Remarks on the Significance of Pentaquark Classification

Original research paper

Abstract

The notion of pentaquark was coined about thirty years ago. During the progress of time the original meaning of pentaquark has been extended and now it is used for describing particles that belong to several distinct classes. This work organized pentaquarks in four classes according to their physical properties as well as the corresponding theoretical basis that explains their structure.

Keywords: Pentaquark, Quantum Field Theory, Nuclear Force, Quantum Chromodynamics

1 Introduction

Language is a primary tool for communication between people. For this reason, they organized words in sentences that have the required meaning which they wish to convey. In particular, a misunderstanding bears a negative effect in a communication between scientists. Therefore, writers of a scientific text strive to use words and statements that have a well defined sense. The need for clarity in a scientific text has been put forward by Dirac in the following words: "In science you want to say something that nobody knew before, in words which everyone can understand. In poetry you are bound to say... something that everybody knows already in words that nobody can understand" [1].

The term *pentaquark* was coined in 1987 [2, 3]. In these articles the authors use Quantum Chromodynamics (QCD) considerations and define a pentaquark as a strongly bound state of four quarks and an antiquark. Each of the five particles has a specific flavor. An example of their idea is the following flavor configuration $uuds\bar{c}$. In general, these authors define a pentaquark as a particle that comprises the following quark flavor $uudQ_1, \bar{Q}_2$, where Q_1, Q_2 have a flavor which is heavier than that of the u, d quarks *and* Q_1, Q_2 do not have the same flavor. (Due to isospin symmetry, also the configuration $uddQ_1, \bar{Q}_2$ is a pentaquark.) It is clearly stated in [2, 3] that a pentaquark is expected to be bound strongly and that it is energetically stable against a decay into a baryon and a meson by strong interactions. These pentaquark attributes indicate how to detect it in experiments. Hereafter, the foregoing pentaquark properties are called *the original pentaquark definition*.

A feature of a human language is that the meaning of some words changes in the course of time. It turns out that one cannot be sure that a scientific terminology is free of this effect. Two different examples where the original pentaquark definition is extended are described below. They show that the present literature deviates from the original pentaquark definition and uses this term for different kinds of quantum particles. This state of affairs means that an organization of pentaquarks in well defined categories may contribute to the accuracy required from a scientific text. Evidently, pentaquarks that belong to the same category should have common physical properties and pentaquarks that belong to different categories should differ by least one physically meaningful property. The organization of pentaquarks in appropriate categories is the main objective of this work.

The second section describes two kinds of extension of the pentaquark notion. The third section shows how pentaquarks can be organized in four well defined distinct categories. The last section contains concluding remarks.

2 Changes in the Meaning of Pentaquarks

It turns out that as time elapses the original meaning of pentaquark has been extended and now it includes other kinds of quantum states. This section substantiates this claim by showing two examples where the current literature uses the term pentaquark for quantum states that do not abide by the original pentaquark definition. These examples refer to the work of many authors whose articles have been published in mainstream journals. Therefore, they indicate that the general community has extended the meaning of the original pentaquark definition.

The first example refers to the possible existence of a particle called Θ^+ whose mass is about 1530 MeV. This particle has been introduced about 20 years ago and it is discussed in the literature by many theoretical and experimental physicists. These discussions refer to the Θ^+ by the term pentaquark. This particle comprises the $uudd\bar{s}$ quarks. Now, the neutron's mass is 939.6 MeV and the K^+ mass is 493.7 MeV [4]. As stated above, the original definition of a pentaquark says that QCD considerations indicate that it is bound strongly. By contrast, the above mentioned mass data prove that the Θ^+ is certainly an *unbound* state of the neutron (udd) and the K^+ meson $(u\bar{s})$, because the sum of the mass of these particles is smaller than that of the Θ^+ $1530 > 939.6 + 493.7$. Due to the unbound state of the Θ^+, the original pentaquark definition means that it is not a genuine pentaquark. By the way, the existence of Θ^+ is not supported by experiment. Indeed, a recently published report states that "it is now generally accepted that there is no substantial evidence for the existence of the Θ^+ state". Moreover, the result of the new experiment "does not support the presence of a positive Θ^+ signal" [5].

Another kind of extension of the pentaquark notion is shown in a recent report published by the CERN LHCb collaboration [6] and in earlier publications (see e.g. [7]). These articles report a detection of two pentaquarks called $P_c(4380)^+$ and $P_c(4450)^+$, respectively. (The number enclosed in parentheses denotes the particle's mass in MeV.) The current literature contains many discussions of these results. The quark configuration of these pentaquarks is $uudc\bar{c}$. These pentaquark states are resonances of the proton and the J/ψ meson. As a matter of fact, the proton is a uud quark state and its mass is 938.3 MeV and the J/ψ meson is a $c\bar{c}$ quark state and its mass is 3096.9 MeV [4]. The sum of these mass values means that the $P_c(4380)^+$ and $P_c(4450)^+$ are *unbound* states of the proton and the J/ψ meson, because $4380 > 938.3 + 3096.9$. Furthermore, the quark configuration of these particles is $uudc\bar{c}$, which means that the additional $c\bar{c}$ quarks are of the *same flavor*. Due to either of these properties, one concludes that the quantum states $P_c(4380)^+$ and $P_c(4450)^+$ do not fit the original pentaquark definition.

These examples show that the present physical terminology does not abide by the the original pentaquark definition. Therefore, an organization of the pentaquark notion in well defined categories is a timely assignment.

3 Categories of Pentaquarks

In this section the term pentaquark describes any configuration of four quarks and one antiquark. It is shown here that such pentaquarks can be found in many physical states. They are organized below in four distinct categories where pentaquarks that belong to the same category have the same physical properties and each category is named appropriately.

1. Bound QFT Pentaquarks

   It is shown here that fundamental properties of Quantum Field Theory (QFT) successfully predict the existence of pentaquarks. QFT describes states and processes where the number of particles may vary due to additional particle-antiparticle pair(s) where flavor is conserved. (see e.g. p. 65 of [8]). This is a general QFT property which is independent of the law of force which determines the specific dynamics of a given quantum system. The proton is a well known particle whose structure has been extensively examined since the beginning of the accelerator era. The quark description of the proton generally takes the form of three components uud, called valence quarks. However, the fact that the proton's state contains a quite significant probability of additional quark-antiquark pairs is already recognized for many years (see p. 282 of [9]). Pairs of the flavors u, d, s have been identified and analyzed (see e.g. [10] and references therein). For this reason, the proton quark structure takes the following form

   $$\psi(p) = a_0\psi_0(uud) + a_u\psi_u(uuud\bar{u}) + a_d\psi_d(uudd\bar{d}) + a_s\psi_s(uuds\bar{s}) + ... \quad (3.1)$$

   Here a_x denotes a numerical coefficient. It can be concluded that pentaquarks are found in elements that compose the proton. Due to its stability, the proton belongs to this pentaquark category. By the same arguments, also the neutron is included to this pentaquark category. Furthermore, there are other baryons like Λ, Σ, Ξ and Ω that are stable with respect to strong interactions. Dynamical properties of these baryons are analogous to those of the proton. Therefore, the state of each of these baryons should have additional quark-antiquark pairs. Hence, also these baryons belong to this pentaquark category.

2. Unbound QFT Pentaquarks

   Particles that belong to this category are unstable and their quark structure is inferred from their decay products. Properties of three particles are discussed below in order to show this issue.

   The four $\Delta(1232)$ baryons $\Delta^{++}, \Delta^{+}, \Delta^{0}$ and Δ^{-} are examples of this kind of pentaquarks. These particles are seen as a conspicuous broad resonance and they decay into a nucleon and a pion (see [4] and p. 131 of [9]). Their πN decay mode proves that their structure has a component of the form $q_1q_2q_3q_4\bar{q}_5$, where each q_i is either a u or a d quark and the specific identity of these quarks is determined by the charge of the specific Δ baryon. For example, the Δ^{++} quark structure can be written as follows

   $$\psi(\Delta^{++}) = a_0\psi_0(uuu) + a_u\psi_u(uuuu\bar{u}) + a_d\psi_d(uuud\bar{d}) + a_s\psi_s(uuus\bar{s}) + ... \quad (3.2)$$

   Relying on the above mentioned decay products, one concludes that each of the Δ baryons has pentaquark components. Due to their instability, the Δ baryons belong to this pentaquark category. Furthermore, the Δ^{++} is a baryon. Therefore, like the case of the proton, QFT laws indicate that the last term of (3.2) should be a component in the description of Δ^{++}. However, effects of this term cannot be seen in the Δ^{++} decay products because of the law of energy conservation. Evidently, each of the four Δ baryons comprises a nucleon and a $q\bar{q}$ pair of the same flavor. Therefore, they belong to this QFT pentaquark category.

Each member of the isospin doublet of the $N(1710)$ baryons (see [4]) is another example of a baryon that belongs to this pentaquark category. Consider the positively charged $N^+(1710)$ baryon. It has several decay modes and one of them is the two-particle ΛK^+ channel. The Λ is characterized by the uds quarks and its mass is 1115.7 Mev. The K^+ is characterized by the $u\bar{s}$ quarks and its mass is 493.7 MeV [4]. Therefore, these values explain the instability of the N(1710) baryons with respect to the ΛK decay channel, because $1710 > 1115.7 + 493.7$. Relying on these decay products, one concludes that the following five quarks $uuds\bar{s}$ compose one of the quark configurations of the $N^+(1710)$ baryon. Due to its instability, the $N^+(1710)$ belongs to this pentaquark category. Moreover, isospin symmetry proves that also its isospin counterpart $N^0(1710)$ is an analogous pentaquark and that the quark configuration $udds\bar{s}$ is included in the description of $N^0(1710)$.

It turns out that the $P_c(4380)$ and the $P_c(4450)$ pentaquarks which have recently been reported by the CERN LHCb collaboration (see section 2) are very close analogs of each of the two N(1710) baryons. Indeed, relying on their decay modes, it is shown in the previous paragraph that each of the N(1710) baryons contains the five quarks $uuds\bar{s}$ configuration. Similarly, as stated in the above mentioned LHCb report, the decay modes of the $P_c(4380)$ and the $P_c(4450)$ pentaquarks show the existence of the five quarks $uudc\bar{c}$ configuration (see the 7th line in [6]). Evidently, the N(1710) baryon is already known for several decades. Therefore, the two states which have been reported by the LHCb collaboration mean just a replacement of the $s\bar{s}$ quarks of the N(1710) by the $c\bar{c}$ quarks of the $P_c(4380)$ and the $P_c(4450)$. Evidently, it is well known that pair production and pair annihilation are ordinary QFT processes [11]. Therefore, the replacement of $s\bar{s}$ by $c\bar{c}$ is nothing more than an ordinary QFT process. For this reason, the recently LHCb discovery certainly does not make a new fundamental change in the pentaquark concept.

3. Lightly Bound Pentaquarks

This type of pentaquarks comprises baryon-meson bound states where the binding energy is rather small and its strength is similar to the nuclear binding energy. The nuclear force is an example of a force that binds two hadron. Similarly, an analogous force may bind a nucleon and a meson, which are another example of two hadrons. Hereafter such a state is called nuclear-like pentaquark. As a matter of fact, the nuclear force is known experimentally and the mean nuclear binding energy per nucleon is less than 9 MeV. For this reason, the existence of this kind of pentaquarks is independent of any specific physical theory and their binding energy should be a few MeV. A nuclear-like pentaquark is expected to be stable with respect to a strong interaction decay.

The following arguments indicate that the existence of nuclear-like pentaquark is very unlikely. Indeed, in order to be stable against a strong interaction decay, the pentaquark's meson should be in a spherically symmetric S-wave state, because the excitation energy of other mesons is measured in hundreds of MeV. Indeed, a 2-particle nuclear-like interaction cannot compensate hundreds of MeV. Moreover, the state of an S-wave meson is similar to that of an atom of a noble gas. It is very well known that noble gases show extremely low chemical reactivity [12]. These arguments mean that a nuclear-like energy cannot compensate the strong interaction energy of a meson whose spin does not vanish and a spin-0 meson is expected to behave like a noble gas. Therefore, it is unlikely to find a nuclear-like pentaquark. Experimental data are consistent with this prediction.

4. Strongly Bound QCD Pentaquarks

The term pentaquark was coined in the 1987 articles [2, 3]. These works deduce from the laws of QCD that strongly bound hadronic states having a pentaquark structure should be found in accelerator data. Hereafter, this kind of particle is called QCD pentaquark. QCD pentaquarks agree with the original pentaquark definition. Experimental efforts aiming to detect pentaquarks as well as theoretical discussions of this kind of particle followed the publication of [2, 3].

The pentaquark proposal of [2, 3] states clearly that the quark configuration of this particle is $uuds\bar{Q}$, where Q denotes a heavy quark which is either c or b. It means that the existence of this state cannot be deduced from general QFT arguments that allow the addition of a $q\bar{q}$ pair of the *same flavor*. It is argued in [2, 3] that specific QCD properties provide an appropriate binding energy that guarantees the stability of the suggested pentaquark against a strong decay.

QCD pentaquark could have been accidentally detected before 1987 and in the dedicated experiments that followed the publication of [2, 3]. As of today, there is no experimental confirmation of the existence of a QCD pentaquark.

4 Conclusions

Pentaquarks are a widely used subject pertaining to hadronic structure. For example, a current google search shows more than 80,000 entries that contain the word pentaquark. The purpose of this work is to use physical properties of pentaquarks for putting them in well defined categories. For this end, experimentally confirmed stability and instability against strong interaction is used for the definition of categories. The theoretical element of the analysis relies on the difference between general QFT properties and QCD. Indeed, QFT is a general quantum field theory aiming to described the strong, electromagnetic and weak forces that affect microscopic processes [11, 13, 14]. In particular, pair production is a well known QFT effect. On the other hand, QCD is a specific theory that refers to hadronic structure and processes. The four pentaquark categories described in section 3 rely on these principles and on the experimentally confirmed phenomenology of the nuclear force. The first and the second categories depend on the pair production QFT effect. The third category depends on the well known phenomenology of the nuclear force and the last category depends on specific QCD properties.

This work shows that the first and the second pentaquark categories which rely on QFT prove that this general theory is successful with respect to experimentally confirmed pentaquark states. On the other hand, in spite of a quite long pentaquark search, nuclear-like and QCD pentaquark states have not yet been detected in experiments. The failure of experimental attempts aiming to detect strongly bound QCD pentaquarks has been predicted [15].

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