Pentaquarks — An Experimental Overview

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Abstract. Since the recent observation of a pentaquark \( (\Theta^{+} = qqq\bar{q}) \) state (see Nakano et al. (LEPS Collaboration), Phys. Rev. Lett. 91 (2003) 012002-1) several positive and negative experimental results have emerged. These results are overviewed, with a trial to find common features among them.

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1. Introduction

The well-known hadrons consist of 3 quarks or a quark–antiquark pair. These are the simplest configurations to build a colorless object from the colored quarks. However, we do not know about any argument which would forbid the existence of more complicated configurations, such as \( qqqq\bar{q} \) (pentaquark baryon) or \( qq\bar{q}\bar{q} \) (tetraquark mesons). We know that sea quarks (in the form of \( q\bar{q} \) pairs) are present, and from many aspects important in hadrons. These states are often difficult to distinguish from true penta- or tetraquarks with 5 or 4 valence-quarks. A clear signal of the existence of penta- or tetraquarks would be the observation of exotic particles, which possess such quantum-number combinations, which cannot exist for 3 (or 2) quark states (for example if the antiquark in a \( qqq\bar{q} \) system is of different flavor than any of the quarks).\(^a\) One example for such an exotic particle is a baryon with \( S = +1 \) strangeness (it contains an uncompensated \( \bar{s} \) quark), or a baryon with charge \( Q = -2 \) and strangeness \( S = -2 \) (due to its strangeness content it must have 2 \( s \) quarks, and taking any quark as the third one we cannot produce \( Q = -2 \)).

Indeed, there were predictions for such states in the very early days of QCD (for a short review see for example [2]). Despite the theoretical predictions and experimental efforts no such particles were observed, until very recently [6]. This first successful search was motivated by a theoretical prediction [1] in the framework of the chiral soliton model. It predicted the existence of a pentaquark-antidecouplet.
Figure 1a shows it on the $S–I_3$ plane, together with the baryon-decouplet (dashed line). The elements of the pentaquark-antidecouplet in the overlapping region (filled circles) are non-exotic, since these quantum-number combinations also exist for ordinary baryons. However, the particles at the three corners of the antidecouplet (squares) do not overlap with the baryon decouplet, and therefore possess such quantum numbers, which do not exist for normal baryons, being exotic. The authors used the nucleon-like doublet of this antidecouplet as an anchor to known particles, identifying it with the N(1710). Using this as input, the topmost element (originally called $Z^+$, today called $\Theta^+$) was predicted to have mass of 1530 MeV, and a width $\Gamma = 15$ MeV. Such a small width is surprisingly small for a particle which has strong decay channels. (Since then the validity of their calculation is heavily criticized [3]). The other isospin-multiplets in this antidecouplet were predicted to have masses and widths $m_\Sigma = 1890$ MeV, $\Gamma_\Sigma = 70$ MeV, $m_\Xi = 2070$ MeV, $\Gamma_\Xi = 140$ MeV.

Today’s other very frequently cited model is the diquark model (or correlated quark model) [2]. In this model, 2 quarks form a diquark $[q_1q_2]$ with total spin 0, and antisymmetric in both color and flavor space (which corresponds to the 3 representation of SU(3)$_{\text{color}}$ and SU(3)$_{\text{flavor}}$). Pentaquarks are thus a bound state of two diquarks and an antiquark $[q_1q_2][\bar{q}_3q_4]$, and tetraquarks are a bound state of a diquark and an anti-diquark: $[q_1q_2][\bar{q}_3\bar{q}_4]$. From the SU(3)$_{\text{flavor}}$ point of view pentaquarks are represented by the product $\overline{\mathbf{3}} \otimes \mathbf{3} \otimes \mathbf{3}$, which (like antibaryons) decomposes into $\mathbf{10} \oplus \mathbf{8} \oplus \mathbf{1}$. This model therefore — beyond the same antidecouplet as before — predicts the existence of a pentaquark-octet as well (all members of which are non-exotic). These multiplets are shown in Fig. 1b. The tetraquark mesons (according to the decomposition of $\overline{\mathbf{3}} \otimes \mathbf{3}$) form an octet and a singlet, all members of which are non-exotic. The interesting point of this model is that with only light quarks (u, d, s) only these penta- or tetraquarks can exist (for other quark combinations antisymmetrization in flavor within a diquark would not be possible). Therefore the observation of any exotic meson, or any exotic baryon with quantum-number combination different from those shown in Fig. 1b would refute the diquark model.

The most striking difference between the two models lies in their mass hierarchies [2]. In the chiral soliton model the lightest member of the antidecouplet is the exotic $\Theta^+$, and the subsequent isospin-multiplets have higher and higher masses: $m_{\Theta} < m_N < m_\Sigma < m_\Xi$, with roughly equidistant steps. In the diquark model the lightest pentaquark is the N, in accordance with our naive expectations (the more s quarks are contained in a baryon, the heavier it is). The $\Theta^+$ and the lighter of the two $\Sigma$-triplets (both containing 4 light (anti)quarks and one (anti)s quark) are predicted to have roughly equal masses. This difference in the mass hierarchies might be an important point in experimentally testing the two models: establishing the mass of the $\Sigma$ close to that of the $\Theta^+$ would clearly contradict the chiral soliton model.

Both models predict positive parity, which is in contradiction with the negative parity predictions of lattice calculations [4, 5]. There are other pentaquark models as well, which predict larger multiplets.