very close to those of $B, \bar{B}^*$ and of $B^*, \bar{B}^*$ implies that these four quark states have a structure of mesonic molecule of $B, \bar{B}^*$. Thus, almost half century after the Gell-Mann's proposal, the four quark hadrons have been observed.

3 Structure of the new particles

In addition to the above three examples, there are many evidences which lead to the new hadrons called X, Y and Z's. A unique feature of these findings is that they are all near or above the "threshold", and contains heavy quarks, either charm or bottom quark-antiquark pair. Herein below, we denote heavy quarks (c, b) by Q and the light (u, d, s) quarks by q. The threshold is the energy for a quakonium $\bar{Q}Q$ being able to decay into more than two hadrons, where pair of light quarks $\bar{q}q$ is created. Thus we can make the following conjecture; below the threshold the quarkonium exist as $\bar{Q}Q$ and are explained by the standard quark model. Above the threshold, however, in the presence of $\bar{q}q$, multiquark component of $\bar{Q}Q\bar{q}q$ dominates. Then they rearrange themselves into a pair of heavy mesons $\bar{Q}q\bar{q}Q$.

This is a molecule of two heavy mesons (hadronic molecule, see Fig. 2), for which we can develop their dynamical description. Heavy mesons may interact through light meson exchanges, in particular pion exchanges may exist between the light quarks q in the heavy mesons. The pion-quark coupling is the inevitable consequence of spontaneous breaking of chiral symmetry of QCD, and their nature is well understood. The pion coupling changes the spin of the quarks, leading to the tensor force, causing the mixing of $\bar{D}D^*$ and of of $\bar{B}B^*$. The mixing force is attractive which is a general consequence of the second order perturbation theory. Then the attractive force can lead to a rich spectrum of composite systems [8].

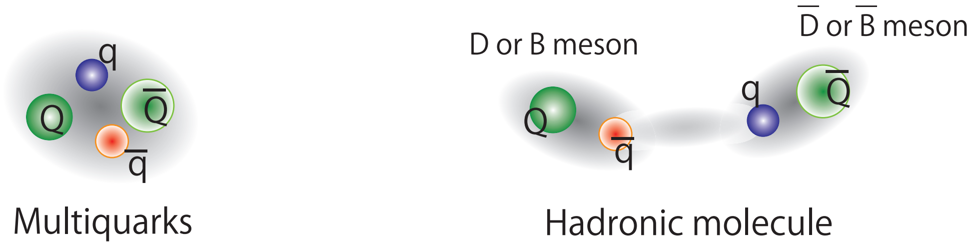

Figure 2: Rearrangement of multiqurk configuration.

Another important role in the formation of rich structure is made by the fact that these mesons are heavy. Due to heavy quark symmetry, the masses of $\bar{D}$ and D^* mesons are similar. Thus the transitions between can occur more easily, providing larger quantum space available to which the system can fluctuate. Thus the system becomes more stable, a general consequence of the uncertainty principle. The above two mechanisms are the unique features for systems of heavy-light quarks which lead to the abundant findings of exotic particles in the heavy quark systems.

For $X(3872)$, in addition to the molecular component, it is pointed out that $\bar{c}c$ one should be important [9]. If so, this provides and interesting example where configurations with different quark numbers mixes. The molecular component of $X(3872)$ implies a spatially extending structure as large as 4 fm, while the $\bar{c}c$ component explains the production and decay properties.

4 Summary

In recent nuclear physics, physics of unstable nuclei has been discussed very extensively. As more neutrons are added, nuclei become less bound, soft and get larger in size. In such systems, interesting internal structures which are not important for the ground state region become possible. These structures may appear as new dynamical degrees of freedom, leading to spectra which are not easily described by the conventional degrees of freedom.

Would it be accidental that in hadron physics similar aspects are discussed? As the energy of the system is increased, additional quark and antiquark pair in almost on-shell are rearranged into energetically stable configurations which are loosely bound, as compared to typical energy scale of quark dynamics, a several hundred MeV. They seem to form intermediate steps of quasi degrees of freedom to generate physically observed hadrons from the original quarks and gluons of QCD. While not have been considered in the conventional quark model, these degrees of freedom seem to play an important role for exotic hadrons.

References

[1] http://www.hepl.phys.nagoya-u.ac.jp/public/new_hadron/index-e.html

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

[3] G. Zweig, in "Developments in the Quark Theory of Hadrons", Volume 1, Edited by D. Lichtenberg and S. Rosen. pp. 22-101, Nonantum, USA: Hadronic Pr. (1980) 508p.

[4] S. K. Choi *et al.* [Belle Collaboration], Phys. Rev. Lett. **91**, 262001 (2003).

[5] S. K. Choi *et al.* [BELLE Collaboration], Phys. Rev. Lett. **100**, 142001 (2008) [arXiv:0708.1790 [hep-ex]].

[6] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **112**, no. 22, 222002 (2014) [arXiv:1404.1903 [hep-ex]].

[7] A. Bondar *et al.* [Belle Collaboration], Phys. Rev. Lett. **108**, 122001 (2012) [arXiv:1110.2251 [hep-ex]].

[8] S. Ohkoda, Y. Yamaguchi, S. Yasui, K. Sudoh and A. Hosaka, Phys. Rev. D **86**, 014004 (2012) [arXiv:1111.2921 [hep-ph]].

[9] M. Takizawa and S. Takeuchi, PTEP **2013**, no. 9, 0903D01 (2013) [arXiv:1206.4877 [hep-ph]].